Oral Presentation Abstracts

Tuesday, June 25, 2019

8:00 AM	9:00 AM	Registration	
8:45 AM	9:00 AM	Welcome	
9:00 AM	9:20 AM	US Radio Astronomy in the 2020s	Tony Beasley
9:20 AM	9:40 AM	ngVLA Programmatic and Technical Update	Mark McKinnon
9:40 AM	10:00 AM	A Vision for ALMA in the 2030s	Crystal Brogan
10:00 AM	10:20 AM	ngVLA Configuration	Chris Carilli
10:20 AM	10:50 AM	Break & Posters (30 min)	
10:50 AM	11:10 AM	ngVLA Reference Observing Program	Joan Wrobel
11:10 AM	11:30 AM	ngVLA Operations Concept	Amanda Kepley
11:30 AM	11:50 AM	Spectrum Management in the ngVLA Era	Ashley Zauderer
11:50 AM	12:00 PM	Poster Flash (10 min)	
12:00 PM	1:30 PM	Lunch (90 min)	
1:30 PM	2:00 PM	A Look into the Birth Cradles of Planets with the ngLVA: Signatures of Planet Formation in Protoplanetary Disks	Nienke van der Marel
2:00 PM	2:30 PM	ngVLA Key Science Goals 2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry	Michiel Hogerheijde
2:30 PM	3:00 PM	ngVLA Key Science Goal: Galaxy Evolution	Adam Leroy
3:00 PM	3:30 PM	Break & Posters (30 min)	
3:30 PM	4:00 PM	Testing Theories of Gravity with Galactic Center Pulsars	Joseph Lazio
4:00 PM	4:30 PM	Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy	Laura Chomiuk
4:30 PM	5:00 PM	US/ELT Update	Mark Dickinson
5:00 PM	6:00 PM	Reception	South Lounge

Tony Beasley (National Radio Astronomy Observatory)

Topic: Project Talk

U.S. Radio Astronomy in the 2020s

Over the next decade, the U.S. astronomy community will develop new instruments and capabilities, allowing for progress across a broad range of exciting science themes. Increasingly, multi-messenger and multi-wavelength approaches are required, and radio astronomy provides key data to essentially all areas of interest. In this talk, I will give a summary of recent efforts to explore opportunities and needs in the coming decade across the nearly five orders of magnitude in spectrum (0.05 and 950 GHz) where current U.S. facilities operate or are planned. The status of several key national and international initiatives, and our contributions to the Astro 2020 Decadal Survey planning process, will be discussed.

Mark McKinnon (NRAO)

Topic: Project Talk

ngVLA Programmatic and Technical Update

With the guidance of Science and Technical Advisory Councils and Science Working Groups, the NRAO has sponsored a series of science and technical community meetings to consider the science mission and design of a next-generation Very Large Array (ngVLA).

The basic ngVLA design emerging from these discussions is an interferometric array with approximately ten times the sensitivity and ten times higher spatial resolution than the VLA and ALMA radio telescopes, optimized for operation in the wavelength range 0.3cm to 3cm. The ngVLA will open a new window on the Universe through ultra-sensitive imaging of thermal line and continuum emission down to sub-milliarcsecond resolution, as well as unprecedented broadband continuum polarimetric imaging of non-thermal processes. The specifications and concepts for major ngVLA system elements have converged into a Reference Design, which forms the technical and cost basis of a project proposal for the Astro2020 Decadal Survey.

An overview of the ngVLA Reference Design will be presented. The concepts for major system elements such as the antenna, receiving electronics, and central signal processing will be described. The major development activities that are presently underway to advance the design will also be described. The current status and future direction of the project will be summarized.

Crystal Brogan (NRAO/NAASC)

Topic: Project Talk

A Vision for ALMA in the 2030s

With input from its science advisory committees, the community, and technical feasibility studies, the ALMA project has crafted the ALMA Development Roadmap [1] which seeks to keep ALMA at the forefront of transformational science for decades to come. Key science drivers that will require significant upgrades to realize include: Investigation of the Origins of Planets, through imaging protoplanetary disks in nearby (150 pc) star formation regions to resolve the Earth formation zone (~1 AU) in the dust continuum at wavelengths shorter than 1 mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation. Tracing the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales (~10-100 AU) by performing full-band spectral scans at a rate of 2-4 protostars per day Tracing the cosmic evolution of key elements from the first galaxies (z>10) through the peak of star formation (z=2-4) by imaging their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum at a rate of 1-2 galaxies per hour. I will present highlights from the ALMA Development Roadmap covering both near- and longer-term goals.

