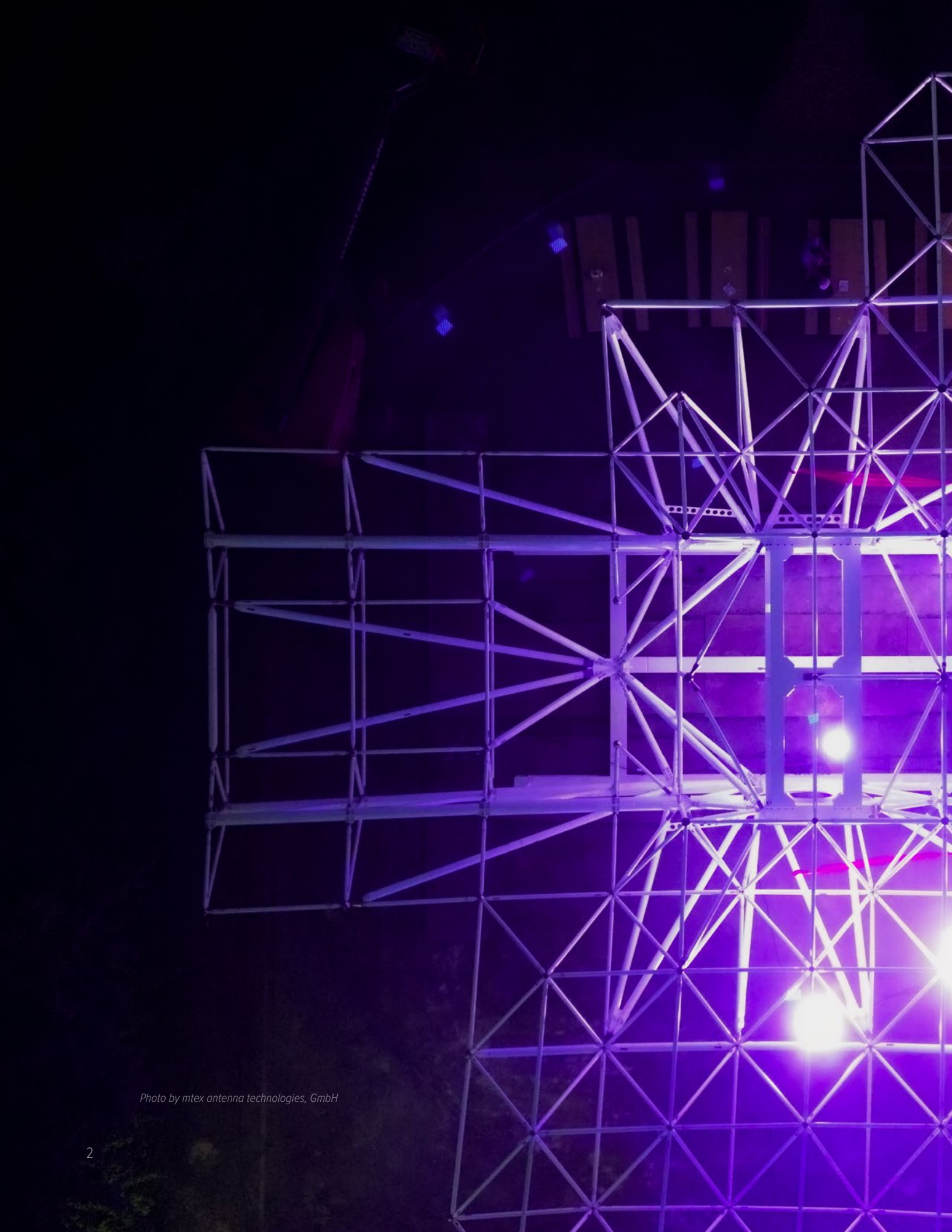


# 2021-23 ANNUAL REPORT



NATIONAL RADIO  
ASTRONOMY OBSERVATORY



*Photo by mtex antenna technologies, GmbH*

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### NRAO FACTS & FIGURES 2021-2023

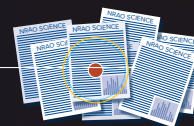
**499**  
EMPLOYEES



**144**  
MEDIA RELEASES



**2948**  
REFEREED  
SCIENCE PUBLICATIONS



FRONT COVER: An ALMA antenna at sunset. Photo by Pablo Carrillo  
LEFT: ngVLA antenna structure begins assembly in Leipzig, Germany



*Photo by Pablo Carrillo, ALMA*

## DIRECTOR'S REPORT



In the past three years, we have emerged from the global covid-19 pandemic. Our Observatory successfully adapted and maintained safe science operations at the Karl G. Jansky Very Large Array (VLA), the Very Long Baseline Array (VLBA), and the Green Bank Observatory (GBO). The Atacama Large Millimeter/submillimeter Array (ALMA) continues to enable groundbreaking science in the areas of planetary disks, astrochemistry, star formation, and black holes in centers of galaxies. The National Radio Astronomy Observatory (NRAO) continues to push the boundaries of astronomical discovery with advanced radio telescope facilities.

The NRAO has returned to in-person functionality, re-establishing science and engineering relationships, and is taking advantage of meeting face to face to collaborate at our facilities and conferences. We have adjusted to a new normal with online meetings and hybrid events, all while successfully carrying out the mission of the Observatory.

I want to express appreciation to everyone who worked to make our facilities as safe as possible through the pandemic surges. I am proud of our proactive response and our ability to emerge successfully from the COVID landscape. NRAO has always been, and will continue to be, a strong, world-class scientific organization that supports its staff and users. NRAO remains committed to fostering collaboration and engagement within the scientific community and beyond. Through workshops, national and international conferences, and educational outreach programs, we strive to inspire the next generation of astronomers and engineers, and share the incredible science to the world's population.

The past three years have seen the development and planning of ALMA's Wideband Sensitivity Upgrade (WSU), the unveiling of the prototype next generation Very Large Array (ngVLA) antenna structure with our European partners, and the continuation of the VLA Sky Survey (VLASS) and its exploration of galaxies and transients.

The NRAO also made excellent progress in 2021-2023 on key strategic initiatives that are improving the Observatory's scientific capabilities and the community's ease-of-use, such as the Science Ready Data Products initiative that will enable the distribution of data products to a wider community of scientific users. On the technology side, the Central Development Lab is leading research and development efforts that build the instrumentation with which we study the Universe, enhancing our telescopes' sensitivity and resolution, and empowering astronomers to study cosmic phenomena with unparalleled precision. New directions such as radar capabilities and advanced spectrum monitoring are developing rapidly.

Our people are, of course, our greatest asset. We support the growth of a diverse and inclusive astronomical community via our Jansky Fellowships, Reber Fellows, student programs, and much more. With cross-Observatory support, these programs are contributing to the recruitment, retention, and success of talent across our field.

The NRAO staff are operating, maintaining, and continuously improving our world-leading radio telescopes, with the strong support of the National Science Foundation and Associated Universities, Inc. This Annual Report documents three pivotal years of NRAO that protected its people and facilities while also supporting the needs and interests of our global scientific community.

**Brief Bio:** Anthony (Tony) J. Beasley was appointed as NRAO Director by the AUI Board of Trustees effective 21 May 2012. After receiving his Bachelor's in Physics in 1986 and his Doctorate in Astrophysics in 1991 from the University of Sydney, Beasley joined NRAO as a Postdoctoral Fellow in 1991. He was appointed as a Deputy Assistant Director in 1997, and served as Assistant Director from 1998 to 2000. In 2000, he left NRAO to become Project Manager for the Combined Array for Research in Millimeter-wave Astronomy. In 2004, he returned to NRAO as an Assistant Director and Project Manager for the Atacama Large Millimeter/submillimeter Array in Chile. Prior to his appointment as NRAO Director, Beasley served as the Chief Operating Officer and Project Manager of the NSF-funded National Ecological Observatory Network (NEON), a continental-scale ecological observatory designed to detect ecological change and enable forecasting of its impacts.

## NRAO FACILITIES IN BRIEF



Created in 1956 by the NSF and AUI, the NRAO designs, builds, and operates world class astronomical telescopes, instrumentation, and research facilities at radio wavelengths. From 2021-2023, the NRAO operated a complementary suite of three world-class telescopes, each the world leader in its frequency domain: the international **Atacama Large Millimeter/submillimeter Array (ALMA)**, the **Karl G. Jansky Very Large Array (VLA)**, and the **Very Long Baseline Array (VLBA)**.

**ALMA** is the largest ground-based global astronomy endeavor in history. Composed of 66 high-precision antennas on an excellent 5000+ meter elevation site in northern Chile, ALMA is delivering orders of magnitude improvements in millimeter-wave sensitivity, frequency coverage, resolution, imaging, and spectral capabilities. ALMA's capabilities span wavelengths from 9.6 to 0.3 mm (31–950 GHz), a key part of the electromagnetic spectrum for observing the first stars and galaxies, directly imaging planet formation, and studying supermassive black holes. The community's strong interest in



ALMA has been repeatedly demonstrated by the substantial oversubscription of each Call for Proposals and the available observing time.

The **Karl G. Jansky VLA** in New Mexico has scientific capabilities at the adjacent centimeter-wavelength range that are complementary to ALMA. The current VLA capabilities exceed the original VLA design by one to four orders of magnitude. These new capabilities were delivered on schedule and on budget via the Expanded Very Large Array project, and the array is meeting all of the project's technical specifications and scientific objectives. The upgraded VLA transitioned to full science operations in January 2013 as the world's most capable and versatile centimeter-wavelength imaging array and is yielding dramatic new science results that range from Galactic protostellar clouds to the molecular gas in early galaxies.

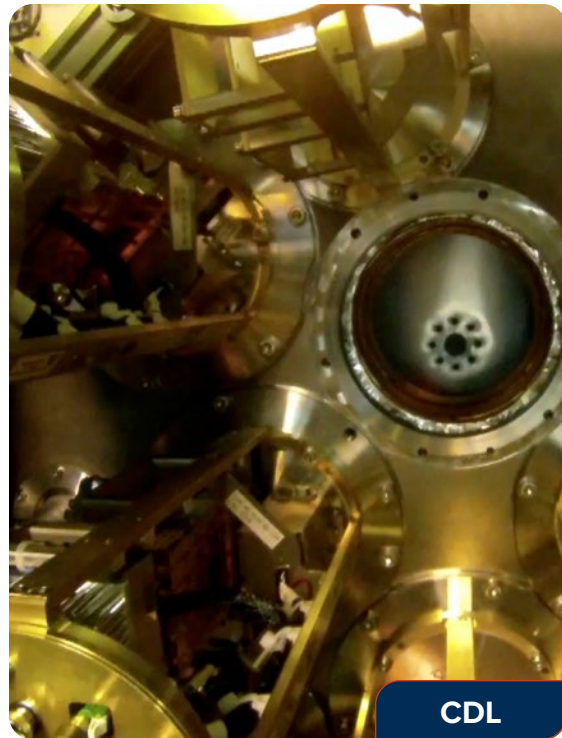
The **VLBA** is the premier dedicated Very Long Baseline Interferometer (VLBI) array. Astrometry with the VLBA has



reached the precision of a few micro-arcseconds, supporting distance and proper motion measurements of astronomical objects in the solar neighborhood, across the Milky Way, within the Local Group, and moving with the Hubble flow. When used in conjunction with the phased VLA and GBT, the resultant High Sensitivity Array (HSA) vastly enhances the sensitivity of VLBI observations and increases the range of novel scientific research.

The **Central Development Laboratory (CDL)** conducts the technological research and development that improves operational NRAO telescopes and helps realize next generation facilities. CDL oversees a science-driven research and development program that supports the community's highest priority goals.

**NRAO Headquarters** in Charlottesville, Virginia is home to the North American ALMA Science Center (NAASC), Business & Administration, Human Resources, Education & Public Outreach, Program Management, and the Director's Office.



NRAO telescopes, operated individually and synergistically throughout 2021-2023 with optical, infrared, and X-ray telescopes to open new frontiers across a broad range of modern astrophysics: proto-planetary disks and extrasolar planet formation; astrochemistry; the early phases of star formation; fundamental physics; molecular gas in early galaxies; the environments of supermassive black holes; cosmology; and much more.

In addition to research, the NRAO informs society about science via its education and public outreach programs. A program of compelling science, technology, engineering, art, and mathematics (STEAM) education programs are introducing students every year to the excitement and opportunities of careers in science, computing, and engineering.

After more than six decades of continual improvement under AUI management, the NRAO comprises the nation's core competency in radio astronomy, an invaluable resource for the astronomical research community in the United States and around the world.

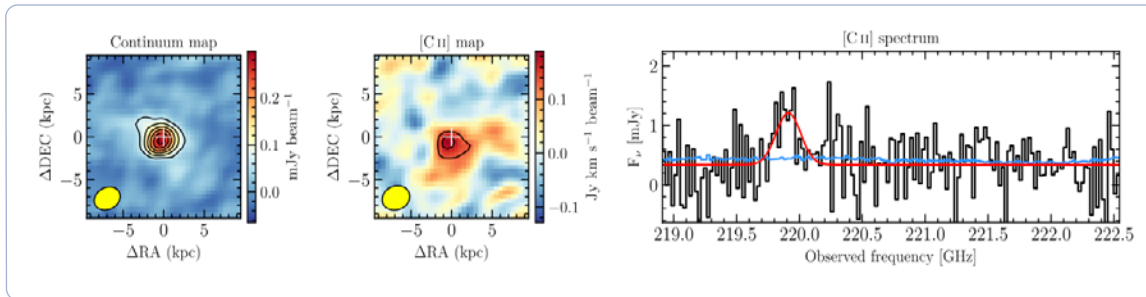
## SCIENCE HIGHLIGHTS



*Galaxy NGC 3627 imaged by the PHANGs Project with ALMA. Credit: ALMA (ESO/NAOJ/NRAO)/ESA/NASA/PHANGS, Sophia Dagnello (NRAO)*

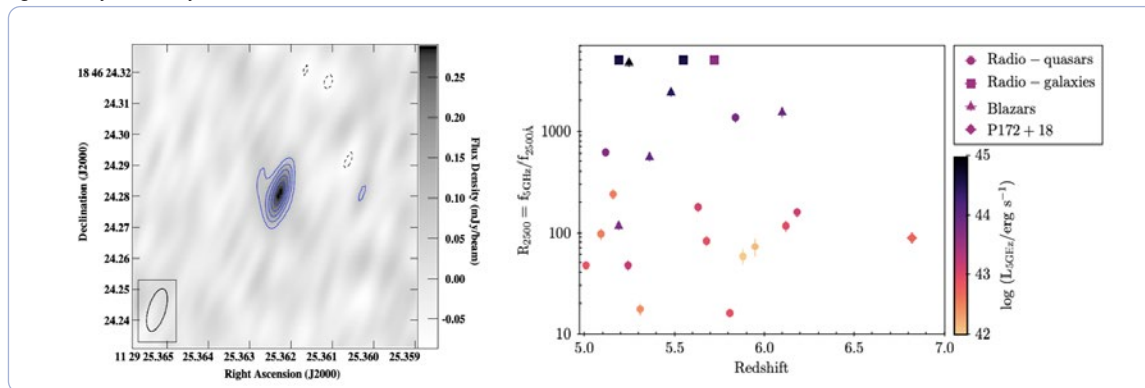


Distant quasars are unique tracers to study the formation of the earliest supermassive black holes (SMBHs) and the history of cosmic reionization. Despite extensive efforts, only two quasars have been found at  $z \geq 7.5$ , due to a combination of their low spatial density and the high contamination rate in quasar selection. Wang et al. report the discovery of a luminous quasar at  $z = 7.642$ , J0313-1806, the most distant quasar yet known. This quasar has a bolometric luminosity of  $3.6 \times 10^{13} L_{\odot}$ . Deep spectroscopic observations reveal a SMBH with a mass of  $(1.6 \pm 0.4) \times 10^9 M_{\odot}$  in this quasar. The existence of such a massive SMBH just  $\sim 670$  million years after the Big Bang challenges significantly theoretical models of SMBH growth. In addition, the quasar spectrum exhibits strong broad absorption line (BAL) features in C IV and Si IV, with a maximum velocity close to 20% of the speed of light. The relativistic BAL features, combined with a strongly blueshifted C IV emission line, indicate that there is a strong active galactic nucleus (AGN)-driven outflow in this system. **Atacama Large Millimeter/submillimeter Array (ALMA)** observations detect the dust continuum and [C II] emission from the quasar host galaxy, yielding an accurate redshift of  $7.6423 \pm 0.0013$  and suggesting that the quasar is hosted by an intensely star-forming galaxy, with a star formation rate of  $\sim 200 M_{\odot} \text{ yr}^{-1}$  and a dust mass of  $\sim 7 \times 10^7 M_{\odot}$ . These observations present the most extreme example of coeval formation of a black hole and galaxy in the very early Universe. Follow-up observations of this reionization-era BAL quasar will provide a powerful probe of the effects of AGN feedback on the growth of the earliest massive galaxies (Wang et al. 2021, ApJL, 907, L1).



ALMA observations of the dust continuum and [C II] line. [Left] The dust continuum map with contour levels of [3, 5, 7, 9, 11, 13]  $\times 0.02$  mJy. [Middle] The integrated [C II] emission with contour levels of [3, 4]  $\times 0.04$  Jy km s<sup>-1</sup>. The sizes of the continuum cutout and the [C II] cutout are 4"  $\times$  4". The white crosses in the left and middle panels highlight the quasar position derived from VISTA Hemisphere Survey infrared images. [Right] The [C II] spectrum (black) and noise vector (blue) extracted from the data cube with an aperture diameter of 15 centered at the peak position of the continuum map. The spectral fitting (red line) gives FWHM =  $312 \pm 94$  km s<sup>-1</sup> and  $z[\text{CII}] = 7.6423 \pm 0.0013$  (Wang et al. 2021, ApJL, 907, L1).

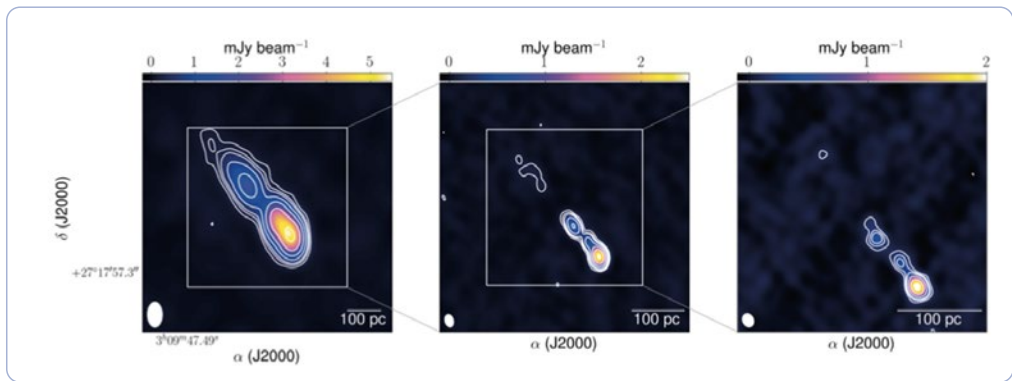
Powerful radio jets from supermassive black holes (SMBHs) have a profound influence on their local environments, regulating star formation in the host galaxy and polluting the intergalactic medium with atoms and magnetic fields. They may also facilitate the formation of SMBH by removing angular momentum from the accretion disk. However, finding radio Active Galactic Nuclei in the early Universe has proven difficult. Radio sources at the highest redshifts provide unique information on the first massive galaxies and black holes, the densest primordial environments, and the epoch of reionization. The number of astronomical objects identified at  $z > 6$  has increased dramatically over the last few years, but previously only three radio-loud sources have been reported at  $z > 6$ , the most distant being a quasar at  $z = 6.18$ . These two contributions—from the **Jansky Very Large Array** (VLA: Bañados et al. 2021, ApJ, 909, 80) and the **Very Long Baseline Array** (VLBA: Momjian et al. 2021, AJ, 161, 207)—report the discovery and characterization of the most distant radio-loud Active Galactic Nucleus to date, at  $z = 6.82$ , or just  $\sim 800$  Myr after the Big Bang. This source has a black hole mass of  $\sim 3 \times 10^8 M_{\odot}$  and is one of the fastest accreting quasars. The VLBA imaging implies a marginally resolved source, with a size  $\leq 10$  milli-arcseconds, or  $\sim 50$  parsecs. The small size, but steep radio spectrum at high frequency, implies a very young radio jet, with an estimated age of only  $\sim 2000$  years.



[Left] VLBA 1.4 GHz image of the  $z = 6.8$  radio loud quasar. [Right] A compilation of all the  $z > 5$  radio loud AGN known (Bañados et al. 2021; Momjian et al. 2021).

Blazars and Radio Structures

Multi-frequency observations were obtained with the **Jansky Very Large Array (VLA)** and the **Very Long Baseline Array (VLBA)** of the blazar PSO J030947.49+271757.31 (hereafter PSO J0309+27) detected at  $z = 6.10 \pm 0.03$ . The milli-arcsecond angular resolution of the VLBA observations at 1.5, 5, and 8.4 GHz unveil a bright one-sided jet extended for  $\sim 500$  parsecs in projection. This high- $z$  radio-loud Active Galactic Nucleus is resolved into multiple compact sub-components, embedded in a more diffuse and faint radio emission, which enshrouds them in a continuous jet structure. The authors derive limits on some physical parameters directly from the observable quantities, such as viewing angle, Lorentz and Doppler factors. If PSO J0309+27 is a genuine blazar, as suggested by its X-ray properties, then its bulk Lorentz factor must be relatively low (less than 5). Such values would favor a scenario currently proposed to reconcile the paucity of high- $z$  blazars with respect to current predictions. Nevertheless, the authors cannot exclude that PSO J0309+27 is seen under a larger viewing angle, which would imply that the X-ray emission must be enhanced, e.g., by inverse Compton with the Cosmic Microwave Background. More stringent constraints on the bulk Lorentz factor in PSO J0309+27 and the other high- $z$  blazars are necessary to test whether their properties are intrinsically different with respect to the low- $z$  blazar population (Spingola et al. 2020, A&A, 643, L12).



[Left to Right] VLBA images of the  $z=6.1$  blazar at 1.5 GHz, 5 GHz, and 8.4 GHz, down to 2 milli-arcsecond resolution (Spingola et al. 202, A&A, 643, L12).

New deep, high-resolution, 1.5 GHz observations of the prototypical nearby Perseus galaxy cluster were obtained from the **Karl G. Jansky Very Large Array**. They isolate for the first time the complete tail of radio emission of the bent-jet radio galaxy NGC 1272, which had been previously mistaken to be part of the radio mini-halo. The possibility that diffuse radio galaxy emission contributes to mini-halo emission may be a general phenomenon in relaxed cool-core clusters, and should be explored. The collimated jets of NGC 1272 initially bend to the west, and then transition eastward into faint, 60 kpc extensions with eddy-like structures and filaments. The authors suggest interpretations for these structures that involve bulk motions of intracluster gas, the galaxy's orbit in the cluster including projection effects, and the passage of the galaxy through a sloshing cold front. Instabilities and turbulence created at the surface of this cold front and in the turbulent wake of the infalling host galaxy most likely play a role in the formation of the observed structures. The authors also discover a series of faint rings, south-east of NGC 1272, a type of structure that has never been seen in galaxy clusters (Gendoon-Marsolais et al. 2021, ApJ, 911, L56).

Sloan Digital Sky Survey mosaic with VLA images of radio jets in the Perseus cluster, showing the strong interaction of the jets with the cluster gas on 100 kpc scales (Gendoon-Marsolais et al. 2021, ApJ, 911, L56).

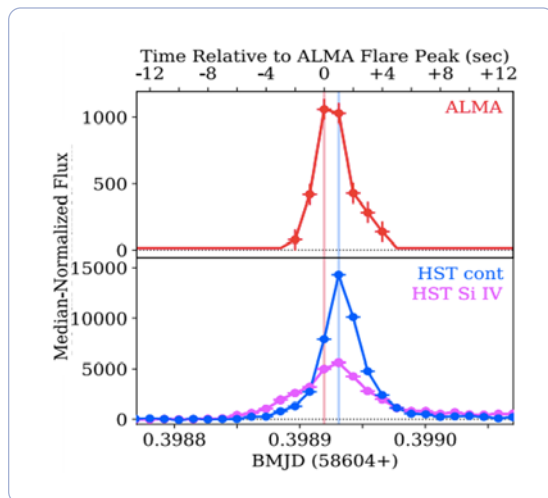
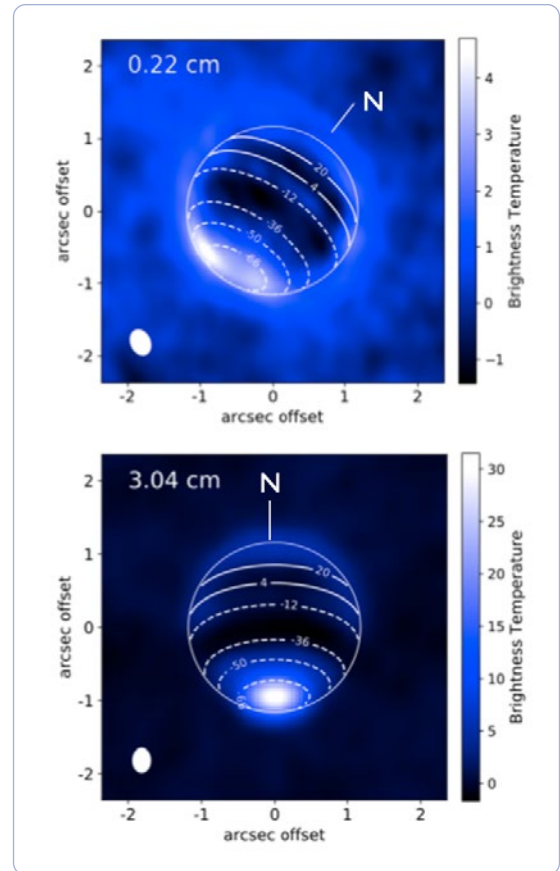


## Our Solar System and Nearby Stars

Spatially resolved (0.1-1.0 arcsec) radio maps of Neptune were acquired with the **Jansky Very Large Array** and the **Atacama Large Millimeter/submillimeter Array** between 2015 and 2017. Combined, these observations probe from just below the main methane cloud deck at  $\sim 1$  bar down to the  $\text{NH}_4\text{SH}$  cloud at  $\sim 50$  bar. Prominent latitudinal variations in the brightness temperature are seen across the disk. Depending on wavelength, the south polar region is 5 K to 40 K brighter than the mid-latitudes and northern equatorial region. The authors use radiative transfer modeling coupled to Markov Chain Monte Carlo methods to retrieve  $\text{H}_2\text{S}$ ,  $\text{NH}_3$ , and  $\text{CH}_4$  abundance profiles across the disk, though only strong constraints can be made for  $\text{H}_2\text{S}$ .

Below all cloud formation, the data are well fit by  $53.8^{+18.9}_{-13.4} \times$  and  $3.9^{+2.1}_{-3.1} \times$  protosolar enrichment in the  $\text{H}_2\text{S}$  and  $\text{NH}_3$  abundances, respectively, assuming a dry adiabat. Models in which the radio-cold mid-latitudes and northern equatorial region are supersaturated in  $\text{H}_2\text{S}$  are statistically favored over models following strict thermochemical equilibrium.  $\text{H}_2\text{S}$  is more abundant at the equatorial region than at the poles, indicative of strong, persistent global circulation. These results imply that Neptune's sulfur-to-nitrogen ratio exceeds unity, as  $\text{H}_2\text{S}$  is more abundant than  $\text{NH}_3$  in every retrieval. The absence of  $\text{NH}_3$  above 50 bar can be explained either by partial dissolution of  $\text{NH}_3$  in an ionic ocean at GPa pressures or by a planet formation scenario in which hydrated clathrates preferentially delivered sulfur rather than nitrogen onto planetesimals, or a combination of these hypotheses (Tollefson et al. 2021, The Planetary Science Journal, 2, Issue 3, L105).

*Examples of VLA and ALMA images of Neptune.*  
(Tollefson et al. 2021)



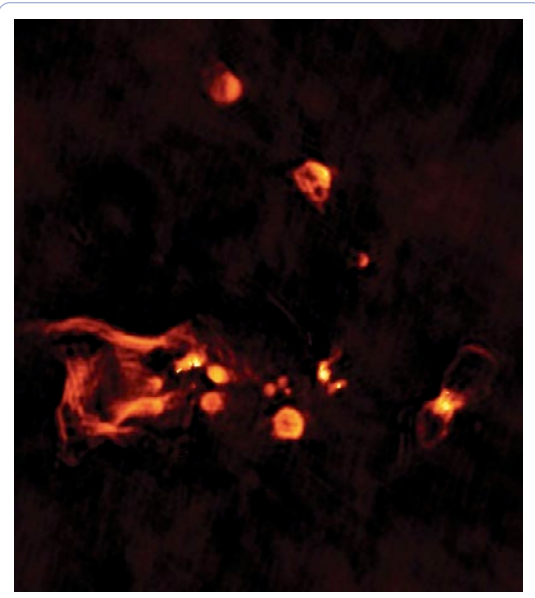
*VLA 1.3cm and HST UV light curves of the extreme flare from Proxima Centauri (MacGregor et al. 2021).*

M-dwarfs are the most common stars, and the most likely to host planets that could harbor life. The M-dwarf Proxima Centauri is at the center of the habitability discussion. It is the nearest exoplanetary system (1.3 parsecs) and has a likely Earth-mass planet with  $T \sim 230$  K at 0.05 AU. MacGregor et al. present here the discovery of an extreme flaring event from Proxima Centauri by the Australian Square Kilometre Array Pathfinder (ASKAP), **Atacama Large Millimeter/submillimeter Array (ALMA)**, Hubble Space Telescope (HST), Transiting Exoplanet Survey Satellite (TESS), and the du Pont Telescope that occurred on May 1, 2019. In the millimeter and far ultraviolet (FUV), this flare is the brightest ever detected, brightening by a factor of  $>1000$  and  $>14,000$  as seen by ALMA and HST, respectively. The millimeter and FUV continuum emission trace each other closely during the flare, suggesting that millimeter emission could serve as a proxy for FUV emission from stellar flares and become a powerful new tool to constrain the high-energy radiation environment of exoplanets. Surprisingly, optical emission associated with the event peaks at a much lower level with a time delay. The initial burst has an extremely short duration, lasting less than 10 seconds. Taken together with the growing sample of millimeter M dwarf flares, this event suggests that millimeter emission is actually common during stellar flares and often originates from short burst-like events. Extreme flares are driven by magnetic reconnection in the stellar atmosphere, and indicate a highly magnetically active star. The heightened magnetic activity of M-dwarfs could be detrimental to the life formation process (MacGregor et al. 2021, ApJL, 911, Issue 2, L25).

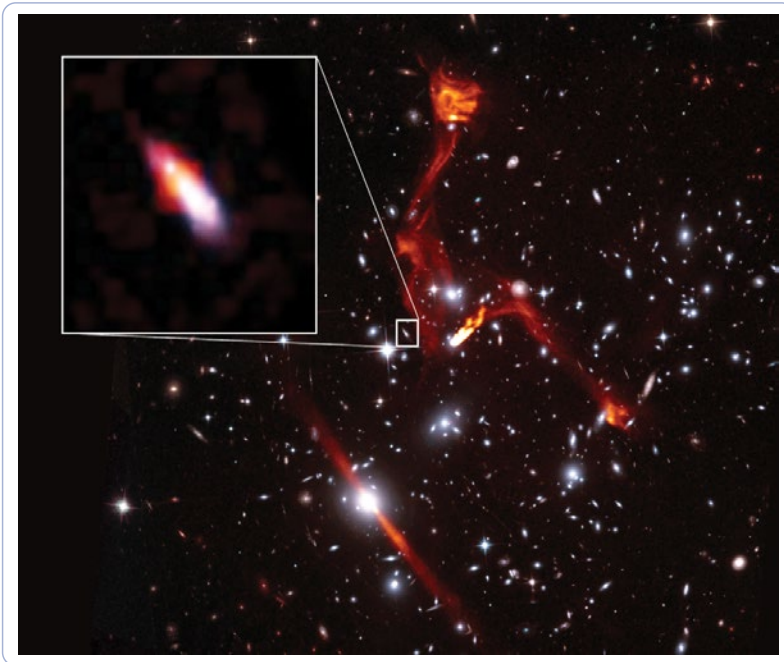
## Star Formation

De Pree et al. present new **Jansky Very Large Array (VLA)** images of the central region of the W49A star-forming region at 3.6 cm and at 7 mm at resolutions of 0.15 arcsec (1650 AU) and 0.04 arcsec (440 AU), respectively. The 3.6 cm data reveal new morphological detail in the ultracompact H II region population, as well as several previously unknown and unresolved sources. In particular, source A shows elongated, edge-brightened bipolar lobes, indicative of a collimated outflow, and source E is resolved into three spherical components.

The authors also present **VLA** observations of radio recombination lines at 3.6 cm and 7 mm, and IRAM Northern Extended Millimeter Array (NOEMA) observations at 1.2 mm. Three of the smallest ultracompact H II regions (sources A, B2, and G2) all show broad kinematic linewidths, with  $\Delta V_{\text{FWHM}} \sim 40 \text{ km s}^{-1}$ . A multi-line analysis indicates that broad linewidths remain after correcting for pressure broadening effects, suggesting the presence of supersonic flows. Substantial changes in linewidth over the 21 yr time baseline at both 3.6 cm and 7 mm are found for source G2. At 3.6 cm, the linewidth of G2 changed from  $31.7 \pm 1.8 \text{ km s}^{-1}$  to  $55.6 \pm 2.7 \text{ km s}^{-1}$ , an increase of  $+23.9 \pm 3.4 \text{ km s}^{-1}$ . The G2 source was previously reported to have shown a 3.6 cm continuum flux density decrease of 40% between 1994 and 2015. This source sits near the center of a very young bipolar outflow whose variability may have produced these changes (De Pree et al. 2020, AJ, 160, 234).



VLA 3.6cm image at 0.15 arcsec resolution of W49A (De Pree et al. 2020, AJ, 160, 234).



Composite Very Large Array (3 GHz) and Hubble Space Telescope image, of the Frontier field MACSJ0717.5+3745 at 0.6 arcsec resolution. The large diffuse structures are radio relics and jets in the lensing cluster. The faintest source (inset) corresponds to a de-magnified flux density of 0.9 micro-Jy and is a star-forming galaxy at  $z \sim 1$  (Heywood et al. 2021, ApJ, 910, 105; Jiménez-Andrade et al. 2021, ApJ, 910, 106).

The **Jansky Very Large Array** has performed ultra-deep (1 micro-Jy rms), high-resolution ( $< 0.6$  arcsec) imaging of the Hubble Space Telescope cluster-lensed Frontier fields. These observations reveal hundreds of distant star-forming galaxies, from which the authors derive star formation rates and source sizes, unbiased by dust obscuration.

The faintest reliably identified radio source corresponds to a galaxy at  $z \sim 1$ , with a star formation rate of only  $10 M_{\odot} \text{ yr}^{-1}$ , making it the faintest high-redshift star-forming galaxy detected to date in the radio continuum.

The observations of strongly-lensed fields provide important information for planning future deep fields with the Square Kilometre Array and the next generation Very Large Array (Heywood et al. 2021, ApJ, 910, 105; Jiménez-Andrade et al. 2021, ApJ, 910, 106).

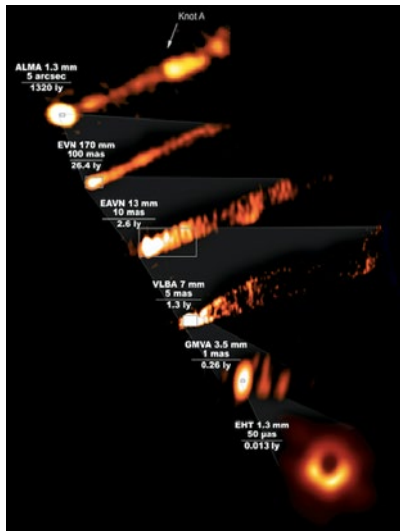
## M87 in the Virgo Cluster

The Event Horizon Telescope (EHT), featuring the **Atacama Large Millimeter/submillimeter Array** (ALMA) as its anchor element, has presented their polarimetric imaging at 240 GHz around the supermassive black hole in M87 on event-horizon scales. This polarized synchrotron radiation probes the structure of magnetic fields and the plasma properties near the black hole. The field geometry appears as a spiral. The fractional polarization is low (<20%), indicating high Faraday rotation, from which the research team estimates  $n_e \sim 10^{4.7} \text{ cm}^{-3}$ ,  $B \sim 1\text{-}30 \text{ G}$ , and  $T_e \sim (1\text{-}12) \times 10^{10} \text{ K}$ , in the radiating plasma.

The collaboration shows that the net azimuthal linear polarization pattern may result from organized, poloidal magnetic fields in the emission region. In a quantitative comparison with a large library of simulated polarimetric images from general relativistic magnetohydrodynamic (GRMHD) simulations, the authors identify a subset of physical models that can explain critical features of the polarimetric EHT observations while producing a relativistic jet of sufficient power. The consistent GRMHD models are all of magnetically arrested accretion disks, where near-horizon magnetic fields are dynamically important. Models enable the team to infer a mass accretion rate onto the black hole in M87 of  $(3\text{-}20) \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ . Strong fields may also be key to the physics of relativistic jet launch (EHT Collaboration 2021, ApJL, 910, L13).

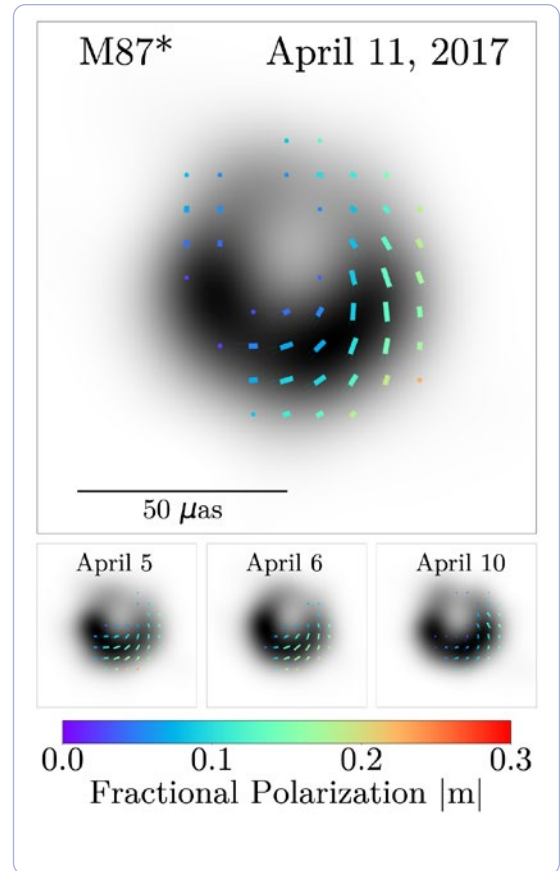
*EHT 240 GHz images of total intensity, and fractional polarization and position angle in M87.*

*ALMA, VLBA, and EHT observations of Virgo Cluster galaxy M87.*



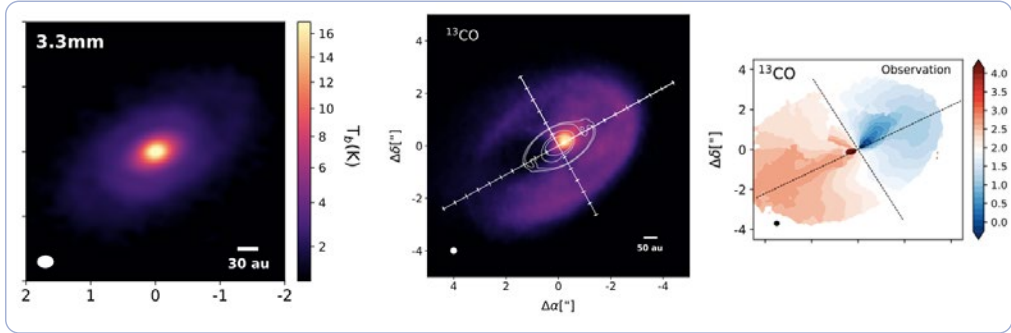
Compton emission in the same region producing the EHT mm-band emission, and further concluded that the  $\gamma$ -rays can only be produced in the inner jets (inward of HST-1) if there are strongly particle-dominated regions. Direct synchrotron emission from accelerated protons and secondaries cannot yet be excluded.

To better understand the black hole at the core of galaxy M87, the EHT Collaboration mounted a multi-wavelength observing campaign. Observations across the electromagnetic spectrum in radio, visible-light, ultraviolet, X-ray, and gamma-ray revealed the far-reaching impact of the supermassive black hole on its surroundings (EHT Collaboration 2021, ApJL, 910, L11).



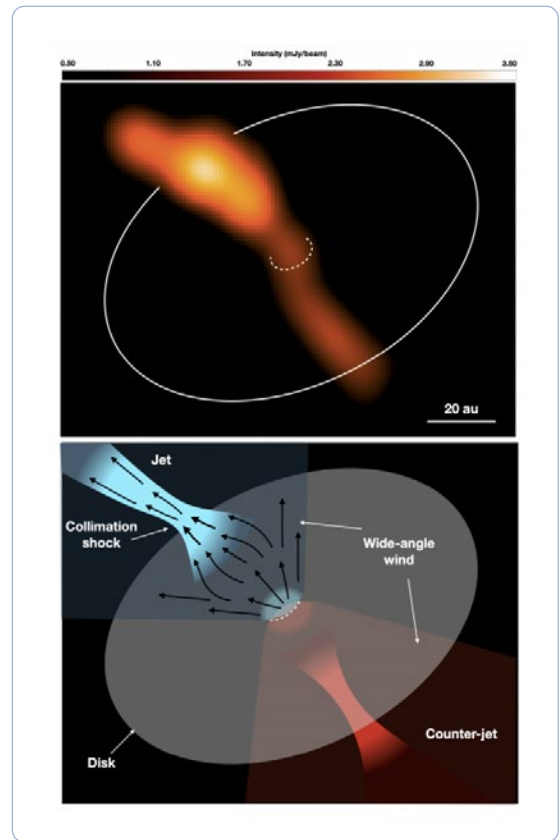
## Protoplanetary Disks and Protostars

Elias 2-27 is a 0.8 Myr old M-star, with a massive protoplanetary disk. The disk has a 14 AU wide gap at 69 AU radius, suggesting a 0.1M<sub>J</sub> forming planet. **Atacama Large Millimeter / submillimeter Array (ALMA)** imaging of the dust and CO(3-2) emission reveals spiral arms, and a rotating disk, providing the first dynamical mass estimate of a protoplanetary disk, with:  $M_{\text{star}} = 0.46 M_{\odot}$  and  $M_{\text{disk}} = 0.08 M_{\odot}$ . Departures from Keplerian rotation suggest instabilities which may lead to planet formation (Paneque-Carreño et al. 2021, ApJ, 914, 88).



*ALMA imaging of the protoplanetary disk of Elias 2-27. [Left] 3.3mm dust emission. [Center & Right] <sup>13</sup>CO 3-2 total intensity and the velocity field (Paneque-Carreño et al. 2021, ApJ, 914, 88).*

Protostellar jets have a fundamental role at the earliest evolution of protostars of all masses. In the case of low-mass (< 8 M<sub>⊙</sub>) protostars, strong observational evidence exists that the launching and collimation is due to the X- and/or disk-wind mechanisms. In these models, it is the protostar/disk system that creates all the necessary conditions to launch and collimate the jets near the protostar via strong magnetic fields. The origin of jets from more massive protostars has been investigated much less, in part because of the difficulty of resolving the collimation zone in these more distant objects. Here, the authors present the highest angular resolution observations of a jet powered by a massive protostar, the Cep A HW2 radio jet. The radio emission was imaged at projected distances of only ~20 AU from the protostar, resolving the innermost 100 AU of a massive protostellar jet for the first time. The morphology of the radio jet emission in this massive object is very different than what is usually observed in jets from low-mass protostars. The authors found that the outflowing material in HW2 has two components: a wide-angle wind launched from the protostar/disk system, and a highly collimated jet starting at 20-30 AU from the protostar. Two possible scenarios are discussed: an extension of the classical disk-wind to a massive protostar, or external collimation of a wide-angle wind. These results have important consequences for understanding how stars of different masses are formed (Carrasco-Gonzales et al. 2021, ApJL, 914, L1).

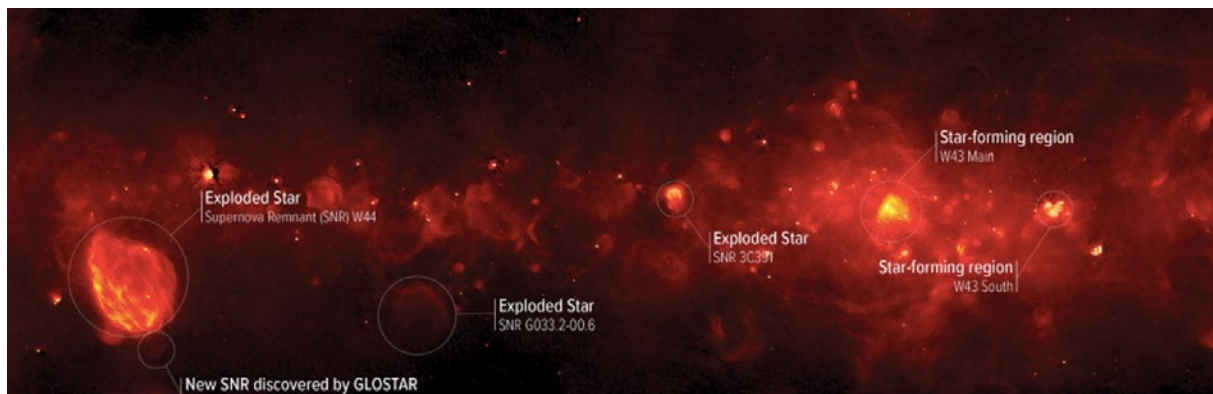


*(Above) VLA 40 GHz image of the jets in the massive protostar, Cep A HW2, at 40 milli-arcsec resolution. (Below) The model for the conical wind and the narrow jet (Carrasco-Gonzales et al. 2021, ApJL, 914, L1).*

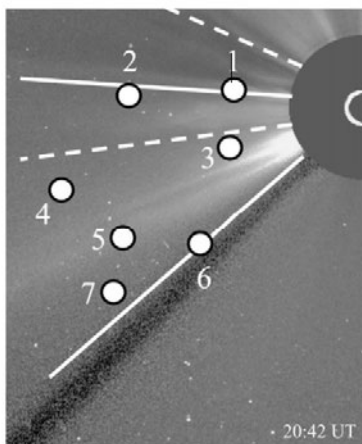
## Galactic Plane First Results

Surveys of the Milky Way at various wavelengths have changed our view of star formation in our Galaxy considerably in recent years. In this paper, the authors give an overview of the Global View on Star formation in the Milky Way (GLOSTAR) survey, a new survey covering large parts (145 square degrees) of the northern Galactic plane using the **Jansky Very Large Array (VLA)** in the frequency range 4–8 GHz, and the Effelsberg 100-m telescope. This provides for the first time a radio survey covering all angular scales down to 1.5 arcsecond, similar to complementary near- and mid-infrared galactic plane surveys. The authors outline the main survey goals and provide a detailed description of the observations and the data reduction strategy.

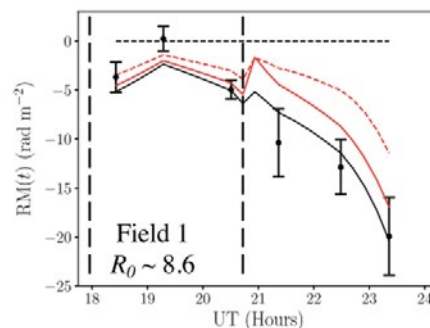
In these observations, the radio continuum is covered in full polarization, as well as the 6.7 GHz methanol maser line, the 4.8 GHz formaldehyde line, and seven radio recombination lines. The observations were conducted in the most compact D configuration of the **VLA** and in the more extended B configuration. This yielded spatial resolutions of 18 arcsec and 1.5 arcsec for the two configurations, respectively. The authors also combined the D configuration images with the Effelsberg 100-m data to provide zero spacing information, and jointly imaged the D- and B-configuration data for optimal sensitivity of the intermediate spatial ranges (Brunthaler et al. 2021, A&A, 651, A85).



GLOSTAR 10 GHz image of the Galactic Plane (Brunthaler et al. 2021, A&A, 651, A85).



(Left) SOHO coronagraphic image of a CME, showing the location of background radio sources used for Faraday rotation measurements with the VLA. (Right) Time behavior of the rotation measures with passage of the CME in front of source 1 (Kooi et al. 2021, Solar Physics, 296, 11).

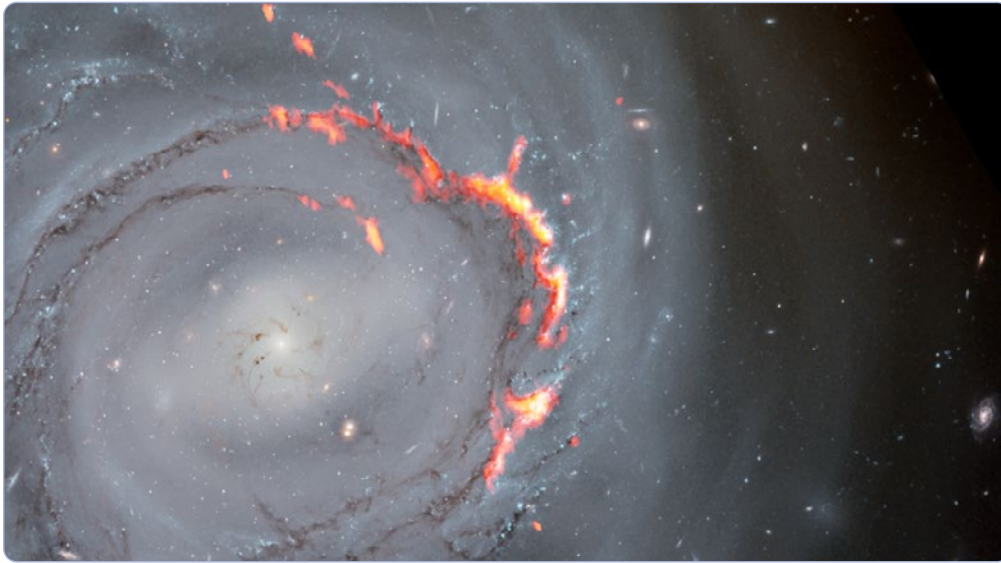


## Magnetic Field in a Coronal Mass Ejection

Coronal Mass Ejections (CMEs) are the most violent of space weather phenomena, traveling at  $\sim 1,000$  km/sec, with potential for major impact on the Earth. Polarization observations with the **Jansky Very Large Array**, coupled with real-time in situ density measurements by the Parker Solar Probe, have provided the most precise measurements of the magnetic field in a CME. Observations of the rotation measures toward background quasars through a CME yields a magnetic field strength of  $\sim 30$  mG at 10 solar radii. The fields help to “sculpt” the CME as it travels away from the Sun (Kooi et al. 2021, Solar Physics, 296, 11).

## Maintaining Future Star Formation

The authors investigate the effects of ram pressure on the molecular Interstellar Medium (ISM) in the disk of the Coma cluster galaxy NGC 4921, via high resolution CO observations. They present 6 arcsec resolution CO(1-0) observations of the full disk from the Combined Array for Research in Millimeter-wave Astronomy (CARMA), and 0.4 arcsec resolution **Atacama Large Millimeter/submillimeter Array** CO(2-1) observations of the leading quadrant, where ram pressure is strongest. They find evidence for compression of the dense ISM on the leading side, spatially correlated with intense star formation activity in this zone. They also detect molecular gas along kiloparsec-scale filaments of dust extending into the otherwise gas stripped zone of the galaxy, seen in Hubble Space Telescope images. The authors find the filaments are connected kinematically as well as spatially to the main gas ridge located downstream, consistent with cloud decoupling inhibited by magnetic binding, and inconsistent with a simulated filament formed via simple ablation. Furthermore, we find several clouds of molecular gas  $\sim 1-3$  kpc beyond the main ring of CO that have velocities which are blueshifted by up to 50 km/s with respect to the rotation curve of the galaxy. These are some of the only clouds detected here that do not have any visible dust extinction associated with them, suggesting that they are located behind the galaxy disk midplane and are falling back towards the galaxy. Simulations



have long predicted that some gas removed from the galaxy disk will fall back during ram pressure stripping. This may be the first clear observational evidence of gas re-accretion in a ram pressure stripped galaxy (Cramer et al. 2021, ApJ, 921, 22).

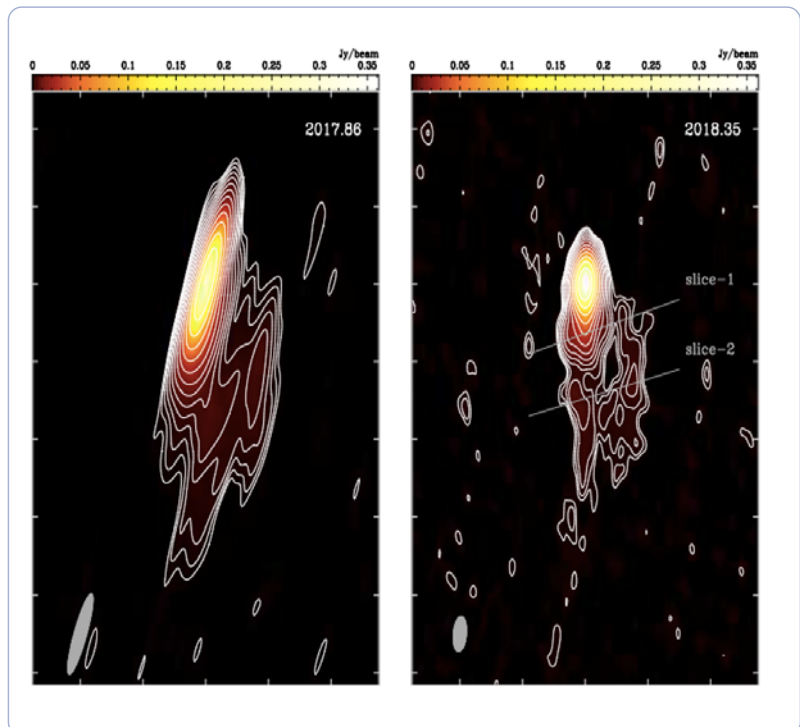
*Composite ALMA CO(2-1) and Hubble Space Telescope image of the Virgo cluster spiral galaxy, NGC 4921 (Cramer et al. 2021, ApJ, 921, 22).*

## VLBA Images the First Extragalactic Neutrino Source

The **Very Long Baseline Array (VLBA)** demonstrated its unique ability to obtain the highest resolution images of parsec-scale relativistic jets with the discovery of a jet in the first known extragalactic neutrino source, the Blazar radio source TXS 0506+056.

High energy neutrinos were detected by IceCube from TXS 0506+056. **VLBA** images with  $\sim 0.5$  milli-arcsec resolution at 43 GHz detect complex jet structure and dynamics. Jet deceleration on scales  $\sim 100$  parsec is seen – likely due to proton loading by jet-star interactions in the inner galaxy (Ros et al. 2020, A&A, 633, L1).

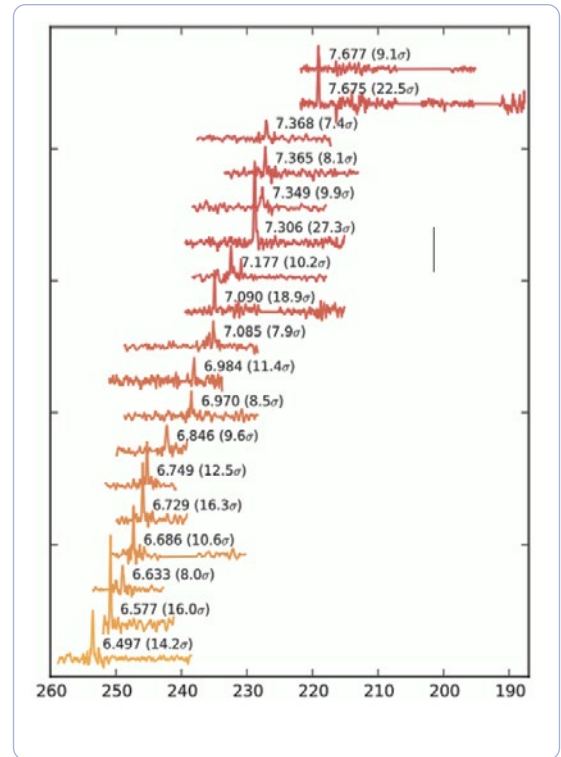
*Nov 2017 and May 2018: Very Long Baseline Array 43 GHz images of the blazar TXS 0506+056 at  $\sim 0.5$  milli-arcsec resolution, showing complex jet structure and dynamics in this first extragalactic neutrino source (Ros et al. 2020, A&A, 633, L1).*



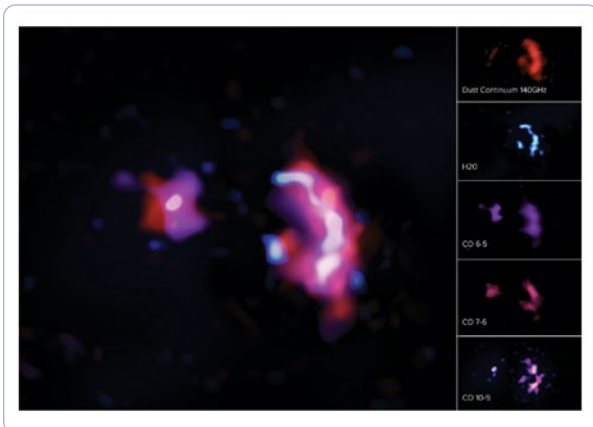


## ALMA and the First Galaxies

The Reionization Era Bright Emission Line Survey (REBELS) is a Cycle 7 **Atacama Large Millimeter/submillimeter Array (ALMA)** Large Program (LP) that is identifying and performing a first characterization of many of the most luminous star-forming galaxies known in the  $z > 6.5$  universe. REBELS is providing this probe by systematically scanning 40 of the brightest UV-selected galaxies identified over a seven square degree area for bright 158-micron [CII] and 88-micron [OIII] lines and dust-continuum emission. Selection of the 40 REBELS targets was done by combining photometric selections, each of which is subject to extensive vetting using three completely independent sets of photometry and template-fitting codes. Building on the observational strategy deployed in two pilot programs, the authors are increasing the number of massive interstellar medium (ISM) reservoirs known at  $z > 6.5$  by  $\sim 4\text{-}5\times$  to  $> 30$ . The authors motivate the observational strategy deployed in the REBELS program and present initial results. Based on the 60.6 hours of **ALMA** observations taken in the first year of the program (November 2019 to January 2020), 18 highly significant  $\sim 7\sigma$  [CII] lines have already been discovered, the bulk of which (13/18) also show  $\sim 3.3\sigma$  dust-continuum emission. These newly discovered lines more than triple the number of bright ISM-cooling lines known in the  $z > 6.5$  universe, such that the number of ALMA-derived redshifts at  $z > 6.5$  already rival Ly $\alpha$  redshift discoveries. An analysis of the completeness of our search results vs. star formation rate (SFR) suggests an  $\sim 79\%$  efficiency in scanning for [CII] when the SFR(UV+IR) is in excess of  $28 M_{\odot} \text{ yr}^{-1}$ . These new LP results further demonstrate ALMA's efficiency as a "redshift machine", particularly in the Epoch of Reionization (Bouwens et al. 2022, ApJ, 931, 160).



ALMA spectra of [CII] 158 micron emission from the REBELS sample at  $z = 6.5$  to 7.7 (Bouwens et al. 2022, ApJ, 931, 160).



Composite showing the H<sub>2</sub>O, CO, and dust emission from a merging galaxy at  $z = 6.9$  (Jarugula et al. 2021, ApJ, 921, 97).

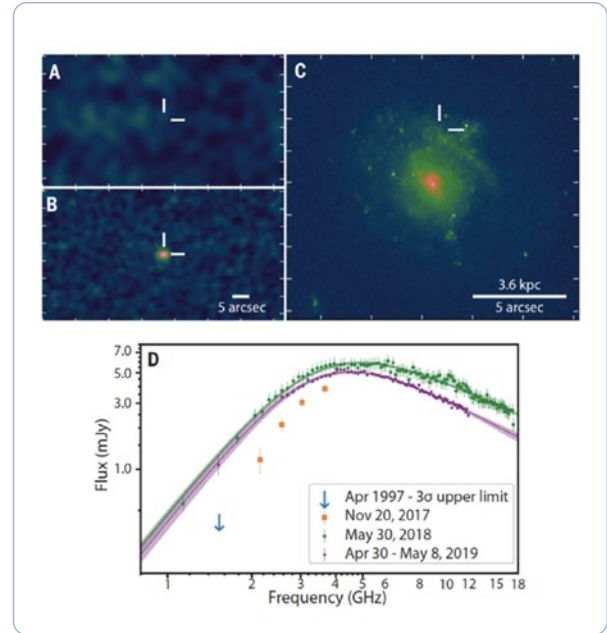
## Water in the Early Universe

SPT0311-58 is the most massive infrared luminous system discovered so far during the Epoch of Reionization (EoR). In this paper, the authors present a detailed analysis of the molecular interstellar medium at  $z = 6.9$ , through high resolution observations of the CO(6 – 5), CO(7 – 6), CO(10 – 9), [CII](2 – 1), and p-H<sub>2</sub>O(2<sub>p</sub>,1 – 2<sub>o</sub>,2) lines and dust continuum emission with the **Atacama Large Millimeter/submillimeter Array (ALMA)**. The system consists of a pair of intensely star-forming gravitationally lensed galaxies (labelled West and East). The intrinsic far-infrared luminosity is  $(16 \pm 4) \times 10^{12} L_{\odot}$  in West and  $(27 \pm 4) \times 10^{11} L_{\odot}$  in East. The authors model the dust, CO, and [CII] using non-local thermodynamic equilibrium radiative transfer models and estimate the intrinsic gas mass to be  $(5.4 \pm 3.4) \times 10^{11} M_{\odot}$  in West and  $(3.1 \pm 2.7) \times 10^{10} M_{\odot}$  in East. They find that the CO spectral line energy distribution in West and East are typical of high-redshift submillimeter galaxies (SMGs). The CO-to-H<sub>2</sub> conversion factor ( $\alpha_{\text{CO}}$ ) and the gas depletion time scales estimated from the model are consistent with the high-redshift SMGs in the literature within the uncertainties. They find no evidence of evolution of depletion time with redshift in SMGs at  $z > 3$ . This is the most detailed study of molecular gas content of a galaxy in the EoR to-date, with the most distant detection of H<sub>2</sub>O in a galaxy without any evidence for active galactic nuclei in the literature (Jarugula et al. 2021, ApJ, 921, 97).

## A New Type of Radio Transient

Comparison of images from the **Very Large Array Sky Survey** with older data from the Faint Images of the Radio Sky at Twenty-cm (FIRST) survey has revealed a new type of transient radio source, consistent with a merger-driven core collapse supernova. The source is associated with a soft gamma-ray burst detected in 2014 with the Monitor of All-sky X-ray Image (MAXI) instrument on the International Space Station. The new radio source is likely the result of a supernova driven by the collision between the neutron star or black hole companion of an evolved massive star. Such an event has been long theorized, but never before seen (Dong et al. 2021, *Science*, 373, 1125).

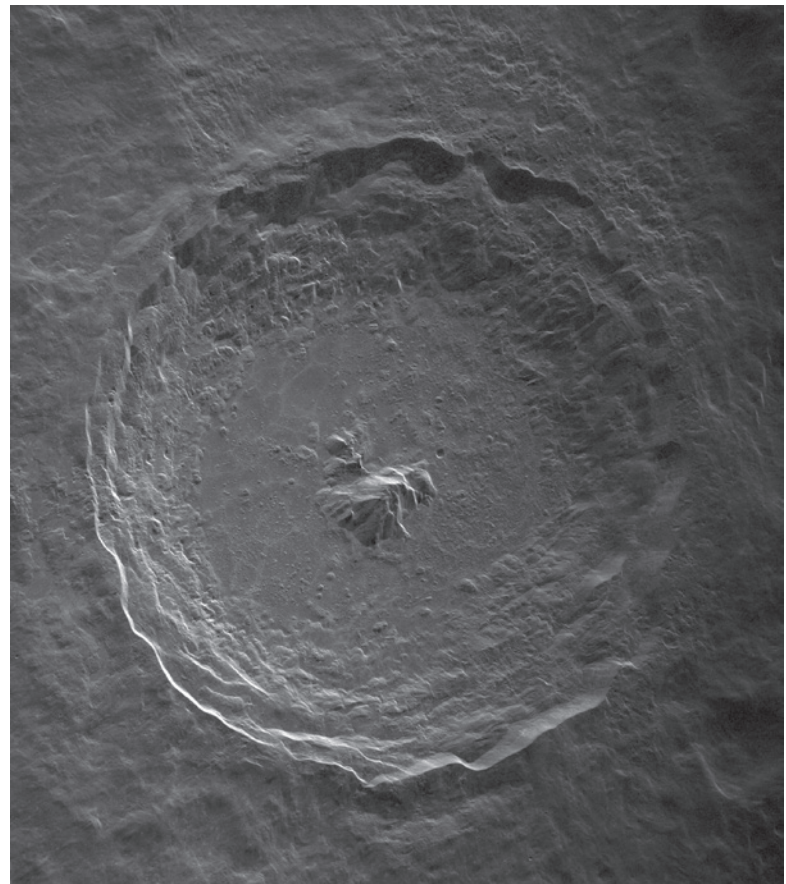
*VT 1210+4956 was not detected in FIRST in 1997 (A), but appears in the first epoch of the VLASS in 2017 (B). C shows the optical location in a dwarf galaxy at  $z = 0.035$ , and D shows the radio spectrum fit with a synchrotron self-absorption model (Dong et al. 2021, *Science*, 373, 1125).*



## GBT and VLBA Team Up To Image the Moon

The Green Bank Observatory, National Radio Astronomy Observatory, and Raytheon Intelligence & Space released a new high-resolution image of the Moon in September 2021, the highest-resolution ever taken from the ground, using new radar technology on the **Green Bank Telescope (GBT)**. The resolution of the new Tycho Crater image is close to five meters by five meters and contains  $\sim 1.4$  billion pixels. The image covers an area of 200 kilometers by 175 kilometers, ensuring that involved scientists and engineers captured the entire crater, which measures 86 kilometers in diameter. For these images, the GBT was outfitted in late 2020 with new technology developed by Raytheon Intelligence & Space and Green Bank Observatory, allowing it to transmit a radar signal into space. Using the GBT and antennas from the Very Long Baseline Array (VLBA), several additional tests have been conducted since that time, focusing on the surface of the Moon, including the Tycho Crater and NASA Apollo landing sites (Image courtesy of Raytheon/NRAO/AUI/NSF).

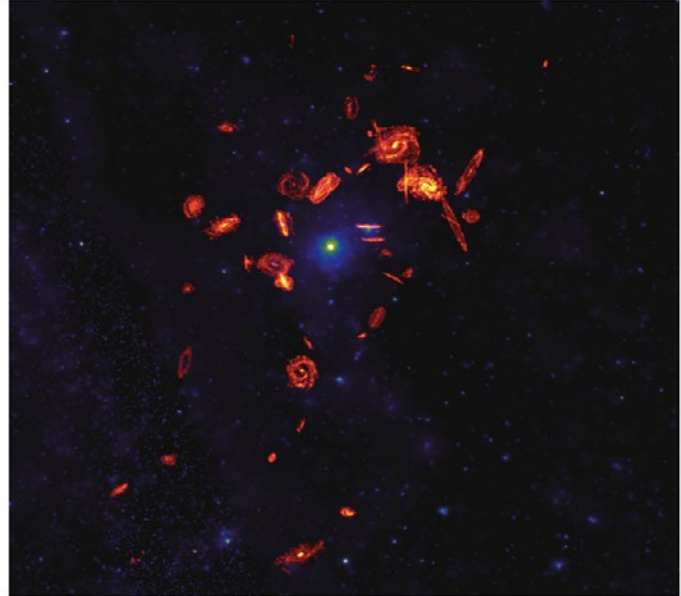
*This dramatic image of a 200 kilometer region with 5 meter resolution around the Tycho crater on the Moon was produced using the proto-type radar system at the GBO with VLBA antenna receiving stations (Image courtesy of Raytheon/NRAO/AUI/NSF).*



## How Galaxies Lose Their Gas

Brown et al. present the Virgo Environment Traced in CO (VERTICO) survey, a new effort to map  $^{12}\text{CO}(2-1)$ ,  $^{13}\text{CO}(2-1)$ , and  $\text{C}^{18}\text{O}(2-1)$  in 51 Virgo Cluster galaxies with the Atacama Compact Array, part of the **Atacama Large Millimeter/submillimeter Array (ALMA)**. The primary motivation of VERTICO is to understand the physical mechanisms that perturb molecular gas disks, and therefore star formation and galaxy evolution, in dense environments. This first paper contains an overview of VERTICO's design and sample selection,  $^{12}\text{CO}(2-1)$  observations, and data reduction procedures. The authors characterize global  $^{12}\text{CO}(2-1)$  fluxes and molecular gas masses for the 49 detected VERTICO galaxies, provide upper limits for the two non-detections, and produce resolved  $^{12}\text{CO}(2-1)$  data products (median resolution = 8 arcsec  $\approx$  640 pc). Azimuthally averaged  $^{12}\text{CO}(2-1)$  radial intensity profiles are presented along with derived molecular gas radii. The authors demonstrate the scientific power of VERTICO by comparing the molecular gas size–mass scaling relation for their galaxies with a control sample of field galaxies, highlighting the strong effect that radius definition has on this correlation. They discuss the drivers of the form and scatter in the size–mass relation and highlight areas for future work. VERTICO is an ideal resource for studying the fate of molecular gas in cluster galaxies and the physics of environment- driven processes that perturb the star formation cycle. Upon public release, the survey will provide a homogeneous legacy dataset for studying galaxy evolution in our closest cluster (Brown et al. 2021, ApJSS, 257, 21).

*Upper: CO(2-1) emission from galaxies in the Virgo cluster, plus the optical image. Lower: Molecular gas in the merging galaxy system NGC 4567 and 4568 (Brown et al. 2021, ApJSS, 257, 21).*



## Time Domain Studies and Fundamental Physics

Astronomers using **ALMA** as the keystone element of the EHT, unveiled the first image of the supermassive black hole Sagittarius A\* at the center of our own Milky Way galaxy, more than a thousand times smaller and less massive than the M87 Black Hole previously imaged. The result is a general relativistic shadow ring of 52 mas diameter, consistent with a Kerr (spinning) black hole of mass  $4 \times 10^6 M_{\odot}$ . One challenge in imaging SgrA\* is its variability, owing to its relatively low mass. In fact, a subsequent analysis showed signs of a hot spot orbiting the black hole. The observations and models suggest this is a bubble of hot gas orbiting SgrA\* clockwise at low inclination, varying in brightness as it travels its orbit every 70 minutes at a projected distance about five times that of the Event Horizon, dimming and brightening as it moves at  $\sim 30\%$  speed of light.

The **VLBA** produced an important measurement of the absolute position of SgrA\* this year (Xu et al. 2022, ApJ, 940, 1), improving the astrometric accuracy to about 0.5 mas, about an order of magnitude better than previous measurements. Also measured was a much-improved proper motion of SgrA\*, found to be  $-3.152 \pm 0.011$  and  $-5.586 \pm 0.006$  mas/year in the easterly and northerly directions, respectively. These measurements are crucial for future studies of general relativistic effects on stellar orbits in the vicinity of SgrA\*.

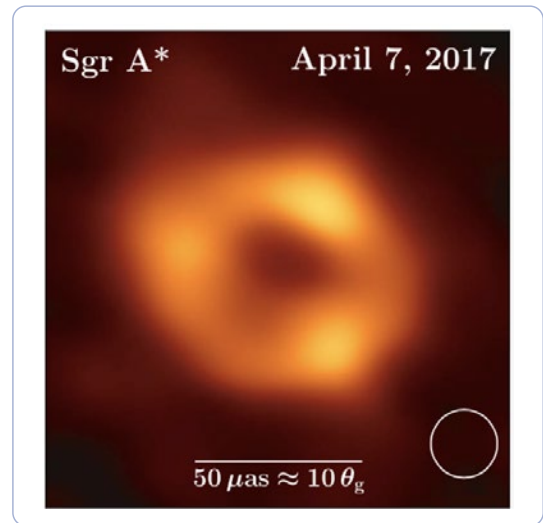
The **VLA Sky Survey (VLASS)** completed its second epoch of observations in February 2022.

It continues to provide unique insights into the nature of transient radio sources. One recent highlight is the discovery of a candidate extragalactic emerging pulsar wind nebula, VT 1137-0337 (Dong et al. 2022, ApJ, 948, 2). This was identified by comparing VLASS Epoch 1 to the earlier Faint Images of the Radio Sky at Twenty-cm (FIRST) survey. Subsequent follow-up showed that it is a flat-spectrum radio source in a dwarf starburst galaxy that is now slowly fading, making it an excellent candidate for a newly emerged pulsar wind nebula.

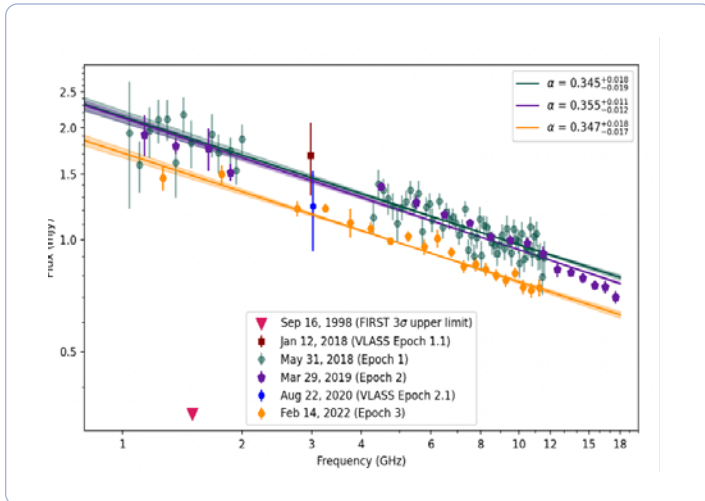
A recent highlight from non-transient applications of **VLASS** is the combined use of VLASS and the southern Rapid ASKAP (Australian Square Kilometer Array Pathfinder) Continuum Survey (RACS) to measure the dipole produced by the motion of the Milky Way relative to the cosmic background. In contrast to some previous studies, this joint VLASS/RACS study showed results consistent with those obtained by measuring the dipole in the Cosmic Microwave Background (CMB) with the Planck satellite (Darling, 2022, ApJL, 931, 14).

Betelgeuse ( $\alpha$  Orionis) is the closest red supergiant, on the verge of a supernovae explosion. The star is variable on yearly timescales. In early 2020, the star faded to an historically low brightness. This dimming may be due to dust formation in a major mass loss event driven by photospheric convection, or unusual photospheric cooling. **VLA** 7mm and 1.3cm observations just prior to the dimming find a gas temperature of 2270 K at twice the optical photospheric radius, about 500 K cooler than previous measurements (Matthews & Dupree 2022, ApJ, 934, 131). No giant convective cells were seen, but the observed radio photosphere is inconsistent with a uniform disk, but has large-scale, ring-like structure. The results are consistent with the passage of a major shock wave through the outer atmosphere, possibly driven by large-scale mass ejection.

Large programs at the **VLA** and **VLBA** continue to explore the new window of time domain astronomy in a broad range of physical regimes. These include programs to identify electro-magnetic counterparts to gravitational wave sources discovered by LIGO, and to determine arc-second positions of Fast Radio Bursts (FRB) and monitor repeating FRBs. The VLA participates in the Nanohertz pulsar monitoring program to discover the gravitational wave background from the Big Bang, while the Monitoring Of Jets in Active galactic nuclei with **VLBA** Experiments (MOJAVE) program continues to set the standard for monitoring the temporal evolution of milliarcsecond structure in powerful relativistic radio jets on decadal timescales.



*The EHT (including ALMA) image at 240 GHz of the general relativistic shadow of the supermassive black hole at the Galactic Center, Sgr A\* (EHT collaboration 2022, ApJ, 930, L12).*



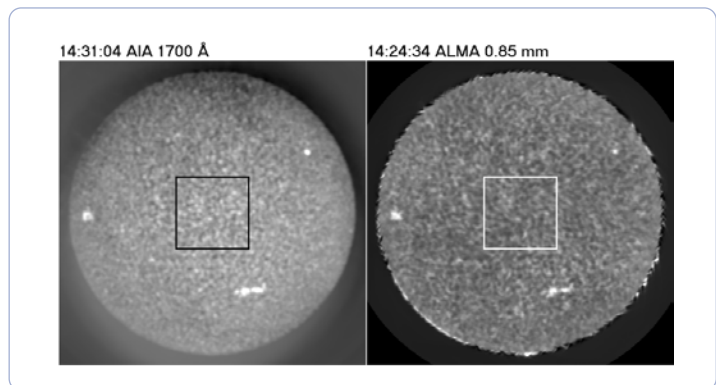
The radio spectrum of the VLASS transient VT 1137-0337. This flat-spectrum radio source appeared between FIRST (1998) and VLASS Epoch 1 (2018) and is seen to slowly fade between 2018 and 2022, making it a good candidate for an emerging pulsar wind nebula (Dong et al. 2022, *ApJ*, 948, 2).

## Solar System and Planetary Science

The NRAO facilities worked in concert with deep space probes and other ground-based facilities to study the physics and chemistry of objects in the Solar System.

Oort-cloud comet C/2014 UN271 (Bernardinelli-Bernstein) was discovered at  $\sim 29$  AU from the Sun (Lellouch et al. 2022, *A&A* 659, 1L), developing cometary activity early with a brightness suggesting a large size. **ALMA** detected thermal emission when the comet was at 20 AU distance from the Sun, from which a surface-equivalent diameter of 137 km is calculated. It is thus the largest Oort-cloud object ever found, (almost twice as large as comet C/1995 O1 Hale-Bopp) and has a normal cometary albedo. Detection of gases is expected in the upcoming years as the comet heads toward a perihelion of 11 AU in 2031.

Solar disk images at  $1700\text{\AA}$  with the Atmospheric Imaging Assembly, and at  $0.85\text{mm}$  with ALMA (Allisandrakis et al. 2022, *A and A*, 661, L4).



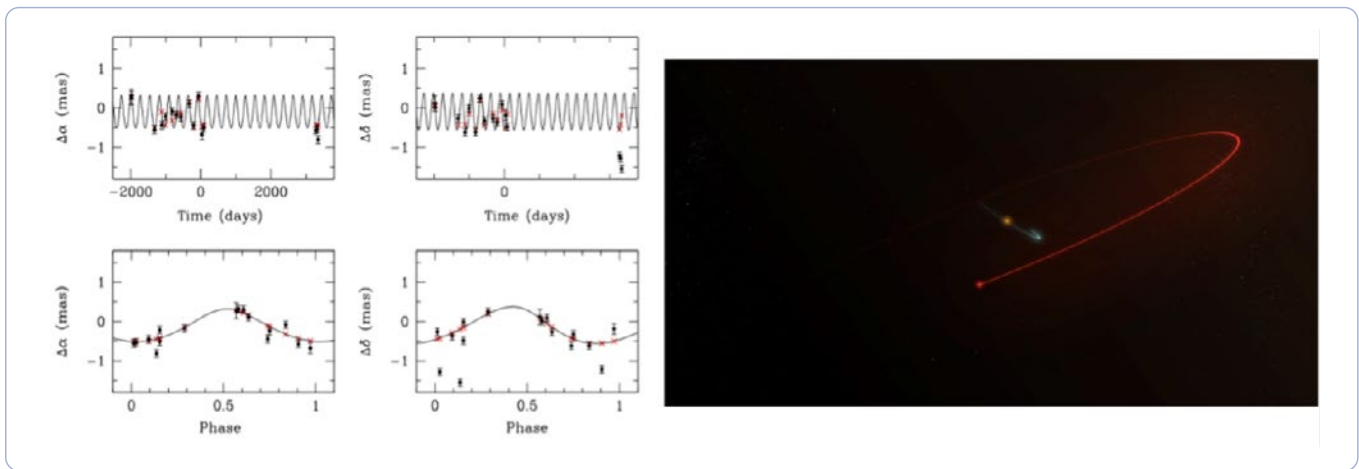
Allisandrakis et al. (2022, *A&A*, 661, L4) present the first full-disk Solar images obtained with **ALMA**, using Band 7 (0.86 mm; 347 GHz). The results show a disk practically devoid of active regions at their  $21''$  resolution. Solar structures on the disk are similar to those in Atmospheric Imaging Assembly images at  $1600\text{\AA}$  and  $304\text{\AA}$ ; they are also similar to negative H $\alpha$  images of equivalent resolution. Small plage regions are about 900K brighter than their surroundings, while the polar coronal holes and small H $\alpha$  filaments are not detectable. The authors deduced a brightness temperature at the center of the disk of 6085 K at 0.85mm, rather than the 5500 K extrapolated from images at 3mm and 1.3mm, an indication that at 0.85mm we are approaching the temperature minimum.

With the ever-increasing number of known exoplanets, many in the habitable zone, understanding the effects of stellar activity (exospace weather), on the potential development of life has become paramount. **ALMA**, working in concert with a multi-wavelength arsenal of space and ground-based telescopes, has measured the faintest flare to date on the nearby (1.2pc distance) M dwarf star, Proxima Centauri, which hosts a planet in the habitable zone (Howard et al. 2022, *ApJ*, 938, 103). The X-ray flare is well within the luminosity range of typical flares on the Sun, while the millimeter emission is two orders of magnitude stronger than typical Solar flares. The findings provide more evidence that millimeter emission is a common feature in weak exo-stellar flares, rising and falling in timescales of seconds. The implied temperature for the corona is  $1.1 \times 10^7$  K.

## Star and Planet Formation and Evolution, and The Search for Life

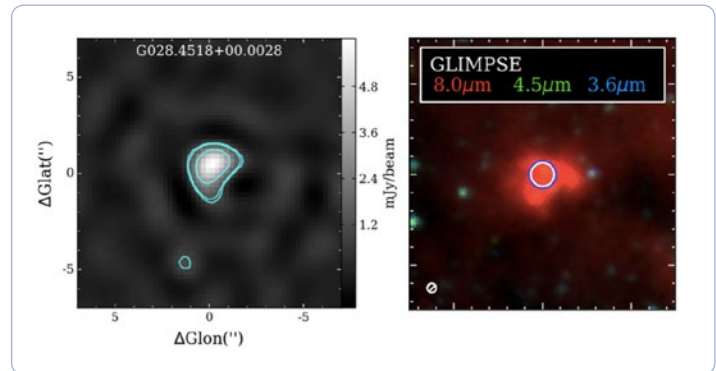
Thousands of planets are now known, but study of planetary orbits in common binary star systems remains under-explored. Precision (tens of mas) astrometry at 8 GHz with the **VLBA** has traced the 3D structure of the orbits of the binary star system, GJ896AB, consisting of  $0.4 M_{\odot}$  and  $0.2 M_{\odot}$  stars with an orbital period of 229 days at Neptunian separation. Both dwarf stars are magnetically active and have sub-mJy, variable radio emission. The motion of star A implies a  $2 M_{\text{Jup}}$  planet orbiting with a period of 284 days at a Venusian distance. The surprise was that the planet is in retrograde orbit relative to the binary stars. Seeing such a large planet in a retrograde orbit in a very compact binary system challenges theories of planet formation (Curiel et al. 2022, AJ, 164, 92).

*Left: astrometric tracks of the star orbits motion in the binary star system GJ896AB made with the VLBA at 8 GHz. These tracks indicate both the star-star orbit, and the planet-induced motion for star A, with an accuracy of  $\sim$  ten of microarcseconds. Right: schematic of the surprising retrograde orbit for the planet (Curiel et al. 2022, AJ, 164, 92).*



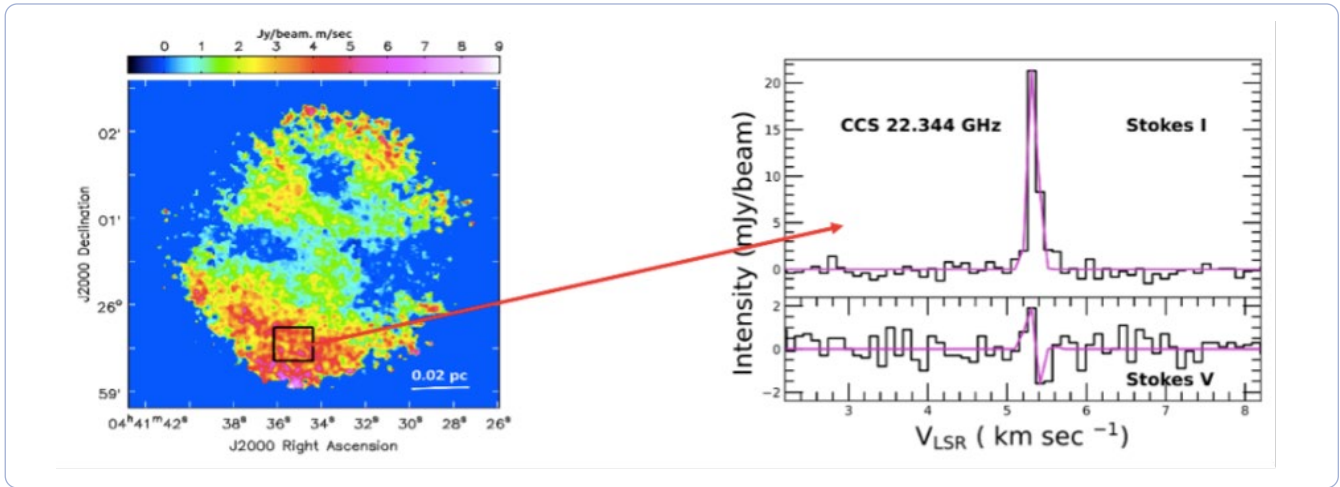
The year 2022 saw the publication of results from the Global View of Star Formation in the Milky Way (GLOSTAR; right; Dzib et al. 2022, A&A, 670, A9) large program at the **VLA**. GLOSTAR is a survey of a large region of the Galactic plane at 4–8 GHz with an unprecedented resolution and sensitivity of  $1''$  and 60 mJy. Almost 1500 radio sources are identified at high significance, including radio stars, planetary nebulae, and HII regions associated with both young stellar objects in clusters and with massive stars.

Results from the **ALMA** Molecules with ALMA at Planet-forming Scales (MAPS) Large Project target were published this year. An important result was the discovery of a circumplanetary disk (CPD) associated with accretion onto a forming planet in the dusty circumstellar disk around the T Tauri star AS209 (Bae et al. 2022, ApJ 934, 20). The CPD is less than 14 AU in size, and is located 200 AU from the parent star. The planet was isolated by velocity perturbations seen in the  $^{13}\text{CO}$  J=2-1 emission. The velocity field suggests kinematic influence of an embedded giant planet of about  $0.1 M_{\text{Jup}}$ ; the data also suggest localized gas heating.



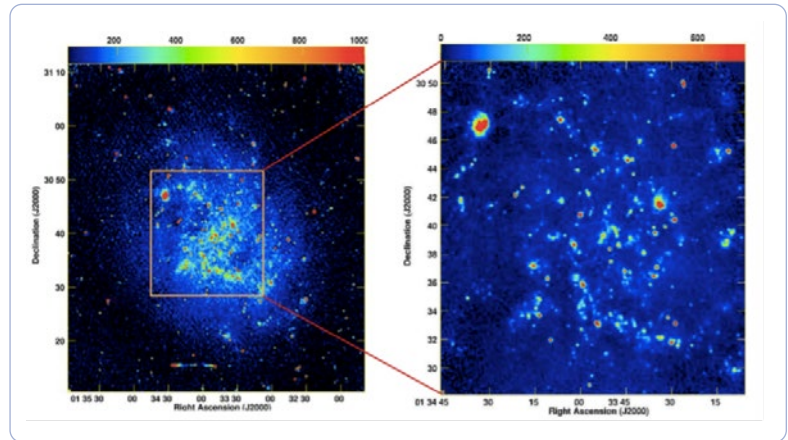
*Images of the Free-Free emission from a Galactic HII region from the GLOSTAR survey at 6 GHz with  $1''$  resolution (left), and in the mid-IR (Dzib et al. 2022, A&A, 670, A9).*

Starless cores are very young, dense molecular clumps seen just before the star itself ignites. TMC-1C, at 140 pc distance, is one of the best studied starless cores, having been observed in multiple molecular transitions. Recent **VLA** measurements of Zeeman splitting of CCS 22.3 GHz line emission from TMC-1C have provided an accurate measure of the magnetic field in the cloud envelope. The 2 mG field is strong enough to affect gas dynamics, implying that the accretion process in the envelope is dictated by ambipolar diffusion across field lines on timescales  $\leq 105$  yrs (Koley et al. 2022, MNRAS, 516, L48).

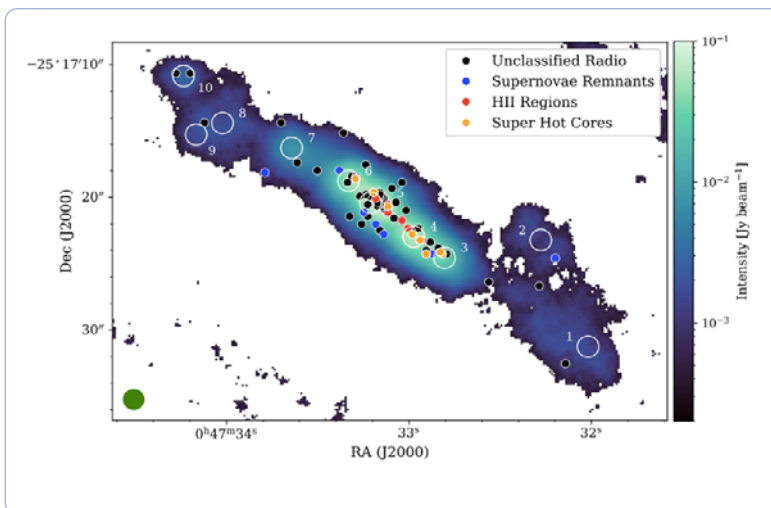


VLA observations of the 22.3 GHz CCS line emission from TMC-1C, plus the Stokes V measurements showing Zeeman splitting (Koley et al. 2022, MNRAS, 516, L48).

The VLA has completed a survey of the M33 galaxy (Tabatabaei et al. 2022, MNRAS, 517, 2) at 1.5 GHz and 6.3 GHz, with resolutions down to 30 pc, sufficient to isolate individual giant molecular clouds (GMC)—the dominant sites for star formation in galaxies. The broadband, multifrequency observations allow for a separation of thermal and non-thermal emission. The results provide the most detailed, dust-unbiased measure of the star formation law relating star formation rate to molecular gas content of GMCs. The non-thermal emission provides details as to the generation of magnetic fields via a turbulent dynamo driven by star formation and supernovae.



Images of the galaxy M33 at 1.5 GHz, 15" resolution (left), and 6.3 GHz, 9" resolution (Tabatabaei et al. 2022, MNRAS, 517, 2).



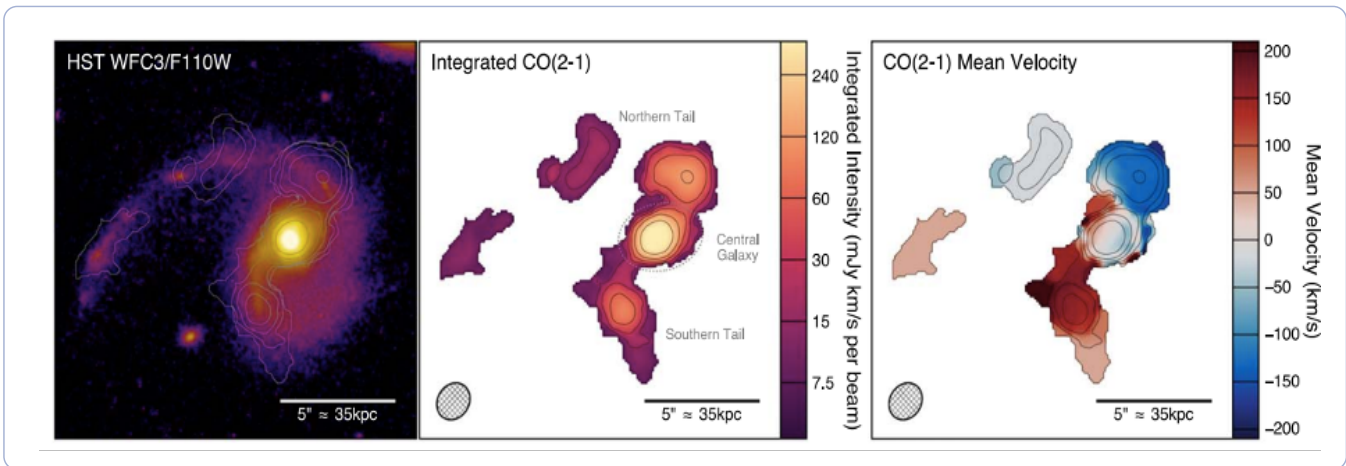
Location of radio continuum sources and super hot cores within the NGC253 CMZ plotted over the 212 GHz ALCHEMI dust continuum emission. Numbered white circles indicate GMCs identified in the ALMA survey (Behrens et al. 2022, ApJ, 939, 2)

The ALMA Comprehensive High-resolution Extragalactic Molecular Inventory (ALCHEMI; Behrens et al. 2022, ApJ, 939, 2) Large Program at ALMA provides a multi-band, beam-matched spectral scan of the Central Molecular Zone (CMZ; 850x340pc) of the starburst galaxy NGC253 at GMC resolution (1" = 17 pc). Five papers this year provide a molecular inventory via reliable templates of chemistry and excitation in one of the closest nuclear starburst galaxies at GMC scales. These papers find major differences in the CMZ relative to the rest of the galaxy disk, including (i) greatly enhanced cosmic ray density, (ii) orders of magnitude lower gas-phase CO<sub>2</sub> abundance at the galaxy center, and (iii) efficient CO<sub>2</sub> sublimation onto ice grains. These differences likely result from the very high star formation rate along the CMZ.

## Galaxies and Galaxy Formation

The **VLA** and **ALMA** provide the unique capability to study the cool gas and dust in galaxies. These are key constituents in fueling star formation, and act as star formation tracers. The **VLBA** provides the complimentary ability to study the bright radio continuum structures on tens of pc-scales, associated with the most distant Active Galactic Nuclei (AGN).

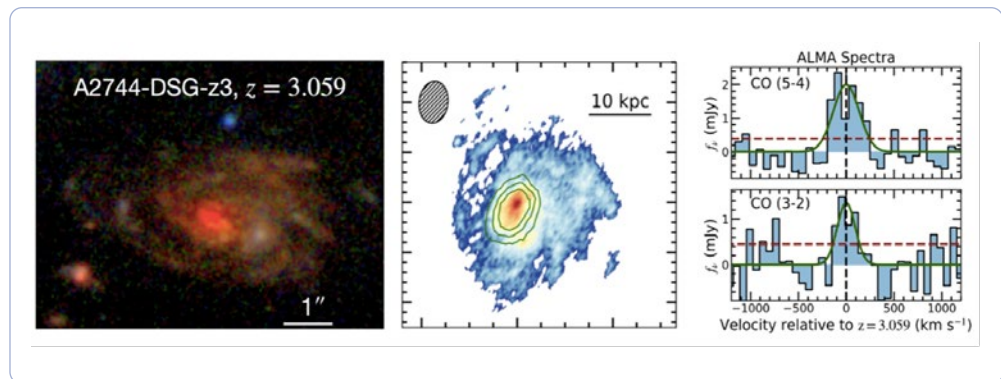
The order of magnitude decline in the cosmic star formation rate density over the last 10 Gyr is a well constrained, but not well understood, phenomenon. It has long been assumed that the cause for cessation of star formation in galaxies is depletion of the molecular gas via strong winds and shocks driven by the star formation itself. SDSS J1448+1010, at  $z = 0.65$ , is a post-merger galaxy which had a sharp drop-off in star formation some 70 Myr ago. **ALMA** observations of CO(2-1) emission show that this system still has plenty of molecular gas, but that the gas has been torn from the main galaxy into a 64 kpc tidal stream due to the recent merger. These observations suggest an alternative mechanism for quenching star formation in galaxies via major mergers, as opposed to just starburst driven dynamics (Spilker et al. 2022, ApJ 936, L11).



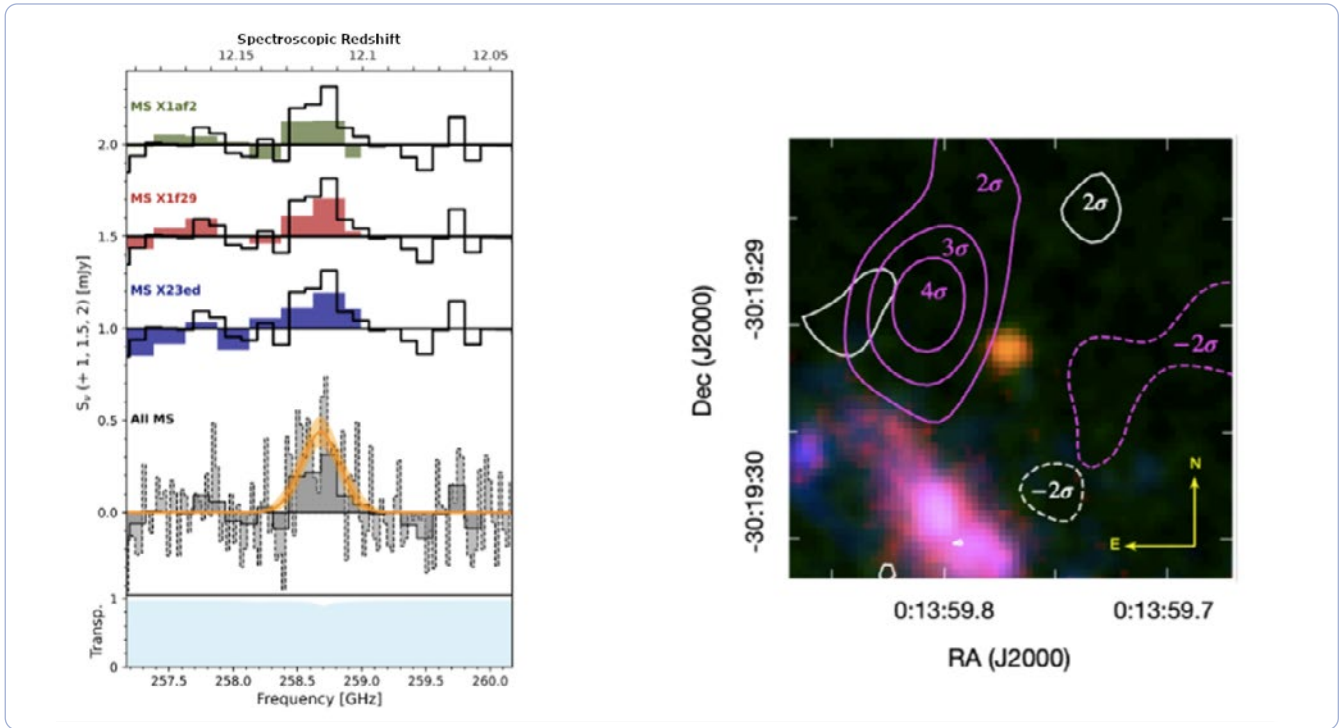
*ALMA observations of CO(2-1) emission from a post-merger, post-starburst galaxy at  $z = 0.64$ . Most of the molecular gas has been stripped into tidal tails extending 64 kpc (Spilker et al. 2022, ApJ 936, L11)*

The **VLBA** remains the only instrument that can probe AGN radio structure down to tens of pc-scales in the most distant galaxies. A recent exciting result came from 1.4 GHz VLBA observations of the low luminosity radio AGN in the  $z \sim 6$  quasar, J2242+0334. These observations imply a highly resolved radio source at 10 mas resolution (60 pc), implying a wind-like radio emitting region, and not a typical high brightness relativistic core-jet. These observations provide clues as to the nature of the radio emission from the lower luminosity radio AGN in the early Universe.

*JWST image of a grand design spiral at  $z = 3.0$ . Center: stellar mass surface density (color) and ALMA 150 GHz dust emission (green contours). Right: ALMA detection of molecular gas (Wu et al. 2022, ApJL, 942, 1).*







*Tentative [OIII] 88um emission seen by ALMA at 256 GHz, from the  $z = 12.1$  JWST galaxy candidate GLASS-z13 (Bakx et al. 2023, MNRAS, 519, 4).*

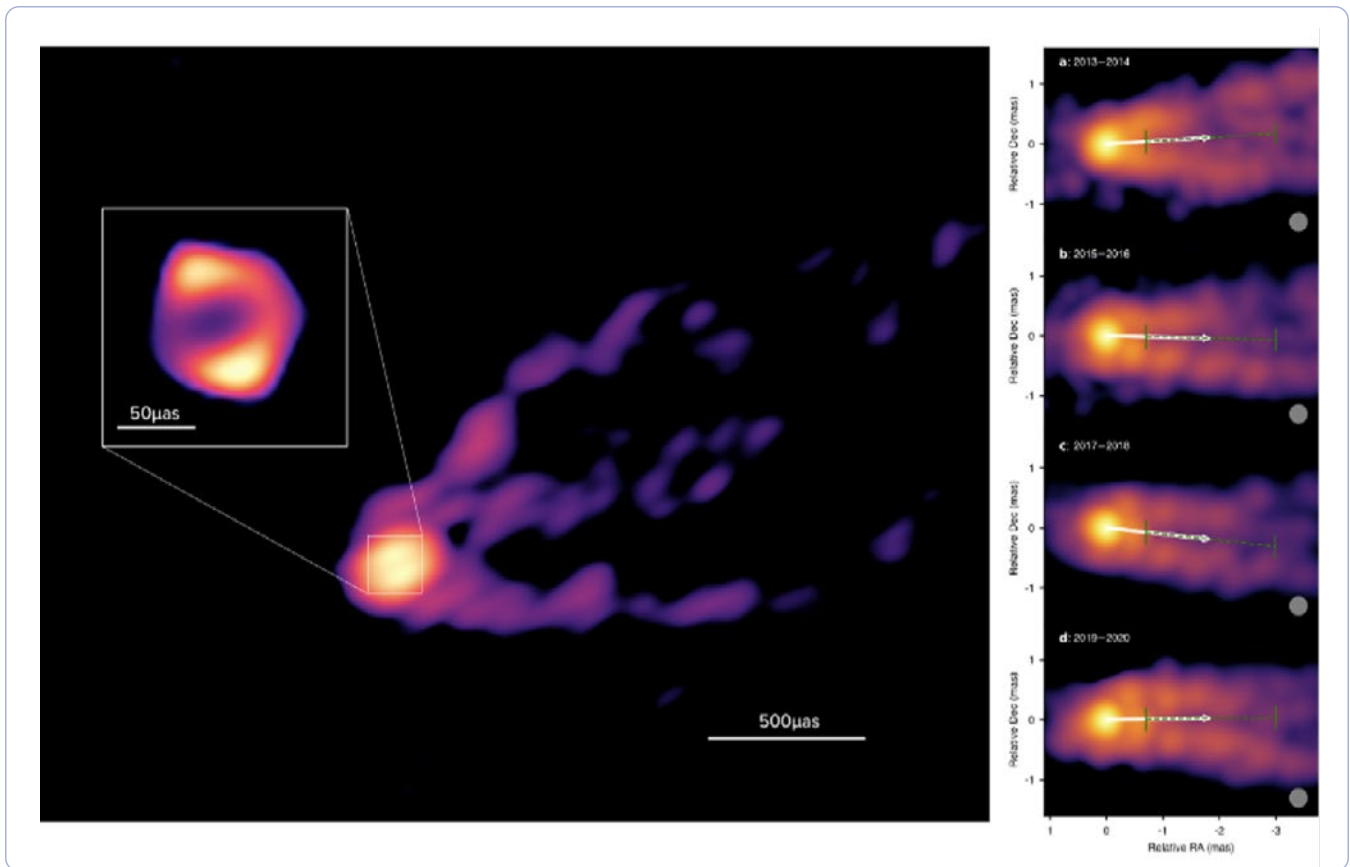
**ALMA**, working in concert with the JWST, has identified a dust and molecule rich grand design spiral galaxy at  $z = 3.06$ . The galaxy has a radius of 7 kpc, and a star formation rate of  $85 M_{\odot}/\text{yr}$ , with the dust and star formation revealed by ALMA concentrated in the galaxy center. The CO lines provided the spectroscopic redshift for this galaxy. Existence of an apparently mature, metal enriched, large spiral galaxy just 2 Gyr after the Big Bang challenges mechanisms for galaxy formation in the early Universe (Wu et al. 2022, ApJL, 942, 1).