[1] https://arxiv.org/pdf/1902.02856.pdf

Chris Carilli (NRAO)

Alan Erickson (NRAO), Eric Greisen (NRAO), Brian Mason (NRAO), Eric Murphy (NRAO), Viviana Rosero (NRAO), Robert Selina (NRAO)

Topic: Project Talk

ngVLA Configuration

We discuss the configuration of the Next Generation Very Large Array. The current reference design involves a non-reconfigurable array, designed to deliver high sensitivity over a wide range of resolutions. The configuration includes a 'main array' of 214 antennas of 18m diameter, centered on the current VLA site, and extending to baselines of a few hundred kilometers. This main array includes: (i) a dense core of 94 antennas with maximum baselines of 1.3 km, to perform high surface brightness science, (ii) another 74 antennas in a five arm spiral, centered on the core and extending out to baselines of 36 km on the plains of San Augustin, and (iii) 46 more antennas beyond the plains, in a rough five arm spiral to maximum baselines of 1000km, extending into Mexico, Texas, and Arizona. The main array delivers science at resolutions ranging from a few mas to 1000 mas at 30 GHz, with roughly constant sensitivity, within a factor two of natural weighting. The reference design also includes 30 antennas of 18m diameter in a 'long baseline array', extending to baselines of 9000 km, to obtain sub-mas resolution, and a close-packed short baseline array of 19 x 6m antennas for imaging of large scale, very low surface brightness emission. Four antennas of the main array will be equipped to measure total power. The array design has incorporated logistical information, such as topography, utility access, local RFI sources, and land accessibility. Detailed characterization of the array through simulations is in progress, focusing on delivering the key science programs. Results will be presented.

Joan Wrobel (NRAO)

Topic: Project Talk

ngVLA Reference Observing Program

We need to evaluate whether or not the ngVLA Reference Design can reach the Key Science Goals (KSGs) in the array's first decade. Our approach is to build an ngVLA Reference Observing Program (ROP) and evaluate its viability. To this end, we have systematically quantified the technical and observing needs of the KSGs' driving use cases that were identified in the ngVLA Science Requirements. We have also assembled the ancillary information needed to evaluate the ROP. In this talk we describe these efforts and present a preliminary evaluation of the viability of the ROP. We emphasize that this exercise is notional and intended only to gauge if the ngVLA Reference Design can do what the community forecasts will be the array's highest priority science.

Amanda Kepley (National Radio Astronomy Observatory)

On behalf of the ngVLA Operations Working Group

Topic: Project Talk

The Next Generation Very Large Array Operations Concept

In this talk, I will describe the next generation Very Large Array Operations Concept. The ngVLA will be operated as a proposal-driven instrument with the science program determined by PI-led proposals. Proposals will be peer reviewed and ranked based on scientific merit and technical feasibility. The scientific program for the telescope will be scheduled dynamically based on environmental conditions and array status, in accordance with the user's scientific requirements. The data will generally be delivered to the PIs and the broader scientific community as Science Ready Data Products, i.e., automated pipelines will calibrate raw data and create higher level data products. Through the delivery of quality assured Science Ready Data Products, and the provision of standard observing strategies, the Observatory will aim to support both a broad community of scientific users and to facilitate multi-wavelength and multi-messenger astronomy. The operation and maintenance of the array will be supported by three primary centers to minimize staff present at the array core. These will include a Maintenance Center located near the array core, an Array Operations and Repair Center near Socorro, NM, and a Science Operations Center and Data Center likely co-located in a large metropolitan area. The array will be operated primarily in sub-array mode, which will allow array maintenance and science time to occur simultaneously. To minimize maintenance costs, the design of the ngVLA will focus on including maintenance efficiency, including modularized components, minimizing preventative maintenance and repair visits, and automated diagnostics. Finally, I will discuss the ngVLA development program including the legacy programs.

B. Ashley Zauderer (National Science Foundation)

Topic: Project Talk

RFI in the ngVLA Era

We provide an update to the radio astronomy community of the RFI environment expected in the ngVLA era. Commercial uses of frequency spectrum have begun to push to higher frequencies for many types of licensed and unlicensed applications. Some of these uses include car radars, cellular services (5G), internet-of-things (IoT), unmanned aerial vehicles (UAVs), and broadband internet coverage from both geostationary (GSOs) and non-geostationary satellites (NGSOs). Regulations governing usage include both domestic and international bodies. Here, we will present a brief overview of the changing RFI landscape in the ngVLA era, efforts to protect frequency bands for radio astronomy, and potential technical and regulatory solutions.

Nienke van der Marel (NRC Herzberg Astronomy and Astrophysics)

Topic: ngVLA Key Science Goal

A Look into the Birth Cradles of Planets with the ngVLA: Signatures of Planet Formation in Protoplanetary Disks

In the last two decades thousands of exoplanets have been discovered, showing that planets are ubiquitous throughout the Milky Way. However, the formation of planets itself remains a mystery. Protoplanetary disks of gas and dust around young stars are the birth cradles of planets, and analyzing their properties and structures give further insight in the planet formation process. ALMA has revolutionized our view of protoplanetary disks: rather than smooth profiles, it has turned out that disks contain gaps, rings, asymmetries and spiral arms in dust and gas, all indicators of active disk dynamics and recently formed planets. The observations are of such exquisite detail that they can be compared directly with predictions of hydrodynamical models of disk evolution and planet-disk interaction. However, millimeter emission is still optically thick and dust structure cannot be fully recovered, in particular in the inner part of the disks where likely most of the planet formation happens. The Next Generation Very Large Array will allow to us to observe protoplanetary disks at even better resolution than ALMA in optically thin centimeter wavelengths on scales of our Solar System. In particular, ngVLA will reveal the distribution of the centimeter-sized dust grains, the building blocks of Earth like planets, and resolve free-free emission in disk winds. I will discuss the future possibilities of ngVLA on planet formation studies.