The **ALMA** Large Programs: Reionization Era Bright Emission Line Survey (REBELS), ALMA Large Program to Investigate C+ at Early Times (ALPINE), and ALMA Lensing Cluster Survey (ALCS), have targeted identifying and performing a first characterization of many of the most luminous star-forming galaxies known in the  $z > 6.5$  universe. REBELS systematically scans 40 bright UV-selected galaxies in a 7 degree square area for bright [C II]158  $\mu\text{m}$  and [O III]88  $\mu\text{m}$  lines and dust-continuum emission. Initial results (Bouwens et al. 2022, ApJ 931, 160) identified 18 objects with [C II] emission, 13 of which also show dust continuum emission. An analysis of these search results vs. Star Formation Rate (SFR) suggests an  $\sim 79\%$  efficiency in scanning for [CII] when the  $\text{SFR}(\text{UV}+\text{IR})$  is in excess of  $28 M_{\odot} \text{ yr}^{-1}$ .

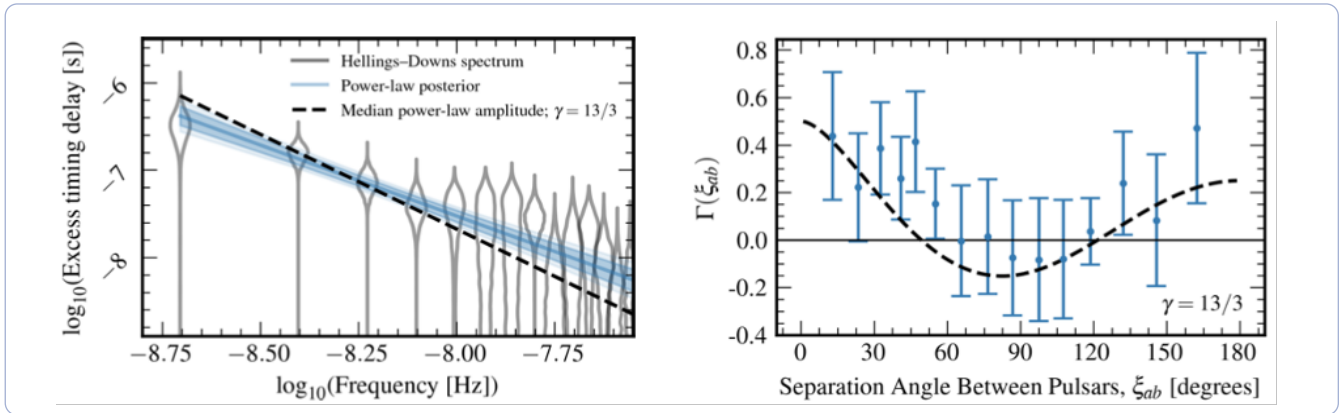
The first ultra-deep fields with the JWST have identified an unexpectedly large number of extreme redshift galaxy candidates at  $z > 10$ , or within 500 Myr of the Big Bang. However, these first galaxy candidates are based on photometric redshifts only—spectroscopic verification of the redshifts remains critical. **ALMA** provides the unique potential to obtain spectroscopic redshifts using fine structure lines. **ALMA** has observed the  $z \sim 12.0$  JWST candidate, GLASS-z13, at 250 GHz, searching for both the [OIII] 83um line and thermal continuum emission. Non-detection of the dust continuum implies a dust-poor galaxy, consistent with the blue optical color. A marginal ( $4\sigma$ ) detection is made of the [OIII] line at  $z = 12.1$ , offset by  $0.5''$  from the optical galaxy. While the probability of this line being noise remains significant (Kaasinen et al. 2022, A&A, 671, A29), the general point remains that ALMA can be an important tool in the spectroscopic verification, and characterization, of the first galaxies candidates from JWST (Bakx et al. 2023, MNRAS, 519, 4).

## Time Domain and Fundamental Physics

The NRAO facilities are critical for imaging Super Massive Black Holes (SMBH) down to scales of the general relativistic shadow of the SMBH. The latest result on the SMBH in M87 (Cui et al. 2023, Nature, 621, 7980, 711) from global VLBI at 3.5mm, anchored by the **VLBA**, **ALMA**, and the **GBT**, shows a 64  $\mu\text{s}$  diameter asymmetric ring, or  $8.4 R_s$ , similar to that seen at 230 GHz by the EHT, but larger in radius by about 50%. The observations also, for the first time, trace the jet down to this ring, possibly indicating a wind driven by the accretion disk. The difference in the M87 ring radius at 90 GHz vs 230 GHz remains a puzzle. Regardless, the fact that the Global 3mm VLBI Array (GMVA) can resolve such a ring, and trace the ring-disk connection down to scales of a few  $R_s$ , opens a new window of opportunity for the **ngVLA** to contribute to future global VLBI experiments at 90GHz, providing dramatic improvements in both the uv-coverage and the total collecting area. Including the **ngVLA** in the GMVA provides baselines that can image structures from 50  $\mu\text{s}$  to  $50''$  at 90 GHz. The **VLBA** has also recently shown a precessional period of 11 years for the M87 jet, consistent with a spinning black hole that induces the Lense-Thirring precession of a misaligned accretion disk.



Left: Global 3.5mm VLBI image down to 37 microarcseconds (hyper-) resolution, including the VLBA, GBT, and ALMA, of the SMBH and jet in M87 from scales of a few gravitational radii to a few parsec (Lu et al. 2023, Nature, 616, 686). Right: VLBA 43 GHz observations showing jet precession with an 11 year period (Cui et al. 2023, Nature, 621, 7980, 711).



Results from the NANOGrav pulsar timing array showing the spectrum of timing residuals for the pulsar array, and the large scale spatial correlation indicative of very low frequency gravitational waves traversing the Galaxy (Agazie et al. 2023, ApJL, 951, 1)

The NRAO facilities also played a major role in the remarkable discovery of a background of low frequency (nanohertz) gravitational radiation, likely arising from merging supermassive black holes distributed throughout the Universe, with a possible contribution from cosmic structure formation during the inflationary epoch, within 10-32 seconds of the Big Bang. The North American Nanohertz Observatory for Gravitational Waves (NANOGrav; Agazie et al. 2023, ApJL, 951, 1) project is a pulsar timing array, comprised of radio telescopes that monitor millisecond pulsars distributed across the Galaxy. Passage of large scale gravitational waves bend space time between these pulsars and the Earth, leading to a characteristic spatial and temporal signature in timing residuals on yearly timescales for the pulsar distribution. The **GBT** and Arecibo were the primary telescopes involved, with an important contribution from the VLA for low declination pulsars. These results are yet another extraordinary contribution by radio astronomy to our understanding of general relativity and cosmology.

The **VLA** is the state-of-the-art survey of the faint, time variable radio sky. One recent discovery from the VLASS was an extreme radio flare from a likely Tidal Disruption Event (TDE)— the disruption of a star as it falls into a SMBH, in a Seyfert galaxy at  $z = 0.074$ . The radio data include a factor of 100 brightening over a decade, suggesting the formation of a relativistic radio jet over a few years, while X-ray and IR data imply the coeval development of an accretion disk. These data provide further evidence for a fundamental relationship between the formation of relativistic jets and Active Galactic Nuclei (AGN) accretion disks (Somalwar et al. 2023, ApJ, 945, 142).

Time domain and ultra-high resolution large programs continue at the **VLBA** for synoptic imaging of powerful radio jets, including the Monitoring Of Jets in Active Galactic Nuclei with VLBA Experiments (MOJAVE) program on radio AGN, and the Blazars Entering the Astrophysical Multi-Messenger Era (BEAM-ME) program targeting Blazars, likely to be the sources of extragalactic neutrinos. The **VLA** has programs geared toward studying the electromagnetic counterparts to gravitational wave sources.

## Star and Planet Formation and Evolutional Physics, and the Search for Life

The NRAO facilities are uniquely suited for the study of stars, star formation, and planet formation. **ALMA** and the **VLA** remain the primary tools for imaging planet formation in proto-planetary disks, while the **VLBA** has produced the first images of what are likely aurorae and radiation belts associated with a low mass brown dwarf, possibly indicating strong star-planet interaction.

Magnetic fields play an important role in star formation, but direct measurements remain scarce. The **VLA** has demonstrated a new method to measure magnetic fields in star forming clouds using the Zeeman effect in the 38.3 and 38.5 GHz Class II methanol ( $\text{CH}_3\text{OH}$ ) masers (as opposed to the classic 6.7 GHz methanol masers). Zeeman measurements of the massive star forming region NGC 6334 find magnetic fields in the range 8 to 46 mG. Since Class II methanol masers are radiatively pumped close to the protostar, occurring in the accretion disk or the interface between the disk and outflow regions, such fields have significant impact on the dynamics of these disks (Momjian and Sarma 2023, ApJ, 958, 1, 75).

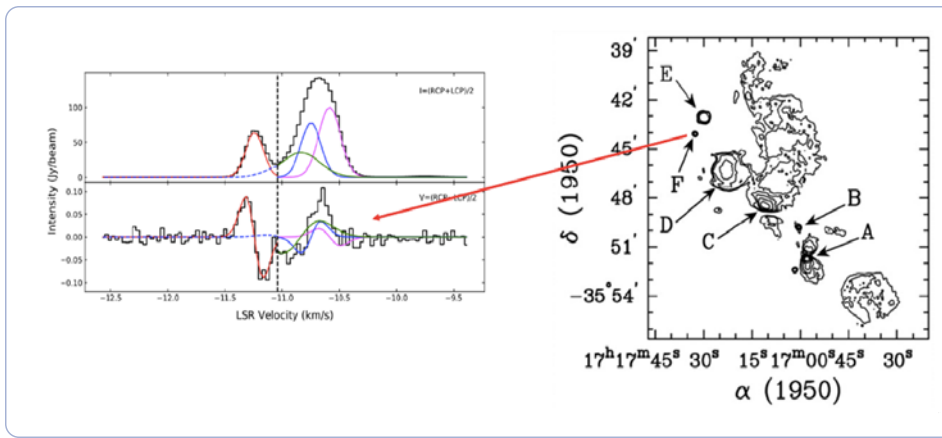
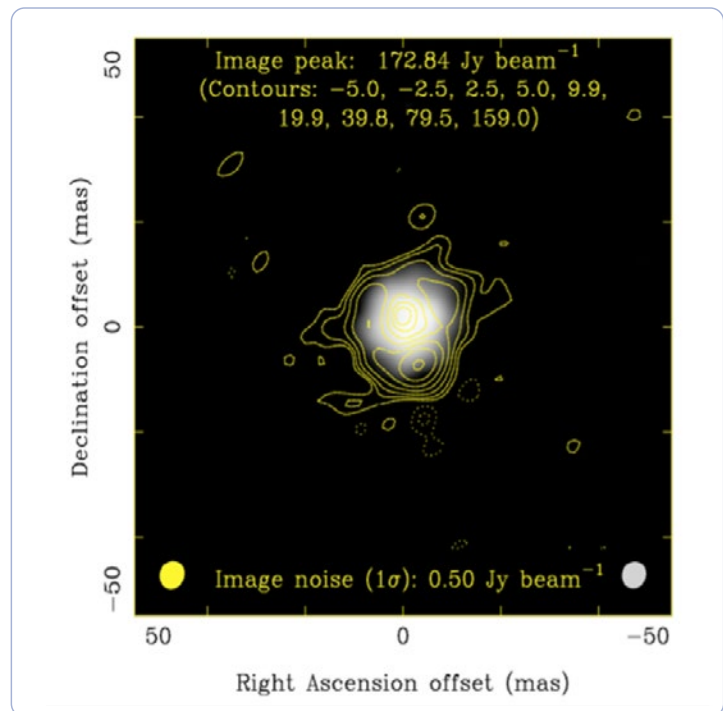


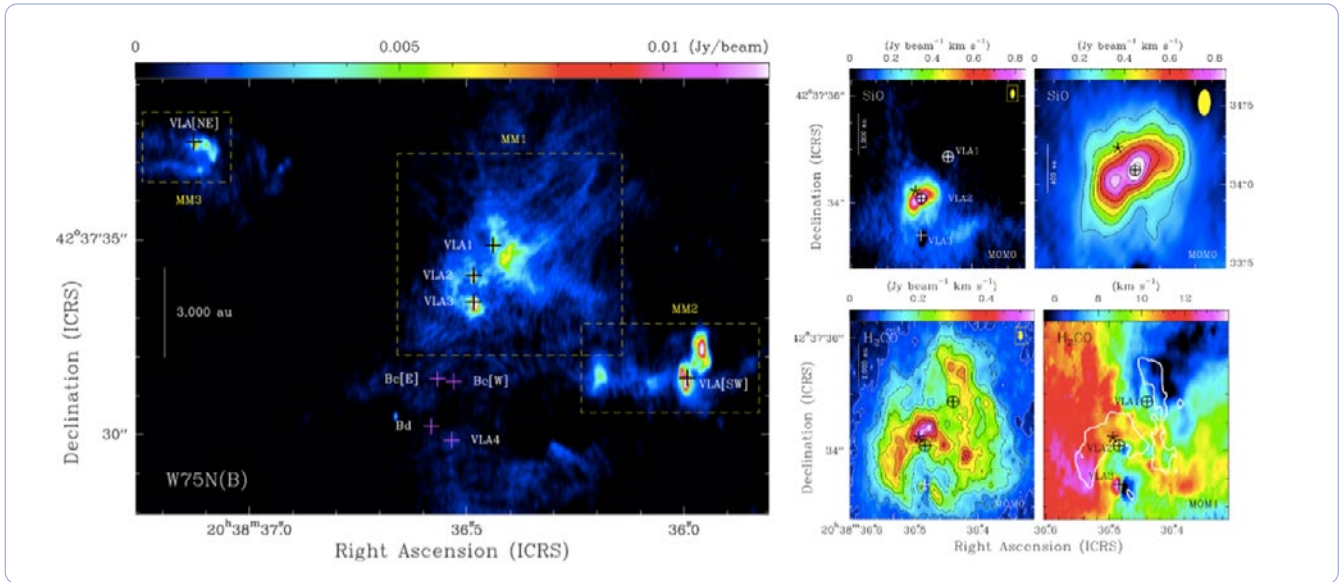
Image of the massive star forming region NGC 6334 at 1.67 GHz plus the Stokes I and V spectra of the methanol lines from feature F, from which magnetic fields are derived from the Zeeman effect (Momjian and Sarma 2023, ApJ, 958, 1, 75).

R Lep is a Mira-type Red Giant variable star, with a period of 445 days at a distance of 471 pc (Asaki et al. 2023, ApJ, 958, 1, 86). **ALMA** was used in 2021 to image the carbon-rich evolved star in Bands 8–10 (397–908 GHz) with baselines up to 16 km. The goal was to validate the calibration, using band-to-band phase referencing with a close phase calibrator. Diffraction limited resolution images were made up to the highest frequencies with resolutions of 5 mas, thereby demonstrating the potential for ALMA to perform very high resolution imaging with the longest baselines at the highest frequencies.

The **ALMA** large program Complex Organic Molecules in Protostars with ALMA Spectral Surveys (COMPASS) is in progress to study complex organic chemistry in star and planet forming regions, while the ALMA survey to Resolve exoKuiper belt Substructures (ARKS) program is targeting exo-Kuiper belt dust emission.

Image of the Mira Red Giant star, R Lep Band 10 HCN maser at 890.8 GHz, plus the continuum emission in greyscale, at 5 mas resolution (Asaki et al. 2023, ApJ, 958, 1, 86).





ALMA 1.3mm continuum image of W75(N)B at  $\sim 0.1''$  resolution. Top right: integrated line intensity of SiO emission. Lower right: the H<sub>2</sub>CO emission (Gomez et al. 2023, ApJL, 956, 2, L45).

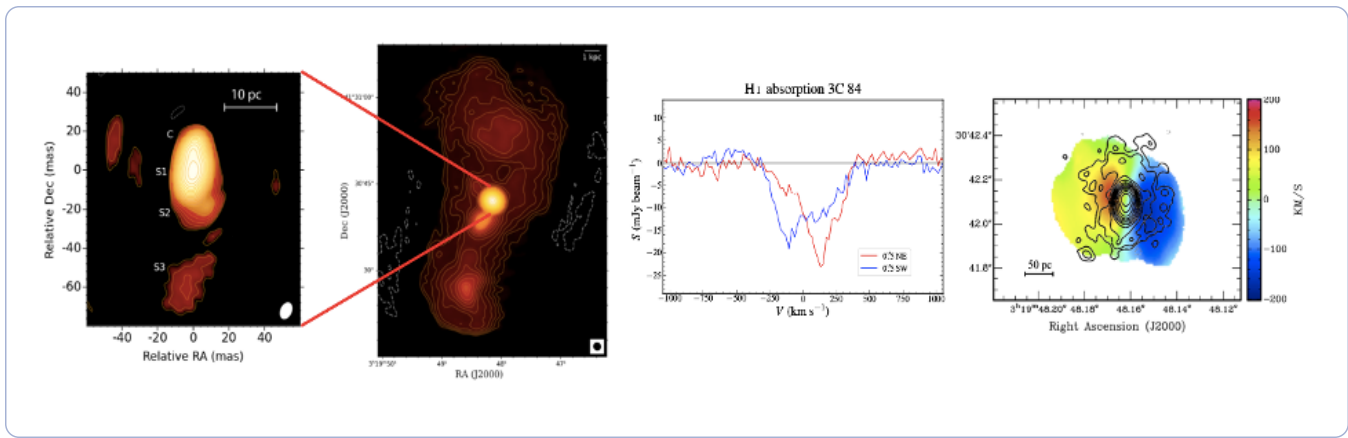
ALMA has observed the star-forming region W75N(B), containing the massive protostars VLA1, VLA2, and VLA3. VLA2 is an enigmatic protostar associated with a wind-driven H<sub>2</sub>O maser shell, which has evolved from an almost isotropic outflow to a collimated one in just 20 years, with the shell expansion halted by an obstacle located to the northeast. ALMA observations of the 1.3 mm continuum and H<sub>2</sub>CO and SiO emission show a region of  $\sim 30''$  ( $\sim 39,000$  AU) diameter, with 40 compact continuum sources, including VLA1, VLA2, and VLA3. The H<sub>2</sub>CO emission is mainly distributed in a fragmented structure around the three massive protostars. The SiO is highly concentrated on VLA2, indicating the presence of very strong shocks generated near this protostar. The SiO emission is resolved into an elongated structure ( $0.6'' \times 0.3''$ ) perpendicular to the major axis of the wind-driven maser shell. The structure and kinematics of the SiO emission are consistent with a toroid and a wide-angle outflow surrounding a central mass of  $\sim 10 M_{\odot}$ , thus supporting previous theoretical predictions regarding the evolution of the outflow (Gomez et al. 2023, ApJL, 956, 2, L45).



## Galaxies and Galaxy Formation

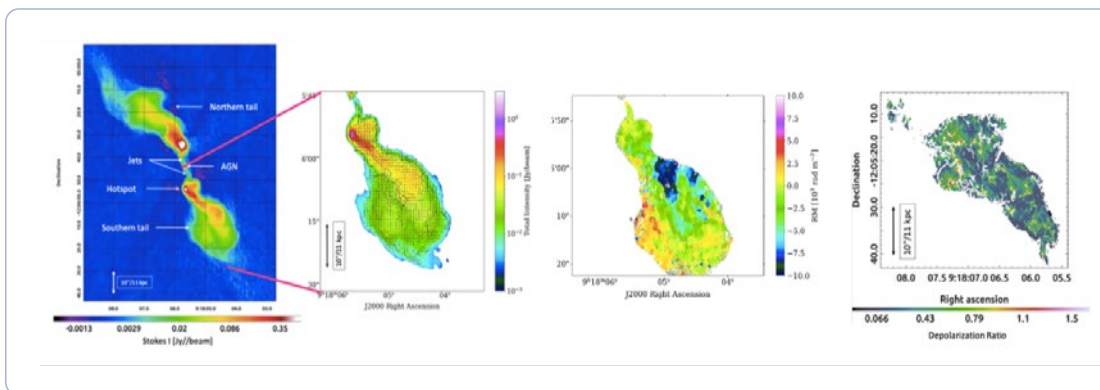
**ALMA** and the **VLA** are primary tools for studying the molecular gas out of which stars form throughout the Universe, while the ultra-high resolution of the **VLBA** can probe radio structures down to sub-parsec scales in the most distant galaxies.

The **VLA** and **VLBA** have observed HI 21cm absorption toward the radio galaxy 3C84 (Morganti et al. 2023, A&A, 678, A42), at the center of the rich Perseus cluster of galaxies. Broad HI 21cm absorption is detected (500 km/s) with the VLA toward the nucleus at arcsec resolution. The line width suggests that the detected gas is close to the SMBH, but no absorption is detected with the VLBA at 7 mas resolution. Comparison with the circumnuclear disk (CND) seen in CO emission with ALMA, shows similar velocity and spatial structure, suggesting the HI is associated with the fast rotating CND down to 20 parsec radius. The radio continuum providing the background for absorption arises from non-thermal synchrotron emission from the star formation activity in the CND, whose presence has been reported by earlier VLBA studies.

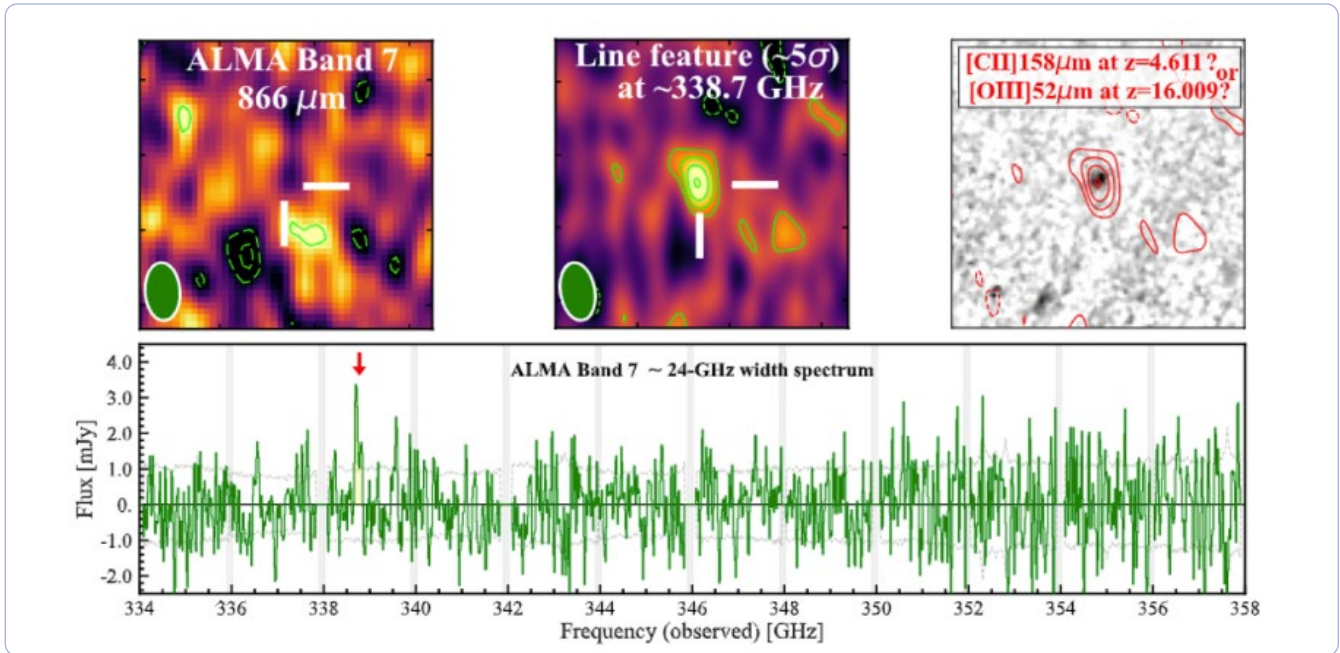


Left to right: VLBA image of 3C84 at 1.4GHz, 7 mas resolution. VLA image at 1.5" resolution. HI 21cm absorption spectra from the VLA in the inner 1" region. ALMA CO velocity field of the circumnuclear disk plus the VLBA 330 MHz image (Morganti et al. 2023, A&A, 678, A42).

Multifrequency **VLA** observations of the prototype Fanaroff-Riley (FRI) radio galaxy, Hydra A (Baidoo et al. 2023, ApJ, 955, 16), reveal extreme Faraday rotation measures (RM), with magnitudes as large as  $-12300 \text{ rad m}^{-2}$ , the majority of which arises in the magnetized thermal cluster gas. The radio emission also depolarizes systematically with decreasing frequency and decreasing resolution. These results can be modeled by a Faraday screen of magnetized cluster gas, external to the radio lobes, with field strengths of a few mG, and with both large scale ordered fields on tens of kiloparsec scales, plus turbulent field structures down to scales of 1 kpc, or less. Such fields have important implications on cluster thermal conductivity and turbulence.



VLA polarimetric imaging of Hydra A, from left to right: total intensity at 2GHz, 1" resolution; magnetic field vectors; rotation measures; depolarization at 6 GHz from 3" to 0.5" resolution (Baidoo et al. 2023, ApJ, 955, 16).



Top: images of dust continuum (non-detection), possible [OIII] 88μm emission, and the JWST near-IR image of a  $z \sim 16$  JWST galaxy candidate (Fujimoto et al. 2023, ApJ, 955, 130). Bottom: ALMA spectrum at Band 7.

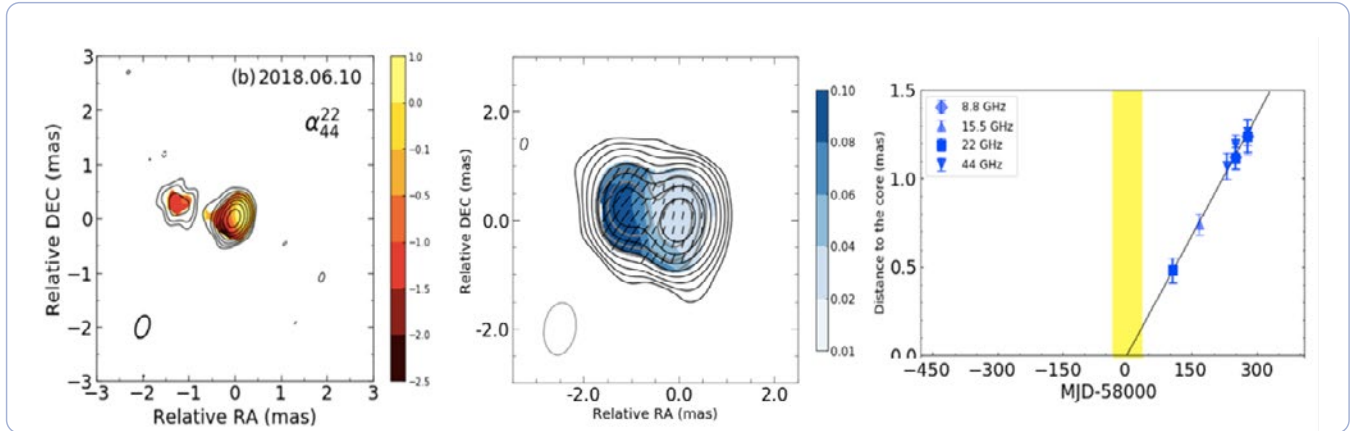
One of the most impressive results from JWST has been the discovery of ultra-high- $z$  galaxies, out to  $z \sim 16$ , or a look-back time of 13.5 Gyr (the Big Bang occurred 13.7 Gyr ago). The mere existence of these ultra-redshift galaxies presents an interesting challenge to models of galaxy formation and cosmology. **ALMA** provides the unique ability to image the gas and dust in these first galaxies. **ALMA** is now regularly detecting fine structure line emission from  $z \sim 8$  to 10 galaxies, revealing gas physical conditions, distribution, and dynamics, complimenting JWST studies of the stars and gas. For the current JWST redshift record holder, a candidate galaxy at  $z_{\text{phot}} \sim 16$ , a tantalizing spectral feature seen with **ALMA** may be [OIII] 52μm emission at this redshift, but requires confirmation, since it could be [CII] 157 μm emission at  $z = 4.6$ . Study of the gas and dust in the ultra-high redshift universe promises to become a major growth area for ALMA in the coming years (Fujimoto et al. 2023, ApJ, 955, 130).



Photo by Pablo Carrillo, ALMA

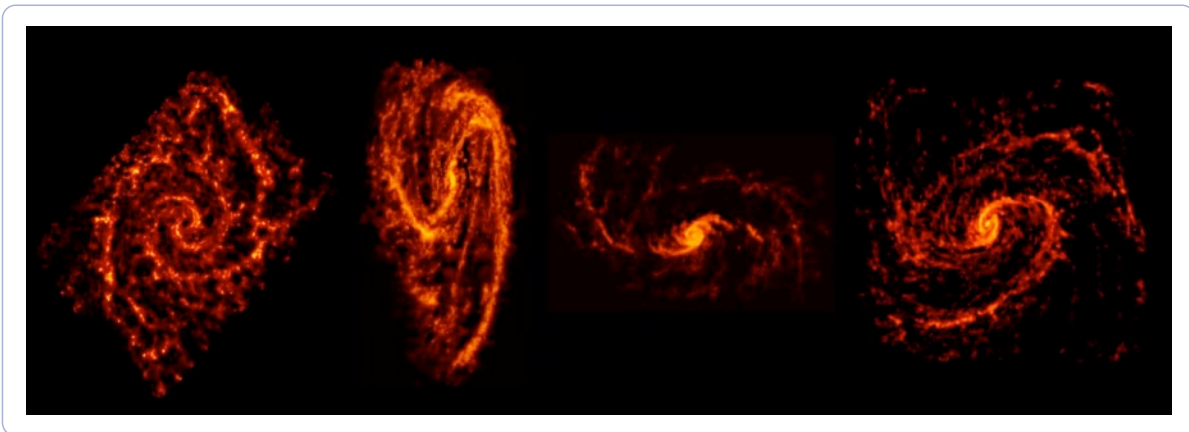
## Galaxies and Galaxy Formation

The VLBI has observed M81\*, one of the closest low-luminosity active galactic nuclei, at 8.8, 22, and 44 GHz. A bright knot in the core-jet is seen at 1.2 mas distance (0.023 pc) from the core. Multi-epoch observations show that the knot has a low apparent speed of 0.1c. X-ray observations show a moderate X-ray flare occurred when the knot launched from the core region. Three possible origins are currently possible: an episodic jet ejection, a low-speed shock wave, or a possible secondary black hole in a binary system (Wang et al. 2023, ApJ, 957, 2, 107).



Left: An image of the core and bright knot in the core-jet in M81\* at 22 GHz with a resolution of 0.4 mas, plus the spectral index between 22 GHz and 44 GHz. Center: fractional polarization of the system at 8.8 GHz plus polarization vectors. Right: measure proper motion of the knot (Wang et al. 2023, ApJ, 957, 2, 107).

The first results from the Physics at High Angular Resolution in Nearby Galaxies (PHANGS; Leroy et al. 2021, ApJS, 257, 43) large program at ALMA have appeared, which, in concert with the JWST, has produced spectacular images of the relationship between the molecular gas, dust, stars, and star formation down to tens of parsec scales in a large sample of nearby galaxies. At higher redshift, the ALMA Large Proposal of galactic Cold gAs (ALPACA) program is probing the molecular gas in a large sample of galaxies at the peak epoch of galaxy formation,  $z \sim 1$ .



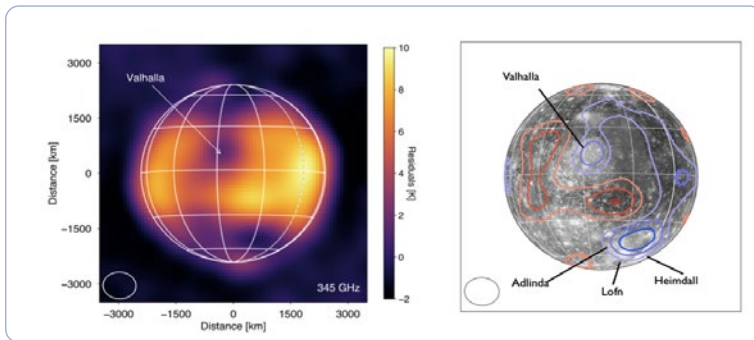
Galaxies imaged with ALMA from the PHANGS large program (Credit: ALMA/ESO/NAOJ/NRAO/PHANGS, S. Dagnello NRAO; Leroy et al. 2021, ApJS, 257, 43).



## Solar System and Planetary Science

The NRAO facilities remain the paramount tools of radio astronomy in the study of planetary science and Solar physics. Working in concert with space missions and ground-based facilities, the **VLA**, **ALMA**, and **VLBA** have contributed in the last year in areas ranging from the energy source of the Solar chromosphere, to winds, storms, and polar vortices in the atmospheres of Saturn, Uranus, Neptune, and Jupiter, to the surfaces of Kuiper belt objects and volcanos on Io.

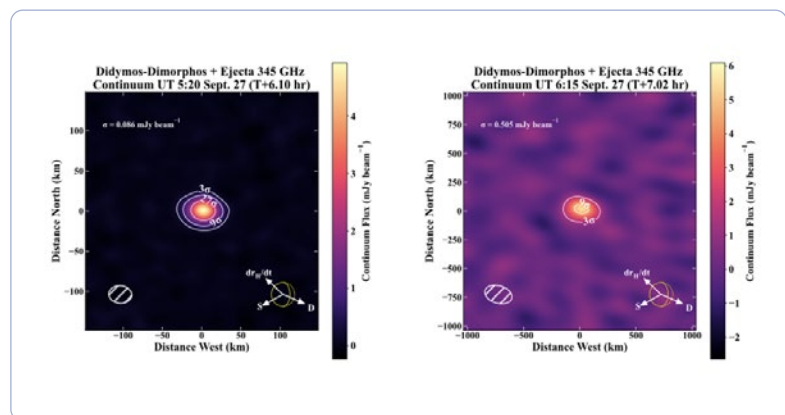
Callisto is the least geologically active of the Galilean moons of Jupiter (Camarca et al. 2023, *The Planetary Science Journal*, 4, 8, 142). ALMA 343 GHz observations at 0.16" resolution find a mean disk thermal brightness temperature of 116 K. The data suggest a regolith with two very different thermal inertial components. They also identify several thermally anomalous regions, including spots ~3 K colder than model predictions co-located with the Valhalla impact basin and a complex of craters in the southern hemisphere, indicating the presence of materials possessing either a higher thermal inertia or a lower emissivity. A warm region confined to the mid-latitudes may be indicative of regolith property changes due to exogenic sculpting.

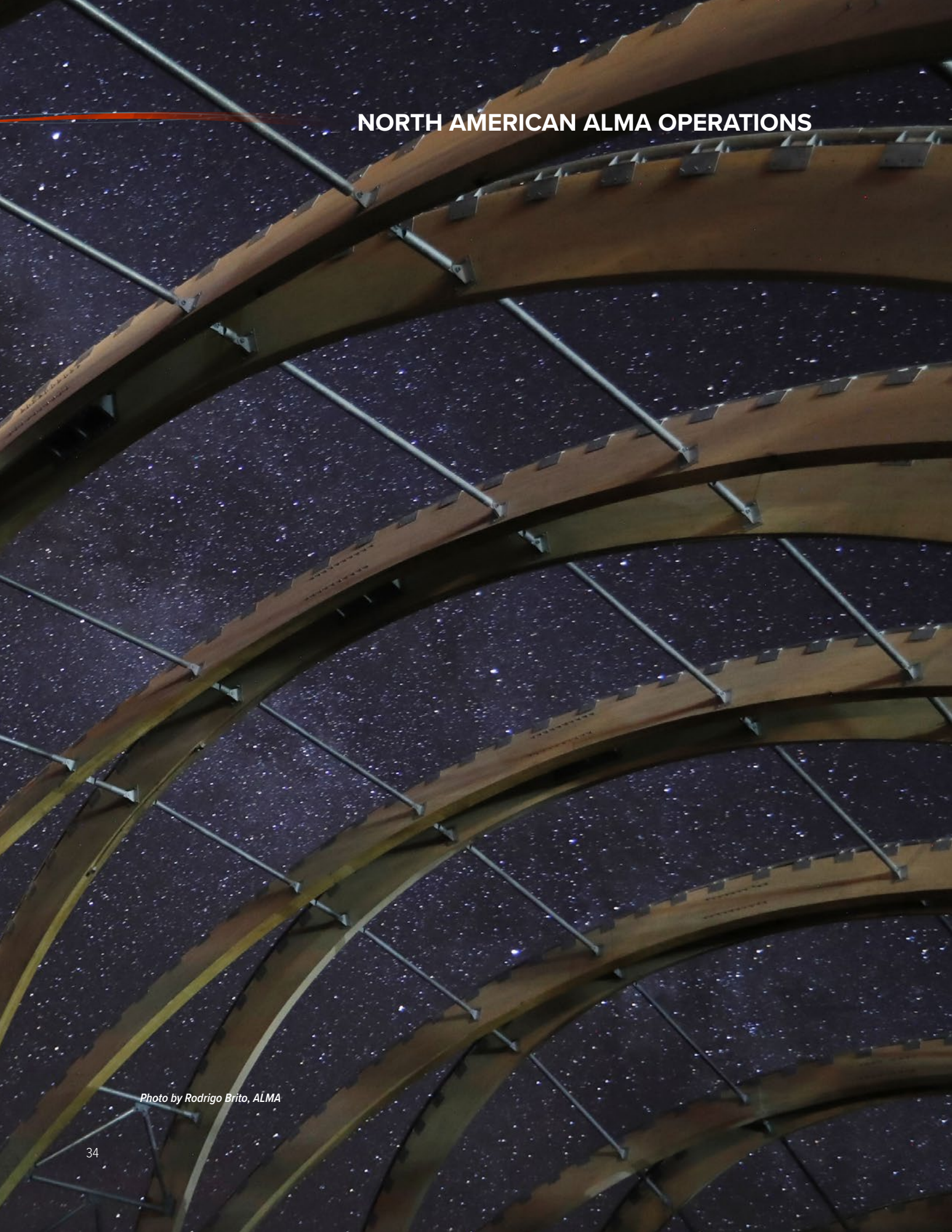


*ALMA 343 GHz image of Callisto at 0.16" resolution with mean disk emission subtracted. Right: ALMA contours plus the albedo map from Voyager and Galileo imaging (Camarca et al. 2023, *The Planetary Science Journal*, 4, 8, 142). A few crater impact regions are indicated, showing higher albedo and cooler mm thermal emission.*

**ALMA** played an important role as a ground facility in the Double Asteroid Redirection Test (DART; Roth et al. 2023, *The Planetary Science Journal*, 4, 11, 206)— a deep space probe designed to investigate the effect of satellite impact on asteroid orbits, as part of the kinetic impactor planetary defense technique program at NASA. ALMA detected thermal emission from the asteroid at 345 GHz both before and after impact. The comparison of the two observations provide the most sensitive measurement of mm-sized ejecta caused by the impact. Depending on the material composition, the ejecta mass was ~ few  $\times 10^7$  kg, representing about 1% of Dimorphos' total mass.

*ALMA 12m and ACA 345 GHz images of the Didymos-Dimorphos binary asteroid system after impact of the DART deep space probe (Roth et al. 2023, *The Planetary Science Journal*, 4, 11, 206).*



A photograph of the ALMA (Atacama Large Millimeter/submillimeter Array) antenna structure. The image shows several curved, brownish-gold metal ribs that form the shape of the antenna's dish. These ribs are supported by a network of silver-colored metal struts. The background is a dark, starry night sky with numerous small, bright stars. The overall composition is a close-up, low-angle shot looking up at the structure.

# NORTH AMERICAN ALMA OPERATIONS

*Photo by Rodrigo Brito, ALMA*

North American ALMA Operations (NA ALMA Ops) is the NRAO department that provides North America’s scientific and technical partnership support to the international ALMA Observatory and supports the North American community in their use of ALMA. NA ALMA Ops ensures that the North American scientific community has the tools, information, support, and access to make optimal scientific use of ALMA. It also provides scientific, technical, and business support to Observatory operations in Chile in concert with the Joint ALMA Observatory (JAO) staff and international partners, and supports a long-term development program for the technical enhancement of ALMA.

NA ALMA Ops includes four divisions: (1) the North American ALMA Science Center (NAASC); (2) the Offsite Technical Maintenance and Support group, including Construction Warranty support; (3) the NA ALMA Development Program; and (4) the NRAO/AUI Office of Chilean Affairs (OCA).

**NA ALMA Ops focused on the following high-level initiatives from 2021-2023:**

- Support JAO Operations and the NA science community with the Cycles 8,9 & 10 Supplemental Call for Proposals utilizing a dual-anonymous proposal review process and Distributed Peer Review (DPR), including the roll-out of joint proposals;
- Continue to expand the ALMA user base to early career researchers and other astronomy subdisciplines;
- Continue to support the NRAO SRDP strategic initiative while continuing to meet ALMA core deliverables;
- Facilitate NA Principal Investigators (PI) in the publication of their ALMA results by providing and enhancing tools, training, and assistance; to this end, continue support of the NRAO Science Ready Data Products initiative;
- Support the ALMA-wide implementation of the Development Roadmap Wideband Sensitivity Upgrade (WSU), including key NA deliverables; submit the Second-Generation Correlator System for approval by the ALMA Board;
- Initiate the strategic plan to expand the ALMA user-base beyond the radio, millimeter, and submillimeter experts;
- Complete the construction of the Multicancha—the multi-purpose staff recreation center at the ALMA Operations Support Facility (OSF);
- Prepare for the next collective bargaining agreements with the two unions of ALMA local staff
- Participate in the implementation of the ALMA 2030 Development Roadmap through NA projects and collaborations, and collaborate on long-range visions for ALMA.
- Enhance and expand PROVOCA, the successful mentoring program that promotes greater participation and retention of girls and women in Science, Technology, Engineering, and Mathematics (STEM) careers.

From 2021-2023, the NAASC focused on the restart of Cycle 7 observations, followed by the successful execution of Cycle 9 and the Cycle 10 Call for Proposals. The NAASC continued to prepare for new ALMA capabilities which will stem from the ALMA 2030 development roadmap, and continued to develop a strategic plan for a shift in priorities (and possible expansion into new areas of software and heuristic development) through the 2030s. NAASC staff continued to focus on user- and telescope-facing tasks, data analysis, and development.

## A New Multicancha Facility

During the operations phase of the Observatory, the OSF is the workplace of some ALMA astronomers and of the teams responsible for maintaining proper functioning of all the telescopes. The ALMA team working at the telescope at the OSF generally work on a turno, living on-site for eight days or so at time before rotating back to their homes. To support the health and welfare of these workers, ALMA North America has recently completed a covered multi-court indoor sports facility, the Multicancha, providing activity space sheltered from the tropical sun and from the dust-bearing winds that scour the site. An Opening Ceremony for the Multicancha was held March 14, 2023, following the March 13 ALMA 10th Anniversary Celebration, also at the OSF.



# NORTH AMERICAN ALMA OPERATIONS

## North American ALMA Science Center

Coming out of the COVID-19 pandemic, the NAASC made excellent progress on its strategic goals for 2021-2023. The ALMA Community Support group interfaces with the North American ALMA user community and supports initiatives such as ALMA Ambassadors and the face-to-face visitor program. The primary goal of the Community Support Group is to improve the end-user experience of ALMA for the scientific community. In FY2023, the ALMA Community Support group performed its core services and planned initiatives, fulfilling its interface role with the North American ALMA user community and the astronomy community at large. Community outreach activities, including initiatives aimed at expanding the ALMA user base, were reinforced by the creation of a dedicated community programs team and new hires.



*ALMA Cycle 10 Ambassadors during the February 2023 training at NRAO headquarters in Charlottesville, VA.*

**Community Support and Outreach:** The NAASC hosts multiple outreach forums designed to increase and facilitate the use of ALMA by the scientific community. The NAASC continued to execute a portfolio of initiatives engaging the astronomy community at large. A new dedicated Community Programs team was established to strategically address three main outreach goals: supporting the general astronomy community in their use and understanding of ALMA and WSU; facilitating scientific productivity; expanding the user base by increasing geographic and scientific participants.

The NAASC organized, supported, and hosted numerous events across North America and Chile to inform, support, and train astronomers on how to propose for and use ALMA data. The flagship ALMA Ambassadors program continued based on the incredibly successful format developed by NRAO/NAASC scientists. The program trains a yearly cohort of early career astronomers to hold proposal preparation and data reduction workshops at their institutions for new and prospective users. The NAASC also hosted a Special Session at the American Astronomical Society (AAS) meeting in Seattle, Washington, January 2023 on the Wideband Sensitivity Upgrade (WSU).

Events were held in webinar form online in 2021, transitioning back to in person events in 2022-2023. The NAASC was a major contributor and/or host to many webinars, workshops, and scientific meetings. The list below summarizes the community contributions hosted by the NAASC, including those hosted and run by the ALMA Ambassadors.

### 2021 Webinars

- *Extragalactic magnetism with ALMA and SOFIA*, Enrique López-Rodríguez (KIPAC/Stanford)
- *Far-infrared Ionized Carbon Emission: the Missing Piece of the ISM Puzzle*, Alberto Bolatto (University of Maryland)
- *Accretion outburst from a massive protostar: a sequence of extraordinary observational results*, Todd Hunter (NRAO)
- *The Force Awakens: How a Growing Black Hole Affects its Host Galaxy*, Allison Kirkpatrick (Kansas University)
- *Tracing the formation/evolution of planetary debris disks with multiwavelength approaches*, Kate Su (University of Arizona)
- *Mapping the surfaces properties of icy and rocky Solar System worlds*, Katherine de Kleer (Caltech)

## 2022 Events

- *Our Galactic Ecosystem: Opportunities in the Infrared and Beyond*, Lake Arrowhead Lodge, CA, February 2022
- *ALMA Support for the 18th Synthesis Imaging Summer School*, Socorro, NM, May 2022
- *75th International Symposium on Molecular Spectroscopy*, in Champaign, Illinois, June 2022

## 2023 Events

- *exoALMA Large Program Workshop* (Boston, MA)
- *DECO Large Program Workshop* (Charlottesville, VA)
- *Gordon Research Conference on Origins of Solar Systems* (South Hadley, MA)
- *76th International Symposium on Molecular Spectroscopy* (Champaign-Illinois, IL)
- *COMPASS Large Program Workshop* (Ann Arbor, MI)
- *Kavli-AUI Symposium, Astrochemistry VIII* (Traverse City, MI)
- *New Era of AGN Science with the Vera C. Rubin LSST* (Charlottesville, VA)
- *The Evolution of Gas in and around Galaxies* (Stanley, ID)

## ALMA Ambassadors, Proposal Preparation, and Data Processing Events

<b>Dates</b>	<b>Location</b>	<b>Ambassador</b>
March 28, 2022	Stanford University	Wren Suess
March 29, 2022	University of Maryland	Nathan Roth
March 29, 2022	Montana State University	Hansung Gim
March 30, 2022	Yale University	Cheng-Han Hsieh
April 01, 2022	Northwestern University	Tarraneh Eftekhari
April 02, 2022	University of Alabama	Hansung Gim
April 08, 2022	University of Arizona	Fengwu Sun
October 05, 2022	University of Florida	Allison Towner
October 05, 2022	University of Arizona	Fengwu Sun
October 11, 2022	Montana State University	Hansung Gim
October 18, 2022	University of Maryland	Nathan Roth
October 24, 2022	Stanford	Wren Suess
October 26, 2022	University of Colorado, Boulder	Hayley Roberts
October 26, 2022	CfA / Harvard University	Charles Law
October 28, 2022	Northwestern University	Tarraneh Eftekhari
April 18, 2023	MIT Haystack	Dongjin Kim
April 14, 2023	University of Texas, Austin	Arianna Long
April 14, 2023	Universidad Católica del Norte	David Rebolledo
April 18, 2023	Canadian Inst. for Theoretical Astrophysics	Jiayi Sun
April 19, 2023	University of Massachusetts, Amherst	Sinclair Manning
April 20, 2023	West Virginia University	Emily Moravec
April 20, 2023	University of British Columbia	Adam Dong
April 26, 2023	IPAC/Caltech	Marion Villenave
April 27, 2023	Universidad Diego Portales	Miguel Vioque
Sept 13, 2023	University of British Columbia	Adam Dong
October 05, 2023	West Virginia University	Emily Moravec
October 05, 2023	Villanova	Dylan Paré
October 19, 2023	National Solar Observatory	Johnathan Stauffer
October 23, 2023	JPL, Pasadena, CA	Marion Villenave

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**User Documentation:** ALMA end user documentation preparation is an annual task in which the NAASC takes a leading role supporting the JAO. The documentation preparation and review include the upcoming Call for Proposals, Proposer's/Users' Guide, ALMA Primer, ALMA Technical Handbook, Guide to the NA ARC, software user guides (including CASA Guides) and additional documentation on how to access NAASC services. The team participates in the international ALMA working groups that prepare these documents for the user community. NAASC staff again took a lead role in the preparation of the new Cycle 10 Call for Proposals and user documentation, including all updates and edits to the ALMA Science Portal. As in Cycles 8 and 9, the Cycle 10 proposal process included dual-anonymous and Distributed Peer Review (DPR). The NAASC provided clear instructions to proposers on the impact of DPR and dual-anonymous review on proposal construction and processing.

**Face to Face Visitor and Helpdesk Support:** The NAASC provides overall management of ALMA Helpdesk activities including routine ticket reviews, enforcement of ticket service-level agreements, and formulation of new Knowledgebase articles based on user questions. Face-to-face (f2f) support includes hosting up to one to two data processing teams from NA institutions per week at the NA ALMA Regional Center (ARC) in Charlottesville, VA or at the National Research Council (NRC) in Victoria, British Columbia, Canada. The visiting teams work with the NAASC data analysts and NAASC or NRC scientific support staff on various aspects of data processing and image analysis. In FY2021, the NAASC continued hosting face-to-face (f2f) visitors despite the COVID-19 pandemic. This was managed by moving the visits virtually and then f2f when scientific visitors were allowed back into NRAO facilities. The NAASC was able to host seven virtual f2f visitors with the first in-person visit in Q4 FY2021. FY2022, as the global pandemic subsided, the NAASC resumed data reduction visits in the traditional, f2f format, as well as continuing to offer f2f visits in the virtual format. In FY2023, the NAASC continued to offer data reduction visits in the traditional in-person format as well as virtually.

**Data Processing:** A main objective of the Data Processing Workflow is to deliver fully calibrated data and representative images of ALMA standard observing modes to PIs within 30 days of the date of last successful execution on the array. In FY2023, NAASC staff continued to work closely with the JAO teams to deliver to the NA ALMA user community an average of 26 datasets per week and a peak rate of 35 data sets per week in some quarters. From Q1 through Q4 FY2023, the staff delivered 229, 456, 403, and 271 data sets, respectively, where Q1 was lower owing to the cyberattack and Q4 lower owing to long baselines. This rate of delivery maintained pace with data acquisition to prevent a data processing backlog. The NAASC continued to coordinate and manage the calibration, imaging, and delivery of PI data products through the ALMA Archive and continued to provide North American PIs access to calibrated Measurement Sets (MS) and value-added data products generated by the ALMA Data Mining Toolkit (ADMIT). The team provided summary reports on data processing and delivery as needed and projections of anticipated workload on a quarterly basis.