Michiel Hogerheijde (Leiden University & University of Amsterdam, the Netherlands)

Topic: ngVLA Key Science Goal

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

The ngVLA wavelength range is rich is transitions of key complex organic molecules that could be connected to the interstellar path towards the origin of life. To place the potential for discoveries with ngVLA in a broad conext, in this talk I will review the basics of astrochemistry with a special focus on emerging chemical complexity. I will provide a cursory overview of the complex organic inventory of star and planet forming regions as currently revealed by instruments like ALMA. I will conclude with a foreward look to the avenues opened up by ngVLA and outline a number of challenges that exist in the interpretation of such observations.

Adam K. Leroy (Ohio State University)

Topic: ngVLA Key Science Goal

ngVLA Key Science Goals: Galaxy Evolution

I will review the large impact that a Next Generation Very Large Array would have on the field of galaxy evolution and baryon cycling. Over the last few years, the community has identified key science goals that span a wide range of scientific topics. Among many other topics, highlights include: 1) making detailed maps of heavily embedded, recent star formation and even finding forming clusters, 2) deploying spectroscopic probes of density and temperature previously restricted to the Milky Way to a diverse population of galaxies, 3) unraveling the mechanisms behind cold gas outflows and galactic superwinds, 4) dissecting the physics of stellar nurseries across the whole local galaxy population, and 5) sharpening and broadening our view of atomic gas by resolving individual HI clouds and capturing HI signatures of accretion onto galaxies. I will review highlights from these areas and other submissions to the ngVLA science book and Astro 2020 process, and discuss how the ngVLA represents a natural successor to both the current VLA and ALMA to address these topics.

Joseph Lazio (Jet Propulsion Laboratory, California Institute of Technology)

Geoffrey C. Bower (Academia Sinica Institute of Astronomy & Astrophysics)
Shami Chatterjee (Cornell Univ.)
James M. Cordes (Cornell Univ.)
Paul Demorest (NRAO)
Julia S. Deneva (George Mason Univ.-NRL)
Jason Dexter (Max Planck Institute for Extraterrestrial Physics)
Ralph Eatough (Max-Planck-Institut für Radioastronomie)
Michael Kramer (Max-Planck-Institut für Radioastronomie)
Kuo Liu (Max-Planck-Institut für Radioastronomie)
Scott Ransom (NRAO)
Lijing Shao (Max-Planck-Institut für Radioastronomie)
Norbert Wex (Max-Planck-Institut für Radioastronomie)
Robert Wharton (Max-Planck-Institut für Radioastronomie)

Topic: ngVLA Key Science Goal

Testing Theories of Gravity with Galactic Center Pulsars

A pulsar orbiting the central supermassive black hole in the Milky Way Galaxy, Sgr A*, represents a clock moving in the gravitational potential of a black hole, with which powerful tests of theories of gravity can be conducted. Furthermore, the number and distribution of pulsars in the Galactic center provide probes of the star formation, stellar dynamics, and stellar evolution of this region. While there is ample evidence to suggest that there should be a (large) population of pulsars within the central parsecs, despite years of searching, only a handful of pulsars in the central 0.5° are known, only one of which is within 1 pc (projected) of Sgr A*. This deficit of pulsars is attributed commonly to significant interstellar scattering. With its combination of high sensitivity and frequency coverage above 10 GHz, the ngVLA would be key to finding many more pulsars in the Galactic center.

A consequence of its combination of frequency coverage and high sensitivity is that the ngVLA could also be capable of finding pulsar-black hole (PSR-BH) binaries in the Milky Way Galaxy. These binaries would also be powerful tests of theories of gravity and complement LIGO-Virgo measurements of the mergers of distant PSR-BH binaries. However, such PSR-BH binaries are likely to be distant and potentially also affected significantly by interstellar scattering.

SC, JMC, PD, JL, and SR are members of the NANOGrav Physics Frontier Center, which is supported by the National Science Foundation award 1430284. MK, LS, NW, and RW acknowledge financial support by the European Research Council (ERC) for the ERC Synergy Grant BlackHoleCam under contract no. 610058. JSD acknowledges support by NASA under grant DPR S-15633-Y. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Laura Chomiuk (Michigan State University)

Tom Maccarone (Texas Tech University)

Topic: ngVLA Key Science Goal

Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

I will review some of the most interesting prospects for the ngVLA shedding light on the formation and growth of black holes across all mass scales. I am grateful to the diverse community who submitted input to the ngVLA science book and Astro2020 white papers, whose exciting ideas I summarize here!

Mark Dickinson (NOAO)

Topic: US/ELT

The US Extremely Large Telescope Program: Status, Science, and Synergies with the ngVLA

NSF's National Optical Astronomy Observatory (NOAO) and the Giant Magellan Telescope (GMT) and Thirty Meter Telescope (TMT) organizations are collaborating to secure 25% or more of the observing time on the TMT and GMT to enable transformational research by the US national community. The US Extremely Large Telescope Program (US-ELTP) would permit scientists anywhere in the US to create and lead projects with the GMT and TMT, taking advantage of their combined full-sky coverage and diverse capabilities.

I will present recent developments in the US ELT Program, including brief reviews of GMT and TMT and their construction status, as well as NOAO's plans for US community user support. The latter includes Key Science Programs (KSPs), which will address fundamental questions that may require tens to hundreds of nights with TMT, GMT, or both observatories working in concert, taking advantage of their combined view both celestial hemispheres, their longitudinal separation for time domain studies, and/or their complementary instrumentation. I will highlight some areas of investigation where ngVLA and TMT/GMT have strong scientific synergies, offering complementary tools for understanding physical processes in the universe.

Wednesday, June 26, 2019

9:00 AM	9:40 AM	New Frontiers in the Physics and Chemistry of Star- and Planet-Forming Regions	Víctor Rivilla
9:40 AM	10:00 AM	Frontiers in Protostellar Disks for the Next Decade, and Beyond	John Tobin
10:00 AM	10:20 AM	Star-Forming Filaments and Cores in Molecular Clouds	Rachel Friesen
10:20 AM	10:40 AM	Magnetism in the Brown Dwarf Regime	Melodie Kao
10:40 AM	10:50 AM	Poster Flash (10 min)	
10:50 AM	11:20 AM	Break & Posters (30 min)	
11:20 AM	12:00 PM	Stormy Dwarfs, Gentle Giants: A Radio View of Stars and How They Shape Their Environments	Jackie Villadsen
12:00 PM	12:20 PM	Unlocking the Secrets of Late-Stage Stellar Evolution and Mass Loss through Radio Wavelength Imaging	Lynn Matthews
12:20 PM	12:30 PM	Poster Flash (10 min)	
12:30 PM	2:00 PM	Lunch (90 min)	
2:00 PM	2:40 PM	Low-mass Black Holes in the Coming Decade	Jenny Greene
2:40 PM	3:00 PM	Identifying Engine-Driven Supernovae: an Optimized Radio Follow-up Strategy	Dario Carbone
3:00 PM	3:20 PM	Frontiers in Radio Transient Discovery	Dillon Dong
3:20 PM	3:50 PM	Break & Posters (30 min)	
3:50 PM	4:30 PM	Linking the Scales of Star Formation	Daniela Calzetti
4:30 PM	4:50 PM	Probing Feedback from Super Star Clusters in the Central Starburst of NGC253	Rebecca Levy
4:50 PM	5:10 PM	Astrometry with Stellar Masers	Ylva Pihlstrom
5:10 PM	5:30 PM	TDEs with the ngVLA: A New Window onto the Evolution and Growth of Supermassive Black Holes	Kate Alexander
6:30 PM	9:30 PM	Conference Dinner	South Lounge & Patio

Víctor M. Rivilla (INAF-Osservatorio Astrofisico di Arcetri)

Topic: Star and Planet Formation

New Frontiers in the Physics and Chemistry of Star- and Planet-Forming Regions

The superb sensitivity and angular resolution provided by the next generation of centimeter and/or millimeter wavelengths telescopes such as the ngVLA will allow us to understand much better the physics and chemistry of star- and planet-forming regions. In this talk I will briefly discuss some science frontiers that will be surely overcome during the next decade. Multi transitions studies of simple molecular tracers, such as NH_3, will allow us to unveil with unprecedented details how stars are formed, following the infalling material down to disc scales. The detections, for the first time, of much complex species with more than 10 atoms, including organic molecules with high prebiotic interest, will push the limits of the known chemical complexity of the interstellar medium, and will give us new clues about the possible origin of life in planetary systems.

John Tobin (National Radio Astronomy Observatory)

Patrick Sheehan (National Radio Astronomy Observatory)

Topic: Star and Planet Formation

Frontiers in Protostellar Disks for the Next Decade, and Beyond

Class 0 & I protostars are thought to represent early stages in the star formation process. Protostellar disks form during these early stages, when both disk and protostar are still embedded in their natal envelope. As such, information about how cloud collapse proceeds, and whether magnetic fields are important for regulating angular momentum, is encoded in the structures of protostellar disks. These disks also represent the initial conditions in disks, from which all of planet formation will ultimately follow. And if gravitational instability is a viable mechanism for the formation of multiple systems, then protostellar disks are most likely to have the requisite conditions. Furthermore, the masses of protostars during these early stages is important for understanding how stellar mass is assembled and how stellar evolution proceeds. Studies of protostars have only recently begun to reach the large sample sizes and spatially resolved observations needed to understand the structure of protostellar disks, with the VLA/ALMA Nascent Disk and Multiplicity (VANDAM) Survey pioneering this effort. However the current generation of millimeter interferometers have fundamental limitations that put a ceiling on how much can be learned from surveys like VANDAM. Here I will discuss what has been discovered about protostellar disks from the VANDAM survey, what limitations remain, and how the next generation of millimeter interferometers will be crucial for unveiling these young stars and their protostellar disks.