**Telescope Interface and Diagnostics:** The Telescope Interface and Diagnostics group is the NAASC technical liaison to the JAO. Communication and interaction between the ARCs and the JAO via this group is of critical importance to ALMA project success. The ALMA Telescope Interface and Diagnostics group was responsible for the activities described below.





**Phase 2 Group (P2G):** NAASC P2G staff provide the technical expertise to review and set up Phase 2 materials (Scheduling Blocks, or SBs) submitted by NA PIs for an observing cycle. This includes modifying SBs that require expert technical input, coordinating with the JAO to request calibrator searches, and ensuring that all SBs are ready to run on the telescope. In FY2023, P2G staff conducted the technical assessments of approved Cycle 10 programs. During a cycle, the NAASC staff also provide any SB changes required following an approved change request or other edits requested by the PI or as needed for scheduling, and also support new programs approved mid-cycle, including Director’s Discretionary Time (DDT), supplementary calls, and Observatory-type projects. In preparation for an upcoming cycle, NAASC staff participate in software testing of the ALMA Observing Tool (OT) and relevant end-to-end tests, as well as software such as the Project Tracker, and closely coordinate with the JAO, other ARCs, and OT working group on developing P2G best practices at the annual P2G face-to-face meeting.

**Contact Scientists:** NAASC staff provide oversight and support for all the approved NA ALMA PI programs for an observing cycle. This includes ensuring PIs have reviewed (and, if necessary, approved) their projects for scheduling prior to the start of a cycle, and, if needed, providing communication between PIs and the JAO during a cycle. NAASC staff also provide oversight of the status of PI SBs and, if needed, coordinate with the JAO on scheduling issues. Throughout FY2021-2023, NAASC staff continued to act as Contact Scientists (CS) and liaisons to the NA ALMA PI observing programs in support of Cycle 8 and 9 observations, and in preparation for Cycle 10 observations.

**Telescope Operations in Chile:** The NAASC coordinates with the JAO and other ARCs on scheduling of Astronomer on Duty (AoD) shifts to Chile and provision of AoDs in support of ALMA telescope operations in Chile. In the past, the NA ARC has been responsible for covering a minimum of 14 shifts in a calendar year. As a result of the pandemic, in 2021 the JAO began use of the Santiago Control Room Extension to provide remote observing with ALMA, which resulted in a significant change in AoD staffing. All Cycle 8 observing programs were assigned a contact scientist and NAASC staff

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provided support to the NA ALMA PI observing programs throughout FY2021. In FY2022, as the pandemic subsided and international travel became possible again, the NAASC resumed AoD shifts for the first time in three years, including AoD shifts from the Santiago Control Room Extension. In FY2023, the NAASC provided AoD shifts by NA ARC staff through Q1-Q4.

**Telescope Diagnostics:** The NAASC continued to play a critical role in the JAO technical and diagnostics-related meetings and teleconferences, such as the Control System and Correlator Group weekly meetings and software readiness review meetings. In FY2022-23, the NAASC continued to coordinate with the JAO on troubleshooting issues and problems found with the telescope systems or in data collection and analysis. NAASC staff also continued to maintain a close interaction between data processing and the telescope diagnostics teams at the JAO to ensure all problems are reported and tracked efficiently.

NAASC staff played an integral role in the identification and subsequent heuristic development of the so-called “renormalization issue.” In short, interferometers require data normalization for correct flux scaling. This normalization is performed by using the data from each individual antenna (the autocorrelations) in combination with the data from each antenna baseline pair (the crosscorrelations). The crosscorrelation data of each baseline are divided by the power of the autocorrelation data of each antenna in the pair. The autocorrelation data are commonly averaged over all observed frequencies. However, at ALMA, we instead divide the crosscorrelation data by the channelized autocorrelation data (i.e., the autocorrelations as a function of frequency). This enables us to obtain extremely flat amplitude baselines without having to perform fits to the data. If an observation targets a very bright, extended source (like carbon-monoxide emission in a star forming region for example) that can be easily detected by a single dish observation, that emission may show up in the autocorrelation data as well. This then leads to an incorrect normalization value in those channels where the emission was detected and therefore an under-scaling of the flux values in those channels.

## North American ALMA Development

### Completed Development Projects

#### Studies Completed in FY2021:

**Wideband Low-Noise Balanced IF Amplifiers for ALMA Band 6, with Future Application to ALMA Bands 3–10 (Lead Institution: NRAO):** This study continued the development of a balanced 4–12 GHz IF amplifier which will have lower noise than the current IF amplifiers and will not require an isolator. The balanced amplifier will have twice the bandwidth of the IF amplifiers in most of the ALMA receivers, which will allow simultaneous measurement of spectral lines more widely spaced in frequency than is currently possible.

**Band 6v2 SIS Mixer Development (Lead Institution: NRAO):** This study continued the development of a Superconductor-Insulator-Superconductor (SIS) mixer/preamplifier combination for a future ALMA Band 6 receiver upgrade. This effort included using SIS junctions with an aluminum nitride tunnel barrier instead of the usual aluminum oxide barrier, single-ended versus balanced sideband-separating (2SB) mixers to reduce LO sideband noise, IF amplifiers with and without ferrite isolators, balanced IF amplifiers (which require no isolator), a substantially expanded IF bandwidth, and a modestly expanded RF bandwidth (beyond 211–275 GHz) to cover additional spectral lines.

**Investigation into Improvement of FE LO Sideband Noise for ALMA Band 6 (Lead Institution: NRAO):** This study was a follow-up to the Band 6v2 CoDR panel recommendation to improve the LO sideband noise will enable simplification of the proposed new receiver architecture. Specifically, the Band 6v2 panel report suggests, “...investigate the options of using a single-ended mixer (with improvement of the local oscillator noise level) and using a single-ended LNA with isolator.”

**TALON-based Correlator (Lead Institution: NRC-Herzberg):** This study investigated the potential of integrating a TALON Frequency Slice Architecture (FSA) Correlator/Beamformer (CBF) into the ALMA Observatory. This includes detailing the capabilities, rack space, and power estimates for a CBF that handles the existing bandwidth and number of antennas and potential expansion for additional bandwidth and antennas. It will investigate existing ALMA CBF interfaces and document how a TALON FSA CBF could be integrated with minimal impact to ALMA systems.



**Upgraded ALMA to Imaging Planet-Forming Disks (Lead Institution: California State Univ. Northridge):** This study quantified the potential of an upgraded ALMA with improved angular resolution and continuum sensitivity, as required to detect substructures expected in planet-forming disks with sub-Astronomical Unit (AU) resolutions at wavelengths <1 mm, and with -1 AU resolution at wavelengths >1 mm. This study could have high impact on the planet formation and exoplanets field, as it would quantify the potential of an upgraded ALMA to observe and characterize forming Earth-like planets at their interaction with the natal disk.

**ALMA Reduction in the CANFAR Data Environment (Lead Institution: NRC-Herzberg):** Since the size of ALMA data sets can be a major barrier, this research built off the computing infrastructure and interfaces developed by the successful Canadian Advanced Network for Astronomical Research (CANFAR) science platform. The prototype performance and usability was fully tested to determine necessary changes, increase the prototype functionality, test the backend technology, and determine additional steps to scale out its deployment.

**Band 6v2 SIS Mixer-Preamp Development (Lead Institution: NRAO):** This study continued the development of the components for a future ALMA Band 6 receiver upgrade, referred to here as Band 6v2. The goals are: (i) to increase the IF bandwidth from the present 4 GHz per sideband per polarization to 12 GHz (4–16 GHz) or 16 GHz (4–20 GHz); (ii) to reduce and flatten the noise temperature across the full IF band; and (iii) to expand the usable RF band from the current 211–275 GHz to 211–280 GHz. While the current ALMA correlator and IF transmission system can only accommodate 4 GHz per sideband per polarization, the new receiver will take advantage of future upgrades enabling increased bandwidth.

#### **Studies Completed in FY2022:**

**Extending IF Bandwidth of the Existing Band 6 SIS Mixers (Lead Institution: NRAO):** This study reports on a preliminary look at how the planned increased bandwidth of Band 6v2 may affect its overall noise performance compared to the original Band 6 receivers.

**ALMA Band 6v2 Mixer-Preamp Development (Lead Institution: NRAO):** This study investigated several options for the ALMA Band 6v2 receiver upgrade architecture, the results of which helped guide the Band 6v2 Receiver upgrade proposal that was reviewed by the ALMA Board in Q1 FY2021.

**Regularized Maximum Likelihood (RML) Techniques for ALMA Spectral Line Imaging (Lead Institution: Penn. State Univ.):** This study developed and implemented RML algorithms for ALMA spectral line imaging, focusing on achieving high image fidelity when utilizing multi-configuration aggregate datasets. As the ALMA archive continues to mature, techniques that can accurately image large and diverse quantities of data will drive science forward in key areas that require sensitivity and angular resolution, such as the kinematic detection of planets in protoplanetary disks and astrochemical domains.

**ALMA Archive Research using ADMIT (Lead Institution: Univ. of Maryland):** This study augmented the existing ALMA Data Mining Toolkit (ADMIT) capabilities with the creation of a prototype Science Query Database that enables broad science driven queries of ALMA projects. This will enable science discovery with ALMA archival data by enhancing users' ability to identify, access, and examine relevant data sets through database access to scientific and observational metadata.

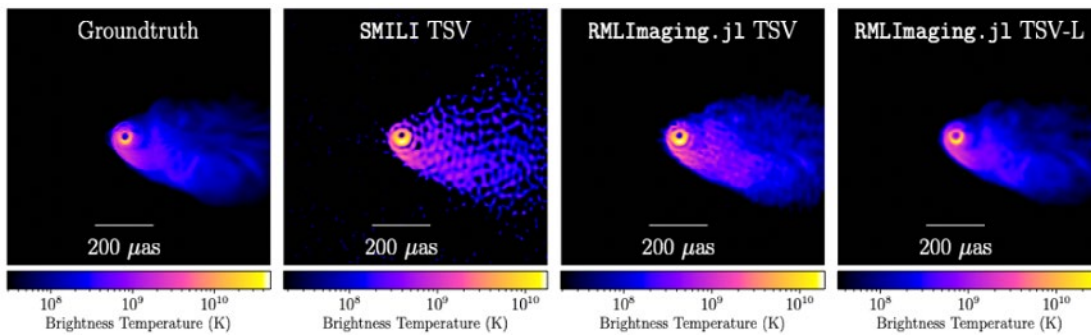
**Link CASA to the Astropy Ecosystem (Lead Institution: Univ. of Florida):** This study explores how to make ALMA data more accessible to the broader astronomical community by establishing a rich suite of analysis tools that extend the existing CASA toolkit. This study intends to make the Astropy Ecosystem accessible from within CASA and produce tools for interoperability with CASA. This project will demonstrate a testing framework to ensure compatibility between CASA and community-provided tools. It will develop compatibility tools to convert files of different formats to and from CASA formats.

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## Studies Completed in FY2023:

### Extending New Imaging Techniques from the EHT to ALMA (MIT Haystack Observatory)

**Ubiquitous Quantum-Limited Wideband 4-Kelvin Amplifiers (NRAO):** Traveling-wave kinetic-inductance parametric amplifiers (TKIPs) are a promising new technology to improve the bandwidth and sensitivity of radio astronomical receivers, especially at millimeter/submillimeter-wave frequencies, where the theoretical limits of SIS-based receivers have almost been realized. Therefore, successful development of TKIPs could significantly improve the performance of ALMA and other future radio telescopes. For this reason, the study of TKIPs is considered a strategic investment in NRAO's long-term technology program.



*Example of Regularize Maximum Likelihood (RML) imaging (right-most panel) compared to model image (left-most panel) and other methods from the Study report.*

## Ongoing Development Studies

**2nd Generation ALMA Correlator/Beamformer – Advanced Technology ALMA Correlator (NRC/NRAO):** The Advanced Technology ALMA Correlator (ATAC) is a cornerstone of the WSU initiative to expand the ALMA System bandwidth by a factor of two (expandable to a factor of four in the future) with vastly more spectral channels, and increased sensitivity. This design and construction project is a collaboration between NRC (hardware and firmware) and NRAO (software and integration) and started in Q2 FY2023 after ALMA Board approval in Q1 FY2023. Submission of this proposal to the ALMA Board was a major FY2023 milestone.

**ALMA Band 6v2 Receiver Upgrade – Phase 1 (NRAO):** This project will design and test a production-ready 2nd Generation Band 6 receiver (Band 6v2) for the WSU. Band 6v2 will at least triple the IF bandwidth of ALMA's most used receiver band, significantly improve its noise performance, and provide the ability to simultaneously observe multiple diagnostic spectral lines. This project will culminate in a Critical Design Review (CDR) in FY2025. A Preliminary Design Review is planned for Q4 FY2024 and a follow-on project will be submitted after successful CDR for the manufacturing phase.

**ALMA Phasing System Phase 2 (APP2) (MIT Haystack Observatory):** The APP2 project includes several initiatives to improve ALMA VLBI capabilities and performance. Major components include enabling spectral line VLBI, extending the frequency range of phasing to Bands 1–7, improving the calibration mechanism to allow observations on weaker sources called the “delay-fix.” This project has been delayed by several unavoidable factors including the COVID-19 pandemic, the ALMA cybersecurity attack, and even poor weather during several of the commissioning campaigns. It is on track to finish in Q3 FY2024.

**Enabling New VLBI Science with the ALMA Phasing System – Phase 3 (APP3) (MIT Haystack Observatory):** The APP3 project has significantly improved ALMA's ability for science operations to carryout VLBI/phasing observations in a more automated fashion. After an anticipated No Cost Extension to complete a Broader Impacts informational video, it will complete in Q3 FY2024.

**Characterization of New Helium Compressor for Cryogenic System (NRAO):** This NRAO project aims to test a new Sumitomo Variable Speed compressor used in the ALMA Front End receiver cryostat due to the limitations revealed during extreme cold weather at AOS. Major aspects include classification of the compressor under field conditions, determination of efficient cold temperature start-up and optimum speed versus thermal loading, and estimates of operational power and science time savings. After a No Cost Extension, it is expected to complete in Q1 FY2024

**Band 3 Cold Cartridge Assembly Magnet and Heater Installation (JAO/NRC-Herzberg):** Production deflux heaters will be installed in the Band 3 cold cartridge to reduce the azimuth-dependent total power variations observed in the ALMA antennas. This project has transitioned from production to implementation with JAO taking over execution responsibility.

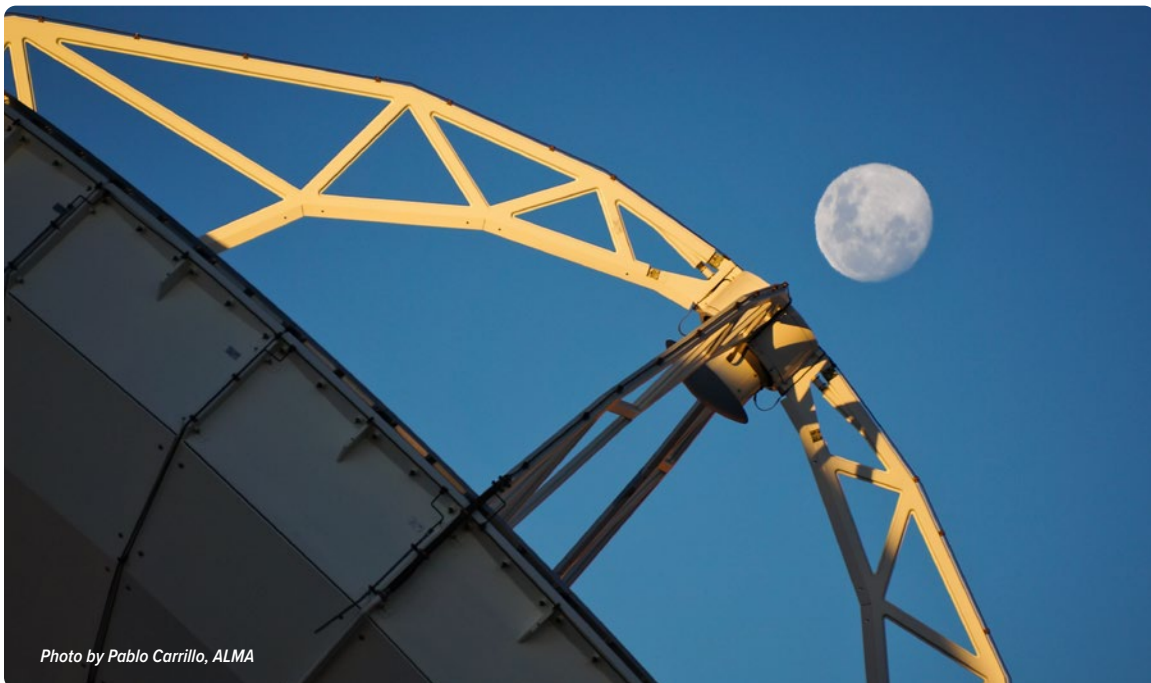
**Investigate Use of Next Generation FPGA Technology in the Advanced Technology ALMA Correlator (NRC):** Study of the cutting edge Agilex Field Programmable Gate Arrays (FPGA) family for use in ATAC.

**Wideband Isolators for Submillimeter Astronomy (SAO):** Development of a wide IF isolator for potential use in Band 6v2.

**Wideband InP and GaAs Intermediate-Frequency Low Noise Amplifiers (NRC):** Investigation of alternative materials for the improved performance of Low Noise Amplifiers, a critical component of sensitive (sub)millimeter receivers.

**A Detailed Characterization of Spectral Regridding and Noise in the WSU Era (SAO):** Development of improved gridding techniques for better spectral noise performance in image cubes.

The last three of these studies are the result of the FY2023 call for Studies, while the first is a two-year strategic study that began in FY2022 (studies that are of particularly strategic importance and are time-critical). All of these studies will provide important input to the WSU and future ALMA upgrades and are expected to finish in FY2024. Completion of the FY2023 Call for Studies review process and the start of the Study funding were major FY2023 milestones.



# NEXT GENERATION VERY LARGE ARRAY



*Photo by mtex antenna technology, GmbH*

The NRAO further engaged the science and technical community from 2021-2023 in the design of a next generation Very Large Array (ngVLA), a world class scientific facility consisting of an interferometric array with 10x the sensitivity and 10x higher spatial resolution than the VLA and the Atacama Large Millimeter/submillimeter Array (ALMA). The ngVLA will open a new window on the Universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcsecond resolution, as well as unprecedented broadband continuum polarimetric imaging of non-thermal processes. These capabilities are required to address a broad range of critical questions in modern astronomy, including: (1) direct imaging of planet formation in the terrestrial zone; (2) studies of dust-obscured star formation, and the cosmic baryon cycle down to parsec-scales out to the Virgo cluster; (3) making a cosmic census of the molecular gas that fuels star formation back to first light and cosmic reionization; and (4) novel techniques for exploring temporal phenomena from milliseconds to years in this multi-messenger astrophysics era. The ngVLA will be optimized for observations at 1.2–50.5 GHz and 70–116 GHz, between ALMA at submillimeter wavelengths and the future Phase I Square Kilometre Array (SKA-1) at decimeter and longer wavelengths.



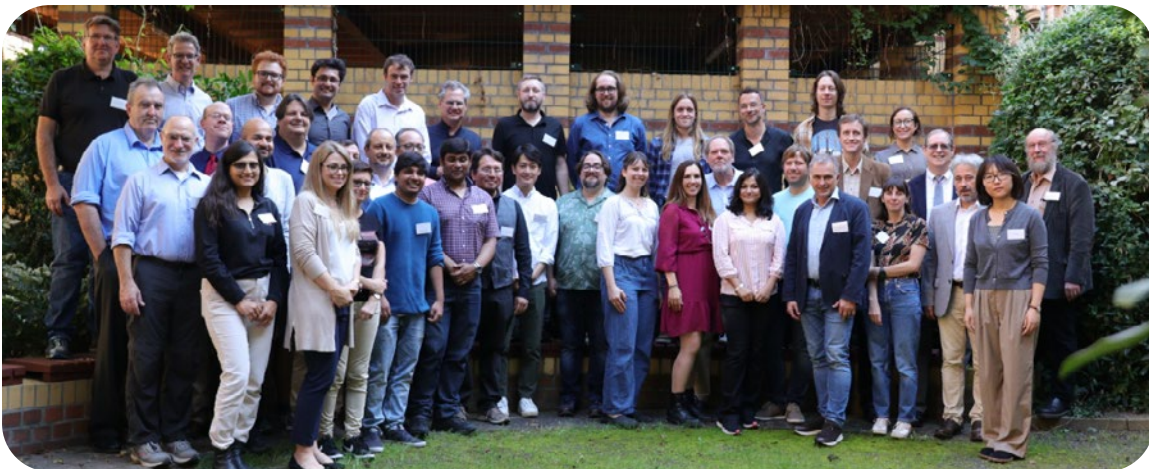
The Astronomy and Astrophysics Decadal Survey (Astro2020) of the U.S. National Academy of Sciences published its report and the Next Generation Very Large Array (ngVLA) received high priority for new ground-based observatories to be constructed during the coming decade. The report, in which ngVLA shared second ranking among ground-based projects, was the culmination of a lengthy process aimed at developing a comprehensive research strategy and vision for a decade of transformative science at the frontiers of astronomy and astrophysics.

In 2023, the ngVLA project has continued to develop the science requirements, system requirements, system architecture, and supporting system design that form the foundation for prototype development and testing.

### Science Goals

The compelling science case and reference design for the ngVLA were developed via a collaboration between NRAO and the international astronomy community, led by the ngVLA Science Advisory Council. More than 80 broad and compelling science cases were developed at 1.2–50.5 GHz and 70–116 GHz. Each of the derived key scientific goals (KSGs) for a future radio/millimeter telescope must: (1) address an important question in astrophysics that has broad scientific and societal implications; (2) require the capabilities of a ngVLA; (3) exhibit synergies with existing or planned facilities in the 2025+ time frame. The five high-priority ngVLA key science goals are:

- *Unveiling the Formation of Solar System Analogs on Terrestrial Scales*
- *Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry*
- *Characterizing the Assembly, Structure, and Evolution of Galaxies Over Cosmic Time*
- *Using Pulsar in the Galactic Center as Fundamental Tests of Gravity*
- *Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy.*



*Above: Second Workshop on German Science Opportunities for the ngVLA, Leipzig, Germany, September 2023*

# NEXT GENERATION VERY LARGE ARRAY

## Technical Concept

The ngVLA technical concept is a synthesis radio telescope operating at centimeter wavelengths that consists of 263 reflectors connected by optical fiber to a signal processing center. Implementation and logistics divide the array into three subsets:

- A Main Array (MA) of 244 reflector antennas each 18m diameter, operating in a phased or interferometric mode, distributed to sample scales from 10s of meters to 1000km. A dense core and spiral arms provide high surface brightness sensitivity, while outer stations increase resolution.
- A Short Baseline Array (SBA) of 19 reflector antennas of 6m aperture will be sensitive to a portion of the larger angular scales poorly sampled by the MA.
- A Long Baseline Array (LBA) of 30 reflector antennas each of 18m diameter located in 10 clusters will provide continental-scale baselines up to ~8860 kilometers and sub-milliarcsecond resolution.

The ngVLA will have ~10x the sensitivity of the VLA and ALMA, continental-scale baselines providing sub-milliarcsecond-resolution, and a dense core on kilometer-scales for high surface brightness sensitivity. The facility will be operated as a proposal-driven instrument. The key deliverable for ngVLA users will be images and image cubes generated using calibration and imaging pipelines. Pipeline products, raw visibilities, and calibration tables will be archived.

## ngVLA Project

In August 2021, the National Science Foundation (NSF) awarded the NRAO \$23 million for the final design and prototype of the selected 18m antenna design.



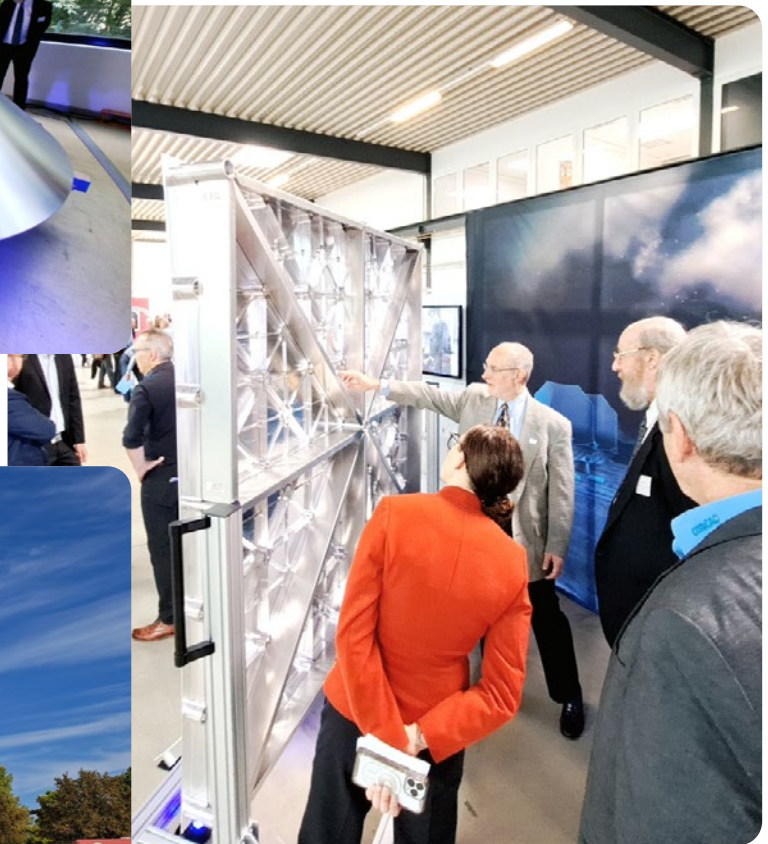
*Photo by Brian R. Kent, NRAO/AUI/NSF*

The ngVLA Project successfully completed its Technical Conceptual Design Review in July 2022. This verifies that the technical design is likely to meet all the performance driving requirements. This successful milestone set the stage for the Programmatic Conceptual Design Review.

NSF formally entered the ngVLA project into the MREFC process, at the Conceptual Design Phase (CDP), in July 2023. This major step forward for the project reflects the strong concept and scientific promise brought forward, and the great execution we have demonstrated in recent years.

In September 2023, NRAO announced that the National Science Foundation (NSF) awarded a 3-year, \$21 million grant to Associated Universities, Inc. (AUI) to further the design of the next generation Very Large Array (ngVLA).

*mtex antenna technology GmbH* was contracted to design, develop, and produce the 18m ngVLA prototype antenna. The National Radio Astronomy Observatory (NRAO) has selected a contractor to develop a production-ready design and produce a prototype antenna for the Next Generation Very Large Array (ngVLA). NRAO officials signed an agreement with *mtex antenna technology GmbH*. At an Open Day Event in Leipzig, Germany, September 2023, portions of the prototype were unveiled to government and business leaders, scientists, engineers, and the press from Germany and the U.S. The event was preceded by a conference showcasing the interests of the German community in ngVLA science and opportunities.



Photos by Brian R. Kent, NRAO/AUI/NSF

# NEXT GENERATION VERY LARGE ARRAY

## Community Engagement

The ngVLA project and community hosted a number of events in partnership with global collaborators, showing the worldwide interest in ngVLA science and engineering.

- New Views of Galaxy Formation and Evolution, Winter AAS Conference, January 2021
- Computational Astrophysics in the ngVLA Era, Flatiron Institute, New York, NY, June 2022
- Chemical Probes of Astrophysical Systems, Winter AAS Conference, Seattle, WA, January 2023
- Transition from VLA/VLBA to an ngVLA, Summer AAS Conference, Albuquerque, NM, June 2023
- New Eyes on the Universe with ngVLA and SKAO, Vancouver, BC, Canada, May 2023
- En Route to the Next Generation Very Large Array with IRyA-UNAM, Morelia, Mexico, September 2023
- Second Workshop on German Science Opportunities for the ngVLA, Leipzig, Germany, September 2023

The ngVLA Project continued to build and refine the conceptual design and science case throughout 2021-2023, driven by the community, coordinated by NRAO, and apropos to NSF Major Research Equipment and Facilities Construction (MREFC) candidacy. Additional science cases identified by the community were incorporated into the ngVLA Science Book. The Project focused on developing the detailed ngVLA conceptual design, working towards an external design review in 2022.



Above: New Eyes on the Universe with ngVLA and SKAO, Vancouver, BC, Canada, May 2023



The ngVLA continues to distribute technical and scientific notices to the community via the online NRAO Newsletter. Five science working groups have also formed, with periodic meetings, chaired by astronomers from the community:

- SWG1: Stars, Planetary Systems, and their Origins  
*Co-Chairs: Brenda Matthews (NRC-Victoria) & David Wilner (Harvard CfA)*
- SWG2: Astrochemistry and the Molecular Emergence of Life  
*Co-Chairs: Brett McGuire (MIT) & Jennifer Bergner (Chicago)*
- SWG3: Galaxies and Galaxy Evolution  
*Co-Chairs: Fabian Walter (MPIA) & Rachel Somerville (Flatiron Institute/CCA)*
- SWG4: Pulsars, Cosmology, and Fundamental Physics  
*Co-Chairs: Megan DeCesar (George Mason) & Alexander van der Horst (George Washington)*
- SWG5: Exploring the Dynamic Universe  
*Co-Chairs: Rachel Osten (STScI) & Alessandra Corsi (TTU)*

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Above: En Route to the Next Generation Very Large Array with IRyA-UNAM, Morelia, Mexico, September 2023

A large radio telescope dish is positioned in a field under a starry night sky. The Milky Way galaxy is visible in the background, stretching across the sky. The dish is illuminated by a warm light source, possibly the setting or rising sun, creating a silhouette effect. The foreground shows a dirt road leading towards the telescope. The overall scene is a mix of natural beauty and scientific technology.

## NEW MEXICO OPERATIONS

The Karl G. Jansky Very Large Array (VLA) and the Very Long Baseline Array (VLBA) are maintained and operated from New Mexico. Both instruments provide unique centimeter-wavelength capabilities to the astronomy community. During 2023, NRAO commissioned new observing modes for these instruments, matched to the latest scientific requirements. The following sections describe the operational, maintenance, and development activities associated with each instrument. Many activities are closely coordinated across the VLA and the VLBA and are carried out by the same personnel.

## Karl G. Jansky Very Large Array (VLA)

The VLA comprises twenty-seven 25-meter diameter antennas in a Y-shaped configuration on the Plains of San Agustin in west-central New Mexico. From 2021-2023, NRAO continued to offer a suite of robust and scientifically powerful observational capabilities designed and tailored to address scientific needs.

### Science Operations

NRAO continued to offer three types of observing programs to VLA users in the Calls for Proposals issued from 2021-2023: General Observing (GO), Shared Risk Observing (SRO), and Resident Shared Risk Observing (RSRO).

In the Call for Proposals for the 2021B observing semester, two capabilities were promoted from SRO to GO: 4-band observing in Stokes I, and dual 4/P bands observing in Stokes I. In the Call for Proposals for the 2022A observing semester, no new GO capabilities were added while the default eLWA (VLA+LWA) observing mode (single 8 MHz subband centered at 76 MHz, and 4-bit VDIF output) was promoted from RSRO to SRO.

For the 2022B and 2023A observing semesters, no new GO or SRO capabilities were added. A little-used, frequency-averaging mode that was causing failures elsewhere in the system was disabled to improve the robustness of General and Shared Risk observing. The online frequency-averaging capability remains available through the RSRO program. Under SRO, several new subarray observing capabilities were added: up to three independent subarrays using standard 3-bit continuum setups, or a mix of standard 3-bit and standard 8-bit continuum setups, and up to three independent subarrays with changing standard continuum setups in a given subarray (e.g., to perform reference pointing at X-band for high frequency observations). RSRO programs supported in FY2022 included fast-dump times, data rates above 100 MB/s, 4-band polarization, 4-band spectral line, 4-band coherent-dedispersion ("Y" Ultimate Pulsar Processing Instrument or YUPPI) pulsar observing, eLWA observations and correlations using options other than the one offered under SRO, subarray observations with setups other than the default continuum setups, or observations with more than three subarrays, and rapid response capability. In 2023, science observing for both the Jansky Very Large Array Sky Survey (VLASS) and extra-large proposals continued.

A large fraction of the 2021-2023 scientific support went toward maintaining receiver, antenna, and array performance and ensuring that the NRAO user community had access to quality instrumentation and updated information to effectively use the VLA. Operational tasks carried out by the scientific staff in support of these functions are listed below.

Technical documentation detailing hardware and software functionality for staff and users was written, as well as operational procedures and documentation for the operations staff. The VLA Observational Status Summary was updated before the 2021B-2023B Call for Proposals, along with the Guide to Proposing with the VLA and the Guide to Observing with the VLA on the NRAO science web site.

The sensitivity and gain response of each antenna at each band was characterized periodically. Surface accuracy checks with holography were carried out to ensure optimal efficiency at the highest frequency bands. Antenna positions, collimation offsets, and pointing accuracy were determined whenever the array was moved into a new configuration.

Antenna positions, collimation offsets, and pointing accuracy were determined each time an antenna came out of the Antenna Assembly Building after a maintenance overhaul. The performance of the new Antenna Control Units (ACUs) was evaluated.

## NEW MEXICO OPERATIONS

Health checks were performed to determine if there were any hardware failures that must be followed up with maintenance tickets. Radio Frequency Interference (RFI) monitoring tests were carried out to characterize and help mitigate RFI contamination in observing bands.

Data quality was evaluated based on pipeline results, and test observations were run to identify and diagnose problems that were not caught by the standardized tests and engineering checks. Detailed data was collected with the array for a range of calibration purposes, including flux density scale calibrator models, and polarization and bandpass calibration.

### Array Operations

Array reconfigurations were completed as follows:

- FY2021 comprised the moves into the BnA configuration to support the VLA Sky Survey (southern sky, epoch 2.1), followed by the A, D, C, and B configurations.
- FY2022 comprised the moves into the BnA configuration to support the VLA Sky Survey (southern sky, epoch 2.2) followed by the A, D, and C configurations.
- FY2023 comprised the moves into the C and B configurations, the BnA configuration to support the VLA Sky Survey (epoch 3.1), followed by A configuration.

In 2022, the VLA Operators were trained on how to address the system health of the commensal VLA Low Band Ionospheric and Transient Experiment (VLITE) P-band observing system. The VLA Operators documented and were trained on how to troubleshoot and resync the Digital Transmission System's (DTS) digitizers, and developed instructions for resetting the Correlator Back End (CBE).

In 2023, one of the VLA Operators was cross-trained to operate the VLBA and assist with the shift schedule. The Array Operations Division also worked closely with the EHS Division to write new, and update existing, safety manuals and protocols, and to determine the required and recommended safety training programs the NM Array Operations staff should take. The VLA thunderstorm monitoring system was moved to the Vaisala Thunderstorm Manager, replacing an in-house system that was no longer reliable.



### Development

**Wideband Interferometric Digital Architecture (WIDAR) Real-time RFI blanking:** Between FY2019 and FY2022, the ability to blank data at high time resolution in the WIDAR correlator as a mechanism for excising RFI was demonstrated and developed. During FY2023, this capability was offered to observers under RSRO, while in Q4, the evaluation that was conducted by the scientific staff concluded its readiness for general science observations on the array. Consequently, this capability was enabled in the NRAO default (continuum) setups for L through Ku-band. For all other use cases (e.g., non-default continuum, spectral line, and pulsar setups) observers will have the ability to opt-in via a toggle in the OPT. These new RFI-blanking-enabled default setups, as well as the toggle to apply WIDAR RFI blanking in all other setups, were made available in the OPT release 1.32.00 (Q4).

**Commensal Open-Source Multimode Interferometer Cluster Search for Extraterrestrial Intelligence (COSMIC SETI):** The NRAO and the SETI Institute have entered into a collaborative agreement to enable SETI using the VLA. A new system has been developed that will allow for state-of-the-art commensal, real-time SETI analysis to happen in parallel with all standard VLA observations. This system receives digitized data (pre-correlation) from each VLA antenna via optical fiber, and distributes the data via ethernet to a compute cluster capable of real-time software correlation and beamforming. Nearby target stars within the VLA field of view will be searched for drifting narrowband (~Hz-bandwidth) signals indicative of advanced technology. The desire is to operate the system during the third epoch of observing for the VLA Sky Survey, during which ~40 million stars will be searched for technosignatures.

A design review for the COSMIC system was held in FY2022, the results of which determined the scope and scheduling for infrastructure improvements in the West Chamber of the Control Building at the VLA site, where the COSMIC equipment is located. The plan is for COSMIC-SETI to become operational as a commensal system on the VLA during FY2023, collecting data during unconflicted PI science observations (including VLASS). The Observatory has implemented a software switch, which will be exposed to the PIs via the OPT when COSMIC is operational, and with which PIs may choose to opt out of allowing COSMIC to run commensally during their observations. The COSMIC system is funded by the SETI Institute, with the construction effort extending through FY2023.



*Above: The Commensal Open-Source Multimode Interferometer Cluster Search for Extraterrestrial Intelligence (COSMIC SETI) system backend at the VLA site.*

## Electronics Maintenance and Renewal

The New Mexico Electronics Division maintains all VLA electronic components, VLA servo and fiber systems, and the Wideband Interferometric Digital Architecture (WIDAR) Correlator. Division staff are located either at the VLA site or at the DSOC in Socorro, with maintenance and renewal activities occurring at both places. Due to the lifecycle stage of the VLA, maintenance and obsolescence management is a critical focus for the Division.

### **Digital:**

- Replaced aging WIDAR power system components.
- Performed checks on the WIDAR Correlator boards and replaced or repaired as needed.

### **Front End and Cryogenics:**

- Overhauled approximately 30 receiver cold heads per quarter to keep VLA receivers operating.
- Reconditioned and replaced receiver desiccant in each of 240 units twice during the year.
- Performed preventive maintenance on 25 VLA compressor lines twice during the year.
- Overhauled two VLA compressors due to normal wear-and-tear.
- Performed preventive maintenance on four helium circuits to maintain cryogenic performance.
- Repaired approximately 25 Front End receivers during the year.
- Repaired and/or upgraded more than 20 Front End M&C modules during the year.
- Ongoing repair of the Low Band Receiver system.

### **Local Oscillator and Intermediate Frequency (LO/IF):**

- Investigated issues with locking, fringing, output power, and general communication dropouts.
- Performed routine power supply and battery maintenance, including replacement of units.
- Repaired or replaced approximately 20 RF Switches (Band Switches).

### **Servo and Fiber:**

- Performed checks of the fiber optics system to ensure proper operations; applied resets as needed.
- Bearing change support.
- Performed maintenance on legacy ACUs and Focus Rotation Mount (FRM) controllers.
- Installed new ACUs in two antennas, in addition to one that was started in FY2022 and carried over to FY2023.

### **Multiple Groups and Systems:**

- Retrofitted upgrades or additions to enhance equipment safety.
- Performed bench work on modules for repair or assembly.
- Monitored modules responsible for array timing and transmission of data and adjusted as needed.
- Identified several new sources of RFI, particularly in L, S, and C bands.

## Site Maintenance and Renewal

The Engineering Services Division is responsible for nearly all of the maintenance and renewal activities performed on the VLA site facilities, antennas, and rail system.

**Antennas:** An azimuth bearing change on antenna 20 was completed in early FY2023. VLA antennas were routinely cycled through the AAB for checkout and overhaul throughout the year. The original plan was to overhaul five antennas. Only four antennas were overhauled during FY2023 because the year's first overhaul took longer than planned, following a bearing change and subsequent troubleshooting of its servo system. Other overhaul delays were caused by the Focus Rotation Mount smart motor supply chain delays and an extended calibration problem with an elevation encoder.

The two transporters used to move the antennas during reconfigurations underwent planned maintenance and repair between move periods. Maintenance on the more-than-40-year-old transporters included servicing the motors, checking the generators that maintain critical power to the antenna during a move, lubricating the moving parts, checking on the total of 24 axles and wheels, and maintaining electrical and hydraulic systems.

**Track:** During FY2023, inspection of the VLA railroad tracks continued, checking for problems that could compromise the safety of the transporters that carry the antennas during array reconfigurations and other antenna moves. These inspections also guarded against problems that could jeopardize the safety of the maintenance rail vehicles that are used by technicians to service the antennas.

A total of 5,123 cross-ties were replaced in FY2023, exceeding the preventive maintenance program’s target goal of 5000 ties for the year. Five track intersections/spurs were replaced in FY2023, also per plan.

**Site Infrastructure:** VLA site buildings, utility systems, and grounds continued to undergo routine annual inspection and preventive maintenance in FY2023. The 3 MW site backup generator was load tested and several generator and switchgear parameters were changed as a result of the recent engineering consultants’ recommendations. These changes resulted in greater system stability and improved the system’s response to minor power grid perturbations. This has greatly reduced the interruptions to observational readiness. Other regular activities included: annual road grading; general roof repairs; heating and cooling systems maintenance; pest and weed control along the railways and central site; fire brigade and emergency medical response team training; and the routine servicing of gas pumps, sewer, and water supply systems. Backup generator power, along with other related systems, also underwent preventive maintenance.



# NEW MEXICO OPERATIONS

## Observing Capability Enhancements

The VLA continued to provide new capabilities to the user community to optimize and enhance the science that can be done with the array. This strategy has proven to be effective in keeping users engaged, and it is a critical factor in keeping the scientific productivity of the VLA high. Scientific staff and RSRO efforts were directed to the following observing capability enhancements in FY2021-2023

**4-band and 4/P Stokes I Continuum Observations:** The 4-band Stokes I and the dual 4/P-band Stokes I continuum observations were promoted from SRO to GO in the 2021B Call for Proposals. The proposing and observing tools were updated accordingly.

**Expanded Long Wavelength Array (eLWA):** In FY2021, the eLWA was added to the NRAO Proposal Submission Tool, and the generation of dynamic eLWA observing schedules has been added to the VLA observing software. As a result, eLWA observing with default settings (8 MHz bandwidth centered at 76 MHz with 4-bit VDIF output) was promoted to SRO in the 2022A Call for Proposals. Relevant user documentation was also updated to reflect this capability.

**Wideband VLA for VLBI:** The phased VLA (Y27) is often used as a single element in VLBI experiments. In addition to the summed array signal for VLBI, VLA imaging data (visibilities) are always obtained in parallel via the WIDAR correlator and can be useful for many experiments. During these observations, the bandwidth has in the past been limited by the VLBI recording capability to a maximum of 512 MHz (4096 Mbps), far less than the bandwidth that can be delivered by the VLA's WIDAR correlator, which can be up to 2 GHz with the 8-bit samplers and up to 8 GHz with the 3-bit samplers. When configured properly, WIDAR can provide wide-band visibility data during these experiments, resulting in a significant increase in the sensitivity of the VLA-only imaging data. In FY2023, this capability was further developed and the relevant software components validated in order to deliver VLA data from the WIDAR correlator with the full bandwidth of the 8-bit samplers (2 GHz). This capability was offered under SRO in the VLBA portion of the 2024A Call for Proposals

## Technical Upgrades and Enhancements

**VLA ACU Replacement:** The electronics components to repair the existing VLA ACUs are no longer available. Without replacement parts, antennas with failed ACUs would no longer be able to participate in observations, posing a serious operational risk. All of the legacy VLA ACUs must be replaced with newer technology units to increase the operational lifetime of the VLA antennas, as well as eliminating some inherent problems with the legacy design and greatly improving the pointing and tracking capabilities of the antennas. The first new ACU was installed in FY2013. Three additional ACUs were installed in FY2023 (one of these was carried over from FY2022, as noted above), leaving six antennas still using the legacy system.

**Variable Frequency Drive (VFD) Development:** A modest amount of additional characterization and optimization of the Variable Frequency Drive (VFD) took place in FY2022 in anticipation of possible future deployment on the green antenna. The combination of the Buffered Compressor Tank and the VFD reduces power consumption while extending the operational time of cryogenic system components.

**Buffered Compressor Tank Development:** The system installed on antenna 14 was monitored during FY2023. It continued to perform as expected, but there were insufficient resources to deploy the design on a second antenna.

**Emergency Notification System:** The NRAO continued to use the Rave Alert system for emergency notifications in New Mexico during FY2023. Approved use of this system at the start of the fiscal year included any event that triggers Emergency Operations Status (EOS), including, but not limited to, inclement weather, network/power outages, evacuations, national and state alerts, and tests/training. Later in the year, changes to FCC regulations around the use of emergency notification systems required modifications of its use and operation. NM Operations assessed the system under these conditions during FY2023 and determined that Rave remains useful for emergency communications in NM.





*Photo by Brian R. Kent, NRAO/AUI/NSF*

## Very Long Baseline Array (VLBA)

The VLBA comprises ten 25-meter diameter antennas at locations extended from Hawaii to the U.S. Virgin Islands. This facility is the highest resolution dedicated ground-based astronomical instrument in use by the worldwide scientific community.

### Science Operations

The NRAO continued to offer three types of observing programs to VLBA users in FY2023: General Observing (GO), Shared Risk Observing (SRO), and Resident Shared Risk Observing (RSRO). As for the VLA, any VLBA observing mode that does not fall under GO or SRO may be proposed under the RSRO program. In the Call for Proposals for both 2021B through 2023B observing semesters, no new GO or SRO capabilities were offered. RSRO programs supported in FY2021 included many pulse cal tones per channel, improved troposphere model, rapid response capability, L/P dual-band observations, Y3 observing with the VLBA, and recording wide-band VLA visibilities in parallel with Y27 VLBI. In the Call for Proposals for the 2024A observing semester, no new GO capabilities were added, while under SRO the delivery of wideband VLA data (from WIDAR) during VLBI observations was offered.

Operational tasks carried out by the scientific staff during FY2021-2023 in support of maintaining receiver, antenna, and array performance and ensuring that the user community had access to quality instrumentation and updated information to effectively use the VLBA are listed below.

Capabilities to be offered from the 2021B through the 2024A semesters were defined, and user documentation for all capabilities for the relevant Call for Proposals updated; scientific testing of user tools needed to prepare proposals (e.g., Proposal Submission Tool (PST), European VLBI Network Sensitivity Calculator and Observation Planner) was undertaken, and technical reviews for proposals and evaluation of proposals for RSRO contributions were performed. As for the VLA, the technical review process for the VLBA proposals was also revised in the 2024A semester.

Technical documentation detailing hardware and software functionality for staff and users was written, as well as operational procedures and documentation for the operations staff. The VLBA Observational Status Summary was updated before the 2023B and 2024A Calls for Proposals, along with the Guide to Proposing with the VLBA and the Guide to Observing with the VLBA on the NRAO science web site. In FY2022, the VLBA observation preparation software (SCHED) version 11.7 and associated user documentation were released to incorporate various enhancements and bug fixes. Scientific testing and validation of SCHED 11.7 were carried out before the release. The new, next generation Python-based VLBA calibrator search tool was also released in FY2022 after extensive testing and scientific validation. This replaced the legacy VLBA calibrator search tool. New user documentation has also been posted online.

**User Support:** VLBA User Support continued to be provided by scientific staff in NM Operations on all aspects of proposing, observing, data access, and data reduction via the helpdesk and/or one-on-one when applicable.

**Track and Measure VLBA Sensitivity, Pointing, and Focus:** The sensitivity, pointing and focus of each antenna at each band were characterized periodically, as receivers and equipment were replaced or as software was upgraded. During FY2022, real-time interferometric pointing developed in FY2021 became the standard method for determining and maintaining VLBA antenna pointing models. In FY2022, VLBA staff also defined the software requirements for the use of real-time interferometry for reference pointing with the long-term goal of improving the high-frequency performance and capabilities.

**Clock Maintenance:** Accurate time keeping is central to VLBI, and is provided by hydrogen masers and reference signals inserted into the astronomical data. Quality assurance checks were performed periodically by scientific staff and data analysts.



*Photo by Jeff Hellerman, NRAO/AUI/NSF*

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**System Health and Maintenance Feedback:** Routine health checks and analysis of the data to determine if there are any hardware failures were followed up with maintenance tickets. RFI monitoring tests were carried out to characterize and help mitigate RFI contamination in observing bands.

**Data Quality Assurance Checks:** Data quality was evaluated and test observations run to identify and diagnose problems that were not caught by engineering checks.

**Coordination for Global Millimetre VLBI Array and the High Sensitivity Array (I):** The VLBA occasionally observed in parallel with other observatories, as requested by users whose scientific goals require the inclusion of baselines to large aperture and/or distant facilities. Scheduling and correlation of these observations required coordination with local schedulers at each participating observatory, a significantly more complex process than normal VLBA-only observations require.

## Array Operations

Standard scheduling and observing procedures were used during FY2021-2023 for the VLBA. The VLBA operations staff also correlated and inspected observations using standard methods.

VLBA Operations is moving towards the ability to perform electronic transfer of incoming data from non-VLBA stations over the internet, in particular, to minimize the need for the shipping of disk packs internationally. During Q3 and Q4 of FY2023, the Phase 1 VLBA E-transfer Operations Plan document was drafted (and will be finalized in Q1 FY2024). The equipment required to conduct electronic transfer was also procured and delivered to the DSOC.

Every day, the USNO used two to five VLBA antennas to perform Earth orientation measurements. After observations were completed, a data quality assessment was performed by VLBA Operators and then the data were made available for download to the USNO correlator. When needed, the VLBA correlator was used as a back-up to the USNO correlator. This capability was tested on a two-station observation every month. In these tests, data from Kōke'e Park, Hawaii, and Wettzell, Germany were transferred to the VLBA correlator and then the data were correlated and post-processed on computers within the DSOC.



## Development

During FY2021-2023, progress was made on a number of development projects.

**VLBA Back-End Retrofit Project (VBER):** After being delayed by the Contreras fire, the final E-Rack was installed at Kitt Peak. Production of the P401 Power Supplies was completed and sufficient network switches and other material procured to outfit the entire VLBA. E-Racks were fully commissioned at Owens Valley and Pie Town and commissioning was nearly completed at Brewster by the end of the fiscal year. A Preliminary Design Review (PDR) of the proposed Timing and Reference Distribution (TRD) solution was completed and the selected commercial equipment passed both lab testing and RFI screening.

**VLBA New Digital Architecture Project (VNDA):** The VNDA team changed its approach in FY2023 due to the difficulties encountered in FPGA programming. The VNDA project has two major modules under development: the Producer, which samples data and formats onto Ethernet, and the Consumer, which channelizes and requantizes the data. The overall functionality of these modules has not changed, but the development

methodology has been modified. In the case of the Producer, FPGA code will be developed by an external contractor. For the Consumer, a separate external vendor will be developing software on Graphical Processor Units (GPUs). Contracts for the two external vendors were established late in FY2023. Detailed planning for acceptance of the externally produced firmware/software were developed. Plans for initial laboratory testing were updated to reflect the project change.

**VLBA ACU Design Development:** The effort to develop a replacement for the obsolete VLBA ACU and other drive system components was initiated with a two-day kick-off meeting in Q4 FY2023. Completion of the ACU conceptual design is anticipated in FY2024, along with some minimal purchases of items needed for evaluation.

**CSA-F (High-speed VLBA networks):** CSA-F funded operation of the high-speed VLBA fiber network links. The remaining budget was evaluated and a plan for spend-down was completed. Remaining funds were sufficient to allow an increased level of service at Saint Croix (increase from 200 to 600 Mbps). Effort continued to further develop capabilities enabled by high-speed fiber. This included the ability to transfer in real-time a subset of data when observing using the Polyphase Filter-Bank (PFB) mode. The available data rates limit the use of the high-speed fiber to testing and diagnostic observations, but enable faster response to system problems. Detailed plans for rolling out user-driven real-time correlation were developed. The fiber connection at Mauna Kea was changed from a Hawaii Telco circuit to the University of Hawaii circuit. This change both reduced monthly costs and increased level of service from 1000 to 10000 Mbps.