Rachel Friesen (NRAO)

Topic: Star and Planet Formation

Star-forming Filaments and Cores in Molecular Clouds

Continuum observations of molecular clouds have revealed a surprising amount of substructure in the form of filaments of a few pc length and cores of ~ 0.1 pc diameter. Understanding the evolution of these substructures towards star formation requires the kinematic and dynamical insights provided uniquely by sensitive cm – mm line observations at high angular and spectral resolution. I will describe the best probes of the dynamics of filaments and cores in nearby star-forming molecular clouds, and recommendations for furthering our understanding of star formation physics through observations over the next decade. In particular, 150 x 18-m antennas with a maximum baseline of 1 km can be used to map sensitively NH3 emission across high column density locations in clouds in roughly an order of magnitude less time than with the current Jansky VLA.

Melodie Kao (Arizona State University)

J. Sebastian Pineda (CU Boulder), Peter Williams (Harvard), Rakesh Yadav (Harvard), Denis Shulyak (Georg-August U.), Joachim Saur (U. Cologne), David J. Stevenson (Caltech), Sarah Schmidt (AIP), Adam Burgasser (UCSD), Gregg Hallinan (Caltech), Kelle Cruz (CUNY)

Topic: Star and Planet Formation

Magnetism in the Brown Dwarf Regime

A suite of discoveries in the last two decades demonstrate that we are now at a point where incorporating magnetic behavior is key for advancing our ability to characterize substellar and planetary systems. The next decade heralds the exciting maturation of the now-burgeoning field of brown dwarf magnetism, and investing now in brown dwarf magnetism will provide a key platform for exploring exoplanetary magnetism and habitability beyond the solar system. We anticipate significant discoveries including: the nature of substellar and planetary magnetic dynamos, the characterization of exo-aurora physics and brown dwarf magnetospheric environments, and the role of satellites in manifestations of substellar magnetic activity. These efforts will require significant new observational capabilities at radio and near infrared wavelengths, dedicated long-term multiwavelength monitoring programs, and committed support for the theoretical modeling efforts underpinning the physical processes of the magnetic phenomena.

Jackie Villadsen (National Radio Astronomy Observatory)

Topic: Stars and Stellar Evolution

Stormy Dwarfs, Gentle Giants: A Radio View of Stars and How They Shape Their Environments

Radio observations trace phenomena in the outer atmospheres of stars and brown dwarfs, including winds, chromospheres, and coronae. Radio wavelengths also offer unique diagnostic power for non-thermal processes such as flares, shocks, and auroral current systems. Radio observations of these magnetically-mediated particle acceleration processes enable diagnosis of magnetic field strength, particularly significant for brown dwarfs and extrasolar planets. Radio also offers the potential to detect stellar eruptions and energetic particle events that shape the environment experienced by planets. Efforts to observe these processes at radio wavelengths, currently in their infancy, will become increasingly significant with the advent of ever-more-sensitive radio facilities, especially low-frequency facilities with wide area coverage. These developments coincide with a growing recognition of space weather as a key element of exoplanet characterization. Efforts to study extrasolar space weather are informed by solar physics, where radio observations play a significant role in studying magnetic fields and plasma properties, particle acceleration, and space weather events.

Radio studies of low-mass stars have traditionally focused on non-thermal processes, since the small stellar size implied that thermal sources were too faint to detect. Radio facilities are now attaining the sensitivity needed to detect the quiet radio Sun at stellar distances, enabling study of thermal emission from chromospheres and coronae of low-mass stars, which can be used to infer atmospheric temperature profile and trace magnetic activity cycles. In massive or giant stars, radio telescopes can detect, and even image, thermal emission from the photosphere, chromosphere, or wind, enabling measurement of wind mass loss rates and atmospheric structure. Across the HR diagram, stellar radio astronomy is benefiting from recent and upcoming improvements in sensitivity and bandwidth, which support time-resolved, multi-frequency studies of dynamic processes in stellar atmospheres.