**E-transfer Filesystem:** Funding was released to embark on developing the VLBA e-transfer filesystem. This system will facilitate electronic transfer of data from foreign antennas and transfer of data to external correlator centers. During FY2023, all of the equipment was procured. Initial operations and software design documentation were developed.

**Real-Time Correlation:** Significant progress was made toward the goal of routine real-time correlation of the VLBA. All VLBA antennas are connected to the internet at speeds no less than 200 Mbps, with identified paths to 10 Gbps at most sites. For reference, the VLBA's current maximum data rate is 4 Gbps, but that will double (or more) over the next few years when VNDA is completed. Using the current network configuration, full array real-time correlation is possible at data rates up to 128 Mbps, corresponding to 32 MHz of bandwidth. In Q2 FY2021, VLBA operations started making use of this capability on a weekly basis after completion of maintenance to verify proper operation of all receivers and the data acquisition systems at all VLBA sites. Plans have also been developed to improve the connectivity of the VLBA correlator to the internet—a necessary update to allow real-time correlation at higher data rates.

## VLBA Maintenance and Renewal

The New Mexico Electronics Division is responsible for maintaining all VLBA electronic components, many mechanical systems, VLBA station infrastructure, and recording and playback hardware. Two VLBA site technicians are located at each VLBA site, and many engineers and technicians provide VLBA support from the DSOC in Socorro.

The site technicians carried out the bulk of the routine maintenance tasks at the VLBA sites. For FY2021-2023 this work consisted of the following:

- Inspection and lubrication of Focus Rotation Mounts (FRM), Azimuth/Elevation drive motors, encoder and pintle bearings, elevation gears, elevation hoist, and changing gearbox oil.
- Check/test encoder motor tachometers, servo limits, ACU, vacuum pumps, all heating, ventilation, and air conditioning (HVAC) systems, dry air system, weather station equipment.
- Perform maintenance on ACUs and FRM controllers.

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- Ensure safety equipment such as UPSs and generators, emergency power, fire alarm systems, fire extinguishers, and security systems are operating normally.
- Ensure all other preventive maintenance tasks are completed, such as check and replace motor brushes and commutators, check of Azimuth wheel position, check for metal in grease samples, perform cable wrap maintenance, and replace oil filters.
- Repair some VLBA specific modules and electronic systems to relieve some of this task from the technical staff at the DSOC and the VLA sites.
- Maintain the grounds and building infrastructure.
- Other diagnostic and repair tasks as needed.
- Support major maintenance visits to two VLBA sites.

Electronics Division staff based at the DSOC or the VLA performed the following routine VLBA work in FY2021-2023:

### Front End and Cryogenics:

- Overhaul ~60 receiver cold heads to keep VLBA Front Ends operating.
- Perform preventive maintenance on four helium circuits to maintain cryogenic performance.
- Repair and/or upgrade/retrofit eight VLBA FE receivers, on average.

### Local Oscillator and Intermediate Frequency (LO/IF):

- Investigate issues with locking, fringing, output power, and general communication dropouts.
- Monitor maser performance and timing, adjusting as needed.

### Data Acquisition:

- Repair of ~10 VLBA recording and playback modules.
- Repair of up to 50 recording disk packs.



*Photo by Jeff Hellerman, NRAO/AUI/NSF*

### **Multiple Groups and Systems:**

- Retrofit upgrades or additions to enhance equipment safety.
- Perform bench work on modules for repair or assembly.
- Monitor for local RFI at the VLBA sites.
- Send calibrated site weather station hardware to each site as needed.
- Support major maintenance visits to two VLBA sites.

**Major Antenna and Site Maintenance:** Scheduled major maintenance was conducted at both the Mauna Kea and Brewster VLBA sites. During these maintenance visits the following work was conducted:

- Inspect and lubricate Focus Rotation Mount (FRM), azimuth wheel, elevation, and pintle bearings.
- Inspect azimuth and elevation gearboxes and elevation gear sector.
- Inspect feeds, feed cone and dichroic reflector system and replace/repair as needed.
- Inspect and repair azimuth rail and grout.
- Inspect and repair cable wrap and pintle structure.
- Several dish panels on the Mauna Kea antenna were damaged from large blocks of falling ice that had accumulated on legs and FRM during a major ice storm. These panels were repaired during the maintenance visit.

**Owens Valley (OV) Elevation Bearing:** During the FY2022 major maintenance visit to the Owens Valley VLBA antenna, one of the elevation bearings was showing signs of impending failure. A maintenance team was scheduled to replace this bearing in July 2023. The bearing failed at the end of May and the repair was rescheduled and completed in June 2023.

**Engineering Inspection Visits:** The VLBA antennas have been in operation for over 30 years. Senior mechanical and electronic engineers conducted inspections at the Fort Davis, St Croix, and Kitt Peak VLBA antenna sites. These engineers were specifically looking for signs of impending failures due to metal fatigue, age, and corrosion. The engineers inspected the entire antenna structure, mechanical and electronic components on the antenna and in the station building. The results from this inspection are being used to focus future preventive maintenance goals to prolong the antenna life and prevent unscheduled down time.

**VLBA Reliability Analysis:** Due to the age of the VLBA, the failure rate of components and systems has been expected to increase. In fact, the number of maintenance issues has risen over recent years, with a noticeable increase in the failure rate of certain subsystems such as the ACU and motors. To further understand the issue, a reliability analysis effort was planned for FY2023 to ascertain the detailed reliability of at least one electronics subsystem on the VLBA antenna. The milestone was cancelled due to the loss of the engineer assigned to this task and the reassignment of the position outside of the engineering divisions.

**Hancock (HN) Elevation Bearings:** Another major maintenance visit occurred in May at the Hancock VLBA site in order to replace the antenna's elevation bearings. These had been showing signs of nearing end of life, as evidenced by grease inspections. They turned out to be noticeably damaged. The elevation bearing change process is quite complicated since support structures have to be built and installed to take the weight off of the bearings. This work required careful coordination between both engineering divisions and also included an overhaul of the cryogenics system.

**Kitt Peak Return to Service:** The 2022 Contreras fire and its aftermath caused significant damage to Kitt Peak infrastructure, including disruption of the usage of the road and destruction of power and communication lines. New Mexico staff spent over six months remediating minor fire and smoke damage to the VLBA site and solving onsite issues necessary to re-energize and renew communications before observations could begin in February.

### Observing Capability, Technical Upgrades, and Enhancements

The VLBA continued to provide new capabilities to the user community to optimize and enhance the science that can be done with the array. This strategy has proven to be effective in keeping users engaged, and it is a critical factor in keeping the scientific productivity of the VLBA high. Scientific staff and RSRO effort were directed to the following observing capability enhancements in FY2021-2023:

**Wideband VLA for VLBI:** During phased VLA observations, the bandwidth is currently limited by the VLBI recording capability to a maximum of 512 MHz (4096 Mbps), far less than the bandwidth that can be delivered by the VLA's WIDAR correlator, which can be up to 8 GHz. In parallel to developing the requirements for the VLA Observation Preparation Tool (OPT), in FY2022 NRAO developed the software requirements for the VLBA's observing software that will allow telescope users to enable this mode and take advantage of the increase in bandwidth. Specifically, these requirements pertain to the software code vex2opt which reads files produced by the VLBA observation preparation software tool (SCHED) to produce the necessary files that the OPT and its Resource Catalog Tool (RCT) need in order to support wideband VLA observations in VLBI sessions.

**Site Weather Station Upgrades:** The initial design deployed at Los Alamos in FY2021 was refined to improve manufacturability and resiliency against lightning strikes. Material, sufficient to complete installation and commissioning at all VLBA sites, was procured. Full fabrication and assembly of two units was nearing completion at the end of the fiscal year. The goal of completing installation at one VLBA site was not met but completion is anticipated at the beginning of FY2024. It is anticipated that Weather Station production will complete in FY2024 and all sites will be commissioned by the end of FY2025.

**Production and Installation of New L404 Synthesizer Modules:** Production of the new L404 Synthesizers was completed in FY2021 with the exception of some spare units requiring additional RF components to complete the build. Enough modules are now ready for use at all antennas.

**Spectrum Analyzer Purchase:** Six spectrum analyzers were procured in FY2021 for the analysis and repair of VLBA equipment. These will be used to improve the diagnostic capabilities for VLBA sites.

**Site Uninterruptable Power Supply Upgrades:** VLBA site UPS systems have undergone a rolling upgrade cycle in order to standardize and improve the original systems. In FY2022, sufficient material was procured to upgrade two UPS systems.

**Antenna Gearbox Replacements:** During the VLBA engineering inspections, several VLBA gearboxes were disassembled and the internal components were inspected for excessive wear. There were multiple internal gears and bearings that will need replacement in the near future. Attempts to procure these components from the original gearbox manufacturer proved unsuccessful. A gear manufacturer was contracted to fabricate the precision-machined gears and associated parts. The new parts will be delivered in FY2024 and will be installed during future major maintenance visits.





Photo by Jeff Hellerman, NRAO/AUI/NSF

## SCIENCE SUPPORT & RESEARCH



*Galaxy NGC 3351. Credit: ALMA (ESO/NAOJ/NRAO)/ESA/NASA/PHANGS, S. Dagnello (NRAO)*

The NRAO Science Support and Research (SSR) department coordinates and manages the efforts to support scientific users of NRAO facilities, seeks to share the Observatory's science through education and visitor programs for scientists, and supports and oversees the research and scientific productivity of the scientific staff. The efforts of SSR enable the astronomical community to maximize the potential of the world class astronomical facilities afforded by the NRAO.

Telescope Time Allocation (TTA) manages the process and tools by which users prepare and submit proposals for use of the VLA, the VLBA, and the GBT. TTA also manages the proposal evaluation and time allocation process. Science Ready Data Products (SRDP) is a new initiative that is facilitating the use of NRAO telescopes by a growing scientific community that extends beyond the radio astronomy domain experts. Scientific User Support (SUS) provides the scientific community with the support necessary to execute successful scientific programs with NRAO facilities.

The NRAO has a world-class staff of over 100 astronomers, computer scientists, and research engineers, recognized internationally for their excellence in telescope design and support, as well as their technical and scientific knowledge and leadership. SSR supports and oversees the research activities of the NRAO scientific staff, related performance reviews, professional development activities, the Jansky Fellowship postdoctoral program, undergraduate and graduate student programs, and other scientific activities, such as the Jansky Lectureship, scientific meetings, colloquia, and seminars. SSR also manages Observatory-wide reference services, including the NRAO Library, the Historical Archives, and Statistics and Metrics.

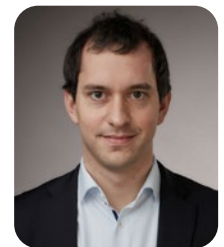
## Jansky Fellows 2021-2023

The NRAO Jansky Fellowship program provides outstanding opportunities for research in astronomy. Jansky Fellows formulate and carry out investigations either independently or in collaboration with others within the wide framework of interests of the Observatory. Multi-wavelength projects, computational studies, and theoretical work leading to a synergy with NRAO instruments are encouraged. Nine new Jansky Fellows joined NRAO in 2021-2023. The Jansky Fellows and NRAO Postdocs meet every spring and host the Postdoctoral Symposium, where science and research are shared among their peer group and science and engineering staff.



**Julia Blue Bird** (NRAO/Socorro) completed her Ph.D. in 2021 at Columbia University working with Jacqueline van Gorkom. Julia's PhD thesis research is focused on galaxy evolution with respect to large-scale structure across cosmic time. A main focus of Julia's thesis research involves interpretation of the COSMOS HI Large Extragalactic Survey (CHILES) measurements. Julia intends to continue her research with the CHILES measurements through a number of studies, including a characterization of the gas/star mass fraction as a function of redshift. Julia also has a strong commitment to education and public outreach. As a member of the Oglála Sioux Tribe of South Dakota, Julia intends to reach out to the Native American communities in New Mexico during her Jansky Fellowship with a goal to advance STEM education and understanding within those communities.

**Michael Rugel** (CfA & NRAO/Socorro) investigates the multiphase interstellar medium (ISM) with surveys of the Milky Way at radio wavelengths. His research focuses on the formation of molecular clouds, as well on feedback on them with studies of tracers of atomic, molecular and ionized gas. As a Jansky Fellow at the Center for Astrophysics | Harvard & Smithsonian and at NRAO Socorro, Rugel will expand his research on star formation, and structure and evolution of the ISM with the THOR-GC survey, an extension of The HI, OH, Recombination Line survey of the Milky Way (THOR) to the Galactic center, and the Bar and Spiral Structure Legacy survey (BeSSeL) extension to the southern Milky Way.



**Dillon Dong** (NRAO/Socorro) completed his Ph.D. in 2022 at Caltech with Gregg Hallinan. Dillon is broadly interested in astronomical objects that evolve over human timescales, and how they interact with their local and large-scale surroundings. He uses a combination of multi-wavelength observations and order-of-magnitude theory to characterize variable and transient sources that he identified in the VLA Sky Survey (VLASS). His current projects involve using supernovae as probes of pre-explosion eruptive mass loss, statistical characterization of black hole and stellar flares, and identifying radio transients with unusual spectral properties. As a Jansky Fellow at NRAO in Socorro, he will continue his study of VLASS transients and variables, with a focus on luminous, extragalactic radio transients. He also will continue his development of flexible tools to automate the detection of transients and variables in future VLA observations.

## SCIENCE SUPPORT AND RESEARCH



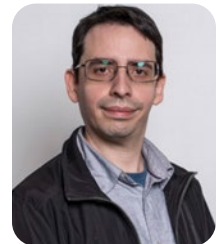
**Tao-Chung Ching** (NRAO/Socorro) earned his Ph.D. study at the National Tsing-Hua University, Taiwan, and CfA under the supervision of Shih-Ping Lai and Qizhou Zhang. He later became a FAST (Five-hundred-meter Aperture Spherical radio Telescope) fellow at the National Astronomical Observatory of China working with Di Li. His research interests are interstellar magnetic fields and star formation studied through observational astronomy from submillimeter to radio wavelengths. Using FAST, Tao-Chung has obtained the first Zeeman-effect detection of the HI Narrow Self-Absorption (HINSA) feature. As a Jansky Fellow at NRAO in Socorro, he will use the VLA to explore HINSA as a systematic Zeeman probe, measuring magnetic field strengths of star-forming regions at high angular resolutions.

**Rebecca Charbonneau** (NRAO/Charlottesville) earned her Ph.D. in History and Philosophy of Science from the University of Cambridge in 2021. Her dissertation focused on the history of radio astronomy and examined the challenges and benefits of international scientific collaboration during the Cold War period. She subsequently worked as the historian-in-residence at the Center for Astrophysics | Harvard & Smithsonian (CfA), during which time she led a project on preserving indigenous astronomical heritage. As a Jansky Fellow, her research program will make use of NRAO's historical archives and will focus on the history of international cooperation within radio astronomy.



**Samantha Scibelli** (NRAO/Charlottesville) received her Ph.D. in Astronomy and Astrophysics at the University of Arizona in Tucson, USA, in 2023. Samantha's research interests include submillimeter studies of the complex chemistry and physical properties of starless and prestellar cores to investigate the initial conditions of low-mass star and planet formation. During observations for her dissertation, she detected a prevalence of complex organic molecules (COMs) in young starless and prestellar cores in the Taurus Molecular Cloud (TMC), causing her to ask, "How are COMs forming so early?" As a Jansky Fellow Samantha continues to investigate the COM formation pathways using the Green Bank Observatory (GBO) legacy GLUCOSE program in combination with detailed chemical modeling of prestellar cores.

**David Monasterio** (NRAO/Central Development Lab) received his Ph.D. in Electrical Engineering from the Universidad de Chile in 2023, where the focus of his dissertation research was new heterodyne receiver architectures for the next generation of astronomical receivers, like those that will be utilized on the next generation Very Large Array (ngVLA) and other radio telescopes. David's primary research interests are in both heterodyne receivers and RF components design. As a Jansky Fellow David continues his research in new heterodyne receiver architectures, focusing in particular on multiband heterodyne receivers with the possibility to cover the entire RF spectrum instantaneously.



**Cosima Eibensteiner** (NRAO/Charlottesville) graduated from the University of Bonn in Germany in 2023 with a Ph.D. in Astronomy. Cosima's research interests include the structure, evolution, chemistry and kinematics of the interstellar medium (ISM), from large scale disk properties to central molecular zones in nearby galaxies. Her thesis, which utilized data from NSF's Karl G. Jansky Very Large Array (VLA), the Atacama Large Millimeter/submillimeter Array (ALMA), NSF's Green Bank Telescope (GBT), MeerKAT and IRAM, focused on disentangling the physical and chemical processes that shape and govern the ISM. As a member of the PHANGS collaboration, Cosima is studying stellar nurseries in nearby disk galaxies. As a Jansky Fellow at NRAO in Charlottesville, Virginia, Cosima is expanding her research into the effects of the ISM on star formation processes.

**Hendrik Mueller** (NRAO/Socorro) graduated with a Ph.D. in astrophysics at the Max Planck Institute for Radio Astronomy in Bonn, Germany, in 2023. Hendrik's research interests include development of novel VLBI imaging algorithms along the lines of multiscalar imaging in the spirit of compressive sensing and multiobjective evolutionary optimization, which are an improvement in resolution, accuracy and supervision over the CLEAN algorithm, and their applications to frontline VLBI projects in preparation for the next generation of high-resolution and high-sensitivity radio interferometers such as the next generation Very Large Array (ngVLA) and next generation Event Horizon Telescope (ngEHT). As a Jansky Fellow at NRAO in Socorro, New Mexico, Hendrik is focusing on the development of imaging and calibration tools for the ngVLA using artificial intelligence applications.



## Telescope Time Allocations: Semesters 2021A-2023B

In FY2021, the TTA group contributed to the new TTA Software Suite by writing software requirements and testing code. The new TTA Software Suite is being developed in conjunction with DMS as part of the SRDP program. The TTA group investigated gender equity in the TTA review process and published a paper in the Publications of the Astronomical Society of the Pacific (PASP).

The NRAO successfully ran two proposal review processes on February 1, 2022 (Semester 22B with 227 proposals submitted requesting time on the VLA, VLBA, GBT and GMVA) and August 1, 2022 (Semester 23A with 295 proposals submitted) with the final rankings for Semester 23A being sent to the PIs after the TAC meeting in Q1 FY2023. In addition, all the associated software tools to run the proposal calls were updated to accommodate accepting and evaluating PI proposals.

NRAO/NSF signed an agreement with ALMA/JAO on a Joint ALMA/VLA Proposal process. Implementation has begun to offer this capability starting with NRAO Semester 23B and ALMA Cycle 10. New staff have also been assigned to continue the demographic analysis work started with the initial gender bias analysis for accepted proposals.

The NRAO successfully ran two proposal review processes on February 1, 2023 (Semester 23B with 212 proposals submitted requesting time on the VLA, VLBA, GBT and GMVA) and August 2, 2023 (Semester 24A with 331 proposals submitted) with the final rankings for Semester 24A being sent to the PIs after the TAC meeting in Q1 FY2024. In addition, all the associated software tools to run the proposal calls were updated to accommodate accepting and evaluating PI proposals. The proposal call dates were moved to be the closest Wednesday to either February 1 and August 1. A new NRAO Users' Policies was published with the Semester 23B Call for Proposals which supersedes previous policies contained over various webpages and other documentation. Finally, the large program page limit was reduced from 10 to 6 pages and the DDT proposal page limit was reduced from 4 to 2 pages.

NRAO/NSF signed an agreement with both the Neutron Star Interior Composition Explorer Mission (NICER) facility on the International Space Station (ISS) and with JWST to offer joint NRAO/NICER proposals starting with Semester 24A and joint NRAO/JWST proposals starting with Semester 24B. New joint proposals with ALMA were offered in Semester 23B.



### New Assistant Director for Science Support & Research

Dr. Anthony Remijan started as the new NRAO Assistant Director for Science Support and Research in May 2022.

Dr. Remijan began his career at the University of Illinois (Urbana-Champaign), doing his undergraduate work and Ph.D. there. After some college teaching and a stint at NASA, he joined NRAO as a postdoc in 2006, eventually becoming a staff scientist, later Division Head for Scientific User Support and Research, and most recently Deputy Assistant Director for the North American ALMA Science Operations. He spent considerable time commissioning ALMA in Chile, and is well-known for his contributions to several NRAO / Green Bank Observatory instruments and science programs. As AD/SSR, he will work with departments and divisions across both Observatories to expand Science-Ready Data Products implementation and adoption, continue our excellent telescope time allocation process, and develop the science environment at NRAO to support the research needs of our scientific staff. His contributions to ALMA and the North American ALMA Science Center over the past decade, both as a staff member and a leader, have been an important part of ALMA's success.

## Science Ready Data Products

The Science Ready Data Products (SRDP) program seeks to increase the impact of the NRAO telescopes via three approaches: (1) remove barriers to the use of NRAO telescopes to encourage a broader user base, (2) curate a rich archive of science quality data images, and (3) perform automated calibration and imaging of data from NRAO telescopes. The three projects constituting the program are Science Ready Archive and Operations, the VLA Sky Survey, and development of a new suite of Telescope Time Allocation tools. The program has made significant progress on all three of its constituent projects during FY2021-2023.

The Science Ready Archive and Operations (SRAO) project represents the original scope of the SRDP program, focused on pipeline development, operations, and development of the archive; incrementally delivering capabilities through a five-year roadmap.

The SRDP heuristics team finalized the heuristics for an initial implementation of automated self-calibration for VLA and ALMA that was implemented in the pipeline infrastructure. An initial release of the capability was made in June 2023 and some refinements for use in operations were added for the ALMA/VLA pipeline release at the beginning of October 2023. The current self-calibration capability supports single-field data and ALMA spectral scans. While the pipeline capability was being implemented, the team further extended the self-calibration heuristics to handle low signal-to-noise cases better (typically long baselines for VLA and ALMA) and mosaics. The extended self-calibration heuristics are scheduled for pipeline implementation and a release is planned in early 2024 to bring the additional capabilities into the NRAO ALMA User-Defined Imaging capability, prior to deployment to full operations.

SRDP is leading an NRAO Archive Enhancement Project to enable better data discovery and delivery of calibrated data to the users. A release was completed in June 2023 that refactored some workflows to begin providing users with a more intuitive data delivery structure. A subsequent release is being prepared to provide users with more complete and usefully displayed VLA metadata.

The SSR Department through the SRDP program provides project management, requirement definition, and product validation for the TTA tools project.

- The ability to create proposals for the GBT and VLA, which includes proposal information such as the Title, Abstract, and Scientific Justification.
- The ability to capture a user's science request for Continuum and Spectral Line observing types.
- A prototype of Observation Specifications, which contain a Scan List and reflects the intent specified by the user.
- An interface for a proposer to navigate through the proposal creation process and view previously created proposals.
- An interface for Observatory staff to view and modify proposals created by any user, to prototype Solicitation Configuration, and to set messaging on the landing page of the TTA Tools.

## VLA Sky Survey

A joint deliverable with New Mexico Operations, the VLA Sky Survey is the third project managed by the SRDP program. The highest resolution all-sky survey ever undertaken at radio wavelengths, the VLA Sky Survey is a joint deliverable with the New Mexico Operations department. A synoptic survey observing the full sky visible to the VLA in three epochs, between 2–4 GHz, the VLA Sky Survey delivers low-latency QuickLook and higher fidelity Single Epoch images for each epoch of observation. VLA Sky Survey Science covers a wide area of exploration:

**Hidden Explosions:** The VLASS will open up new parameter space for finding supernovae, tidal disruption events, gamma-ray bursts and mergers of compact objects (e.g. two neutron stars).

**Peering through our Dusty Galaxy:** Dust is transparent to radio waves, allowing us to see structures in the Galaxy hidden at other wavelengths. Additionally, the survey will reveal extreme pulsars and cool stars with active coronae that are likely to be variable in the optical and radio.

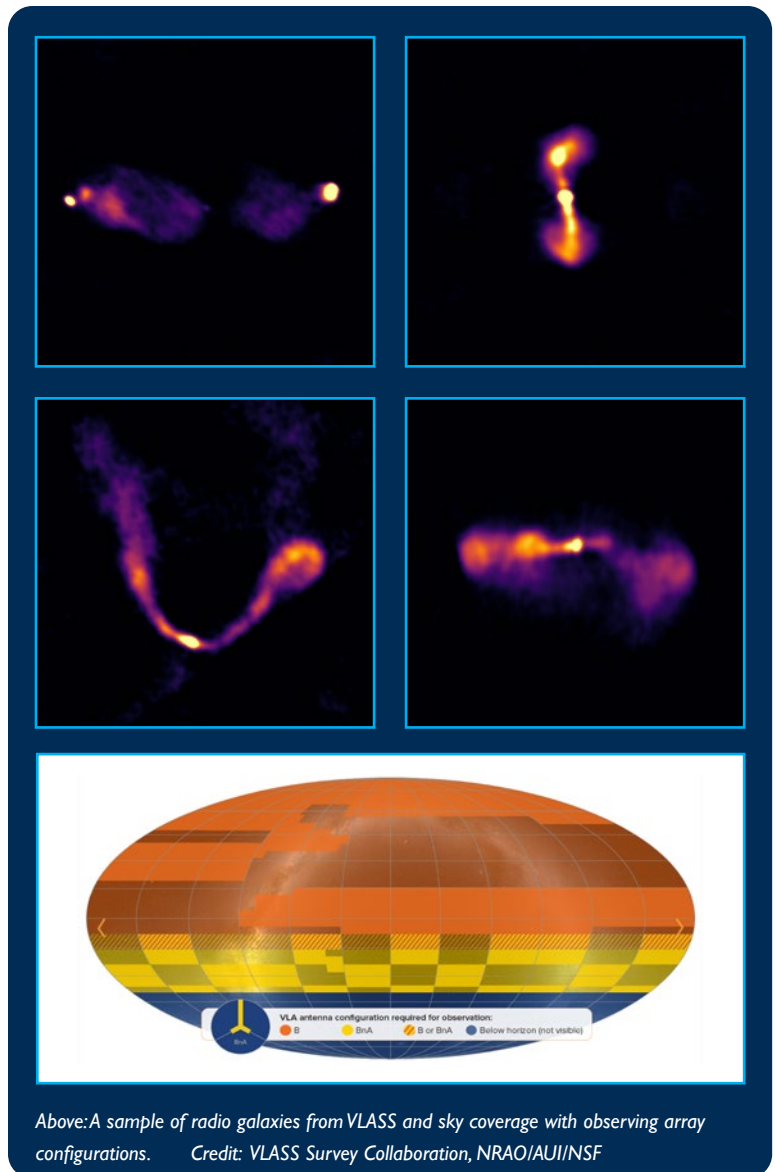
**The Magnetic Sky:** Our understanding of how and when magnetic fields arose in the Universe is poor. The VLASS will be able to measure the Faraday Rotation of the plane of polarization of radio waves that occurs when they pass through a magnetized plasma. Faraday Rotation is one of the few techniques for finding magnetic fields in space, from the surroundings of radio sources in dense galaxy clusters, to the magnetic field of our own Milky Way.

**Galaxies through Cosmic Time:** Jets of radio-emitting plasma can heat the gas within and around galaxies, slowing the formation of stars. The VLASS will help obtain a full census of these radio jets and AGN, needed to determine whether this heating is sufficient to restrict the growth of galaxies via this feedback mechanism.

**Missing Physics:** Whenever a survey breaks new ground in parameter space there will be discoveries unanticipated by the survey team. The radio part of the spectrum, in particular, provides unique diagnostics for a whole range of physical processes. Combining the VLASS data with ambitious new optical and infrared surveys will inevitably lead to significant discoveries.

The first half of the 3rd epoch of VLASS was completed in 2023 and 99% of QuickLook (QL) images were quality assured and delivered. Also, the first 1130 Single Epoch (SE) continuum images and 12 demonstration SE data cubes were processed with the VLASS pipeline. VLASS has demonstrated running computing jobs at scale showing that more than 1000 imaging jobs can be run at once which is a good test and demonstration for future ngVLA processing which will need nearly 106 jobs processed to keep pace with observations. Finally, VLASS provided impetus for new *aw*-project gridded in CASA, enabling wide-field, GHz-frequency mosaicking at high dynamic range. VLASS will need this for observations at southern declinations. This new algorithm is ~5x faster with Central Processing units (CPU), and using Graphics Processing Unit (GPU) gives another factor of 2x in processing speed. To date, VLASS data has been used in over 118 refereed papers and the VLASS survey description paper (Lacy et al. 2020) has been cited over 340 times. VLASS data is also widely used by NRAO REU student projects (four in FY2023) and is the main topic of the NRAO NINE student projects in machine learning. Given the success of the past several epochs of VLASS, the scientific community has been solicited to provide feedback for a possible 4th epoch.

The VLASS Science conference “*The VLA Sky Survey in the Multi-Wavelength Spotlight*” was held in September 2022 as a hybrid meeting, with over 100 in-person and 100 virtual participants.



Above: A sample of radio galaxies from VLASS and sky coverage with observing array configurations. Credit: VLASS Survey Collaboration, NRAO/AUI/NSF

### Robert L. Brown Outstanding Doctoral Dissertation Awards

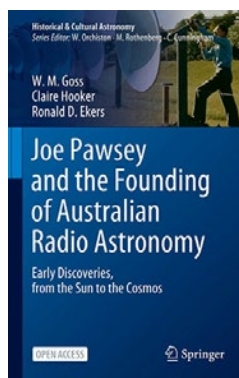
The NRAO and Associated Universities, Inc. (AUI) are pleased to announce that **Dr. Ci Xue** as the winner of the 2021 Robert L. Brown Outstanding Doctoral Dissertation Award. Dr. Xue's University of Virginia Dissertation, "Discovery and Morphology of Complex Molecules toward Interstellar Molecular Clouds," used observations performed with the Atacama Large Millimeter/submillimeter Array, the Green Bank Telescope, and the Very Large Array to explore diverse star-forming dense clouds in the Milky Way. Her remarkable research expands our understanding of the initial chemical conditions of star formation and the voyage of complex organic chemicals as building blocks of bio-macromolecules. The results of Dr. Xue's thesis will guide future projects in astrochemistry for new and powerful instruments to come. Dr. Xue is currently a postdoctoral associate at the Massachusetts Institute of Technology, where she is expanding her dissertation work to study aromatic chemistry in the interstellar medium.



The NRAO and Associated Universities, Inc. (AUI) are pleased to announce that **Dr. Patrick Kamieneski**, currently a postdoctoral scholar at Arizona State University, as the winner of the 2022 Robert L. Brown Outstanding Doctoral Dissertation Award. In his University of Massachusetts, thesis, Dr. Kamieneski developed an innovative use of gravitational lensing to interpret his ALMA and JVLA observations of high redshift galaxies to study the extreme rate of star formation in the distant Universe.

Both receipts received their awards at ceremonies at NRAO Headquarters in Charlottesville, Virginia.

### New Historical Radio Astronomy Books



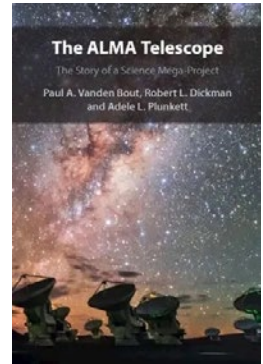
***Joe Pawsey and the Founding of Australian Radio Astronomy: Early Discoveries***, from the Sun to the Cosmos by W. M. Goss, Claire Hooker, and Ronald D. Ekers examines not only the life of Joe Pawsey, but the birth and growth of the field of radio astronomy and the state of science itself in twentieth century Australia. The book tells a previously untold story based on primary sources and explains how an isolated continent with limited resources grew to be one of the leaders in the study of radio astronomy and the design of instruments to do so.

***Star Noise: Discovering the Radio Universe*** by Ken Kellermann and Ellen Bouton tells the fascinating story of the remarkable, mostly accidental, or serendipitous discoveries in radio astronomy that have transformed our view of the Universe. Star Noise is about the men and women who made the discoveries, the circumstances that enabled them, and the unanticipated ways that scientific research really works.





**The ALMA Telescope: The Story of a Science Mega-Project** by Paul Vanden Bout, Bob Dickman, and Adele Plunkett tells the history of the ALMA Project from its earliest beginnings to its inauguration and first decade of science. The ballet that led to the merger of the US, European, and eventually Japanese concepts is recounted. The lucky breaks and near-death crises along the way are documented. Vignettes by key players around the world offer additional perspectives. The book ends by presenting significant science results and addressing several compelling questions: Was ALMA worth the cost and effort? Did ALMA meet its specifications? An Appendix lists some lessons learned along the way, hoping to inform future generations of transformational astronomical mega-projects.



## Scientific User Support

The Scientific User Support (SUS) group provides the scientific community with the support to execute successful scientific programs with the VLA and the VLBA. While the SUS group supports VLA users, the SRDP initiative has a goal to increase that scientific user base beyond traditional radio astronomers. In the longer term, SUS will use the products of the SRDP project to provide the scientific support for users to access, reduce, calibrate, and analyze their data as well as to help the community generate new and innovative ideas for science by fostering cross-disciplinary and cross-field ideas and techniques. Over the course of FY2022, NRAO staff hosted 28 face-to-face visitors for observing and data reduction at the DSOC in Socorro, NM.

The NRAO organized and hosted the 9th VLA data reduction workshop from October 11-20, 2022. The first week was dedicated to lectures by scientific staff and data analysts covering topics related to calibration and imaging of VLA data and pipeline products. The lectures were also broadcast online for the virtual participants, and recorded for future reference. The second half of the workshop was devoted to data reduction by the in-person participants on their own data with the help of the staff. The workshop drew 17 in-person participants, and a similar number online who tuned in for the lectures.

The NRAO organized two community day events (CDE) in FY2023. The first CDE was hosted by MIT Haystack Observatory, and was organized in collaboration with the resident ALMA ambassador. The event took place on April 3-4, 2023, and covered VLA, VLBA, and ALMA topics. Up to 15 individuals participated in this event. The second CDE was hosted by UNAM-Morelia in Mexico on September 28-29, 2023, and also covered VLA, VLBA, and ALMA topics. Forty individuals participated in this event.

The 19th NRAO Synthesis Imaging Summer School (SISS) was held June 13-21, 2023 in Charlottesville. The workshop consisted of lectures on aperture synthesis theory and techniques at a level appropriate for graduate students in astrophysics. The program included discussion groups, and tutorials demonstrating data collection, calibration, and imaging of various types of observations, including new data from the VLA, VLBA, and ALMA. Participants also toured the Green Bank Observatory and were also given the opportunity to participate in lectures and discussions on science and engineering.



### 2021 Jansky Lectureship Awarded to Dr. Luis F. Rodriguez



Associated Universities, Inc. (AUI) and the National Radio Astronomy Observatory (NRAO) awarded the 2021 Karl G. Jansky Lectureship to Dr. Luis F. Rodriguez, of the National University of Mexico (UNAM). The Jansky Lectureship is an honor established by the AUI trustees to recognize outstanding contributions to the advancement of radio astronomy.

Rodriguez is being honored for his significant contributions to the understanding of star formation and X-ray emitting binary star systems, his distinguished career as an educator and popularizer of astronomy, and as a mentor to a generation of radio astronomers. As a member of one of two teams that co-discovered outflows from regions of star formation, he contributed to shaping

the current paradigm of star formation. With Felix Mirabel, he discovered the first microquasars in the Milky Way — nearby and smaller analogs to quasars at the hearts of distant galaxies. They received the American Astronomical Society's Bruno Rossi Prize in 1996 for that work.

In 1992, Rodríguez obtained a grant from the Mexican government to equip the VLA with its first 43-GHz receivers, enabling some of the first images of dust emission from protoplanetary disks around young stars — disks that eventually will produce planets. He was the founding director of the Institute of Radio Astronomy and Astrophysics at UNAM, and is considered the father of radio astronomy in Mexico. As a professor at UNAM since 1979, he has directed 28 student theses. He is author or coauthor of more than 500 scientific publications that have received more than 25,000 citations.

Rodriguez earned a B.S. in Physics from UNAM in 1973 and a Ph.D in Astronomy from Harvard University in 1978. He has received the Mexican Award of Sciences, the most important such recognition given in that country, the Robert J. Trumpler Award of the Astronomical Society of the Pacific, and is one of only 40 members of Mexico's National College, which brings together the country's foremost scientists and artists. He is a foreign member of the U.S. National Academy of Sciences and of the Spanish Royal Society of Exact, Physical, and Natural Sciences.

He now is a Professor Emeritus of UNAM's Institute of Radio Astronomy and Astrophysics, and also is Coordinator of the Mesoamerican Center for Theoretical Physics in Chiapas, Mexico. He is working with NRAO on selecting locations in Mexico for key antennas of the proposed Next Generation Very Large Array.

## 2022 Jansky Lectureship Awarded to Professor Françoise Combes



Associated Universities, Inc. (AUI) and the National Radio Astronomy Observatory (NRAO) have awarded the 2022 Karl G. Jansky Lectureship to Professor Françoise Combes, Chair of Galaxies and Cosmology at the College of France and Astronomer at the Paris Observatory. The Jansky Lectureship is an honor established by the trustees of AUI to recognize outstanding contributions to the advancement of radio astronomy.

Professor Combes is being honored for her significant contributions to the fields of galaxy evolution, the interstellar medium, dark matter, and radio astronomy. Her expertise in a wide range of fields over the course of an outstanding scientific career has extended her influence to the entire breadth of astronomy. She is author of more than

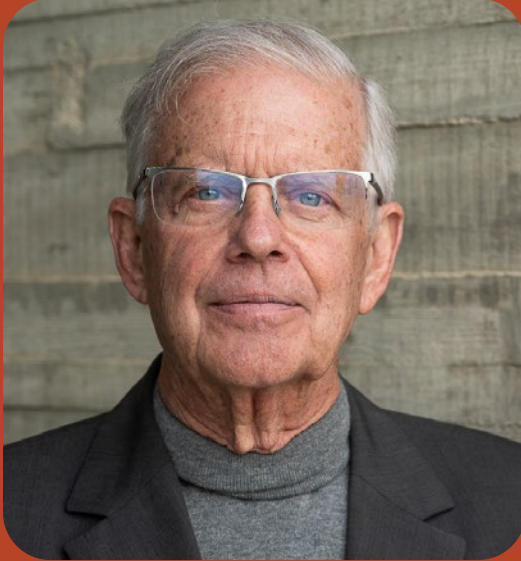
1,200 publications and more than 20 books.

She received a Ph.D in astrophysics from the Ecole Normale Supérieure in Paris, and her work has been recognized by numerous honors and awards. These include Fellowship in the American Astronomical Society, the R.M. Petrie Prize of the Canadian Astronomical Society, the Tycho Brahe Prize from the European Astronomical Society, the Gothenburg Lise Meitner Award, and an Honorary Fellowship of the Royal Astronomical Society. Professor Combes also received the prestigious L'Oréal-UNESCO Award for Women in Science in 2021, where she was recognized for her outstanding contribution to astrophysics with research crucial to the understanding of the birth and evolution of stars and galaxies, including the role played by supermassive black holes in galactic centers.

A longtime scientific editor of *Astronomy & Astrophysics*, she has served in advisory roles for the Atacama Large Millimeter/submillimeter Array, the Square Kilometer Array, the Hubble Space Telescope, and the International Astronomical Union.

Professor Combes delivered her lecture, entitled "*Symbiosis between black holes and galaxies*," covering observations with facilities across the electromagnetic spectrum, including ALMA and the VLA at NRAO and GBO locations in Charlottesville, Virginia, Green Bank, West Virginia, and Socorro, New Mexico.

### 2023 Jansky Lectureship Awarded to Dr. Paul Vanden Bout



Associated Universities, Inc. (AUI) and the National Radio Astronomy Observatory (NRAO) awarded the 2023 Karl G. Jansky Lectureship to Dr. Paul Vanden Bout, Senior Scientist, Emeritus at the National Radio Astronomy Observatory. The Jansky Lectureship is an honor established by the trustees of AUI to recognize and celebrate outstanding contributions to the advancement of radio astronomy.

During his tenure as NRAO Director from 1985 to 2002, a pivotal moment arose when the Subcommittee on Millimeter- and Submillimeter-Wavelength Astronomy, chaired by Alan Barrett, highlighted the necessity for a large millimeter array. Dr. Vanden Bout played a crucial role in turning this idea into reality, culminating in the creation of ALMA (Atacama Large Millimeter/

submillimeter Array). His leadership was instrumental in forming the ALMA partnership, and he successfully secured funding for the construction of ALMA even before stepping down from his Director position. His vision and efforts have significantly contributed to the radio astronomy landscape in the United States today not just with ALMA but also with the construction of both the VLBA and the GBT and the planning for and initiation of the EVLA project.

After earning his A.B. degree from Calvin College in 1961 and his Ph.D. from the University of California, Berkeley, in 1966, he has remained deeply engaged in scientific pursuits, with a particular focus on interstellar molecular spectroscopy. His primary interest lies in using molecular spectroscopy, especially at millimeter wavelengths, to deduce the physical characteristics of star-forming interstellar clouds. Throughout his career, he has actively served on various committees, showcasing his commitment to advancing scientific research. Some of the notable committees he has been a part of include the LIGO Program Advisory Committee, the NAS Committee on Radio Frequencies, and the NSF Astronomy Advisory Committee. He has also been involved with the American Astronomical Society (AAS) Council, served on several AAS committees, and held the position of AAS vice-president from 2005 to 2008.

His dedication to the field of astronomy extended to being a member of the Committee for a Decadal Survey of Astronomy and Astrophysics for the 2010-2020 decade, contributing his expertise to shape the direction of research in the field during that period. Dr. Vanden Bout has also published a new book with co-authors Bob Dickman and Adele Plunkett, titled *The ALMA Telescope: The Story of a Science Mega-Project*, and tells the history of the ALMA Project from its earliest beginnings to its inauguration and first decade of science.

## Reference Services: Library and Archives

The NRAO Library maintains distributed access to research and reference materials for NRAO staff and the community. Library staff aim to maximize the available resources and new material acquisitions within the operating budget. The NRAO Library is responsible for the publication, posting, and maintenance of 125 NRAO Memo and Report series, newsletters, publications, and collections of instrument-related documentation. All documents the library hosts are used by the NRAO and the scientific community in the operation and development of, and planning for, NRAO instruments and systems, as well as accountability to NSF.

Over the course of FY2023, the NRAO Library supported the publication of 120 papers from ALMA, VLA and the VLBA. The third phase of a comprehensive memos database project to support ease of discovery of NRAO memos and reports expanding author information and connecting authors to memos was underway in FY2023 and will be completed early in FY2024. The establishment of a faceted search index by DMS will close the Library's decade-long digitization project. Results from the first survey of journal subscriptions were collected and will lead to the strategic planning for library operations starting in FY2024.

The Library staff support internal and external reporting functions by collecting a variety of data and metrics in coordination with Statistics and Metrics services. This effort includes standard metrics requested monthly, quarterly, or annually. Closely related to the effort to track the impact of NRAO instruments in the literature, the library administers support for publication charges of qualified authors.

The NRAO/AUI Historical Archives seeks out, collects, organizes, preserves, and provides access to NRAO institutional records as well as personal papers of staff, former staff, and others with connections to the NRAO, preserves multimedia materials relating to NRAO history, and conducts oral history interviews. As resources permit, Archives makes these materials publicly available through an extensively documented web site and personal contact with internal staff and external individuals and organizations. As the national facility for radio astronomy, the NRAO/AUI Historical Archives also includes materials on the history and development of radio astronomy. It is one of the few Archives worldwide that already provides such a wide range of materials online without the need for researchers to physically visit the Archives, and its growing reputation has made the NRAO Archives the de facto repository for the history of U.S. and Canadian radio astronomy.

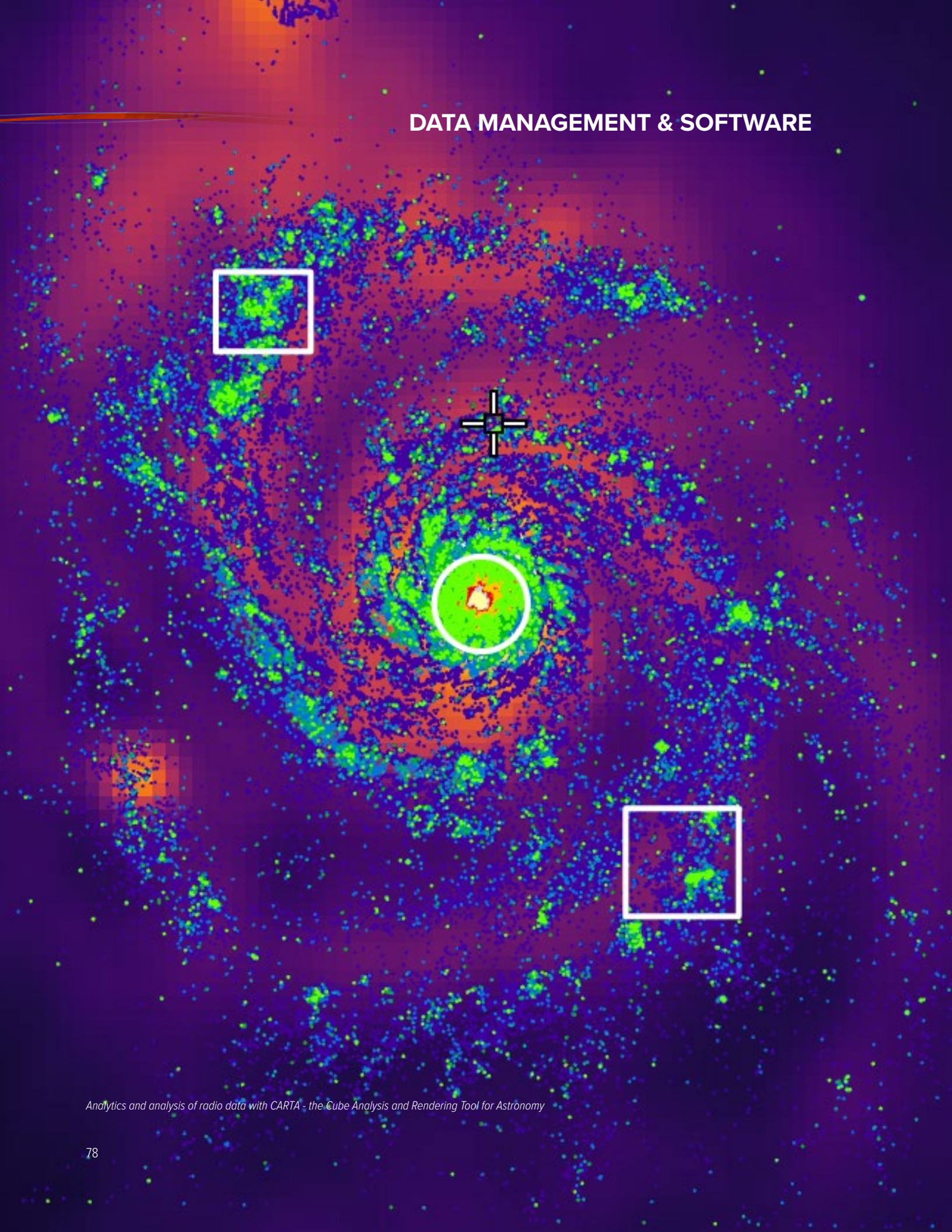
Over the course of FY2023, Historical Archives completed processing of collections from Bridle and Clark, and added material to several existing collections; hired an external contractor to complete the transcriptions of the remaining 108 Sullivan audio interviews as well as 18 Kellerman audio interviews; purchased additional shelving to house our expanding collection; mounted an exhibit in the Edgemont Road building lobby commemorating Karl Jansky; and hired NRAO's first full-time archivist.

The NRAO Historical Archive chronicles the rich history and milestones achieved by the NRAO. In 2023, the Very Long Baseline Array celebrated 30 years of scientific discovery and engineering design.



*Photo by Jeff Hellerman, NRAO/AUI/NSF*

# DATA MANAGEMENT & SOFTWARE



*Analytics and analysis of radio data with CARTA - the Cube Analysis and Rendering Tool for Astronomy*

The **Data Management and Software (DMS)** Department delivers scientific computing infrastructure, software, and algorithms to support current Observatory functions and to develop new capabilities for future needs. The department consists of Scientific Information Systems (SIS), Software Development, and the Algorithm Research and Development Group (ARDG). DMS works closely with the ngVLA project and Information Services. Computing management and personnel supporting the development of the ngVLA project are matrix managed by DMS.

### Scientific Computing Group

The Scientific Computing Group provided technology-driven scientific computing support and was tasked with delivering the next generation of data processing solutions, working in close cooperation with the DMS software division, telescope operations, and external cyber infrastructure partners. In FY2023, the lead of this small group retired. With the reorganization of the SIS division, the responsibilities and remaining members of the SCG were reassigned to the Algorithm Research and Development Group (ARDG) and the restructured SIS Division.

**Testing Scaling of GPU Processing:** The ARDG in collaboration with the Center for High Throughput Computing (CHTC) utilized the htclean distributed imaging library and Roadrunner GPU interface to demonstrate distributed imaging on the Partnership to Advance High Throughput Computing (PATH) infrastructure. Using only up to 10 GPUs, initial results suggest an imaging throughput of 1 TB per hour. The test image has a noise floor of about 0.9  $\mu\text{Jy/B}$ —which already represents the deepest high-resolution image with the VLA.

**Investigate ALMA Unmitigated Imaging:** Prior to the reorganization, the SCG completed a joint effort with NAASC and ALMA staff to investigate and document the performance of CASA and the CASA pipeline and describe the compute capacity required to support unmitigated ALMA science imaging pre- and post-ATCA correlator upgrade.

**Develop Second Generation Cluster Operating System (OS) Support:** Before the reorganization, the SCG planned to work with SIS to develop an updated cluster OS model. This is the first of several milestones which have been replanned for FY2024, as the restructured SIS group focuses on developing the next generation of technical infrastructure at NRAO.

**Planning for DSOC SIS Infrastructure Upgrade:** Development of a plan to replace the aging Lustre filesystem was deferred in FY2023 due to the many changes in the SIS division. This milestone has been replanned for FY2024 as part of the SIS effort to secure the legacy technical infrastructure.

**RADIAL Remote Cluster Compute Support:** Project RADIAL (Radio Astronomy Data Imaging and Analysis Labs) addresses current and future astronomy big data challenges while cultivating a diverse and globally competitive STEM workforce. Although delayed by long procurement times for key components, SIS designed, integrated, and tested a prototype RADIAL cluster. This prototype was used to document procedures for construction and support of remote RADIAL clusters. DMS is currently supporting our partners in the construction of the first node at University of Puerto Rico Mayagüez.

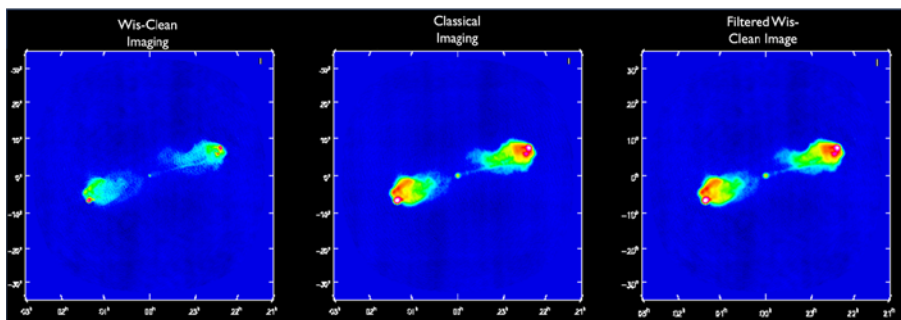
**ALMA Systems Group (ASG):** The ALMA Systems Group was formed in FY2020 to support and manage the ALMA software and infrastructure used by the NAASC for data processing. The ASG is now part of the newly refocused SIS division. The responsibilities of the group include deployment-testing and deployment of the offline software, including the new workflow software ALMA Data Processing Toolchain (ADAPT); maintaining the NA ALMA Archive; triaging issues from NA staff with regards to data processing and workflow; improving local infrastructure; and diagnosing and troubleshooting problems found in verification and validation of the software.