Lynn D. Matthews (MIT Haystack Observatory)

Mark J. Reid (Center for Astrophysics | Harvard & Smithsonian)
Karl M. Menten (Max Planck Institut für Radioastronomie)
Kazunori Akiyama (National Radio Astronomy Observatory/MIT Haystack Observatory)

Topic: Stars and Stellar Evolution

Unlocking the Secrets of Late-Stage Stellar Evolution and Mass Loss through Radio Wavelength Imaging

During the late phases of evolution, low-to-intermediate mass stars like our Sun undergo periods of extensive mass loss, returning up to 80% of their initial mass to the interstellar medium. This mass loss profoundly affects the stellar evolutionary history, and the resulting circumstellar ejecta are a primary source of dust and heavy element enrichment in the Galaxy. However, many details concerning the physics of late-stage stellar mass loss remain poorly understood, including the wind launching mechanism(s), the mass loss geometry and timescales, and the mass loss histories of stars of various initial masses. These uncertainties have implications for stellar astrophysics, as well as fields ranging from star formation to extragalactic astronomy and cosmology. Observations at cm through sub-mm wavelengths that resolve the surfaces and extended atmospheres of evolved stars in space, time, and frequency are able to provide unique and powerful insights into these questions. I will describe results from recent resolved imaging observations of nearby evolved giants using the VLA and ALMA that exploit new advances in radio imaging methods. I will also discuss the exciting prospects for advances in stellar imaging that will come from new and upgraded radio wavelength facilities in the coming decade.

Jenny Greene (Princeton)

Topic: Formation and Evolution of Compact Objects

Low-mass Black Holes in the Coming Decade

We do not know how supermassive black holes (BHs) form. We know that there must be a channel that can operate rapidly, to form the first billion solar mass BHs only hundreds of millions of years after the Big Bang. But to really pin down whether seeds form from Population III stars or are formed directly to a more massive state will require additional constraints that only low-redshift observations can give. I will review the prospects for constraining the formation of BH seeds using next-generation extremely large telescopes, and how these efforts will complement next-generation radio and X-ray prospects.

Dr. Dario Carbone (Texas Tech University)

Dr. Alessandra Corsi (Texas Tech University)

Topic: Formation and Evolution of Compact Objects (FECO)

Identifying Engine-Driven Supernovae: an Optimized Radio Follow-up Strategy

How exactly massive stars die is still an open question as the zoo of supernovae (SNe) explosions is very wide and variegate. The most extreme and rare type of supernova explosion is an engine-driven supernova associated with relativistic ejecta (gamma-ray burst; GRB), and bright radio emission. In the near future, several synoptic optical surveys (e.g., ZTF and LSST) will offer the unprecedented opportunity of discovering larger samples of the rarest forms of core collapses. Therefore, we need to have an efficient radio follow-up plan to detect and correctly identify engine-driven SNe, as well as promptly distinguish them from other types of radio bright (but non-relativistic) explosions such as e.g. CSM-interacting SNe. The next generation Very Large Array (ngVLA) will significantly contribute to the discovery of new engine-driven supernovae, extending the distance to which we can expect to detect them, increasing the number of detections, and allowing us to infer physical parameters of these sources. In this talk, I will present two new statistical methods that allow us to quantify the efficacy of radio follow-up strategies in detecting and classifying radio bright SNe, as well as potential off-axis GRBs. These methods allow us to optimize the follow-up so as to maximize either the detection probability in general, or the accuracy in identifying relativistic events in particular. I will conclude by providing an example follow-up strategy that correctly identifies most of the relativistic SNe, about half the CSM-interacting SNe, and about a third of the off-axis GRBs.

Dillon Dong (Caltech)

Gregg Hallinan (Caltech)

Topic: Formation and Evolution of Compact Objects

Frontiers in Radio Transient Discovery

Optical transient searches have entered an industrial era in which new supernovae are discovered nightly, and rare optical transients are being uncovered at an increasing rate. This transition has been driven in large part by the combination of galaxy-untargeted high cadence surveys (e.g. PTF, ZTF, ATLAS, ASAS-SN, Panstarrs, etc.) and increasingly rich contextual information from galaxy and stellar surveys (e.g. SDSS, the Census of the Local Universe, Gaia). Yet despite this success, our understanding of the dynamic sky has much room for growth. There are many classes of transients, including off-axis gamma ray bursts, highly obscured supernovae, and supernovae with late-time CSM interaction which are readily accessible to radio facilities such as the VLA, but are difficult to identify at other wavelengths. Building a sample of these transient classes will help answer long-standing questions about the physics of central-engine jets, the rate of "missing supernovae", and the diverse modes of late-stage mass loss in high mass stellar evolution. These transients shine brightly in a vast and underexplored stretch of parameter space that, in addition, may hold as-yet undiscovered classes of transients that will solve and create a new wave of astrophysical mysteries.

In this talk, we discuss new results from our exploration of this parameter space with the two largest-volume radio transient searches: the Caltech-NRAO Stripe 82 Survey (CNSS) and the VLA Sky Survey (VLASS). We highlight the increasing evidence for a class of compact, luminous radio afterglows that may dominate the rates of off-nuclear transients in future sky surveys. Finally, we discuss implications for radio transient searches in the ngVLA era, with an eye for synergies with future transient searches at other wavelengths such as the LSST.

Daniela Calzetti (University of Massachusetts, Amherst)

Topic: Resolved Stellar Populations and Their Environments

Linking the Scales of Star Formation

Understanding galaxy evolution requires understanding star formation and its dependence on the local environment, spanning the scales from individual stars to kpc-size structures. The physical conditions of the gas within galaxies determine the formation of stars, star clusters, and larger structures. Dynamics contributed to their evolution.