## Algorithm Research and Development Group (ARDG)

The NRAO Algorithm Research and Development Group pioneers algorithms necessary to support the scientific objectives of the Observatory. Currently the expertise within the ARDG is working closely with the ngVLA and ALMA WSU projects to understand the processing challenges posed by the projects.

**Full field polarization imaging:** Shortly after the FY2023 Program Operating Plan was finalized, the development of full field polarization imaging was deprioritized. While still an interesting area of research, the operational use cases have been satisfactorily addressed, and research effort redirected to other areas.

**Wide-scale imaging R&D:** This research project intends to develop imaging techniques which do not assume a scale-invariant telescope transfer function. Existing imaging algorithms require significant down-weighting, equivalent to a significant loss in effective telescope sensitivity, to conform to this assumption.



*Left: Results from the new Wis-Clean algorithm. Using simulated ngVLA data we compared imaging performance with Wis-Clean with the imaging performance of classical imaging that requires data down-weighting. By filtering the Wis-Clean image to match the spatial resolution of the Classical image (third panel) direct comparison is possible. This suggests that it is possible to reconstruct the sky emission without sacrificing sensitivity.*

**Memos:** The following memos were published by the ARDG group and are available from the NRAO library at <https://library.nrao.edu/>.

- Bhatnagar, S., Madsen, F. and Robnett, J. *Baseline HPG Runtime Performance for Imaging*. May 2022.
- Hsieh, M. Bhatnagar, S. Hiriart, R., and Pokorny, M. *Recommended Developments for Applying (W)Asp*. March 2022.
- Hsieh, M., Rau, U., and Bhatnagar, S. *Wide-band Implementation of the Asp-Clean Algorithm*. March 2022.
- Bhatnagar, S. *The Design of the AWProject Framework*. February 2022.
- Pokorny, M. *High Performance Gridding*. August 2021.
- Bhatnagar, S., Hiriart R., and Pokorny, M. *Size-of-Computing Estimates for ngVLA Synthesis Imaging*. August 2021.
- Bhatnagar, S., et al. *Full-Mueller Imaging with ALMA: ALMA Study Project Report*. February 2021.
- Hsieh, M and Bhatnagar, S. *Narrow-band Implementation of the Asp-Clean Algorithm*. January 2021.

## Scientific Information Services

The restructured Scientific Information Services (SIS) division is focused on providing the technical infrastructure to support the scientific operations of the Observatory. The SIS division works closely with the Information Technology (IT)-centric Computing and Information Services (CIS) division (Section 9). There are three major functional groups in SIS.

**Computing Operations (NAASC, NM):** These site-based groups directly support the day-to-day telescope operations for reliable data delivery to the archive for pipeline processing, and then the community. They ensure that telescope capability development projects are appropriately staffed, with resources assigned based on commitments and timelines defined within the PMD, and in coordination with local operations support priorities. Projects and milestones for these resources are tracked under the appropriate telescope support sections.

**Networking:** This science data capacity-driven group is responsible for provisioning the long-haul, high-bandwidth connectivity needed to uplink the telescopes and then deliver reliable throughput in support of PI access and general data delivery. Operational support for commodity circuits will be handed off to communication services in CIS once a network service has been accepted into production.



## Software Development

**ALMA System Software:** ALMA priorities are set at the JAO in cooperation with the other partners. Many areas of work depend on coordination with JAO for access to operational resources. The NRAO has worked closely with the JAO and partners to address the highest priorities as efficiently as possible.

**ALMA Control Subsystem, Bug Fixing:** The Control subsystem team spent approximately 50% of its time fixing bugs. Some are latent bugs being discovered as new ALMA capabilities are developed, tested, and used in science operations. Other bugs are triggered by software maintenance activities or changes to the software and/or hardware environment. Critical bugs were fixed as soon as possible and backported to the software used for ALMA operations. Lower priority bugs and bugs found in testing and validation were prioritized and deployed as appropriate in collaboration with affected stakeholders.

**ALMA Sustainability Project - Ethernet-to-CAN (E2C):** As part of the ALMA Sustainability Project, the E2C Project is an initiative to address some of the most pressing obsolescence issues facing the ALMA antennas and the Control subsystem software. The E2C project is an effort to replace the ALMA Bus Master (ABM) units. The ABM is a real-time computer that controls each antenna. Purchased in 2010, these computers are responsible for receiving, translating, and relaying messages from the Control subsystem to the antennas and providing monitoring and status information from the antennas to the Control subsystem. The current ABMs are obsolete and cannot be replaced or reliably maintained. Phase 2 of the E2C project implemented a prototype design for the next generation of real-time computers that adopts standard computer interfaces which can be easily upgraded, moves the real-time code into firmware, uses a new generation of processors, and provides the capability for faster monitoring and control that is expected in the next decade.

**ALMA Sustainability Project - Final Adder (FNL):** As part of the ALMA Sustainability Project, the Correlator team is working on a project to upgrade the interface between the correlator hardware and the Correlator Data Processing (CDP) cluster from DPI/hpdi32 to 10Gb Ethernet. Changing the interface to use 10Gb Ethernet allows the use of commercially available hardware options, industry standard communication links, and well-supported device drivers. In addition, it reduces the number of CDP nodes from 16 to 4, simplifies the data ingestion into the CDP nodes, and allows for debugging with industry-standard tools. During FY2023, the new Baseline Correlator Final Adder Board successfully completed ALMA Product Acceptance In-house (PAI), and the hardware was shipped to the JAO for assembly, commencing the next phase of Product Acceptance On-site (PAS).

**New Advanced Technology ALMA Correlator (ATAC):** The ALMA software team at NRAO obtained funding in January 2023 to commence the next generation ALMA Correlator as a Co-PI with National Research Council of Canada (NRC) to the ALMA Development Program. The ATAC will provide a broad range of new capabilities as part of a five-year proposal with the aim to be ready for science observations in 2029. Foundational project management and systems engineering efforts commenced in FY2023 with preparations for a Systems Requirements Review that will take place in Q1 FY2024 and a Preliminary Design Review in Q2 FY2024.

**ALMA Scheduling Subsystem - Technology Improvements:** In FY2023, the Scheduling subsystem allocated effort to a refactoring of the Dynamic Scheduling Algorithm (DSA) software. This planned activity transformed into a re-implementation of the DSA software stack. A new implementation of the DSA database was delivered with improvements focused on an upgrade of technologies, performance and concurrency improvements, and a mechanism based on custom schemas for cost-free extensibility in terms of new data to be handled on the ALMA Project Data Model (APDM).

**Science Data Model - Performance updates and Improvements:** The Science Data Model (SDM), which is the metadata that describes a given observation and the collected data, is shared between three major stakeholders: ALMA, the VLA, and CASA. The data model is maintained by the software group at the NRAO. Discussions commenced in FY2023 regarding the suitability of the current data model to support the ALMA WSU.

### New Mexico System Software

The responsibilities of this group involve the system software for the VLA and VLBA—primarily monitor and control, but also other operational functions, notably dynamic scheduling.

**VLA System Software and VLBA New Digital Architecture (VNDA):** On an ongoing basis, much of the work involves maintenance, including troubleshooting and bug fixes. Deployments for PI observing use for Semesters 2022B and 2023A occurred as planned in Q1 and Q3, respectively. Software was incrementally made available for commissioning new 2023A and 2023B capabilities in Q2 and Q4. During FY2023, support was provided for major VLA projects including Realfast (fast transient detection), VLASS, and ngVLA. Delays in the VNDA FPGA development resulted in the cancellation of the monitor and control software demonstration that was anticipated in FY2023. A new milestone has been established for FY2024.

**VLA Observing Preparation and VLBA Systems Software Support:** Two software releases for the Observation Preparation Tool (OPT) occurred as planned in FY2023. Version 1.31, released during Q1 and provided a COSMIC SETI off switch mechanism and RCT/SCT improvements. Version 1.3.2 was released during Q4 and provided a mechanism for using RFI blanking and will support wideband VLA recording during VLBI projects. The Q4 release will also include high-priority user enhancements and bug fixes. The related utility, vex2opt, was updated to support wideband VLA recording during VLBI projects. VLBA System Software Support for VLBA commissioning and observing followed the same deployment cycles as the VLA. The NMS group supported work on a new e-transfer file system.

### CASA

Development of the Common Astronomy Software Applications (CASA) package, the NRAO post-processing software, continues to emphasize support for the VLA and ALMA, unlocking the scientific potential of these world-leading telescopes. During FY2023, the NRAO continued to add capabilities in support of current operations while positioning CASA to handle future upgrades to ALMA and the anticipated demands of ngVLA-scale processing.

CASA development continued its more frequent continuous release strategy in FY2023, with up to three releases per quarter, bringing new capabilities, bug fixes, and improvements to the community faster and improving the responsiveness of the development team. CASA continued to coordinate with Pipeline and SSR to provide validated deployments for users.

In FY2021 and 2022, a cross-DMS team investigated the possibility of significantly reducing CASA image processing time via GPU use and demonstrated useful speedups for the VLASS observatory project. In FY2023, CASA integrated this new capability in production software and provided test versions to the VLASS project.

The CASA Next Generation Infrastructure (CNGI) study concluded in FY2021 with a proposed parallel processing framework and data structures. In FY2023, CASA participated in DMS system design efforts and studies to derive an architecture and specification for a next generation CASA. A data model definition project was also begun in collaboration with the SKA consortium. This work continues in FY2024.

Work on the Cube Analysis and Rendering Tool for Astronomy (CARTA) visualization software continued through the collaboration with the ASIAA CASA Development Center (ACDC) and the South African Institute for Data Intensive Astronomy (IDIA) with the intention of improving the user interface and expanding capabilities. With the successful release of CARTA 3.0 in FY2022, most capabilities of the old CASA viewer have been superseded. During FY2023, work continued towards filling a small number of remaining capability gaps.

The ngVLA project has funded work on a prototype antenna, the commissioning of which requires CASA development. During FY2023, CASA began development to support these use-cases, in accordance with project requirements and timelines.

CASA continues its partnership with the Joint Institute for VLBI in Europe (JIVE), supporting tasks to enable the use of CASA for VLBI data. CASA continued to include VLBI/VLBA development work in the continuous releases to the community. Work is underway on VLBA migration to CASA



in conjunction with the work already undertaken by JIVE. During FY2024, CASA will be including VLBI/VLBA development work in the continuous releases to the community.

Additional collaborations are extending CASA use and capabilities. The Australia Telescope Compact Array (ATCA) and Giant Metrewave Radio Telescope (GMRT) support CASA use for reduction of their data products by making a staff member available through the NRAO Helpdesk to answer questions specific to these telescopes. The international CASA development team, led by NRAO, continues to increase support for single dish data reduction and HPC capabilities working on the integration of those capabilities with the standard reduction pipelines. The team continues to add new algorithms based on prototypes from the NRAO ARDG.

**Publication:** Bean et al. 2022. *CASA, the Common Astronomy Software Applications for Radio Astronomy*, PASP, 134, 1041

## CASA Pipeline

During FY2023, the CASA Pipeline supported ALMA, VLA operations, and SRDP/VLASS with a major release for ALMA Cycle 9. For ALMA, the release included:

- Improved QA heuristics and infrastructure;
- Refactored calibration heuristics for faint calibrators (particularly common at high frequencies and low atmospheric transmission) to maximize the information that can be obtained from different calibrator sources with different flux densities;
- Performance optimizations in single-dish processing;
- Inserting additional information in the weblog to facilitate more efficient data reduction quality assurance.
- Review of “renormalization,” the mitigation of fluxscale variations with frequency that can result from ALMA’s correlator normalization scheme.

For the VLA, the release included a generalized compression correction for S-band and L-band, updates to Total Electron Content (TEC) map support, and various smaller improvements and bug fixes. An additional release in Q2 FY2023 supported VLA and ALMA self-calibration in the SRDP reprocessing interface and a pipeline update in Q4 FY2023 provided new capabilities and served as a test release for ALMA Cycle 10.

## Science Support and Archive (SSA)

The SSA group is responsible for the NRAO Archive and most of the user-facing software to support NRAO telescope use. In addition to bug fixes, the group updates the software functionality and user interfaces and provides integration.

**NRAO Archive:** The legacy archive was deprecated in FY2022 and was replaced by the new archive (<https://data.nrao.edu>). In FY2023, SSA continued to enhance the functionality of the new archive and add user-requested features including a scripting query interface using VO technologies. Work on automated data flagging will carry forward into FY2024. Archive work also continued in FY2023 to improve retrieval of image data and to address technical debt in the software.

**Proposal Process Support:** The PST and PHT were updated to support NRAO and GBO observing for the Semester 2023B and Semester 2024A Calls for Proposals, and the PST and PHT were updated for the Semester 2023B and Semester 2024A TAC process.

**Science Ready Data Products (SRDP):** The SSA team’s primary development focus for FY2023 was SRDP. The following goals support SRDP with a theme of image generation, discoverability, and delivery.

- Re-implement VLA Sky Survey QuickLook image product generation to use fewer resources and facilitate processing at other sites, as was done in FY2022 with Single Epoch Continuum imaging.
- Support discovery, retrieval, and CARTA viewing of ALMA Standard images will be carried forward to FY2024
- A deployment supporting production VLASS Single Epoch coarse cube product generation and archiving took place in FY2023.

**Telescope Time Allocation Tools:** In conjunction with the SRDP program, the SSA team is designing and implementing a new suite of tools to support the Observatory time allocation process. The first pre-release version was completed Q4 FY2022. The second pre-release version of the tool suite occurred in Q4 FY2023 and is undergoing user testing.



CENTRAL DEVELOPMENT LABORATORY

*Sub-Kelvin Dewar system.  
Photo by Jeff Hellerman NRAO/AUI/NSF*

The CDL mission is to support the evolution of NRAO facilities by developing the technologies and expertise critical for the next-generation of radio astronomy instrumentation. CDL-developed technology is integral to all NRAO-operated telescopes and to many other radio telescopes around the world, and so, another important mission of the laboratory is providing maintenance and upgrades to these instruments. CDL maintains a staff of approximately fifty personnel organized into teams of engineers and technicians working across crucial radio telescope technologies, including digital design and signal processing; low noise amplifiers; millimeter and submillimeter detectors; optics and electromagnetic components; and new receiver architectures. The laboratory is the world leader in the application of many of these technologies to radio astronomy.

The NRAO, in collaboration with the U.S. radio astronomy community at-large, continued to plan and develop an engineering design for a next-generation Very Large Array (ngVLA) after receiving a favorable outcome from NSF's Decadal Survey. By participating as members of several Integrated Product Teams, CDL actively supported this process throughout FY2021-2023. CDL also supports the greater NRAO mission of developing the next generation of instrumentation engineers and scientists and advancing inclusive participation in science and engineering by:

- Hosting Jansky post-doctoral instrumentation engineers and scientists,
- Hosting post-doctoral and co-op women engineers as part of CDL's Women in Engineering program,
- Advising, mentoring, and employing undergraduate and graduate engineering and astronomy students, and,
- Participating in student co-operative and internship engineering programs.

CDL continued to engage in cross-Observatory repair, maintenance, support, and in several programmatic and work-for-other construction projects. All this while carrying out design and development of technologies for future instrumentation—including for the ngVLA and for ALMA. In addition, CDL continued investigating new and emerging technologies that have the potential to advance the state-of-the-art in instrumentation.

A key component of CDL's strategic plan is establishing talent pipelines into the laboratory. A significant achievement in the effort to establish such pipelines, as well as to address the Observatory's mission of advancing inclusive participation in science and engineering was secured in FY2022 by a grant from the Heising-Simons Foundation to establish a Women in Engineering (WiE) program at the laboratory. This grant continues to support two women co-op students and two women post-doctoral fellowships at the CDL. In FY2023, CDL hired three co-op students under this WiE program.

The WiE program augments CDL's ongoing co-op program, in which eight other co-ops have participated since FY2019. The first former co-op was hired on as a staff engineer in FY2023, bringing to fruition the planned talent pipeline. Additionally, post-doctoral candidates were interviewed and one candidate was offered a Jansky post-doctoral fellowship position in FY2023— this candidate is scheduled to relocate to the CDL and start in the Jansky position in the fall of calendar year 2023.

CDL continues to work with the NRAO Technology Transfer Manager to commercialize technology developed in the laboratory. At present, patents have been issued for 17 CDL inventions, 6 of which have been licensed. One CDL invention submitted in 2023 has non-provisional patent status.

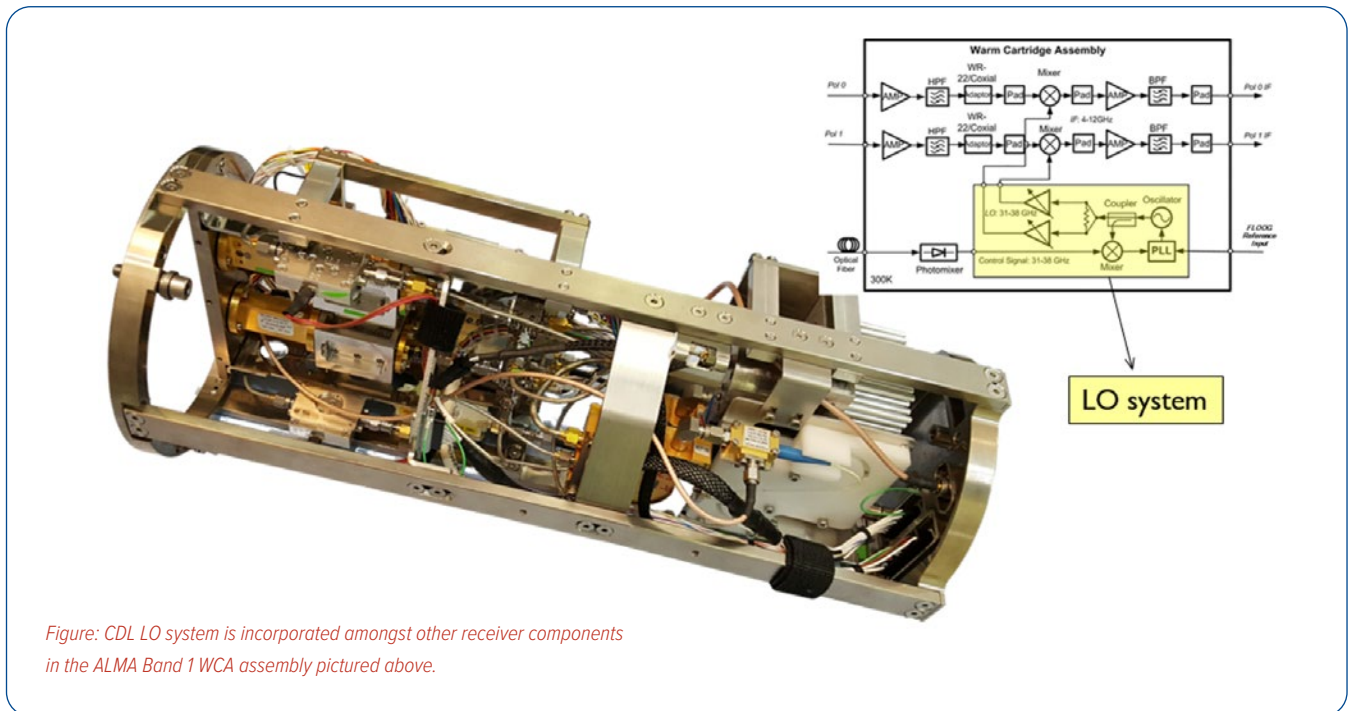
Under NSF's Partnerships for Innovation (PFI) program, work continued in FY2023 to develop high-frequency transmission-line reflectionless filters (existing patents) with Mini-Circuits using their Low Temperature Co-fired Ceramic (LTCC) process. This has the potential to allow use of reflectionless filter technology in ALMA receivers and to significantly expand the commercial market for the devices. At the same time, CDL has successfully prototyped reflectionless filters at millimeter-wave frequencies using advanced thin-film processes from Anritsu Corporation. The thin film process shows promise at even higher frequencies than the LTCC process. CDL has co-authored a paper on this technology with Anritsu that will be published in *Microwave Journal* and is planning to work with Anritsu in 2024 to further refine the process.

## Repair, Maintenance, Production & Support

The CDL core production and support activities for FY2021-2023 are described below.

### Low Noise Amplifiers (LNAs)

The low noise amplifier group continued production, maintenance, and support of CDL-produced amplifiers. In FY2023, the CDL amplifier group provided support for all VLA, GBT, and VLBA receivers in the field (a total amplifier population of about 1000 amplifiers in all). The CDL amplifier group also refurbished ALMA Band 6 IF preamplifiers for the continued upkeep of receivers on the ALMA telescope. The LNA team did this using commercial devices (transistors) from Diramics AG (Switzerland). The LNA team used Diramics devices in rebuilding Millimeter-wave Integrated Circuit (MIC)-based IF preamplifiers for use with ALMA Band 6 mixers. This use of the commercially available Diramics devices is critical, as they serve as a substitute for the Cryo-3 devices used over the past two decades. The Cryo-3 devices are no longer available as their supply has been depleted. The laboratory's LNA group also continues to support the cryogenic amplifier needs of the greater radio astronomical community as Work for Others (WFO) outside the Observatory's NSF award.



*Figure: CDL LO system is incorporated amongst other receiver components in the ALMA Band 1 WCA assembly pictured above.*

### Millimeter and Submillimeter Receivers (MSMRx)

CDL continued to support the offsite maintenance of the ALMA Band 6 receivers originally built by NRAO, with focus on additionally building a sufficient quantity of spare mixer-preamplifiers. During the same period, CDL also supported community projects and provided consultancy and/or hardware for the South-pole Telescope, and the Taiwanese Greenland Telescope (based on the Vertex ALMA prototype antenna). With the exception of the ALMA support, these activities were outside the scope of the Observatory's NSF award and carried out on a Work for Others (WFO) basis and undertaken only when it did not interfere with work required under the NSF award.

To help with expedited acceptance testing of Band 6 cartridges, one mixer test set and two cartridge test sets were kept operational throughout the year. Progress was slowed due unexpected failures in both repaired cartridges as well as the test set hardware; nevertheless, one repaired Band 6 cold cartridge assembly was shipped to the OSF after completion of all post repair testing during the course of the year. One additional repaired cartridge is nearing its acceptance test completion. The support team is down to the last few broken Band-6 cartridges that need to be fixed, but progress is hindered since very few optics components (specifically, RF horns and OMTs). During FY2021-2023, the team was able to successfully refurbish an old OMT block and return it to use for repairing a cartridge.

### **Integrated Receiver Development**

The Integrated Receiver Development (IRD) group continued to support and nurture NRAO-heritage telescopes such as the VLA and VLBA by providing construction and repair services on the multi-chip modules used in those facilities. The IRD group is uniquely qualified to carry out the specialized design and micro-fabrication tasks for such instruments, and takes seriously its responsibility to keep that institutional knowledge current via cross-training within the group.

### **ALMA Offsite Hardware Support**

The CDL offsite hardware support team provided extensive support to ALMA operations during FY2023, this effort included software and firmware support (bug fixes, implementation of new requested features), providing expertise to diagnose and fix problems during telescope operations, and repairing and returning broken LRUs removed from service. In all, 15 Front-end LRUs (including receiver cartridges), 32 Warm Cartridge Assembly LRUs, and 30 Back-end Local Oscillator and Photonics LRUs were returned to the ALMA site after repairs. A few notable LRUs (not a comprehensive list) that were repaired during FY2021-2023 includes: Band 6 cold cartridge assemblies, FE Monitor Control, warm cartridge/local oscillator assemblies (a mix of various bands), line-length correctors, sub-array switches, fiber optic wraps, BE IF processors, LO Photonic Receiver fiber cables, and LO Photonic Receivers. Lower level hardware repair was carried out on 283 sub-assemblies during this period. Hardware for the FE Test and Measurement Systems including the IF processor modules and tilt tables were also repaired/replaced or worked upon during FY2023. Effort was also initiated with an external vendor to repair LO Reference Test Modules as well as in laser synthesizers. Hardware and software for the bias module test system was also updated, and one copy of this test system was delivered to the OSF laboratory. In FY2023, a FE team comprising of four NA staff members, visited the OSF laboratory during the February shutdown period to provide onsite support by the way of upgrading FE test systems, delivering and commissioning a bias module test set, and assisting with assembly, integration, and verification of the first Band 2 receiver in the ALMA cryostat.

A member of the photonics support group concluded a visit to the hydrogen-maser manufacturer to conduct the pre-delivery in-plant test and inspection of the new hydrogen-maser unit on order for the ALMA observatory. Following this successful visit, the unit is scheduled to be delivered to the observatory in November 2023.

The Ethernet to CAN project (E2C) was another effort that was supported by the offsite support group staff. The E2C project is an obsolescence mitigation effort focused on replacement of the legacy real-time computing platforms with an Ethernet enabled embedded computing platform. During FY2023, phase-2 of this effort was executed and the E2C project team produced a production-quality prototype based on the conceptual design developed during Phase-1. This project entailed both software and hardware components, with the CDL team primarily responsible for the latter. A series of CDL-led in-house and onsite test campaigns in Chile were conducted to validate the design and to help develop appropriate documentation, required for the upcoming critical design review for the project.

In FY2023, the LO support team of the offsite support group was also involved in WFO construction projects outside the Observatory's NSF award. For ASIAA: the team recalled and repaired an LO assembly for Band 1; for The University of Chalmers: the team began the process of qualifying a Band 6 AMC, PA and frequency tripler set. The Band 6 cartridge support team built and delivered a mixer preamplifier set for the East Asian observatory.

## Development Plan

The CDL Research and Development (R&D) efforts supported NRAO Strategic Goals:

- Developing technologies necessary for the long-range objectives of the Observatory.
- Advancing the state-of-the-art in mission-related technology.



*Figure: Family of cryogenic LNAs (from L-band to W-band) developed and built for the Very Large Array and Green Bank Telescope.*

### Low Noise Amplifiers

In FY2022, work was undertaken to design new ALMA Band 6v2 LNAs with optimal noise performance over the extended bandwidth of the project using Diramics devices. The predicted performance was presented in the last annual progress report. During FY2023, a prototype of this design was implemented and tested with satisfactory results over the 4–18 GHz frequency range.

A new line of investigation to develop a capability to design Microwave Monolithic Integrated Circuit (MMIC) based amplifiers, was initiated by the new cryogenic group lead engineer. Such devices would be better suited for populating large arrays like the ngVLA. MMIC foundries were contacted for their design-kit information in order to start using the technology for designing a set of amplifiers that could be used for ngVLA bands 2, 3, and 4, and the MMIC design work was subsequently initiated. A balanced amplifier design, which could eliminate the need for using inter-stage isolators, realized on a MMIC with constraints placed on power dissipation is also being considered by the group to meet future advanced receiver needs.



*Figure: The small size and cost of the iW-RainboW-G35D board is suitable for continued SCREAM development under work-from-home conditions.*



## **MMIC Technology**

In the past, and as is the case with the new Band-6v2 amplifier design described above, the LNA group designed and fabricated amplifiers based on Millimeter-wave Integrated Circuit (MIC, or chip and wire) technology exclusively. For multi-receiver projects which require a large number of amplifiers (such as ngVLA), as well as for designs requiring higher component density, MMIC technology is more appropriate. During FY2023, the Northrop Grumman Corporation (NGC) design kit and process was selected for the first CDL-designed MMIC amplifiers. The first designs are for the lower bands of ngVLA (Band-2 to Band-4; i.e. 3.5 GHz to 34 GHz). Electromagnetic simulations were performed, and the designs were prepared and submitted to the foundry.

## **Millimeter and Submillimeter Detectors (MSMRx)**

CDL and UVA's Innovations in Fabrications Laboratory (IFAB) continued to make progress in developing the technology for the next generation of ALMA receivers, including a new generation of SIS mixers and efforts towards restarting the development of ALMA-compatible Traveling wave Kinetic Inductance Parametric amplifiers (TKIP).

UVA/IFAB completed the first wafer containing the newly designed Band 6v2 SIS mixers in Q4 FY2022. The chips were separated and delivered, and have passed the initial DC I-V characteristic screening. They also meet the target critical current density requirement to enable improved wide-band RF and IF operation. These mixers have been mounted in the chip test blocks (which were themselves described in the last year's performance report), and are awaiting cool down and RF evaluation in the THz-test set. This effort has been delayed because of an accident in the IFAB lab.

The design of a new stand-alone mixer test set for Band 6v2 use was also completed, and most of the components and parts needed to assemble it were ordered during this period. Work was also initiated on the revised layout of the components in the receiver cartridge, in close consultation with the team responsible for the optics design.

During this period, progress was also made with regard to testing the W-band TKIP amplifier prototypes from JPL/Caltech. RF instrumentation hardware procured for the TKIP milli-kelvin dewar during the past reporting period was incorporated into the test system. This hardware and test system were used for evaluating a W-band parametric amplifier at 4 K. Transmission (S<sub>21</sub>) was consistent with the design, but overall, the measurements were too lossy and no gain was measured.

## **Optics, Electromagnetic Components, and Orthomode Transducer Development**

Initial tests on three OMTs of the reverse-coupler design produced results that were inferior compared to predictions. Eventually the problem was traced to missing features due to still mysterious machining errors. This OMT was re-made on a different machine and retested with encouraging results. However, questions related to lateral shift of the two block halves and the impact of plating thickness were studied and remedied on a subsequent fabrication run (on the now repaired 5-axis Matsuura milling machine). Two OMTs of this type were also manufactured commercially. The final version of the reverse coupler implementation of the new Band 6v2 OMT was evaluated during FY2023 and found to meet the system requirements. Four OMTs of the double ridged type were completed in the workshop and tested, yielding encouraging but non-compliant results. Work was carried out on correlating the measured machining tolerances to their measured performance, in an effort to better understand the performance tolerance sensitivity with respect to various mechanical design features.

The Band-6 receiver optics path—a horn, two ellipsoidal mirrors, IR filter, and a vacuum window—were analyzed in FY2023 with the goal to improve cross-polarization levels and correct a sidelobe issue for the Band-6v2 receiver cartridge. It was determined that the existing mirror designs are adequate for Band-6v2; however, evaluation of the current IR filter and vacuum window to correct for cross-polarization issues continues. While direct measurements of these devices are planned by NAOJ collaborators, as a secondary approach to this analysis, the CDL team plans to make measurements on a Band 6v1 receiver cartridge with and without the filters in the cartridge test system. In addition to the Band-6v2 optics work described, the design of the dielectrically loaded quad-ridge feed horn design for ngVLA Band-1 was also finalized.

## CENTRAL DEVELOPMENT LABORATORY



### Digital Signal Processing and Correlators

The digital team completed the hardware, firmware, and software work on the Phase-1 demonstrator of the novel Scalable Reconfigurable Modular (SCREAM) architecture for the ngVLA Central Signal Processor, and successfully tested the prototype to demonstrate its operation including generation of signal spectrum, beamforming, and correlation capability. The SCREAM prototype consists of two beamforming and channelizing (B&C) nodes with basic functionality and a control/gateway node (master FPGA with a built in X-engine). These nodes are implemented on the iWave SoM (System on Module) boards. Interlaken transceivers (up to 150 Gbps) are used for data I/O from the B&C and the gateway nodes.

CDL staff also worked on building and validating a prototype for the new Ethernet to CAN (E2C) modules for ALMA. This hardware is required replacement hardware for the obsolete ALMA bus master computers, and it also forms the platform for enabling future migration of the ALMA M&C system to ethernet bus in order to support the more stringent ALMA WSU requirements.

During FY2023, the E2C was installed and tested at multiple locations at ALMA, including, the digital racks in several antennas (PM03, DA60 and DA63), HiLS correlator rack at the OSF and the computing rack at the AOS. Subsequently, fringes were achieved with a hybrid E2C/ABM system using three antennas. This was a major milestone for the project and validates the E2C concept. A special troubleshooting trip was made in September to determine the cause of a communications bug between the E2C and the FEMC. An updated version of the firmware for the FEMC AMBS11 board resolved the bug, as did disconnecting the Ethernet cable to the FEMC for remote firmware updates. The E2C project is preparing for a preliminary design review and approval for Phase 3, which will involve build out of the eE2C to replace all ABMs in use at ALMA.

## **LO Reference and Timing**

In preparation for a conceptual design review in early FY2024, work continued in FY2023 to follow through and build upon the trade studies and requirement development for the ngVLA conceptual design phase that occurred in FY2022. For the purpose of reference and timing, ngVLA antennas are broadly classified into two categories— the “near” ones that have central timing (nominally, 217 antennas fall in this category) and the “far” ones which have standalone timing (nominally 46 antennas fall in this category). 30 antennas with standalone timing are grouped into 10 clusters of three each with shared timing distribution over local fiber. The remaining 16 are truly standalone with their own reference. The CDL Time and Frequency group continued to be involved in research and development of:

- New techniques for accurate frequency generation, distribution, and synchronization for new and next generation telescopes;
- Leveraging new technologies in optics, lasers, optoelectronics, and fiber optics for radio astronomy;
- Collaboration with industrial and scientific partners in time and frequency research activities in radio astronomy and other fields.

## **LO Group**

Following the delivery of a prototype Band-6v2 local oscillator (Warm Cartridge Assembly) to the Band 6 cartridge group for end-to-end noise evaluation in FY2022, a Band 6v2 LO test plate and an extended RF range beam scanner test source were manufactured, tested and delivered in FY2023. Another Band 6v2 local oscillator is in the works and scheduled to be delivered soon.

The Band-6v2 requirements call for increased IF bandwidth from the present 4–12 GHz, to 4–18 GHz (at least), consequently, the LO AM sideband noise measurement test set needs to be enhanced and validated to support measurements over the increased offsets from the LO carrier frequency. Following a single channel proof-of-concept version that was demonstrated in FY2022 using equipment on hand in the laboratory, requisite components were procured in FY2023 and a two-channel measurement test set with lower LO AM sideband noise to cover the extended frequency range was produced.

A Band-7 WCA built using an alternate commercial HBT MMIC power amplifier was delivered to the OSF for functional testing. This necessitated changes to the firmware to make the operation of this new configuration transparent to higher level ALMA software. The new firmware was regression tested on the telescope before this new ALMA Band 7 warm cartridge assembly was deployed on an antenna. Another WCA with the original GaAs high-electron-mobility transistor (pHEMT) power amplifier, but incorporating an AMC built using the alternate commercial HBT MMIC power amplifier, was also delivered to the OSF and is in use as part of functional testing.

## **Integrated Receiver Development (IRD)**

The IRD program aims to develop compact, mass- producible, and field-replaceable Front-End hardware for the next generation of radio telescope facilities. Goals include: early digitization as near to the telescope focal point as possible; and relatively seamless integration of analog, digital, and photonic technologies into lightweight, low-overhead, Front End modules. The goal is for the architecture to be optimized to exploit the complementarity of integrated construction techniques and Digital Signal Processing, achieving a level of precision and stability that is unmatched by state-of-the-art radio astronomy receivers. The IRD program is working together closely with the CDL Digital Design team.

## **IRD ngVLA Work**

The IRD team continued to support the ngVLA receiver design and prototyping effort. It has completed the design of the analog portion of the RF receiver modules for ngVLA Bands 2 through 6, while that for Band-1 is nearing completion as well. Testing for the Band-2 prototype was completed, and currently the Band-6 is under construction in preparation for its evaluation.

# CENTRAL DEVELOPMENT LABORATORY

## Hydrogen Epoch of Reionization Array (HERA)

This was an ongoing development project, and the remaining goals of this multi-year work package that were addressed during FY2023 included the following: (1) A comparison of an antenna beam measured by the portable OrbComm system deployed at Milton Airfield near Charlottesville, measured by the UAV-based system, and modeled using an electromagnetic simulator. (2) HERA Vivaldi feed evaluation using the UAV-based system. (3) Initial testing of the prototype phase measuring system developed for the UAV. The field work was completed this past summer and the graduate student involved with this effort is currently working on his PhD dissertation..



## Network for Exploration and Space Science (NESS)

The second-generation Cosmic Twilight Polarimeter (CT receiver prototype) was completed. Two variants of the 1/15th scale model of the patch antenna were designed while a third variant is currently being designed; its engineering drawing is expected soon. The ceramic material for this antenna has already been ordered and received. Once the patch antennas are assembled, the beam patterns of all three scale models will be measured in Green Bank. A full-scale version of the selected variant will be built.

## Receiver System for Absolute Flux Measurements with the GBT

During FY2023, remaining modifications to the complete receiver, feed, and backend system that was developed for measuring the absolute sky synchrotron flux at 310 MHz using the GBT, were completed. Ground level drift scans are planned for October 2023, in preparation for the initial 24-hour run on the GBT scheduled for early 2024. The team received a three-year grant from the NSF Astronomy and Astrophysics Research Grants (AAG) program to make the polarized sky map for the low frequency radio astronomy community.

## Next Generation Radar (ngRADAR)

The ngRADAR project is a partnership between NRAO, GBO, and Raytheon Intelligence and Space (RIS) to develop the use of the GBT to transmit and the VLBA to receive radar signals. The NRAO Radar Division and its team members, are located at the CDL.

This team, along with GBO and RIS, started work on a concept design for a high-power, multistatic, next generation planetary radar system, which is funded through FY2023 as NSF Mid-Scale Research Initiative (MSRI-1) award from the NSF. The goal is to develop the full concept design for a high-power phased-array radar to be deployed at the GBT. The system will operate in multi-static mode using GBT to transmit and VLBA array to receive the signal enabling imaging of planetary surfaces, study of planetary structures and spin studies (non-imaging), tracking and imaging of near-Earth objects (NEO) and comets.

In FY2022, trade studies were initiated so as to mature the design for a Conceptual Design Review (CoDR). The design goals include:

- 85% GBT sky coverage (transmit at 13.7 GHz, bandwidth 200-600 MHz), MMIC based phased array with peak radiated power of 0.5 MW.
- VLBA receive, with GBT-VLBA "close-loop" ephemeris correction.
- GBT Transmit + VLBA Receive - comparable or better than Goldstone.
- GBT Transmit + ngVLA Receive - comparable or better than Arecibo.

The effort is supported by an NSF MSRI-1 award, and the key deliverable is a concept design for a high-power (500 kW), high-frequency (13.7 GHz; Ku-band) transmitter on the GBT with reception by the VLBA. The team completed an internal concept design review for the ngRadar project in March 2023 and successfully obtained the supplemental funding for project extension through FY2024. The team continues preparation for an external concept design review, scheduled for Q1 FY2024.

During FY2023, analysis of the proof-of-concept observations were carried out using a low power (700 W) transmitter on the Green Bank Telescope (GBT). Also, in FY2023, GBT radar observations (receiving from Goldstone) helped confirm the success of the NASA Double Asteroid Redirect Test (DART) mission.

### **Advanced Spectrum Monitoring**

In FY2022, this team, located at the CDL, worked to mature the design to the Conceptual Design Review stage, completed the review, and subsequently, began procurement of electronic components, and manufacture of mechanical parts, antennas etc. The mechanical design as well as the construction of the housing for the instrument was completed. Most of the on-order receiver components were received, and the antenna build, electronics circuits, and software design are nearing completion.

The design, construction, and testing of the first ASM prototype receiver took place during FY2023. The original scope of the prototype ASM receiver, which required coverage from 1–120 GHz, was substantially reduced with coverage specified only up to 20 GHz (with no down-conversions) for the initial phase of the project, ASM-1. The prototype was RFI testing in an anechoic chamber at Green Bank and subsequently deployed and successfully completed its field testing over the period of about one week.

Following the completion of testing of the ASM-1 prototype, the ASM-2 project was kicked off with goals to improve upon the shortcomings of the ASM-1 device and addressing the lessons learned during its construction and deployment. The ASM-2 design will follow a modular approach, and cover up to 50 GHz split into four bands: 1–20 GHz; 18–30 GHz; 28–40 GHz; and 38–50 GHz. It will improve upon the sensitivity of ASM-1 by use of improved antennas and their close integration with low noise block downconverters, followed by switching only at the IF (as opposed to the switching at RF used by ASM-1). The LO design will be simple in order to exercise control over unwanted self-generated spurious lines. The system will also incorporate internal noise calibration and initially feature dual polarization sensitivity from 1–20 GHz, but only single polarization observations above 20 GHz. Significant progress was made on the design of ASM-2 during FY2023.



# EDUCATION & PUBLIC OUTREACH



# VLA SPRING OPEN HOUSE

Free Tours & Talks  
GIVEN BY NRAO SCIENTISTS & ENGINEERS

Saturday, Apr 20  
9 AM - 4 PM

FREE ADMISSION  
ADVANCE TIMED-ENTRY  
TICKETS REQUIRED



National Radio Astronomy Observatory

[public.nrao.edu](http://public.nrao.edu) · [VisitVLA.com](http://VisitVLA.com)



The NRAO Education and Public Outreach (EPO) department serves the strategic Observatory goal of increasing public appreciation of and participation in Science, Technology, Engineering, Arts, and Mathematics (STEAM). EPO's four divisions had a busy year highlighting the discoveries, technologies, and careers pioneered and exemplified by the NRAO. In person tours restarted, and visitor centers reopened to the public to share in the exploration and discovery of the NRAO facilities.

## News and Public Information

**Press and Image Releases:** The news division released 144 press products to the public from 2021-2023. Press releases included incredible ALMA and VLA discoveries, VLBA observation results, NRAO milestones, student achievements, and in depth looks at employees and observatory operations. EPO also used Tip Sheets, Announcements, Feature Stories, and social media channels to publicly celebrate milestones, programs and staff accomplishments that are significant to the organization but not likely to be picked up as a press release.

**Blog Entries and Images Gallery:** The EPO group has committed to publishing blog entry stories not driven by individual press releases, but by exploring certain topics in more depth. The public image gallery is also continually populated with spectacular science images, telescope facility photos, and night sky photography. Visits were made to the St. Croix and Owens Valley VLBA station for photography and documentation.



### Beaming With Knowledge

Astrophysical masers are microwave lasers that occur naturally in space. They are found in regions of gas that have...

7 JUN 2023 - By Brian Koberlein



### A Research JOURNEY

The Jets and OUtflows Revealing the Nature and Evolutions of massive YSOs (JOURNEY) Project aims to better understand High...

7 JUN 2023 - By Brian Koberlein



### Small Wavelengths and Big Stars

The birth of a star begins with the collapse of cold molecular gas under its gravitational weight. But once...

6 JUN 2023 - By Brian Koberlein

**Media Outreach:** The Public Information Officers (PIOs) committed to several major media events with two audiences in mind: the researchers who use NRAO data to make discoveries, and the reporters and science writers who bring those discoveries to the public. A number of major science meetings were at the heart of these efforts, the American Astronomical Society (AAS) conferences and the annual meeting of the American Association for the Advancement of Science (AAAS). EPO offers media relation support to users to promote their research and scientific discoveries.

**Communications Training:** As HR expands the onboarding of new managers, the news manager was included in their agenda to emphasize that most employees are not considered spokespersons for the organization and that they should always reach out to the PIOs for media training before talking with the press. In addition to this broad staff training, individuals were coached before their press conferences.

**Spanish Translations:** Contracted services were used to translate press releases and premiere video content into Spanish.

**Liaison with ALMA Partners:** As part of the NRAO collaboration with the ALMA partners, the EPO Public Information Office coordinated its ALMA media relations efforts with the partners and the JAO through monthly telecons. This ensured the broadest possible exposure for ALMA news while maintaining the autonomy and individual outreach goals for each partner.

## EDUCATION & PUBLIC OUTREACH



*Photo by Bettymaya Foott, NRAO/AUI/NSF*

**ngVLA Communications Plan:** A new Public Information Specialist was hired in June 2023, and together with the News and Press Information Manager and NRAO Director, an existing ngVLA Communications plan was reviewed. Revisions are being implemented and a FY2024 release of the plan is expected.

**Social Media:** Social media provides a platform for unique content and to amplify the distribution of new content on the NRAO public website and press products. In addition to regular blogs on the NRAO public website, four social media platforms are maintained: Facebook, Twitter (X), Instagram, and LinkedIn all have a different format and audience.

### Multimedia Engagement

A dedicated, creative team of animators, artists, illustrators, designers, writers, and web developers designed and developed unique multimedia materials, in support of the news and information page, social media, and STEAM efforts, as well as creating new products that were distributed through the public-facing website, school programs, and the VLA Visitor Center.

**Press Products and Revised/Improved Image Gallery:** New workflows have been developed to keep the public-facing gallery populated with the latest images from press releases and other multimedia group projects. The overall gallery was still a challenge to search for particular images, so the organization and tagging of images was revised.

**Baseline Hosted Videos:** This is an original product of the Multimedia Group, that can be viewed on [public.nrao.edu](http://public.nrao.edu), [vimeo.com](https://vimeo.com), and YouTube in the Baseline playlist. The Baseline series transitioned to a short-form style in the attempt to reach an even larger audience.

**Year in Review Videos:** The top news highlights were once again created in partnership with Bad Astronomer host Phil Plait. They are released early in 2022, highlighting the discoveries in 2021.

**NRAO Brand and Style Guide:** This is a work in progress. As new projects are developed, like Augmented Reality, they are being added to the scope of the style guide.

**Augmented Reality:** Augmented reality was developed for press releases, but the first applications of it were for our telescope pages on the public website. Along with the fast facts for each facility, a 3D model of the ALMA 18m dish and the VLA 25m dish were placed on the website. The public can





interact with the 3D model, on the computer with a mouse or through the camera of their mobile device, they can bring the model into their room or space with them.

**Virtual Reality:** A central landing point has been established for the NRAO VR tours, with portals to each of the possible destinations. Within the ngVLA portal, there is now a simple way to view each of the science case videos in an interactive way.



**VLA Walking Tour Signs:** A new set of signs featuring updated content, including ngVLA information, were installed in July. They replaced the existing set that had been on site for approximately ten years. The installation and some custom fabrication of posts and mounting hardware was completed by the VLA Facilities team in record time.

**Blog:** Public website blogs are an opportunity to give a voice to diverse participants and provide an informal avenue to promote stories and information about the Observatory and the people connected to it, and will be published quarterly by Brian Koberlein.

**VLA Legacy Photography:** Bettymaya Foote was contracted to visit the VLA quarterly to capture day and nighttime images of the VLA throughout the year and in different configurations. Escorted by NRAO's art director, a spectacular series of images have been added to the image library.



*Photo by Bettymaya Foote, NRAO/AUI/NSF*

## EDUCATION & PUBLIC OUTREACH

A major pivot that happened with social media during the pandemic was a series of Facebook live events. Seven events were hosted as well as major support of the virtual tours offered by the STEAM Ed staff in lieu of touring visitors at the VLA.

### STEAM Education and Outreach

#### Lesson Plan Development:

The NRAO STEAM Education team designs teaching and learning experiences for K-12 learners, with the exception of authentic research experiences for undergraduates that are managed by colleagues in SSR. Initiatives for FY2023 include the following:

**Virtual Outreach:** An increase of in-person tours and events limited the ability to also hold virtual events. However, new virtual outreach events have been requested and scheduled providing opportunities to reach a global audience.

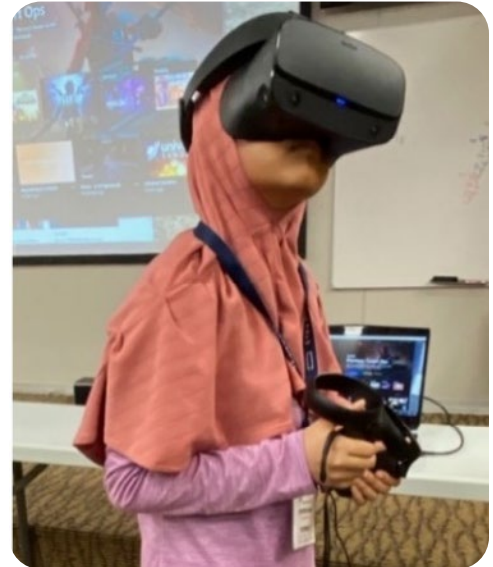
**VLA Tours:** In-person tours at the VLA have been numerous. Two part-time tour guides were recently hired to help meet demand.

**VLA Open House:** The Spring Open House was a great success. More than 700 guests were received at the site. The addition of food trucks and more interpreters enhanced the visitor experience.

**Staff Outreach Tracking:** The Google Form developed by the STEAM Ed team has proven to be a useful tool, and has allowed NRAO staff volunteering at outreach events to get the support they need to be successful.

**Stakeholder Engagement with Local Communities:** In New Mexico, new relationships were established with Alamo School, the NM State Fair Science and Technology Day team, STEM Challenge Schools and multiple home school groups, as well as the Northern New Mexico STEAM Collation. In Charlottesville, the NRAO partnered with Starr Hill Pathways and Girls Geek Day, and strengthened the collaboration between the NRAO and UVA Astronomy resulting in an increased number of events and students reached.

**Virtual Reality:** A variety of events utilizing VR capabilities were held both in the Charlottesville area and in Albuquerque. New outreach events have been scheduled for the Fall. EPO partnered with New Mexico STEMarts as VR content experts and presenter. EPO continued collaboration with Engage to create the “Path of Light” animation which explains the process of collecting radio light from space and how images are created. ngVLA antennas were updated to the latest design and a new ALMA VR scene was created. In addition, development began on a molecular cloud VR experience.



The NRAO public website is rich with new and sometimes interactive content (e.g., colorizing app and interferometry app). The STEAM team worked with the African American Teaching Fellows (AATF) STEAM Education Think Tank in Virginia to create a suite of lesson plans that are available for testing.

**Sister Cities and Observatories:** This NRAO-funded program partners two high school students and a teacher near the VLA in New Mexico with two high school students and a teacher near the ALMA site in northern Chile in a joint cultural/learning exchange, using a scientific experiment as a connecting thread of inquiry. This 10-day exchange seeks to reinforce the school curriculum through STEAM education activities. The emphasis this year will be to expand the shared experiences of the two cohorts leveraging the packaged STEAM Education lesson plans. A commitment and involvement will be required by students and school teachers from New Mexico and the Likan Antai C-30 School in Toconao, Chile. The students

and teachers will be responsible for participating in shared research experiences and for being ambassadors in local schools. EPO staff will work with teachers and students to refine their proposed curriculum projects. Travel for the New Mexico cohort was cancelled because of the pandemic.

**Outreach Events:** Most outreach events have been postponed during the pandemic. Before the shutdown, the STEAM Ed team participated in community events in local Socorro schools including Sarracino STEAM Night, Enchanted Skies Star Party, Festival of the Cranes, and San Antonio Elementary Science Day. The one virtual outreach event was for Project Rousseau, which hosted EPO educators in a classroom Zoom visit.

**VLA Visitor Experiences:** As a team, the STEAM Ed group completed certified interpretive guide training. This is a shift in mindset from specific content-learning goals to creating interpretive experiences at the VLA that are audience centered and mission driven focused. These skills will be applied to the revised virtual tours.



## Visitor Center Operations

NRAO operates a visitor center at the VLA, west of Magdalena, NM. The site has indoor and outdoor public exhibits, a small auditorium, a gift shop, and monthly tour program. The VLA serves local and international students and tour group. Many international visitors and groups were able to virtually tour the VLA from 2021-2022.

At the start of FY2023, the Visitor Center (VC) was reopened to the public after being closed for almost two and half years due to the COVID pandemic. New ticket selling and Point-of-Sale systems were in operation, as will an advance online sale ticket option. The goal for FY2023 is to increase the number of schools able to visit the site on field trips to lay the groundwork for the ngVLA milestone in FY2024 of engaging with sixth grade classes across New Mexico.



# MANAGEMENT & ADMINISTRATION



## Senior Management Organization

The NRAO organization from 2021-2023 consisted of departments, which were made up of divisions, which consisted of groups. This organization emphasizes Observatory-wide management and coordination in key areas, including Program Management, Data Management and Software, Education & Public Outreach, Science Support & Research, and Science Communications.



**Phil Jewell** continued as Assistant Director for the North American ALMA department. Jewell oversees the NA ALMA Science Center and the ALMA Development Program, coordinates the ALMA maintenance program, and is the face of ALMA to the North American scientific community. Jewell also continued in a part-time role as the NRAO Deputy Director.

The New Mexico Operations department, based in Socorro, was led by Assistant Director **Trish Henning**. New Mexico Operations includes all NRAO staff engaged in the operation, maintenance, calibration, performance, and further development of the scientific capabilities of the Jansky VLA and the VLBA.