HST observations of external galaxies have enabled the characterization of the young stellar populations with unprecedented accuracy and detail, thus aiding the census and characterization of those populations. These observations are being used to quantify the spatial distributions and clustering of young stars, and investigate the impact and imprint of the physical conditions of both the local and global environment on the formation and evolution of the multi-scale structures. I will concentrate mainly on the results of the HST Treasury program Legacy ExtraGalactic UV Survey (LEGUS), but also provide an outlook for progress that will be enabled by recent (ALMA) and future (JWST) facilities to garner new, complementary insights into the process of star formation.

Rebecca C. Levy (University of Maryland)

Alberto D. Bolatto (University of Maryland), Adam K. Leroy (The Ohio State University)

Topic: Resolved Stellar Populations and Their Environments

Probing Feedback from Super Star Clusters in the Central Starburst of NGC253

Large-scale, multiphase outflows seen in nearby prototypical starburst galaxies, such as NGC253, are thought to be powered by feedback from massive stellar clusters. Resolving these dusty compact structures outside the Milky Way system requires the spectral resolution and sensitivity of ALMA and future instruments such as the ngVLA. Using ALMA data at 350 GHz with 0.025" (0.4 pc) resolution, we present direct evidence for outflows from super star clusters (SSCs) in the nuclear starburst of NGC253. We detect blue-shifted absorption and red-shifted emission towards four of the candidate SSCs in multiple lines, including HCN(4-3), $H^{13}CN$(4-3), HCO^{+}(4-3), and CS(7-6). These P-Cygni profiles are direct evidence for massive outflows from these SSCs. This is the first time outflows from stellar clusters have been identified outside the Milky Way system. The brightest SSC has an outflow velocity of ~50 km/s. We model the P-Cygni line profiles to constrain the outflow opening angles and inclinations. These observations are the first of their kind, showing the formation and feedback of massive stellar clusters. This analysis allows us to determine the feedback they exert on their environment and how the cluster-scales are related to the galaxy-scale outflow. From our high resolution dust continuum data, we identify 25 compact sources, with several of the clusters previously identified at lower resolution (1.9 pc; Leroy et al. 2018) breaking apart into multiple components. By combining this dust continuum data with 36 GHz radio continuum measurements made by the VLA (Gorski et al. 2019), we can constrain the ionizing flux, cluster spectral energy distributions (SEDs), and the cluster mass function (CMF). The CMF is related to the stellar initial mass function (IMF), and these SSCs provide a unique test in a region where a top-heavy IMF may be expected if it exists (see Astro2020 White Papers by Hosek Jr. et al. and Calzetti et al.). The VLA measurements are critical to constraining the SEDs needed to derive the CMF, but we are limited by the current resolution of the VLA (~1.7 pc in NGC253) to probe these small scales and to take full advantage of the exquisite resolution of our ALMA data. The ngVLA will allow for these measurements to be made at the necessary sub-parsec resolution.

Ylva Pihlström (University of New Mexico)

Lorant Sjouwerman (NRAO)

Topic: Resolved Stellar Populations and Their Environments

Astrometry with Stellar Masers

Stellar masers and their line-of-sight velocities can be observed throughout the Milky Way, and thus can be used as probes of both the structure and dynamics of the Galaxy. Methanol and water masers in star forming regions are used to map out the spiral structure, while SiO masers in evolved stars sample the inner Galaxy and Galactic bulge regions. In the Bulge Asymmetries and Dynamical Evolution (BAaDE) survey, we are mapping velocities and positions of tens of thousands of infrared selected red giant stars using SiO maser transitions. These new kinematic probes and their individual stellar properties (e.g., infrared colors) can subsequently be used in dynamical and evolutionary models to significantly improve our understanding of the dynamics, structure and the range of stellar ages in the bulge and inner Galaxy populations. Including long baselines and increased instantaneous sensitivity, the ngVLA would greatly enhance the scientific yields of this and similar projects, allowing for proper motion and parallaxes to be determined. This approach would be complementary to Gaia, which cannot measure parallax distances for most of our targets due to optical extinction not perpetrating deep into the Galactic bas, and the angular extent of the star itself.

Kate D. Alexander (Northwestern University)

Topic: Galaxy Evolution

TDEs with the ngVLA: A New Window onto the Evolution and Growth of Supermassive Black Holes

Tidal disruption events (TDEs) in which a star is torn apart by a supermassive black hole (SMBH) offer a unique opportunity to discover lower mass SMBHs than with existing techniques (~10^4 - 10^7 $M_\odot$), to probe models of SMBH growth and accretion, and to study the physics underlying the formation and growth of relativistic jets and outflows. Radio observations of TDEs allow us to precisely localize the emission (confirming its TDE origin), to determine the properties of outflowing material (energy, size, expansion velocity), and to trace the ambient density profile around previously-dormant SMBHs on otherwise unresolvable scales of ~0.1 - 10 pc. However, the sample of radio-detected TDEs remains small and the weakest observed outflows are below the detection threshold of current radio facilities for all but the nearest events. The broad frequency coverage and increased sensitivity of the ngVLA are essential to characterize the physical conditions required to produce jets and outflows in the bulk of the TDE population. The ngVLA will be a key player in a new era of exquisite multi-wavelength and multi-messenger capabilities (LSST, eROSITA, SKA, LISA, etc.) that will characterize large numbers of TDEs out to high redshift, probing changes in SMBH environments over cosmic time.