**Faye Giles**, Assistant Director for Human Resources, directs Observatory-wide human resources policies and programs; including compensation, benefits, recruiting, employment, employee relations, organizational development, performance management and training.

The Program Management department (PMD) led by Assistant Director **Diane Paulson** provides program and project management support and systems engineering services to NRAO project leaders and PIs. The PM department strives to: provide visibility, transparency, and consistency in reporting within NRAO and externally to NSF and outside partners or customers; identify and provide resources for program management and systems engineering needs across all NRAO projects; review new projects for alignment in supporting the Observatory's long-term strategic goals; and compile deliverables.



Assistant Director **Barbara Gruber** leads the Education & Public Outreach department. The NRAO EPO program provides major components of the public's return-on-investment, marshaling NRAO resources in support of Science, Technology, Engineering, Art, and Math (STEAM) education. EPO also inform the science-interested public about the Observatory, its facilities, and the latest technical and scientific achievements of its users and staff.

The Data Management and Software (DMS) department led by Assistant Director **Jeff Kern** manages data archiving at NRAO, including access, distribution, provisioning, and operations. DMS manages the data reduction pipeline infrastructure implementation and technical operation; high-performance computing platform definition, acquisition, and operation; and network provisioning to the external community and between sites. DMS also has primary responsibility for all user-facing and telescope software.



The Central Development Laboratory (CDL) led by Assistant Director **Bert Hawkins** supports the evolution of NRAO's existing facilities and provides the technology and expertise needed to build the next generation of radio astronomy instruments. CDL accomplishes this through development of the enabling technologies: low-noise amplifiers, millimeter and submillimeter detectors, optics and electromagnetic components, including feeds and phased arrays.

## MANAGEMENT & ADMINISTRATION



Based in Charlottesville and led by Assistant Director **Laura Lockledge**, the Administration department provides the administrative and non-programmatic services to NRAO; including: business services, contracts and procurement, environmental safety and security, management and information systems, and technology transfer. **Jason Jennings** is the Charlottesville-based Assistant Director for the NRAO Budget Department, leading a team of fiscal and accounting experts.



Assistant Director **Anthony Remijan** leads the Science Support & Research (SSR) department. SSR is responsible for the Observatory's scientific interface to the NRAO user community. This Observatory-wide department also coordinates, aligns, and manages the collective efforts of scientific staff in Charlottesville and Socorro.



The NRAO / AUI Office of Chilean Affairs (OCA) supports the interests of the Observatory and its parent organization, AUI, in Chile, particularly the North American participation in ALMA. Led by Assistant Director **Paulina Bocaz**, OCA provides ALMA with legal, payroll, and travel support, and provides the legal and institutional support for numerous contracts and procurements for ALMA Operations in Chile.



The Science Communications Office (SciCom) led by **Brian Kent** is also attached to the Director's Office and is responsible for communicating NRAO science, accomplishments, priorities, and plans to the science community, the NSF, and other key external stakeholders. The office leads the NRAO exhibitions at science, engineering, and technical conferences worldwide.

The NRAO Chief Scientist, **Chris Carilli**, also reports to the Director about the Observatory's scientific mission and community requirements.





FESV 1

## Spectrum Management

### VLA and VLBA Radio Frequency Interference Mitigation

Spectrum management is a regulatory process whereby spectrum is apportioned into bands that are allocated to various radio services and applications, subject to rules intended to shield them from mutual interference. Spectrum allocations and spectrum rules are formulated at national and international levels. The NRAO participates in national and international spectrum management to protect and improve upon observing conditions for all astronomers, and has done so since its inception.

In the coming decades, the radio spectrum will become increasingly crowded at ever higher frequencies, and the NRAO will need to remain aware of threats and build both internal and cooperative (external) capabilities to use the spectrum in flexible ways.

The ability to observe without harmful radio frequency interference (RFI) is fundamental to NRAO science. The NRAO undertakes a variety of activities directed at understanding existing and emerging RFI sources, and maintaining a clean electromagnetic environment at and around its facilities. Activities include testing of installed equipment, formulating rules regarding operation of installed and visiting equipment, and mitigating or remediating externally interfering sources. The main areas of activity for Spectrum Management at the NRAO are: (1) Site Spectrum Management, (2) National and International Spectrum Management, (3) activities related to the NRZ Project, and (4) the regular monitoring and concurrence duties (Zone Regulatory Services) of the National Radio Quiet Zone (NRQZ) and the Puerto Rico Coordination Zone (PRCZ).

### VLA and VLBA Radio Frequency Interference Mitigation

The NM Operations Interference Protection Office coordinates spectrum usage for the VLA site by:

- (1) Responding to requests for Special Temporary Authority submitted through the NSF from the National Telecommunications and Information Administration (NTIA). The requests are analyzed for their potential impact to radio astronomy observing by performing propagation simulations and mapping terrain profiles, calculating the expected power flux density at the array antenna, and comparing the results to internationally recognized detrimental interference thresholds. Negotiations with the active spectrum user are conducted to limit, reduce, or eliminate the potential interference.
- (2) Informing external spectrum users at the U.S. Space Command, the tethered aerostat radar system (TARS) sites, and other military and commercial shared-spectrum users of NRAO and Arecibo Observatory planned spectrum usage each month. Jointly used spectrum may then be scheduled on a first-come-first-served basis, by priority, or by prior cooperative agreements.
- (3) Monitoring VLA site spectrum conditions using array observations and external monitoring equipment, and reviewing the resulting spectral plots and observer reports to detect new, unknown RF emissions. Detections in spectrum allocated to radio astronomy trigger source identification and technical discussions with the responsible spectrum user. Particularly detrimental emissions in non-radio astronomy spectrum allocations lead to goodwill discussions with the responsible spectrum user with the goal of interference reduction or elimination via technical means.
- (4) Performing RF emissions tests on incoming commercial or NRAO-designed equipment and reviewing the results to determine interference potential. Equipment found to exceed the detrimental limits is either rejected, modified, shielded, or submitted for re-design.

### National Spectrum Management

The NRAO comments on issues arising at the Federal Communications Commission (FCC) as they occur. The NRAO will continue to participate in the domestic activities of International Telecommunication Union Radiocommunication (ITU-R) Working Party 7D for radio astronomy, hosted by NSF, and other working parties hosted at FCC and NTIA. There is also a continuing interaction with the National Academies Committee on Radio Frequencies (CORF) and a presentation at their annual open meeting in May every year.





Photo by Chris De Pree, NRAO/AUI/NSF

## MANAGEMENT & ADMINISTRATION

The NRAO made six FCC filings in FY2023, mostly concerned with satellite communications with cell phones. These filings included responses to:

- Apple-Globalstar and Android-Iridium deals that will make cell phones behave like satellite phones, but without implementing the rules that apply to Globalstar's and Iridium's own phones. Low bandwidth use in spectrum is already implemented by Globalstar/Iridium. This possibility is less impactful than Direct to Cell (D2C).
- D2C satellite communication with cell phones in cell phone bands. SpaceX has outfitted 2000 Gen2 Starlink satellites w/ German-made L-band transmitters (1.6–2.7 GHz). Similar operations have been previously proposed by AST&Science (ASTSpaceMobile) and Lynk, Global. AST's ¼-sized 64m2 prototype is already one of the brightest objects in the sky. AST's final system would consist of ~256 full-sized systems.

The main problem with D2C proposals is that they moot the protections of radio quiet zones where RFI in cell phone bands has been coordinated away on the ground but will be introduced from overhead.

**Coordinated RFI Monitoring at Other AUI-Managed Observatories:** The GBO also has an Interference Protection Group (IPG) that is charged with monitoring local RFI conditions. This group meets biweekly and consists of scientific and technical personnel at GBO. GBO has also developed a highly capable RFI GUI for internal users, and is in the process of developing an online version of the GUI. ALMA has a number of scientists that are assigned to RFI issues at the Atacama, Chile site.

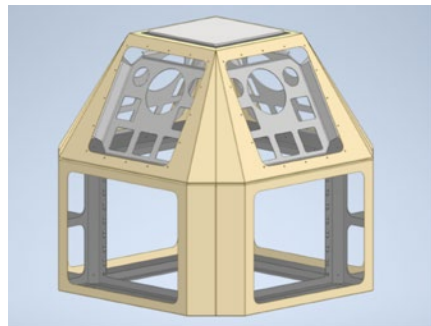
### International Activities

The NRAO spectrum manager served on the Scientific Organizing Committee (SOC) of the 2nd Workshop on Dark and Quiet Skies for Science and Society that was held in La Palma, Spain, in October 2022, again leading the radio astronomy working group. This meeting reined the recommendations from the first workshop in October 2021 that were presented at the April 2021 Meeting of the U.N. Committee on Peaceful Uses of Outer Space, for reconsideration at the 2022 meetings of that group and its Scientific and Technical Subcommittee. The NRAO spectrum manager was on the SOC for RFI2022 held in Reading, UK, 14–18 February 2022 to consider interference to radio astronomy and remote sensing with a new discussion of effects on meteorology given the host location at the European Center for Medium Range Weather Forecasting, (ECMWF). Adverse spectrum management decisions regarding 5G operations near 2.4 GHz have the potential to greatly impair weather forecasting.

The NRAO spectrum manager participates as a member of the Lunar-Martian Steering Group of the Space Frequency Coordination Group, representing the interests of radio astronomy in preserving the shielded zone of the Moon for future scientific activity in the face of new initiatives by the U.S. and other nations to exploit the lunar surface commercially under NASA's Artemis Accords. Commercial plans foresee implementing the current frequency arrangements used on Earth and in orbit about the Earth in the lunar environment, limiting the Moon's ability to provide a uniquely quiet RF environment for research in the shielded zone on the side facing away from Earth.

Both the NRAO spectrum manager and deputy spectrum manager attended ITU-R meetings in April and September 2022. The NRAO spectrum manager attends these meetings in person in his position as chair of IUCAF (Scientific Committee on Allocation of Frequencies for Radio Astronomy and Space Science), which is chartered by the International Council for Science. The deputy spectrum manager attends as part of the U.S. delegation.

Preparations for WRC-23 at ITU-R are in full swing with a full schedule of Working Party meetings that are once again taking place in Geneva. The NRAO spectrum manager attends these in his position as Chair of IUCAF, the Scientific Committee on Allocation of Frequencies for Radio Astronomy and Space Science, which is chartered by the International Council for Science. The NRAO Spectrum Manager was involved in the preparation for ITU-R Radio Assembly and WRC-23 in Dubai, November 13 to December 15, 2023. Key areas: (1) trying to preserve protections for radio astronomy that are embedded in draft treaty text, and (2) trying to influence agenda items for WRC-27 to consider radio astronomy adequately.



*The ASM-2 enclosure is being redesigned based on lessons learned from ASM-2, deployed and tested at the GBO in May 2023.*

## National Radio Dynamic Zone (NRDZ)

The NRDZ project began in 2021, and with additional funding that arrived in 2022 (SII-NRDZ), has been able to expand its goals and mission. The NRDZ project is now fully staffed with the hiring of an RFI Scientist, and RFI Data Analysts for VLA and GBT data. The NRDZ project is divided into three parts: (I) Concept Definition, (II) ASM, and (III) Broader Impacts. The Concept Definition and Broader Impact portions of the NRDZ project were completed in FY2023, with the ASM work continuing into FY2024. The additional funding of a SII-NRDZ grant (PI: Chris De Pree) will allow NRAO to explore (1) improvements

to the ASM device and (2) a pilot program entitled Operational Data Sharing (ODS) for sharing telescope status with satellite network operators.

**Concept Definition:** NRDZ Lean Coffee events and Workshops, co-organized with SUNY-Albany and the U.S. Naval Academy (USNA) led to the definition of a number of stakeholder requirements for an eventual NRDZ and the ASM device in 2022). These requirements were shared with the NSF for NSF to formulate a new call (SII-NRDZ-STUDY and SII-NRDZ-EEL). NRDZ Project Director was co-author on an IEEE Radio Communications paper and a popular article in *The Conversation* in FY2023. The NRAO participated in Spectrum Week/NRDZCOM2 at NSF in Spring 2023 and plans to present at NRDZCOM3 in Fall 2023.

**Advanced Spectrum Monitor (ASM):** In FY2023, the CDL completed and tested the first ASM prototype (ASM-1) at the CDL and GBO sites. These initial tests provided input and lessons learned for the design of ASM-2 that will undergo a CDR in November 2023. Current NRDZ-ASM related milestones and associated deliverables are covered by CDL.

## Zone Regulatory Services (ZRS)

In early summer 2023, the NRQZ PA was promoted to Zone Regulatory Services Coordinator, overseeing both the NRQZ and the PRCZ. The ZRS Co-ordinator is in close contact with the GBO/IPG group, meeting biweekly and updating other members of this group about current and upcoming NRQZ activities.

**National Radio Quiet Zone:** The National Radio Quiet Zone (NRQZ) was established by the Federal Communications Commission (FCC) in 1958 to minimize possible harmful interference to the NRAO in Green Bank, WV and the radio receiving facilities for the United States Navy in Sugar Grove, WV. The NRQZ encloses a land area of ~13,000 square miles, mostly in Virginia and West Virginia.

The NRQZ office is continuing the reconfiguring of the concurrence application process from an email-based system to a helpdesk system, with a new helpdesk becoming operational in Q1 FY2023. Internal and external documentation on the NRQZ process was completed in Q2, and computational and archiving machines were moved to NRAO-CV. The NRQZ received additional NSF support to make the concurrence application process simpler and web-based. NRAO plans to start piloting web-based submissions to the NRQZ by Q4 FY2024.

In FY2023, the NRQZ office began the process to visualize completed applications around GBO, with a focus on location, transmitter power, and frequency.

**Puerto Rico Coordination Zone:** In August 2023, NSF provided funding to the NRAO to take over coordination efforts in the PRCZ through 2026. The NRAO hired an experienced spectrum manager and telescope operator from Arecibo to serve as PRCZ Program Administrator. The PRCZ PA is working closely with the ZRS Coordinator to document and update concurrence processes in the PRCZ. PRCZ processes are now documented on the NRAO website.

## MANAGEMENT & ADMINISTRATION

### Science Communications

The Science Communications Office (SciCom) collaborated with the Observatory's scientific staff, senior management, and Director's Office to communicate the NRAO vision, science, accomplishments, and plans to the U.S. and international science communities, NRAO/AUI staff, and key external stakeholders, including NRAO advisory committees and the NSF.

SciCom managed a large island exhibit at the June 2022 AAS Conference in Pasadena, California, along with a Town Hall reception, hosting the astronomical community, user base, and new students in person.

SciCom participated in the November 2022 National Society of Black Physicists (NSBP) conference with our exhibit displays and prominent placement in the conference lobby. The NRAO was able to promote opportunities and research to student and faculty participants. The NRAO and Charlottesville hosted this annual conference.

The FY2023 winter AAS conference was held in Seattle, Washington, from January 7-12, 2023. The NRAO sponsored three special event proposals. The first splinter session on *NRAO Science Ready Data Products using the VLA Sky Survey* allowed users to access, understand, and utilize the archived images and catalogs from this large community driven initiative. The second special session informed the astronomical community on plans for increasing the capabilities of ALMA, including the WSU. The third special session examined *Chemical Probes of Astrophysical Systems with ngVLA*. In addition to the NRAO exhibit displays, the Observatory hosted a Town Hall reception so that meeting attendees could interact with NRAO staff and learn about the latest science capabilities. The NRAO and AUI also participated in the REU and Grad Student Fair event. This event has grown in recent years as young students and recent graduates are interested in educational and employment opportunities during their university years and beyond.

SciCom sponsored a large exhibit at the American Association for the Advancement of Science (AAAS) annual conference in Washington, DC from 1-6 March 2023. As a prominent display representing the astrophysical sciences, the NRAO was able to showcase facilities and science to the broader scientific community.

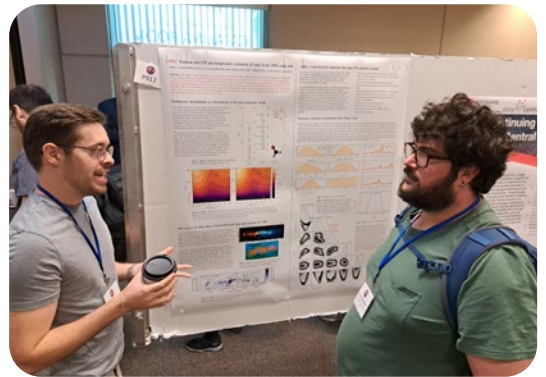
SciCom participated in the joint ngVLA-SKA New Horizons conference from May 1-5, 2023 in Vancouver, British Columbia. The conference explored the science and synergies between these two large observatory projects. Over 300 attendees gave talks and posters on science covering three frequency decades that will be observed by these facilities.

The FY2023 summer AAS conference was held in Albuquerque, New Mexico from June 4-8, 2023. The NRAO sponsored two special session proposals. One event showcased *An Explorer's Guide to the VLA Sky Survey*. The second splinter session gave community members an update and forum on the ngVLA. Both sessions were hybrid, growing the participant list.

A joint event between manufacturing partner *mtex antenna technologies* and NRAO was held September 26-29, 2023 in Leipzig, Germany. The week started with a Germany Science symposium with the ngVLA, and included participants from the American and German science communities. A large event at the new Leipzig mtex antenna assembly facility brought together mtex, NRAO, German politicians, consulate diplomats, and the New Mexico State Department to unveil the new prototype ngVLA antenna structure. The week concluded with mtex and NRAO hosting local high school students who came to learn about radio astronomy, engineering processes, and careers in STEM.

In collaboration with the scientific and technical staff, and contributors across the Observatory, SciCom continued to edit and improve the Observatory's monthly digital NRAO Newsletter, and the occasional electronic announcements series, NRAO Announcements. The subscription base for the NRAO Newsletter and the Announcements stands at 9,500+ addresses. SciCom also continued to edit and publish the semi-annual CASA News in collaboration with the CASA team.

From 2021-2023, SciCom continued to edit, improve, publish, and expand the subscription base for the Observatory's monthly electronic newsletter, NRAO eNews, and the periodic electronic announcements series, NRAO Announcements, with 9,700+ subscribers in North America and around the world. SciCom also updated the NRAO Research Facilities brochure prior to the all the winter AAS conferences.



Photos by Brian R. Kent, NRAO/AUI/NSF

# PERFORMANCE METRICS

## Observing Hours

Telescope performance for the VLA and VLBA is characterized by the NRAO in the following categories: Scheduled, Maintenance, Test, Unscheduled, or Shutdown. The sum of these categories is the total number of available hours each month: 720 hours in a 30-day month, and 744 hours in a 31-day month. Scheduled science operations time is either Astronomy or Downtime.

ALMA telescope time is reported by the Joint ALMA Observatory in two categories: Observing and Other.

### Observing hours for each NRAO telescope are divided into the following categories:

#### **Scheduled: Planned hours of observing time for peer-reviewed science proposals**

Scheduled = [ Astronomy + Downtime ]

**Astronomy: Actual hours of observing time for peer-reviewed science proposals**

**Downtime: Hours lost during scheduled observing time for peer-reviewed science proposals**

**Maintenance:** Actual hours of scheduled service of infrastructure, structure, electronics, and software.

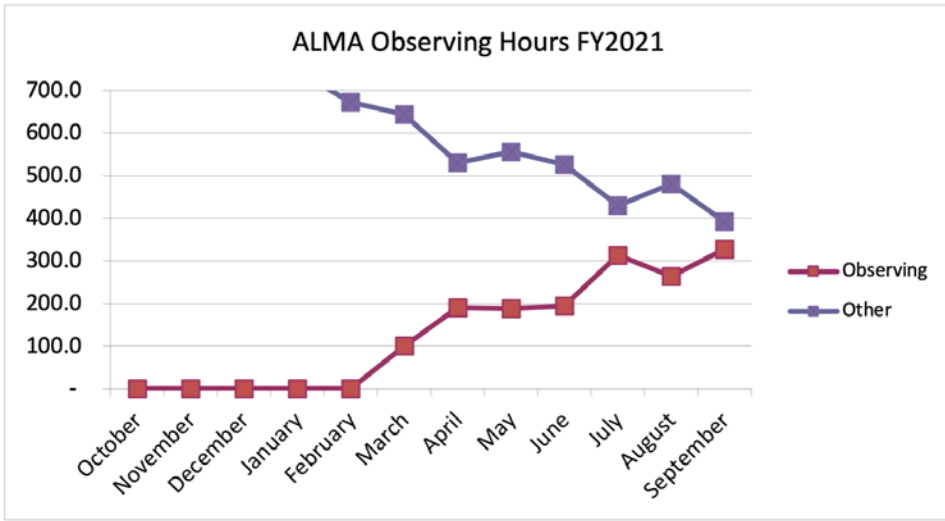
**Test:** Actual hours for test observations rather than peer-reviewed science proposals.

**Unscheduled:** Actual idle hours owing to gaps between observing programs that cannot be scheduled and to predicted, extended inclement weather.

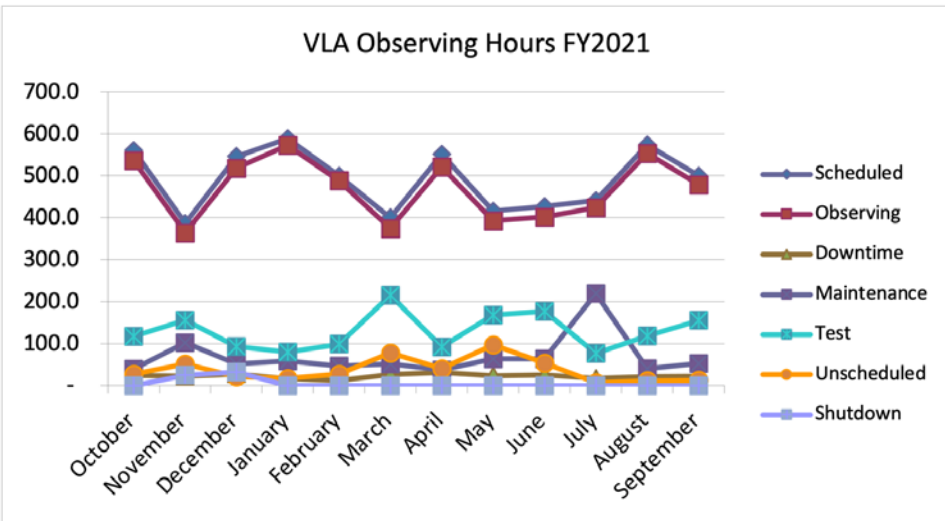
**Shutdown:** Actual shutdown hours, usually for a holiday. Other major shutdowns occur for major equipment work.

## 2021 PERFORMANCE METRICS

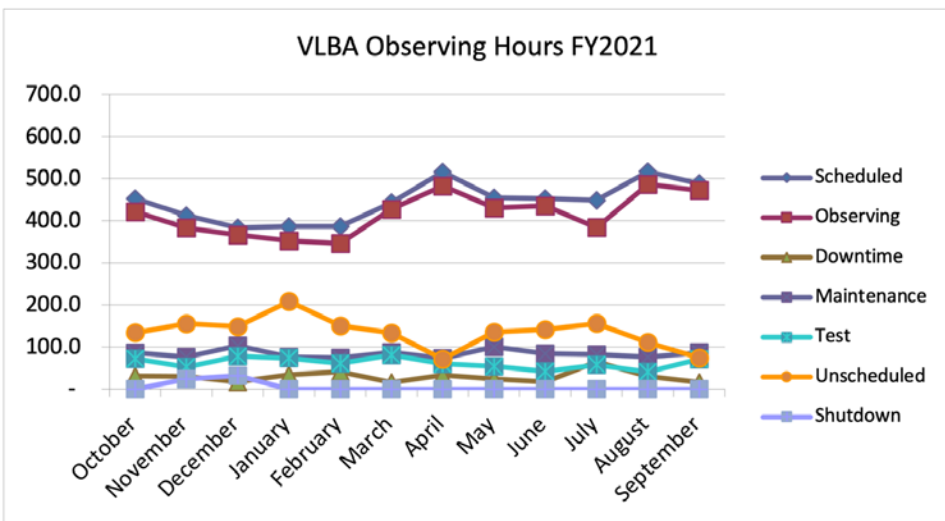
ALMA Observing Hours



VLA Observing Hours

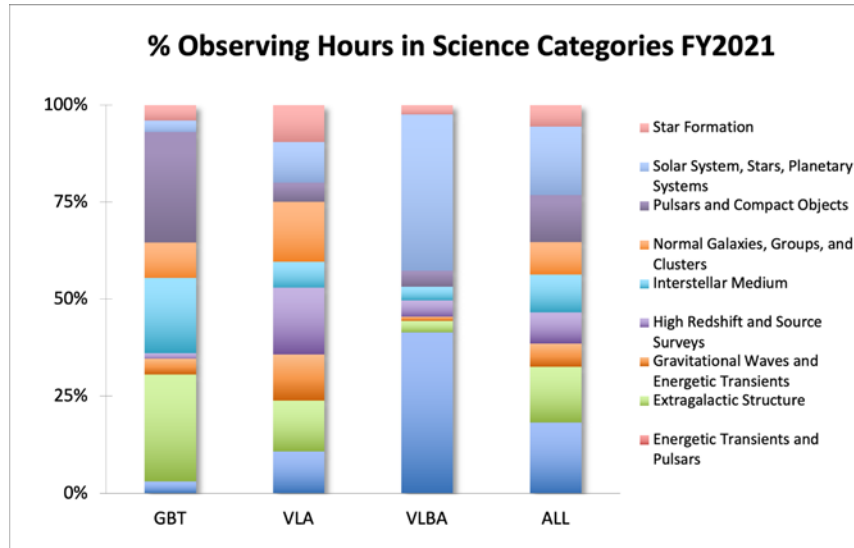


VLBA Observing Hours



# 2021 PERFORMANCE METRICS

## Observing Hours by Science Category



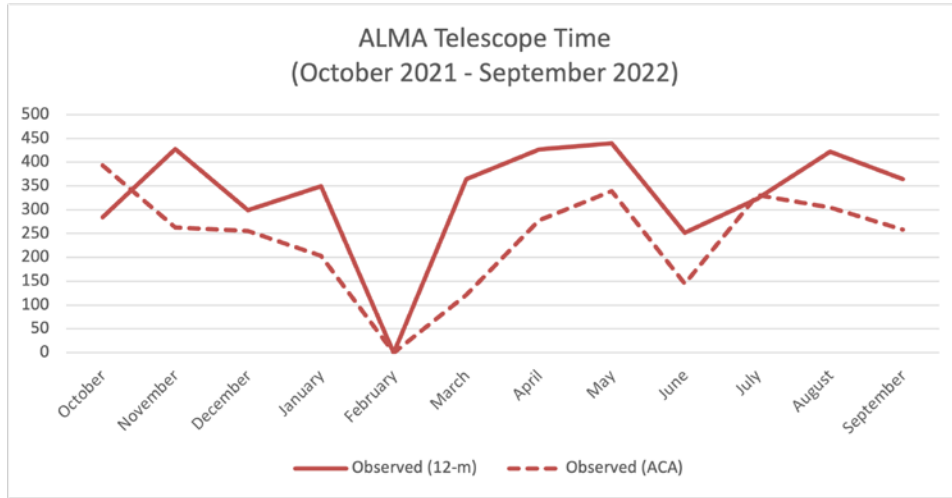
Observing hours for each of the GBT, VLA, and VLBA are tracked in the nine science categories defined in the NRAO-GBO proposal evaluation and time allocation process.



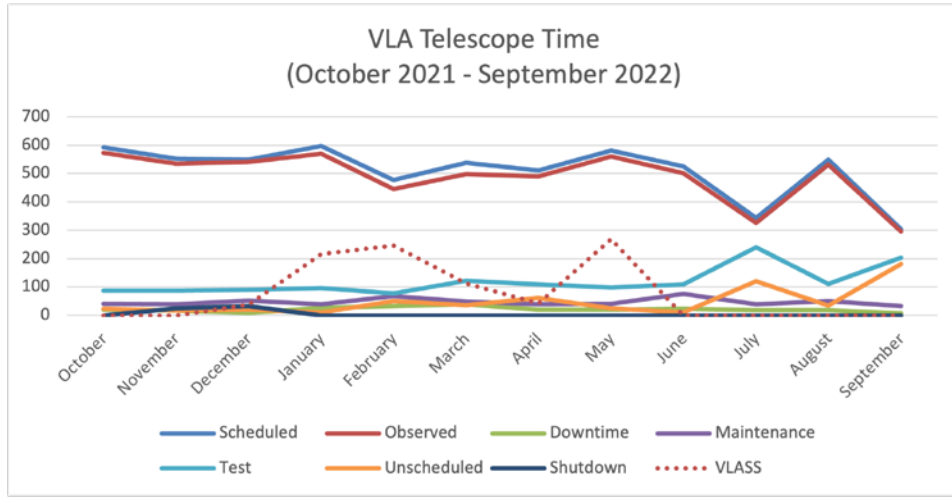


## 2022 PERFORMANCE METRICS

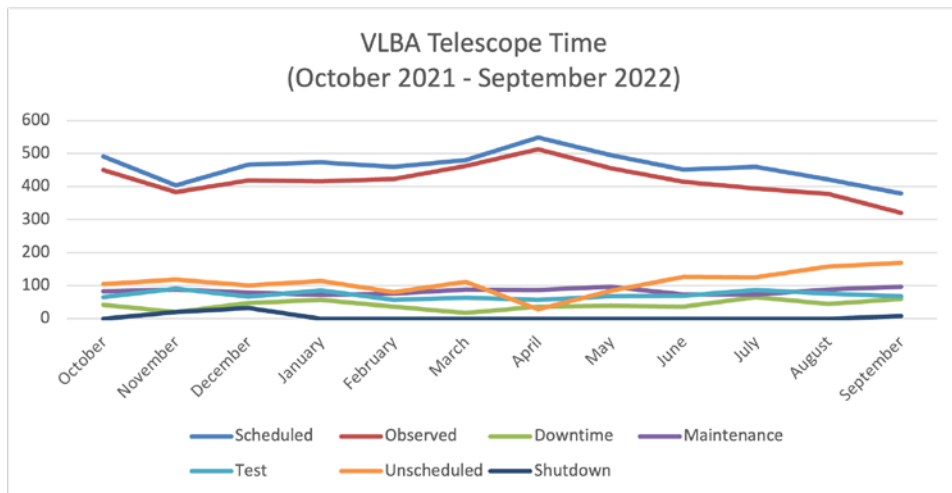
ALMA Observing Hours



VLA Observing Hours

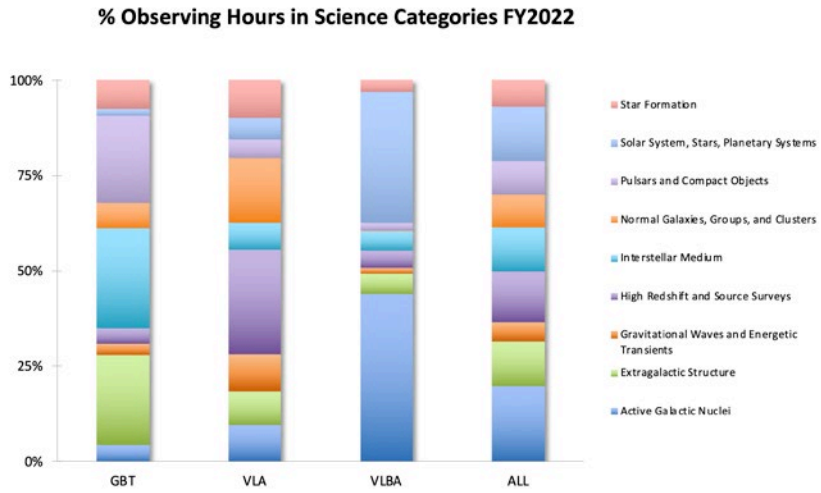


VLBA Observing Hours



# 2022 PERFORMANCE METRICS

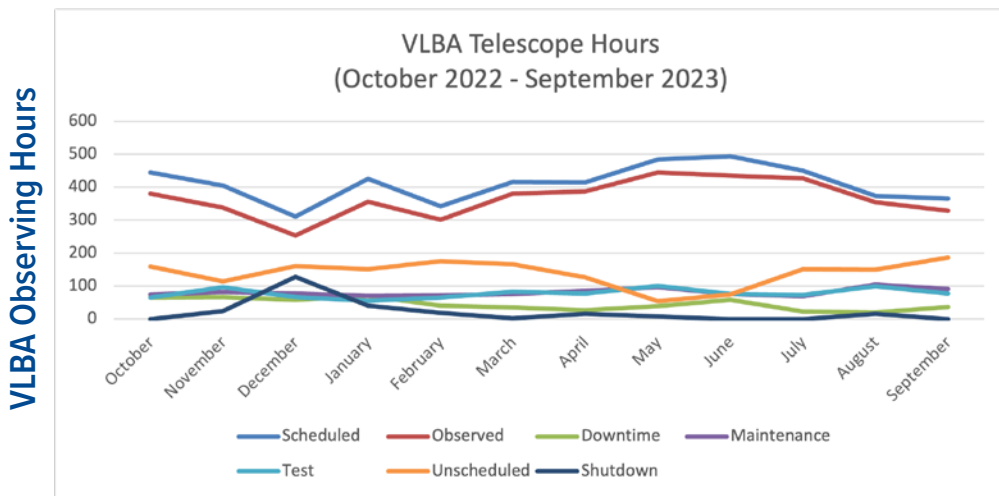
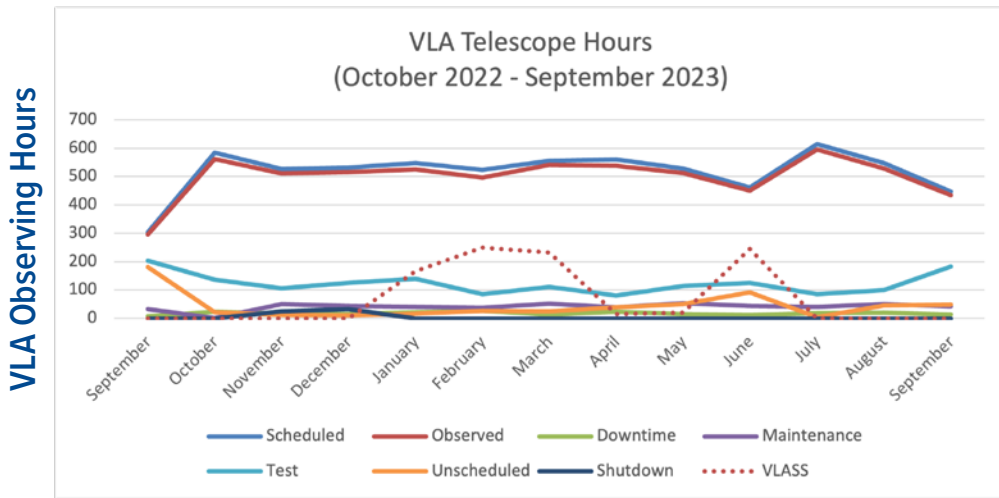
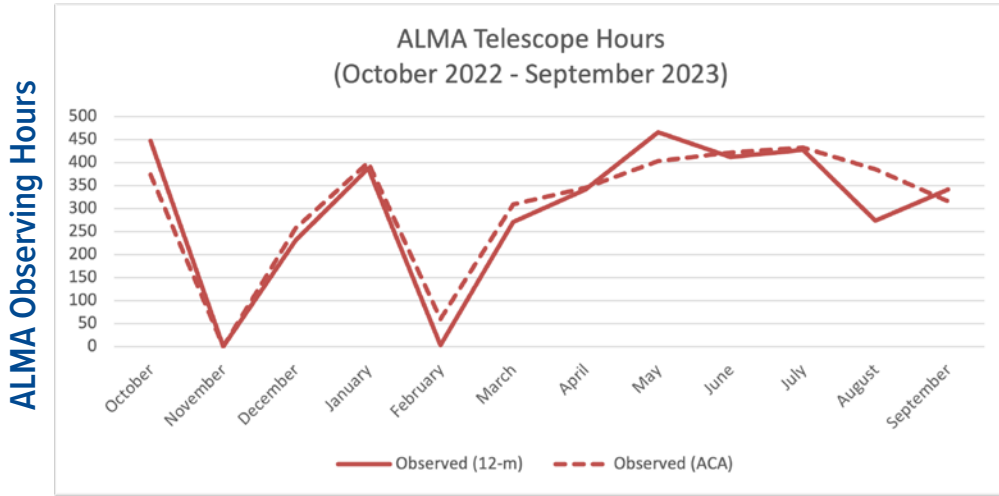
## Observing Hours by Science Category



Observing hours for each of the GBT, VLA, and VLBA are tracked in the nine science categories defined in the NRAO-GBO proposal evaluation and time allocation process.

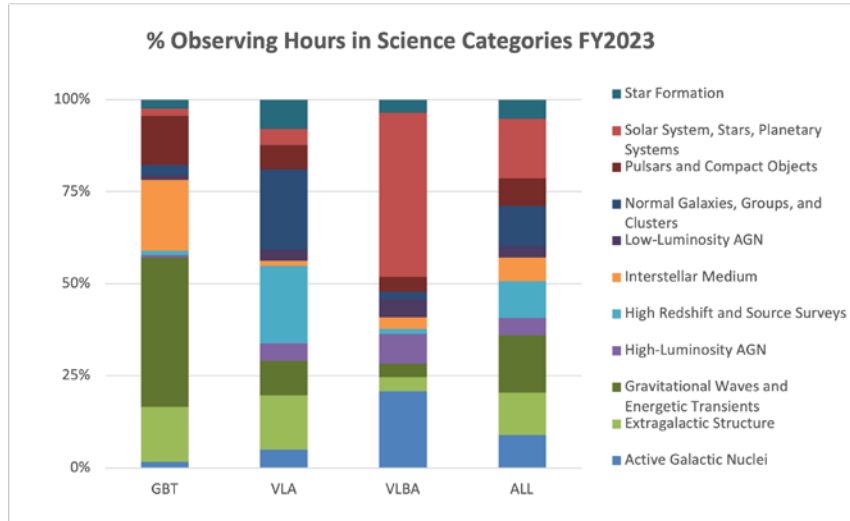


## 2023 PERFORMANCE METRICS



# 2023 PERFORMANCE METRICS

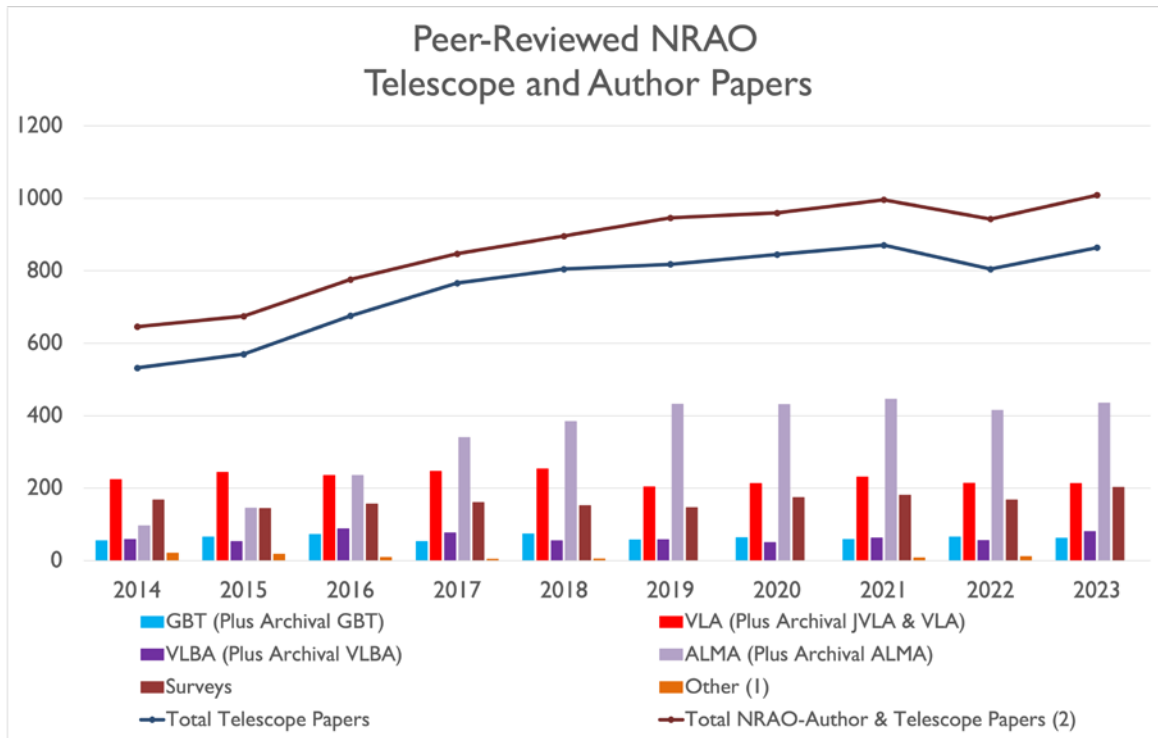
## Observing Hours by Science Category



Observing hours for each of the GBT, VLA, and VLBA are tracked in the eleven science categories defined in the NRAO-GBO proposal evaluation and time allocation process.

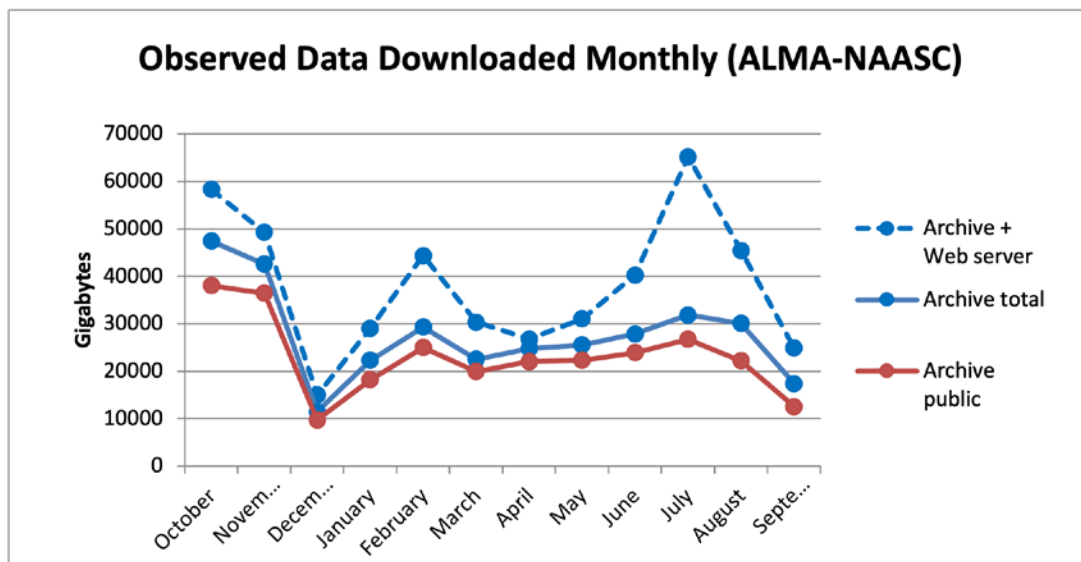


## 2021-2023 Refereed Telescope and Author Papers



**Total Peer-Reviewed NRAO-Author and Telescope Papers:** Peer-reviewed publications that include NRAO telescope data, plus peer-reviewed publications by NRAO staff based on non-NRAO telescope data. **Total Peer-Reviewed Telescope Papers:** Peer-reviewed publications that include NRAO telescope data. **Other:** Peer-reviewed publications based on data from NRAO telescopes other than ALMA, VLA, VLBA, and GBT.

## 2023 ALMA Science Data Archive Volume



## 2021 NRAO REFEREED PUBLICATIONS

- Acciari, V. A.; Ansoldi, S.; Antonelli, L. A.; Arbet Engels, A.; Artero, M.; Asano, K.; Baack, D.; Babić, A.; Baquero, A.; Barres De Almeida, U.; Barrio, J. A.; Batković, I.; Becerra González, J.; Bednarek, W.; Bellizzi, L.; Bernardini, E.; Bernardos, M.; Berti, A.; Besenrieder, J.; Bhattacharyya, W.; Bigongiari, C.; Biland, A.; Blanch, O.; Bošnjak, Ž.; Busetto, G.; Carosi, R.; Ceribella, G.; Cerruti, M.; Chai, Y.; Chilingarian, A.; Cikota, S.; Colak, S. M.; Colombo, E.; Contreras, J. L.; Cortina, J.; Covino, S.; D'Amico, G.; D'Elia, V.; Da Vela, P.; Dazzi, F.; De Angelis, A.; De Lotto, B.; Delfino, M.; Delgado, J.; Delgado Mendez, C.; Depaoli, D.; Pierro, F. Di; Venere, L. Di; Do Souto Espiñeira, E.; Dominis Prester, D.; Donini, A.; Dorner, D.; Doro, M.; Elsaesser, D.; Fallah Ramazani, V.; Fattorini, A.; Ferrara, G.; Fonseca, M. V.; Font, L.; Fruck, C.; Fukami, S.; García López, R. J.; Garczarczyk, M.; Gasparyan, S.; Gaug, M.; Giglietto, N.; Giordano, F.; Gliwny, P.; Godinović, N.; Green, J. G.; Green, D.; Hadasch, D.; Hahn, A.; Heckmann, L.; Herrera, J.; Hoang, J.; Hrupec, D.; Hütten, M.; Inada, T.; Inoue, S.; Ishio, K.; Iwamura, Y.; Jiménez, I.; Jormanainen, J.; Jouvin, L.; Kajiwara, Y.; Karjalainen, M.; Kerszberg, D.; Kobayashi, Y.; Kubo, H.; Kushida, J.; Lamastra, A.; Lelas, D.; Leone, F.; Lindfors, E.; Lombardi, S.; Longo, F.; López-Coto, R.; López-Moya, M.; López-Oramas, A.; Loporchio, S.; Machado De Oliveira Fraga, B.; Maggio, C.; Majumdar, P.; Makariev, M.; Mallamaci, M.; Maneva, G.; Manganaro, M.; Mannheim, K.; Maraschi, L.; Mariotti, M.; Martínez, M.; Mazin, D.; Menchiari, S.; Mender, S.; Mićanović, S.; Miceli, D.; Miener, T.; Minev, M.; Miranda, J. M.; Mirzoyan, R.; Molina, E.; Moralejo, A.; Morcuende, D.; Moreno, V.; Moretti, E.; Neustroev, V.; Nigro, C.; Nilsson, K.; Nishijima, K.; Noda, K.; Nozaki, S.; Ohtani, Y.; Oka, T.; Otero-Santos, J.; Palatiello, M.; Paneque, D.; Paoletti, R.; Paredes, J. M.; Pavletić, L.; Peñil, P.; Perennes, C.; Persic, M.; Prada Moroni, P. G.; Prandini, E.; Priyadarshi, C.; Puljak, I.; Rhode, W.; Ribó, M.; Rico, J.; Righi, C.; Rugliancich, A.; Saha, L.; Sahakyan, N.; Saito, T.; Sakurai, S.; Satalecka, K.; Schleicher, B.; Schmidt, K.; Schweizer, T.; Sitarek, J.; Šnidarić, I.; Sobczynska, D.; Spolon, A.; Stammer, A.; Strom, D.; Strzys, M.; Suda, Y.; Surić, T.; Takahashi, M.; Tavecchio, F.; Temnikov, P.; Terzić, T.; Teshima, M.; Torres-Albà, N.; Tosti, L.; Truzzi, S.; Van Scherpenberg, J.; Vanzo, G.; Vazquez Acosta, M.; Ventura, S.; Verguilo, V.; Vigorito, C. F.; Vitale, V.; Vovk, I.; Will, M.; Zarić, D.; Arbet-Engels, A.; Baack, D.; Balbo, M.; Beck, M.; Biederbeck, N.; Biland, A.; Bretz, T.; Bruegge, K.; Buss, J.; Dorner, D.; Elsaesser, D.; Hildebrand, D.; Iotov, R.; Klinger, M.; Mannheim, K.; Neise, D.; Neronov, A.; Noethe, M.; Paravac, A.; Rhode, W.; Schleicher, B.; Sliusar, V.; Theissen, F.; Walter, R.; Valverde, J.; Horan, D.; Giroletti, M.; Perri, M.; Verrecchia, F.; Leto, C.; Sadun, A. C.; Moody, J. W.; Joner, M.; Marscher, A. P.; Jorstad, S. G.; Lähteenmäki, A.; Tornikoski, M.; Ramakrishnan, V.; Järvelä, E.; Vera, R. J. C.; Righini, S.; Lien, A. Y. "Multiwavelength variability and correlation studies of Mrk 421 during historically low X-ray and  $\gamma$ -ray activity in 2015-2016" *Monthly Notices of the Royal Astronomical Society*, 504 :1427, 2021.
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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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D.; Hoffmann, R.; Hokanson-Fasig, B.; Hoshina, K.; Huang, F.; Huber, M.; Huber, T.; Hultqvist, K.; Hünnefeld, M.; Hussain, R.; Hyman, K.; In, S.; Iovine, N.; Ishihara, A.; Jansson, M.; Japaridze, G. S.; Jeong, M.; Jin, M.; Jones, B. J. P.; Kang, D.; Kang, W.; Kang, X.; Kappes, A.; Kappesser, D.; Kardum, L.; Karg, T.; Karl, M.; Karle, A.; Katz, U.; Kauer, M.; Kellermann, M.; Kelley, J. L.; Kheirandish, A.; Kin, K.; Kintscher, T.; Kiryluk, J.; Klein, S. R.; Koirala, R.; Kolanoski, H.; Kontrimas, T.; Köpke, L.; Kopper, C.; Kopper, S.; Koskinen, D. J.; Koundal, P.; Kovacevich, M.; Kowalski, M.; Kozynets, T.; Kun, E.; Kurahashi, N.; Lad, N.; Lagunas Gualda, C.; Lanfranchi, J. L.; Larson, M. J.; Lauber, F.; Lazar, J. P.; Lee, J. W.; Leonard, K.; Leszczyńska, A.; Li, Y.; Lincetto, M.; Liu, Q. R.; Liubarska, M.; Lohfink, E.; Lozano Mariscal, C. J.; Lu, L.; Lucarelli, F.; Ludwig, A.; Luszczak, W.; Lyu, Y.; Ma, W. Y.; Madsen, J.; Mahn, K. B. M.; Makino, Y.; Mancina, S.; Mariş, I. C.; Martinez-Soler, I.; Maruyama, R.; Mase, K.; Mcelroy, T.; McNally, F.; Mead, J. V.; Meagher, K.; Mechbal, S.; Medina, A.; Meier, M.; Meighen-Berger, S.; Micallef, J.; Mockler, D.; Montaruli, T.; Moore, R. W.; Morse, R.; Moulai, M.; Naab, R.; Nagai, R.; Naumann, U.; Necker, J.; Nguyên, L. V.; Niederhausen, H.; Nisa, M. U.; Nowicki, S. C.; Obertacke Pollmann, A.; Oehler, M.; Oeyen, B.; Olivas, A.; O'Sullivan, E.; Pandya, H.; Pankova, D. V.; Park, N.; Parker, G. K.; Paudel, E. N.; Paul, L.; Pérez De Los Heros, C.; Peters, L.; Peterson, J.; Philippen, S.; Pieper, S.; Pittermann, M.; Pizzuto, A.; Plum, M.; Popovych, Y.; Porcelli, A.; Prado Rodriguez, M.; Price, P. B.; Pries, B.; Przybylski, G. T.; Raab, C.; Raissi, A.; Rameez, M.; Rawlins, K.; Rea, I. C.; Rehman, A.; Reichherzer, P.; Reimann, R.; Renzi, G.; Resconi, E.; Reusch, S.; Rhode, W.; Richman, M.; Riedel, B.; Roberts, E. J.; Robertson, S.; Roellinghoff, G.; Rongen, M.; Rott, C.; Ruhe, T.; Ryckbosch, D.; Rysewyk Cantu, D.; Safa, I.; Saffer, J.; Sanchez Herrera, S. E.; Sandrock, A.; Sandroos, J.; Santander, M.; Sarkar, S.; Sarkar, S.; Satalecka, K.; Schaufel, M.; Schieler, H.; Schindler, S.; Schmidt, T.; Schneider, A.; Schneider, J.; Schröder, F. G.; Schumacher, L.; Schwefer, G.; Sclafani, S.; Seckel, D.; Seunarine, S.; Sharma, A.; Shefali, S.; Silva, M.; Skrzypek, B.; Smithers, B.; Snihur, R.; Soedingrekso, J.; Soldin, D.; Spannfellner, C.; Spiczak, G. M.; Spiering, C.; Stachurska, J.; Stamatikos, M.; Stanev, T.; Stein, R.; Stettner, J.; Steuer, A.; Stezelberger, T.; Stürwald, T.; Stüttard, T.; Sullivan, G. W.; Taboada, I.; Ter-Antonyan, S.; Tilav, S.; Tischbein, F.; Tollefson, K.; Tönnis, C.; Toscano, S.; Tosi, D.; Trettin, A.; Tselengidou, M.; Tung, C. F.; Turcati, A.; Turcotte, R.; Turley, C. F.; Twagirayezu, J. P.; Ty, B.; Unland Elorrieta, M. A.; Valtonen-Mattila, N.; Vandenbroucke, J.; Van Eijndhoven, N.; Vannerom, D.; Van Santen, J.; Verpoest, S.; Walck, C.; Watson, T. B.; Weaver, C.; Weigel, P.; Weindl, A.; Weiss, M. J.; Weldert, J.; Wendt, C.; Werthebach, J.; Weyrauch, M.; Whitehorn, N.; Wiebusch, C. H.; Williams, D. R.; Wolf, M.; Woschnagg, K.; Wrede, G.; Wulff, J.; Xu, X. W.; Yanez, J. P.; Yoshida, S.; Yu, S.; Yuan, T.; Zhang, Z.; Zhelmin, P.; Icecube Collaboration "Search for neutrino emission from cores of active galactic nuclei." *Physical Review D*, 106: 022005, 2022.
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- Abdurashidova, Zara; Aguirre, James E.; Alexander, Paul; Ali, Zaki S.; Balfour, Yanga; Beardsley, Adam P.; Bernardi, Gianni; Billings, Tashalee S.; Bowman, Judd D.; Bradley, Richard F.; Bull, Philip; Burba, Jacob; Carey, Steve; Carilli, Chris L.; Cheng, Carina; Deboer, David R.; Dexter, Matt; De Lera Acedo, Eloy; Dibblee-Barkman, Taylor; Dillon, Joshua S.; Ely, John; Ewall-Wice, Aaron; Fagnoni, Nicolas; Fritz, Randall; Furlanetto, Steven R.; Gale-Sides, Kingsley; Glendenning, Brian; Gorthi, Deepthi; Greig, Bradley; Grobbelaar, Jasper; Halday, Ziyaad; Hazelton, Bryna J.; Hewitt, Jacqueline N.; Hickish, Jack; Jacobs, Daniel C.; Julius, Austin; Kern, Nicholas S.; Kerrigan, Joshua; Kittiwisit, Piyanat; Kohn, Saul A.; Kolopanis, Matthew; Lanman, Adam; La Plante, Paul; Lekalake, Telalo; Lewis, David; Liu, Adrian; Macmahon, David; Malan, Lourence; Malgas, Cresshim; Maree, Matthys; Martinot, Zachary E.; Matsetela, Eunice; Mesinger, Andrei; Molewa, Mathakane; Morales, Miguel F.; Mosiane, Tshegofalang; Murray, Steven G.; Neben, Abraham R.; Nikolic, Bojan; Nunhokee, Chuneeta D.; Parsons, Aaron R.; Patra, Nipanjana; Pascua, Robert; Pieterse, Samantha; Pober, Jonathan C.; Razavi-Ghods, Nima; Ringuette, Jon; Robnett, James; Rosie, Kathryn; Sims, Peter; Singh,



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Sophia; Damke, Guillermo; Darling, Jeremy; Davidson, James W., Jr.; Davies, Roger; Dawson, Kyle; De Lee, Nathan; Diamond-Stanic, Aleksandar M.; Cano-Díaz, Mariana; Sánchez, Helena Domínguez; Donor, John; Duckworth, Chris; Dwelly, Tom; Eisenstein, Daniel J.; Elsworth, Yvonne P.; Emsellem, Eric; Eracleous, Mike; Escoffier, Stephanie; Fan, Xiaohui; Farr, Emily; Feng, Shuai; Fernández-Trincado, José G.; Feuillet, Diane; Filipp, Andreas; Fillingham, Sean P.; Frinchaboy, Peter M.; Fromenteau, Sebastian; Galbany, Lluís; García, Rafael A.; García-Hernández, D. A.; Ge, Junqiang; Geisler, Doug; Gelfand, Joseph; Géron, Tobias; Gibson, Benjamin J.; Goddy, Julian; Godoy-Rivera, Diego; Grabowski, Kathleen; Green, Paul J.; Greener, Michael; Grier, Catherine J.; Griffith, Emily; Guo, Hong; Guy, Julien; Hadjara, Massinissa; Harding, Paul; Hasselquist, Sten; Hayes, Christian R.; Hearty, Fred; Hernández, Jesús; Hill, Lewis; Hogg, David W.; Holtzman, Jon A.; Horta, Danny; Hsieh, Bau-Ching; Hsu, Chin-Hao; Hsu, Yun-Hsin; Huber, Daniel; Huertas-Company, Marc; Hutchinson, Brian; Hwang, Ho Seong; Ibarra-Medel, Héctor J.; Chitham, Jacob Ider; Ilha, Gabriele S.; Imig, Julie; Jaekle, Will; Jayasinghe, Tharindu; Ji, Xihan; Johnson, Jennifer A.; Jones, Amy; Jönsson, Henrik; Katkov, Ivan; Khalatyan, Arman, Dr.; Kinemuchi, Karen; Kisku, Shobhit; Knapen, Johan H.; Kneib, Jean-Paul; Kollmeier, Juna A.; Kong, Miranda; Kounkel, Marina; Kreckel, Kathryn; Krishnarao, Dhanesh; Lacerna, Ivan; Lane, Richard R.; Langgins, Rachel; Lavender, Ramon; Law, David R.; Lazarz, Daniel; Leung, Henry W.; Leung, Ho-Hin; Lewis, Hannah M.; Li, Cheng; Li, Ran; Lian, Jianhui; Liang, Fu-Heng; Lin, Lihwai; Lin, Yen-Ting; Lin, Sicheng; Lintott, Chris; Long, Dan; Longa-Peña, Penélope; López-Cobá, Carlos; Lu, Shengdong; Lundgren, Britt F.; Luo, Yuanze; Mackereth, J. Ted; De La Macorra, Axel; Mahadevan, Suvrath; Majewski, Steven R.; Machado, Arturo; Mandeville, Travis; Maraston, Claudia; Margalef-Bentabol, Berta; Masseron, Thomas; Masters, Karen L.; Mathur, Savita; Mcdermid, Richard M.; Mckay, Myles; Merloni, Andrea; Merrifield, Michael; Meszaros, Szabolcs; Miglio, Andrea; Di Mille, Francesco; Minniti, Dante; Minsley, Rebecca; Monachesi, Antonela; Moon, Jeongin; Mosser, Benoit; Mulchaey, John; Muna, Demitri; Muñoz, Ricardo R.; Myers, Adam D.; Myers, Natalie; Nadathur, Seshadri; Nair, Preethi; Nandra, Kirpal; Neumann, Justus; Newman, Jeffrey A.; Nidever, David L.; Nikakhtar, Farnik; Nitschelm, Christian; O'Connell, Julia E.; Garma-Oehmichen, Luis; Luan Souza De Oliveira, Gabriel; Olney, Richard; Oravetz, Daniel; Ortigoza-Urdaneta, Mario; Osorio, Yeisson; Otter, Justin; Pace, Zachary J.; Padilla, Nelson; Pan, Kaike; Pan, Hsi-An; Parikh, Taniya; Parker, James; Peirani, Sebastien; Peña Ramírez, Karla; Penny, Samantha; Percival, Will J.; Perez-Fournon, Ismael; Pinsonneault, Marc; Poidevin, Frédéric; Poovelil, Vijith Jacob; Price-Whelan, Adrian M.; Bárbara De Andrade Queiroz, Anna; Raddick, M. Jordan; Ray, Amy; Rembold, Sandro Barboza; Riddle, Nicole; Riffel, Rogemar A.; Riffel, Rogério; Rix, Hans-Walter; Robin, Annie C.; Rodríguez-Puebla, Aldo; Roman-Lopes, Alexandre; Román-Zúñiga, Carlos; Rose, Benjamin; Ross, Ashley J.; Rossi, Graziano; Rubin, Kate H. R.; Salvato, Mara; Sánchez, Sebastián F.; Sánchez-Gallego, José R.; Sanderson, Robyn; Santana Rojas, Felipe Antonio; Sarceno, Edgar; Sarmiento, Regina; Sayres, Conor; Sazonova, Elizaveta; Schaefer, Adam L.; Schiavon, Ricardo; Schlegel, David J.; Schneider, Donald P.; Schultheis, Mathias; Schwöpe, Axel; Serenelli, Aldo; Serna, Javier; Shao, Zhengyi; Shapiro, Griffin; Sharma, Anubhav; Shen, Yue; Shetrone, Matthew; Shu, Yiping; Simon, Joshua D.; Skrutskie, M. 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- Abdurro'Uf; Lin, Yen-Ting; Hirashita, Hiroyuki; Morishita, Takahiro; Tacchella, Sandro; Akiyama, Masayuki; Takeuchi, Tsutomu T.; Wu, Po-Feng "Dissecting Nearby Galaxies with piXedfit. I. Spatially Resolved Properties of Stars, Dust, and Gas as Revealed by Panchromatic SED Fitting," *The Astrophysical Journal*, 926: 81, 2022.
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## APPENDIX A: PUBLICATIONS

- Zheng, Haoxuan; Hera Collaboration "Validation of the HERA Phase I Epoch of Reionization 21 cm Power Spectrum Software Pipeline," *The Astrophysical Journal*, 924: 85, 2022.
- Akins, Hollis B.; Fujimoto, Seiji; Finlator, Kristian; Watson, Darach; Knudsen, Kirsten K.; Richard, Johan; Bakx, Tom J. L. C.; Hashimoto, Takuya; Inoue, Akio K.; Matsuo, Hiroshi; Michałowski, Michał J.; Tamura, Yoichi "ALMA Reveals Extended Cool Gas and Hot Ionized Outflows in a Typical Star-forming Galaxy at  $z = 7.13$ ," *The Astrophysical Journal*, 934: 64, 2022.
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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

- Walter, Fabian; Jiang, Linhua; Li, Qiong; Li, Jianan; Fei, Qinyue; Xu, Fuxiang "Exploring the Radio Spectral Energy Distribution of the Ultraluminous Radio-quiet Quasar SDSS J0100+2802 at Redshift 6.3," *The Astrophysical Journal*, 929: 69, 2022.
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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

- Jixing; Saha, Anindya; Chakali, Eswaraiah; Zhang, Qizhou; Kim, Kee-Tae; Ristorcelli, Isabelle; Shen, Zhi-Qiang; Li, Jin-Zeng "ATOMS: ALMA Three-millimeter Observations of Massive Star-forming regions - XI. From inflow to infall in hub-filament systems," *Monthly Notices of the Royal Astronomical Society*, 514: 6038, 2022.
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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

- Young, Olivia; Nanograv Collaboration "The NANOGrav 15 yr Data Set: Bayesian Limits on Gravitational Waves from Individual Supermassive Black Hole Binaries," *The Astrophysical Journal*, 951, L50, 2023.
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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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## APPENDIX A: PUBLICATIONS

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*Image by Brian R. Kent, NRAO/AUI/NSF*

## APPENDIX B: EVENTS & MILESTONES

### 2021

#### 8 January

NRAO Community Day

#### 11 - 15 January

237th AAS meeting

NRAO Town Hall

ALMA Opportunities & Status Webinar

New Views on Galaxy Formation

Summer Student Presentations

#### 3 February

NRAO Semester 2021B Call for Proposals submission deadline

#### 15 March - 1 April

8th VLA Data Reduction Workshops

#### 21 February

AUI Executive Committee Meeting (Hybrid)

#### 6 March 6

ALMA Ambassadors Cycle 8 Proposal Preparation Workshops (Virtual)

#### 17 March

ALMA Cycle 9 Call for Proposals opens

#### 22 April

ALMA Board Meeting (Virtual)

#### 1 May

Cycle 8 Call for North American ALMA Development Study proposals deadline

#### 12 May

AUI Executive Committee Meeting (Hybrid)

#### 19 - 21 May

16th NRAO Postdoctoral Symposium

#### 26-28 May

NRAO Users Committee/ANASAC Meeting (Virtual)

#### 1 - 3 June

238th American Astronomical Society meeting (Virtual)

NRAO Town Hall

NRAO Virtual Exhibit

#### 18-19 June

AUI Board Meeting (Virtual)

#### 15 - 24 June

6th US-China Radio Astronomy Science Workshop

#### 6 July

NRAO Semester 2021A Call for Proposals opens

#### 14-15 July

Compact Objects and Energetic Phenomena in the Multi-messenger Universe (Virtual)

#### 15 July

Call for Proposals for ALMA Development Projects opens

#### 3 August

NRAO Semester 2022A Call for Proposals deadline

#### 4 - 7 August

The Past, Present, and Future - VLA: Celebrating 40 Years

#### 27 August

AUI Executive Committee Meeting (Virtual)

#### November 17 & 19

Jansky Lecture: Prof. Luis F. Rodriguez

(Virtual)

## 2022

### 2 January

NRAO Semester 2022B Call for Proposals opens

### 20 January

Community Webinar Series: VLA/VLBA Call for Proposals

### 17 February

Webinar: Outcomes from the ALMA Cycle 8 Review

### 16 March

Webinar: ALMA Wideband Sensitivity Upgrade (WSU)

### 24 March

Advanced Synthesis Imaging with CASA

### 27 April

NAASC Data Analyst Recruitment Event

### 18 - 25 May

18th Synthesis Imaging Workshop

### 7 - 9 June

Computational Astrophysics in the ngVLA Era  
New York, NY

### 11-14 June

American Astronomical Society Meeting  
NRAO Science & Development Webinar  
NRAO Town Hall  
Pasadena, CA

### 25 August

Webinar: Cube Analysis and Rendering Tool  
for Astronomy (CARTA)

### 7 - 9 September

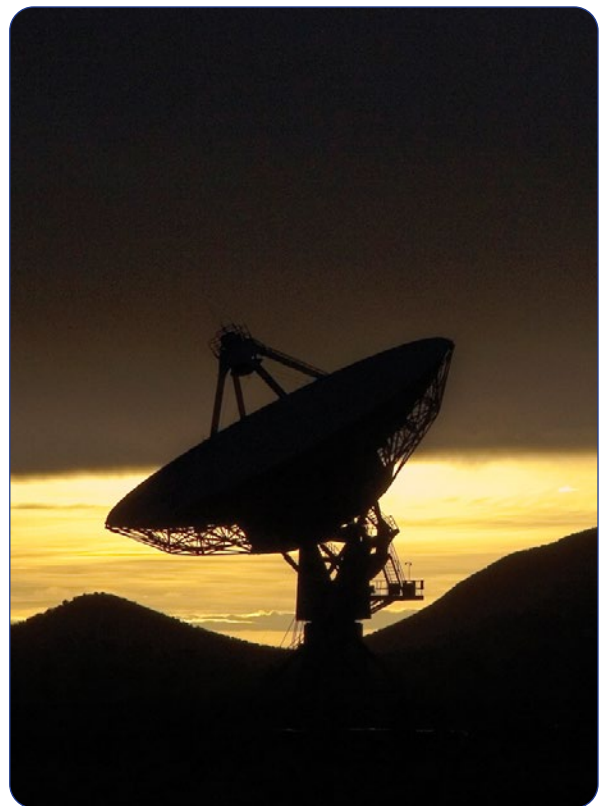
The VLA Sky Survey in the Multiwavelength Spotlight  
Socorro, NM

### 21 - 23 September

From Cells to Galaxies: Exploring the Synergies between  
Radio Astronomy & Medical Imaging

### 11 - 20 October

9th VLA Data Reduction Workshop



*Very Long Baseline Array (VLBA) antenna, Pie Town, New Mexico.  
Photo by Ian Parker.*

## APPENDIX B: EVENTS & MILESTONES

### 2023

#### 2 January

NRAO Semester 2020B Call for Proposals opens

#### 8 - 11 January

*AAS meeting*

Science Ready Data Products and the VLA Sky Survey

ALMA Status and Plans for Increased Capability

NRAO Town Hall

ngVLA Special Session: Chemical Probes of Astrophysical Systems

#### 14 - 17 February

Jansky Lecture: Prof. Francoise Combes

#### 17 February

28th New Mexico Symposium

Socorro, NM

#### 3 - 4 April

NRAO Community Day at MIT Haystack

Westford, MA

#### 14 - 27 April

ALMA Cycle 10 Proposal Preparation Workshops

#### 1 - 5 May

New Eyes on the Universe: SKA & ngVLA Conference

Vancouver, British Columbia, Canada

#### 15 - 17 May

18th NRAO/GBO Postdoc Symposium

Socorro, New Mexico

#### 4 - 8 June

American Astronomical Society

Albuquerque, New Mexico

#### 13 - 21 June

19th Synthesis Imaging Workshop

#### 10 - 16 June

Gordon Research Conference: Solar Systems

#### 24 - 26 July

New Era of AGN Science with the Vera C. Rubin LSST

Charlottesville, Virginia

#### 1 - 4 August

The Evolution of Gas in and around Galaxies

Stanley, Idaho

#### 6 - 11 August

GBO Single Dish Summer School

Green Bank, WV

#### 11 - 15 September

15th DiFX Users and Developers Meeting

Socorro, New Mexico

#### 25 - 27 September

Morelia ngVLA Science Meeting

Morelia, Mexico

#### 28 - 29 September

NRAO Community Days - IRyA-UNAM Morelia

Morelia, Mexico

#### 28 September

mtex-ngVLA Open Day Event

Leipzig, Germany

#### September - October

Cycle 10 ALMA Data Processing Workshops

#### 6 - 8 November

ALMA Data Reduction Workshops - Data Combination

#### 5 - 9 November

Astronomical Data Analysis & Software Systems (ADASS)

Tucson, Arizona

#### 8 - 17 November

Jansky Lecture: Dr. Paul Vanden Bout

#### 4 - 8 December

ALMA at 10 years: Past, Present, and Future

Puerto Varas, Chile



*Image by Pablo Carillo, ALMA*

## APPENDIX C: ADVISORY COMMITTEES

### NRAO Users and ALMA North American Science Advisory Committees

The NRAO Users Committee (UC) membership includes users and potential users of NRAO facilities from across the scientific community. It advises the Director and the Observatory staff on all aspects of Observatory activities that affect the users of the telescopes. This Committee is appointed by the Director and normally meets in-person annually.

The membership of the NRAO Users Committee from 2021-2023 is given below. In 2014, NRAO integrated the ALMA North American Science Advisory Committee (ANASAC) as a standing subcommittee of the Users Committee. Users Committee members who also serve on the ANASAC are indicated, as are the ANASAC representatives to the international ALMA Science Advisory Committee (ASAC).

Each member's last year in their UC and ANASAC term of service is given.

- **Edo Berger**, Harvard University (2021)
- **Casey Law**, California Institute of Technology (2022)
- **Ilse Cleeves**, Vice-Chair, University of Virginia (2021)
- **Laurent Loinard**, UNAM (2021)
- **Kate Su** (ANASAC), University of Arizona (2021)
- **Alessandra Corsi**, Texas Tech University (2024)
- **Thomas Maccarone**, Texas Tech University (2023)
- **Christopher DePree** (CASA UC), Agnes Scott College (2021)
- **Jin Koda**, Chair (ANASAC), Stony Brook University (2021)
- **Susan Neff**, NASA/GSFC (2022)
- **Meredith Hughes**, Wesleyan University (2023), ANASAC/ASAC
- **James Jackson**, USRA/SOFIA Science Center (2025)
- **Melodie Kao**, ASU (2025)
- **Jin Koda**, Stony Brook University (2021), ANASAC
- **Duncan Lorimer**, West Virginia University (2025)
- **Karen Masters**, Haverford College (2025)
- **Brett McGuire**, Massachusetts Institute of Technology (2025)
- **Stefanie Milam**, NASA/GSFC (2024)
- **Alexandra Pope**, University of Massachusetts Amherst (2023), ANASAC/ASAC
- **Erik Rosolowsky**, University of Alberta (2023), ANASAC/ASAC
- **Kazushi Sakamoto**, Academia Sinica Institute of Astronomy & Astrophysics (2024), ANASAC
- **Melissa Soriano**, NASA Jet Propulsion Laboratory (2025)
- **Kate Su**, University of Arizona (2021), ANASAC
- **Stephen White**, AFRL (2021), ANASAC/ASAC
- **Sean Andrews**, Harvard-Smithsonian Center for Astrophysics (2026), ANASAC
- **Cherry Ng**, University of Toronto (2026)
- **Jennie Paine**, University of Colorado Boulder (2026)
- **Daniel Perley**, Liverpool John Moores University (2026)
- **Elisabeth (Betsy) A. C. Mills**, University of Kansas (2027)
- **Tony Wong**, University of Illinois Urbana-Champaign (2027)



## ALMA North American Science Advisory Committee

The ALMA North American Science Advisory Committee (ANASAC) provides scientific advice to the NRAO Director on the science operation of ALMA and the North American ALMA Science Center, as representatives of the wider North American astronomical community.

Each member's last year in their ANASAC term of service is listed.

- **Sean Andrews**, Chair (ANASAC), Harvard-Smithsonian Center for Astrophysics (2026)
- **Sara Eillson**, University of Victoria (2026)
- **Leslie Looney**, University of Illinois Urbana-Champaign (2027)
- **Meredith MacGregor**, Johns Hopkins University (2027)
- **Brett McGuire**, Massachusetts Institute of Technology (2025)
- **Stefanie Milam**, NASA/GSFC (2024)
- **Kazushi Sakamoto**, Academia Sinica Institute of Astronomy & Astrophysics (2024)
- **Karin Sandstrom**, University of California, San Diego (2027)

## AUI Visiting Committee

The Visiting Committee is appointed by the AUI Board of Trustees to review the management and research programs of the Observatory. The Committee membership follows. Each member's last year in their Visiting Committee term of service is given in parentheses.

- **Lewis Ball**, SKAO (2025)
- **Jeremy Darling**, University of Colorado at Boulder (2025)
- **Lynn Matthews**, Haystack Observatory (2025)
- **Beth Willman**, CEO LSSTC (2025)
- **Rafael Rodriguez Solis**, University of Puerto Rico (2023)
- **Adam Leroy**, Ohio State University (2023)
- **Joan Najita**, National Optical Astronomy Observatory (2023)
- **Greg Taylor**, University of New Mexico (2022)
- **Belinda Wilkes**, Chandra X-ray Center (2021)



## APPENDIX C: ADVISORY COMMITTEES

### NRAO Time Allocation Committee

The persons listed below served on the NRAO Time Allocation Committee (TAC) for Semesters A&B of 2023, 2022, and 2021. The scientific purview of each TAC member is indicated.

#### Semester 2023B

**Poonam Chandra**, GWT,NRAO  
**Craig Heinke**, PCO, University of Alberta  
**Andrew Fox**, ISM, STScl  
**Tracy Clarke**, NGA, NRL  
**Lynn Matthews**, SSP, MIT Haystack Obs.  
**Jaime Pineda**, SFM, MPE  
**Preeti Kharb**, LLA panel, NCRA-TIFR  
**Robert Laing**, HLA, SKAO  
**Katherine Rabidoux**, EGS, UW Platteville  
**James Bartlett**, HIZ, University of Paris/JPL

#### Semester 2022B

**Poonam Chandra**, GWT, NRAO  
**Craig Heinke**, PCO, University of Alberta  
**Conelia Lang**, ISM, Iowa State  
**Andrew Baker**, NGA, Rutgers  
**Lynn Matthews**, SSP, MIT Haystack Obs.  
**Stan Kurtz**, SFM, UNAM  
**Preeti Kharb**, AGN panel, NCRA-TIFR  
**Katherine Rabidoux**, EGS, UW Platteville  
**Paola Andreani**, HIZ, ESO

#### Semester 2021B

**Alexander van der Horst**, GWT, George Washington University  
**Craig Heinke**, PCO, University of Alberta  
**Christina Lacey**, ISM, Hofstra University  
**Andrew Baker**, NGA, Rutgers  
**Lynn Matthews**, SSP, MIT Haystack Obs.  
**Stan Kurtz**, SFM, UNAM  
**Denise Gabuzda**, AGN, University College Cork  
**John Cannon**, EGS, Macalester  
**Paola Andreani**, HIZ, ESO

#### Semester 2023A

**Katherine Rabidoux**, EGS, UW Platteville  
**Preeti Kharb**, LLA panel, NCRA-TIFR  
**Robert Laing**, HLA, SKAO  
**Andrew Baker**, NGA, Rutgers  
**Paola Andreani**, HIZ, ESO  
**Lynn Matthews**, SSP, MIT Haystack Obs.  
**Andrew Fox**, ISM, STScl  
**Stan Kurtz**, SFM, UNAM  
**Poonam Chandra**, GWT,NRAO  
**Craig Heinke**, PCO, University of Alberta

#### Semester 2022A

**Katherine Rabidoux**, EGS, UW Platteville  
**Denise Gabuzda**, AGN, University College Cork  
**Andrew Baker**, NGA, Rutgers  
**Paola Andreani**, HIZ, ESO  
**Lynn Matthews**, SSP, MIT Haystack Obs.  
**Cornelia Lang**, ISM, Iowa State  
**Stan Kurtz**, SFM, UNAM  
**Alexander van der Horst**, GWT, George Washington University  
**Craig Heinke**, PCO, University of Alberta

#### Semester 2021A

**John Cannon**, EGS, Macalester  
**Denise Gabuzda**, AGN, University College Cork  
**Loreto Barcos**, AGN, NRAO  
**David Sanders**, AGN, University of Hawaii'i  
**Lynn Matthews**, SSP, MIT Haystack Obs.  
**Christina Lacey**, ISM, Hofstra University  
**Betsy Mills**, , ISM, University of Kansas  
**Alexander van der Horst**, GWT, George Washington University  
**Craig Heinke**, PCO, University of Alberta

## CASA Users Committee

The NRAO Data Management and Software Department established a Common Astronomy Software Applications (CASA) Users Committee (CUC) to advise it on matters important to CASA users. The scope of the committee's responsibility includes the capabilities, usability, reliability, and performance of CASA with ALMA and VLA data from the perspective of the CASA users community.

The CUC includes five members appointed by the NRAO Assistant Director for Science Support and Research (SSR); two appointed by the East Asian ALMA Regional Center (ARC) manager at the National Astronomical Observatory of Japan; two appointed by the European ARC manager at ESO, and one appointed by the head of the JAO Department of Science operations.

**Adam Leroy** (NA, Chair), Ohio State University

**Ruta Kale** (IN), National Centre for Radio Astrophysics

**Yoshimasa Watanabe** (EA), Shibaura Institute of Technology

**Jihyun Kang** (EA), Korea Astronomy and Space Science Institute

**Olga Bayandina** (EU), INAF, Osservatorio Astrofisico di Arcetri

**Yu-Nung Su** (NA), Academia Sinica Institute of Astronomy and Astrophysics

**Abhijeet Borkar** (EU), Astronomical Institute of the Czech Academy of Sciences

**Imke de Pater** (NA), University of California, Berkeley

**Jane Huang** (NA), Columbia University

**Kristina Nyland** (NA), Naval Research Laboratory

*NA: North America, EU: Europe, EA: East Asia, IN: India*



*Image by Jeff Hellerman, NRAO/AUI/NSF*

## APPENDIX C: ADVISORY COMMITTEES

### ngVLA Science Advisory Council

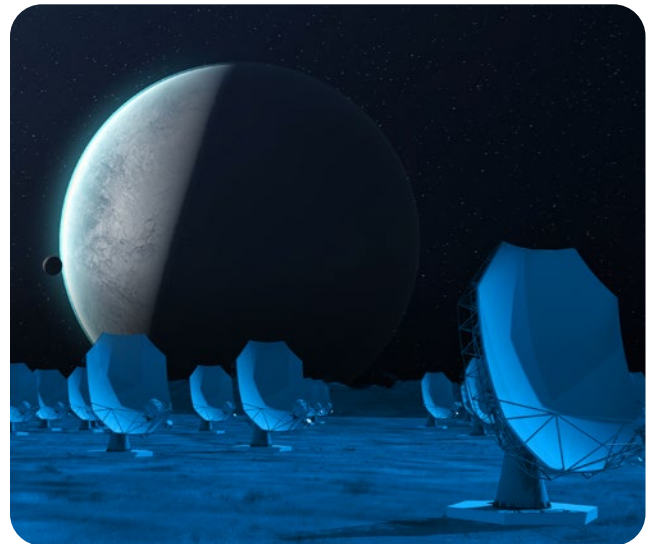
<b>Andrew Baker</b>	Rutger University	<b>Thomas Maccarone</b>	Texas Tech University
<b>Ted Bergin</b>	University of Michigan	<b>Brenda Matthews</b>	NRCI – Canada
<b>Jennifer Bergner</b>	University of Chicago	<b>Brett McGuire</b>	MIT
<b>Laura Blecha</b>	University of Florida	<b>Betsy Mills</b>	University of Kansas
<b>Geoff Bower</b>	ASIAA	<b>Munetake Momose</b>	Ibaraki University
<b>Sarah Burke-Spolaor</b>	West Virginia University	<b>Cherry Ng</b>	SETI Institute
<b>Carlos Gonzalez</b>	UNAM-IRyA	<b>Rachel Osten</b>	STScI
<b>Alessandra Cori</b>	Texas Tech University	<b>Erik Rosolowsky</b>	University of Alberta
<b>Katherine de Kleer</b>	California Institute of Technology	<b>Nami Sakai</b>	Rikagaku Kenkyūsho
<b>Imke de Pater</b>	University of California, Berkeley	<b>Rachel Somerville</b>	Flatiron Institute
<b>Megan DeCesar</b>	George Mason University	<b>Alexander van der Horst</b>	George Washington Univ.
<b>Mark Dickinson</b>	NOIRLab	<b>Fabian Walter</b>	MPIA
<b>Maria Drout</b>	University of Toronto	<b>David Wilner</b>	Harvard-Smithsonian CfA
<b>Gregg Hallinan</b>	CalTech	<b>Anton Zensus</b>	MPIRA
<b>Bunyo Hatsukade</b>	University of Tokyo		
<b>Takuma Izumi</b>	NAOJ	Ex-Officio Members	
<b>Megan Johnson</b>	United States Naval Observatory	<b>Eric Murphy</b>	NRAO
<b>Joseph Lazio</b>	NASA – Jet Propulsion Lab	<b>Alberto Bolatto</b>	University of Maryland
<b>Adam Leroy</b>	The Ohio State University	<b>Andrea Isella</b>	Rice University

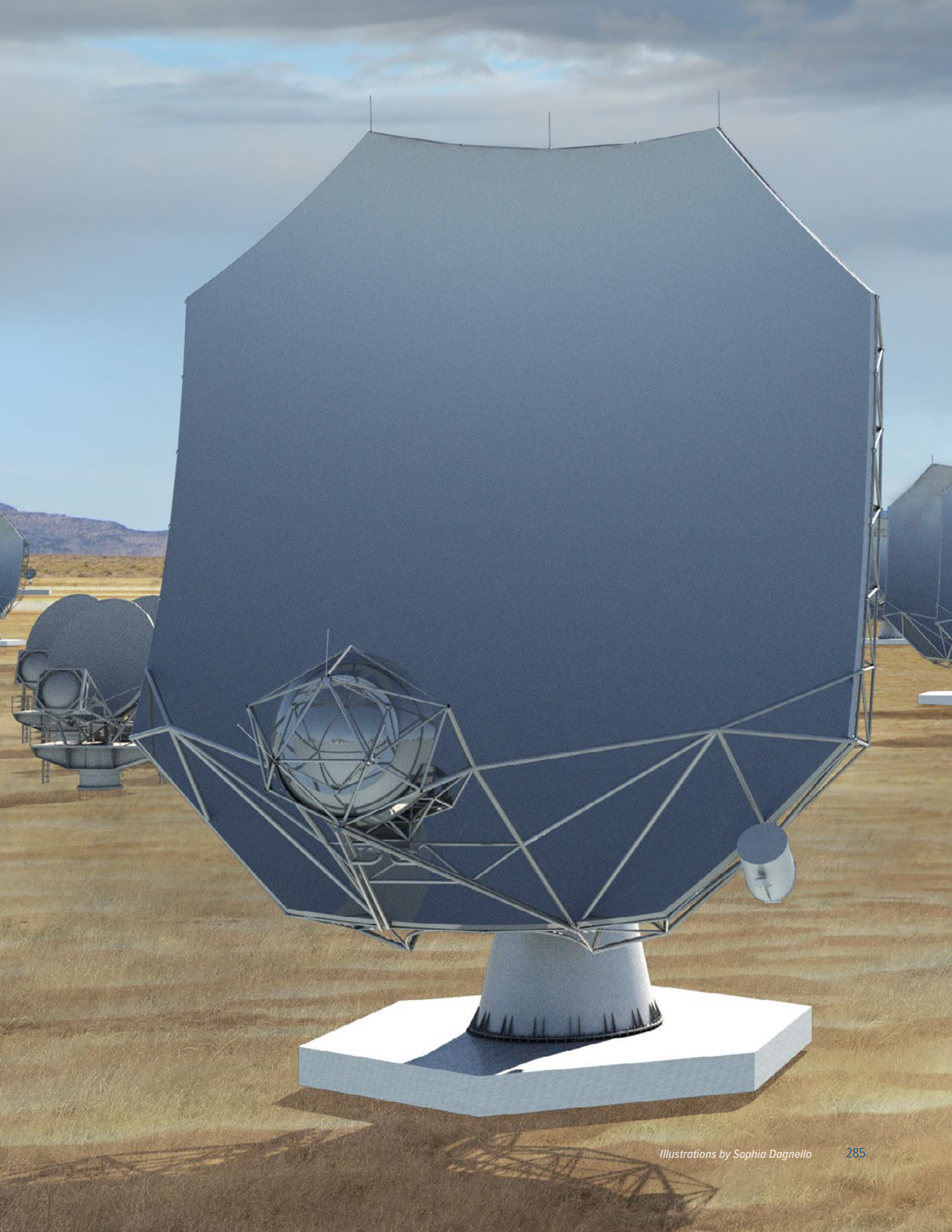
### ngVLA Technical Advisory Council

<b>Lewis Knee</b>	NRCC
<b>Larry D’Addario</b>	NASA – Jet Propulsion Lab
<b>Alvaro Gonzalez</b>	NAOJ
<b>Tetsuo Hasegawa</b>	NAOJ
<b>Yuh-Jing Hwang</b>	ASIAA
<b>Stan Kurtz</b>	UNAM
<b>Michael Rupen</b> (co-chair)	National Research Council – Canada
<b>Melissa Soriano</b> (co-chair)	NASA – Jet Propulsion Lab

Ex-Officio Members

**Rob Selina** NRAO (ngVLA Project Engineer)



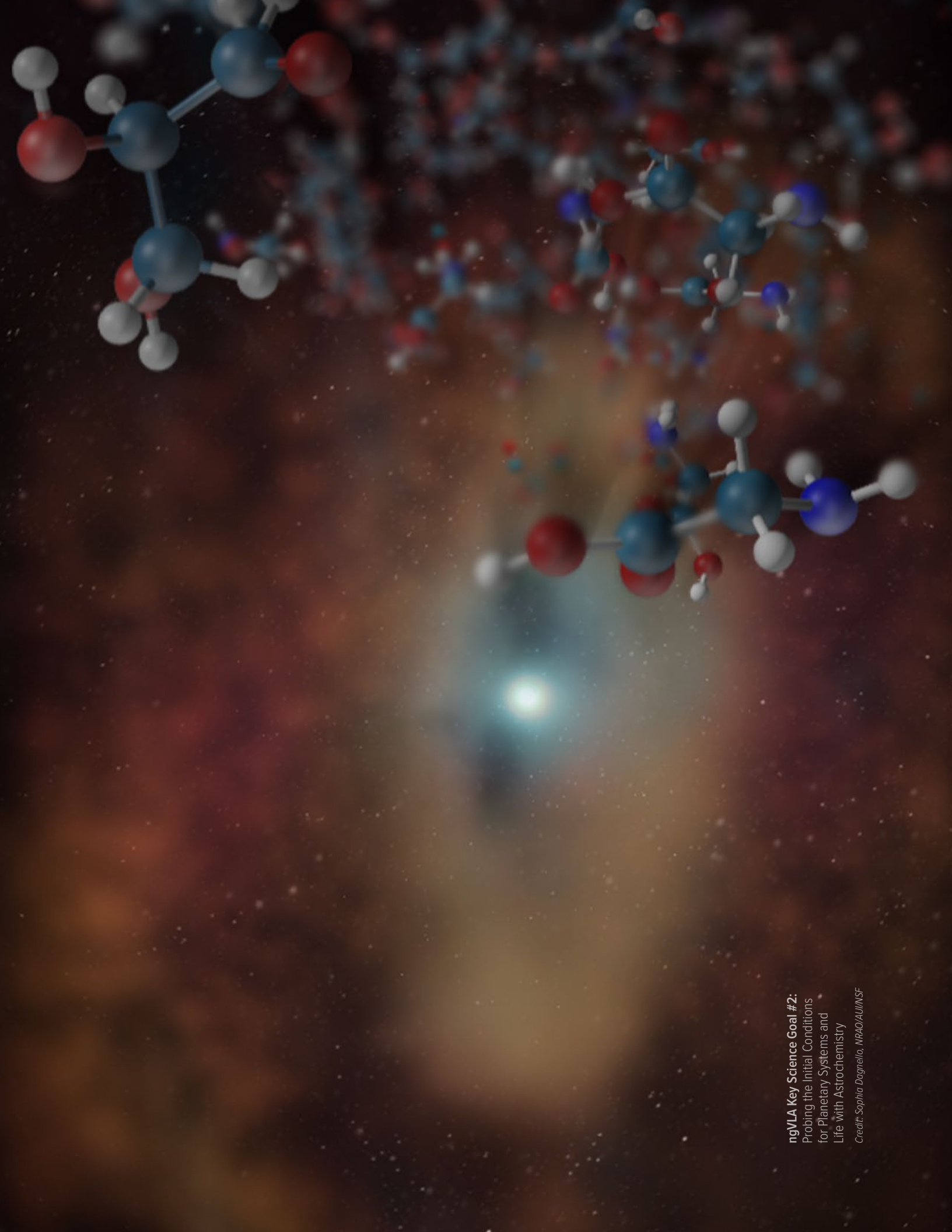


## APPENDIX D: FISCAL YEAR 2021 FINANCIAL SUMMARY

(all figures are \$k USD)

Functional Work Breakdown Structure Element	CSA-V	CSA-A	ICC	CSA-L	Total
Administrative Services	\$11,832	\$12,114	(\$5,574)	\$2,718	\$19,540
Development Programs	\$4,191	\$14,158	\$482	0	\$18,831
Director's Office	\$3,031	\$3,519	\$1,979	\$518	\$8,848
Education & Public Outreach	\$859	\$936	\$0	\$0	\$1,634
Science Operations	\$9,125	\$8,610	\$2,895	\$0	\$20,630
Telescope Operations	\$11,386	\$23,607	\$102	\$6,766	\$41,862
<b>Grand Total</b>	<b>\$40,795</b>	<b>\$61,035</b>	<b>(\$116)</b>	<b>\$10,003</b>	<b>\$111,346</b>

Fiscal Year 2021 = 1 October 2020 – 30 September 2021; CSA = Cooperative Support Agreement, V = VLAN/LBA, A = ALMA, L = LBO, ICC = Internal Common Costs



**ngVLA Key Science Goal #2:**  
Probing the Initial Conditions  
for Planetary Systems and  
Life with Astrochemistry

*Credit: Sophia Dagnello, NRAO/AUI/NSF*

## APPENDIX D: FISCAL YEAR 2022 FINANCIAL SUMMARY

(all figures are \$k USD)

Functional Work Breakdown Structure Element	CSA-V	CSA-A	ICC	CSA-L	Total
Administrative Services	\$11,137	\$10,817	(\$2,095)	\$2,736	\$22,595
Development Programs	\$5,085	\$7,423	\$500	\$0	\$13,008
Director's Office	\$3,064	\$3,859	\$2,143	\$518	\$9,584
Education & Public Outreach	\$843	\$839	\$0	\$0	\$1,682
Science Operations	\$8,782	\$8,752	\$2,980	\$0	\$20,514
Telescope Operations	\$11,072	\$24,110	\$113	\$5,819	\$41,114
<b>Grand Total</b>	<b>\$39,983</b>	<b>\$55,800</b>	<b>\$3,641</b>	<b>\$9,073</b>	<b>\$108,497</b>

Fiscal Year 2022 = 1 October 2021 – 30 September 2022; CSA = Cooperative Support Agreement; V = VLA/VLBA; A = ALMA; L = LBO; ICC = Internal Common Costs





ngVLA Key Science Goal #5:  
Understanding Black Holes  
Credit: Sophia Dagnello, NRAO/AUI/NSF



## APPENDIX D: FISCAL YEAR 2023 FINANCIAL SUMMARY

(all figures are \$k USD)

Functional Work Breakdown Structure Element	CSA-V	CSA-A	ICC	Total
Administrative Services	\$16,335	\$10,282	(\$6,574)	\$20,043
Development Programs	\$4,511	\$22,093	\$528	\$27,132
Director's Office	\$3,688	\$3,815	\$2,654	\$10,156
Education & Public Outreach	\$979	\$936	\$0	\$1,915
Science Operations	\$10,310	\$10,020	\$3,362	\$23,692
Telescope Operations	\$23,185	\$32,607	\$212	\$56,004
<b>Grand Total</b>	<b>\$59,007</b>	<b>\$79,753</b>	<b>\$182</b>	<b>\$138,942</b>

Fiscal Year 2023 = 1 October 2022 – 30 September 2023; CSA = Cooperative Support Agreement, V = VLAV/LBA, A = ALMA, ICC = Internal Common Costs



ngVLA Key Science Goal #4:  
Gravity Studies

Credits: Sophia Dagnello, NRAO/AUI/NSF

## APPENDIX E: ACRONYMS

### Acronym Definition

AAAS	American Association for the Advancement of Science
AAB	Antenna Assembly Building
AAS	American Astronomical Society
AATF	African American Teaching Fellows
ACA	Atacama Compact Array
ACEAP	Education Ambassadors Program
ACS	ALMA Common Software
ACU	Antenna Control Unit
AGN	Active Galactic Nuclei
ALMA	Atacama Large Millimeter/submillimeter Array
ANASAC	ALMA North American Science Advisory Committee
AoD	Astronomer on Duty
AOS	Array Operations Site
AR	Augmented Reality
ARC	ALMA Regional Center
arcsec	arcsecond
ASIAA	Academia Sinica Institute for Astronomy and Astrophysics
ASIC	Application Specific integrated Circuit
ASKAP	Australian Square Kilometre Array Pathfinder
ASPECS	ALMA Spectroscopic Survey in the Hubble Ultra Deep Field
AST	NSF Division of Astronomical Sciences
AU	Astronomical Unit
AUI	Associated Universities, Incorporated
B&C	beamforming and channelizing
BI	Broader Impacts
BLC	Baseline Correlator
CARF	Committee on Radio Astronomy Frequencies
CARMA	Combined Array for Research in Millimeter Astronomy
CARTA	Cube Analysis and Rendering Tool for Astronomy
CASA	Common Astronomy Software Applications
CBE	Correlator Back End
CDL	Central Development Laboratory
CDR	Critical Design Review
CHILES	Cosmos HI Large Extragalactic Survey
CHIME	Canadian Hydrogen Intensity Mapping Experiment
CHTC	Center for High Throughput Computing
CIRADA	Canadian Initiative for Radio Astronomy Data Analysis
CIS	Computing Information Systems
CoDR	Conceptual Design Review
CO-I	Co-Investigator
CORE	Council of Representative for Engagement
CORF	Committee on Radio Frequencies
COSPAR	Committee on Space Research
CPM	Conference Preparatory Meeting
CSA	Cooperative Support Agreement
CSIRO	Commonwealth Scientific and Industrial Research Organization
CSP	Central Signal Processor

CTP	Cosmic Twilight Polarimeter
CUP	Correlator upgrade Project
DAPPER	Dark Ages Polarimeter Pathfinder
DDT	Director's Discretionary Time
DMS	Data Management & Software
DOMT	Digital Orthomode Transducers
DSACore	Dynamic Scheduling Algorithm
DSN	Deep Space Network
DSOC	Domenici Science Operations Center
DSP	Digital Signal Processing
EBG	Electromagnetic Band Gap
EGS	Extragalactic Structure
EHT	Event Horizon Telescope
EM	Electromagnetic
EMSS	ElectroMagnetic Software and Systems
Eol	Expression of Interest
EPO	Education and Public Outreach
ERIC	European Research Infrastructure Consortium
ESO	European Organisation for Astronomical Research in the Southern Hemisphere
ETP	Energetic Transients and Pulsars
EVLA	Expanded Very Large Array
f2f	face-to-face
FBOT	Fast Blue Optical Transient
FCC	Federal Communications Commission
FE	Front End
FEHV	Front End Handling Vehicles
FIRST	Faint Images of the Radio Sky at Twenty Centimeters
FPGA	Field Programmable Gate Array
FRB	Fast Radio Bursts
FRM	Focus Rotation Mount
FSA	Frequency Site Architecture
FTE	Full Time Equivalent
GBO	Green Bank Observatory
GBT	Green Bank Telescope
GDMS	General Dynamics Mission Systems
GHz	Gigahertz
GMVA	Global 3mm VLBI Array
GO	General Observing
GOST	General Observing Setup Tool
GRB	Gamma Ray Burst
GW	Gravitational Wave
GWT	Gravitational Waves & Energetic Transients
HBCU	Historically Black Colleges and Universities
HEMT	High Electron Mobility Transistor
HERA	Hydrogen Epoch of Reionization Array
HiLS	Hardware in the Loop Simulations
HIZ	High Redshift & Source Surveys

## APPENDIX E: ACRONYMS

HPC	High Performance Computing
HR	Human Resources
HSA	High Sensitivity Array
HSI	Hispanic Serving Institutions
HST	Hubble Space Telescope
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IRD	Integrated Receiver Development
ISM	Interstellar Medium
IT	Information Technology
ITU-R	International Telecommunication Union – Radiocommunication
IUCAF	Inter-Union Committee on the Allocation of Frequencies
JAO	Joint ALMA Observatory
JPL	Jet Propulsion Laboratory
kpc	kiloparsec
KSG	Key Science Goals
LA	Los Alamos
LBA	Long Baseline Array
LNA	Low Noise Amplifier
LNF	Low Noise Factory
LO	Local Oscillator
LRU	Line Replaceable Unit
LWA	Long Wavelength Array
MA	Main Array
M&C	Monitor and Control
MHz	Megahertz
MIT	Massachusetts Institute of Technology
MMIC	Monolithic Millimeter-wave Integrated Circuit
MoU	Memorandum of Understanding
MPIfR	Max Planck Institut für Radioastronomie
MPIfA	Max Planck Institut für Astronomie
MREFC	Major Research Equipment and Facility Construction
MSI	Minority Serving Institution
MSV3	Measurement Set Version 3
Myr	Megayear
NA	North American
NAASC	North American ALMA Science Center
NAOJ	National Astronomical Observatory of Japan
NASA	National Aeronautics and Space Administration
NEON	National Ecological Observatory Network
NESS	Network for Exploration and Space Sciences
NGA	Normal Galaxies, Groups, and Clusters
NGC	New General Catalog
ngVLA	next generation Very Large Array
NINS	National Institutes of Natural Sciences (Japan)
NM	New Mexico



*Photo by Jeff Hellerman, NRAO/AUI/NSF*

## APPENDIX E: ACRONYMS

NMT	New Mexico Institute of Mining and Technology
NRAO	National Radio Astronomy Observatory
NRCC	National Research Council-Canada
NRC-HIA	National Research Council of Canada-Herzberg Astronomy and Astrophysics
NRL	Naval Research Laboratory
NRQZ	National Radio Quiet Zone
NSF	National Science Foundation
NSBP	National Society of Black Physicists
NVSS	NRAO VLA Sky Survey
OCA	Office of Chilean Affairs
OMT	OrthoMode Transducer
OPT	Observation Preparation Tool
OSF	Operations Support Facility
OT	Observing Tool
pc	parsec
PCO	Pulsars and Compact Objects
PDR	Preliminary Design Review
PEP	Performance Evaluation Process
PHT	Proposal Handling Tool
PI	Principal Investigator
PIO	Public Information Officer
PM	Program Management
PST	Proposal Submission Tool
PT	Pie Town
QA	Quality Assurance
R&D	Research & Development
RADIAL	Radio Astronomy Data Imaging and Analysis
RAP-NM	Radio Astronomy and Physics in New Mexico
REU	Research Experiences for Undergraduates
RF	Radio Frequency
RFI	Radio-Frequency Interference
RFP	Request for Proposal
RHEL	Red Hat Enterprise Linux
RMS	Radio-Millimeter-Submillimeter
RSRO	Resident Shared Risk Observing
SBA	Short Baseline Array
SAC	Science Advisory Council
SADC	Serial Analog to Digital Converter
SB	Scheduling Blocks
SciCom	Science Communications Office
SC	Saint Croix
SCG	Science Computing Group
SCO	Santiago Central Office
SCR	Silicon Controlled Rectifiers
SCREAM	Scalable Reconfigurable Modular
SDM	Science Data Model
SFM	Star Formation
SIS	Superconductor–Insulator–Superconductor



SKA ..... Square Kilometre Array  
 SMBH ..... Supermassive Black Hole  
 SOC ..... Scientific Organizing Committee  
 SOL ..... Standard of Learning  
 SOS ..... Student Observing Support  
 SRAO ..... Science Ready Archive and Operations  
 SRDP ..... Science Ready Data Products  
 SRO ..... Shared Risk Observing  
 SRP ..... Science Review Panel  
 SSP ..... Solar System, Stars & Planetary Systems  
 SSR ..... Science Support and Research  
 STEAM ..... Science, Technology, Engineering, Art, and Mathematics  
 STScI ..... Space Telescope Science Institute  
 SUS ..... Scientific User Support  
 SWG ..... Science Working Group  
 TAC ..... Time Allocation Committee  
 TKIP ..... Traveling-wave Kinetic Inductance Parametric  
 TTA ..... Telescope Time Allocation  
 U/LIRG ..... Ultraluminous/Luminous Infrared Galaxies  
 UAV ..... Unmanned Aerial Vehicle  
 UC ..... Users Committee  
 UNM ..... University of New Mexico  
 URSI ..... International Union of Radio Science; Union Radio Scientifique Internationale  
 UVA ..... University of Virginia  
 UVML ..... University of Virginia Microfabrication Laboratory  
 VA ..... Virginia  
 VANDAM ..... VLA/ALMA Nascent Disk and Multiplicity  
 VFD ..... Variable Frequency Drive  
 VLA ..... Very Large Array  
 VLASS ..... Very Large Array Sky Survey  
 VLBA ..... Very Long Baseline Array  
 VLBI ..... Very Long Baseline Interferometry  
 VLT ..... Very Large Telescope  
 VME ..... VLBA Versa Model Eurocard  
 VNDA ..... VLBA New Digital Architecture  
 WFO ..... Work for Others  
 WIDAR ..... Wideband Interferometric Digital Architecture  
 WISE ..... Widefield Infrared Survey Explorer  
 WRC ..... World Radio Conference  
 WVR ..... Water Vapor Radiometer  
 YUPPI ..... Y Ultimate Pulsar Processing Instrument  
 ZTF ..... Zwicky Transient Facility

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