Thursday, June 27, 2019

9:00 AM	9:40 AM	Radio/mm View on Galaxy Evolution in ASTRO2020	Min Yun
9:40 AM	10:00 AM	PHANGS Result: The Dependence of Star Formation Efficiency on Molecular Gas Properties in Nearby Galaxies	Dyas Utomo
10:00 AM	10:20 AM	Precision Gas-dynamical Mass Measurement of Supermassive Black Holes with the ngVLA	Benjamin Boizell
10:20 AM	10:40 AM	Parsec-scale Observations of Jets in the ngVLA Era: From Physics to Feedback	Kristina Nyland
10:40 AM	11:10 AM	Break & Posters (30 min)	
11:10 AM	11:30 AM	Constraints on the Molecular Gas Mass Density Evolution over Cosmic Time from Serendipitous CO Detections in PHIBSS2	Laura Lenkic
11:30 AM	11:50 AM	A Multi-Frequency View on the Faint Star-forming Radio Population	Hiddo Algera
11:50 AM	12:10 PM	Tracing the Star Formation History of the Universe via Free-free Emission	James Condon
12:10 PM	12:20 PM	Conference Photo	
12:20 PM	1:40 PM	Lunch (80 min)	
1:40 PM	2:20 PM	Cosmological and Extragalactic Science Cases for Incompatible Versions of the ngVLA	Jeremy Darling
2:20 PM	2:40 PM	H2O Megamaser Cosmology with the ngVLA	James Braatz
2:40 PM	3:20 PM	Frontiers in Planetary System Astrophysics with Next-Generation Radio Facilities	Katherine de Kleer
3:20 PM	3:50 PM	Break & Posters (30 min)	
3:50 PM	4:30 PM	Message Received: Radio Observations in the Multi-Messenger Era	Nicole Lloyd-Ronning
4:30 PM	4:50 PM	The ngVLA as a Precision Pulsar Timing Instrument for NANOGrav	Ryan Lynch
4:50 PM	5:10 PM	Supermassive Black Hole Pairs and Binaries: Multi-Messenger Astrophysics and Long Baselines with the Next-Generation Very Large Array	Laura Blecha
5:10 PM	5:30 PM	Summary and Final Remarks	

Min S. Yun (University of Massachusetts)

Topic: Galaxy Evolution

Radio/mm View on Galaxy Evolution in ASTRO2020

I will review and summarize the key science topics presented in the Astro2020 science white papers relevant for the radio/mm astrophysical frontiers in the next decade, particularly on the formation, evolution, dynamics, and properties of galaxies and supermassive black holes. I will also review the current state of knowledge and technical capabilities in the radio/mm regime and introduce proposed ideas for the next decades to come.

Dyas Utomo (Ohio State University)

Adam Leroy (Ohio State University)
Jiayi Sun (Ohio State University)
Andreas Schruba (Max Planck Institute for Extraterrestrial Physics)
Eva Schinnerer (Max Planck Institute for Astronomy)
Eve Ostriker (Princeton University)
PHANGS collaboration

Topic: Star and Planet Formation

PHANGS Result: The Dependence of Star Formation Efficiency on Molecular Gas Properties in Nearby Galaxies

We present recent results using the PHANGS-ALMA Large Program to estimate the star formation efficiency per free-fall time, SFE_{ff}, across ~80 nearby galaxies and compare it to the properties of galaxies and giant molecular clouds. This represents the largest sample of cloud-scale SFE_{ff} measurements ever. I will show that SFE_{ff} is in the order of 1% (consistent with some theoretical expectations), but with significant scatter from galaxy-to-galaxy and between regions inside a galaxy. Then, I will show the trend between SFE_{ff} and the global properties of galaxies (stellar mass, specific SFR, and offset from the "main-sequence" of star forming galaxies). Finally, I will show the dependence of SFE_{ff} on local molecular gas properties (mass surface density, velocity dispersion, and virial parameter) and compare to theoretical expectations. These results are only possible thanks to high resolution mm-wave imaging. I will close by discussing how the ngVLA can push this field to the next level by providing high resolution measurements tracing both gas and star formation.

Benjamin Boizelle (Texas A&M University)

Kristina Nyland (Naval Research Lab), Tim Davis (Cardiff University)

Topic: Galaxy Evolution

Precision Gas-dynamical Mass Measurement of Supermassive Black Holes with the ngVLA

Emission-line observations of circumnuclear disks in the ALMA era are opening a new avenue for studying the demographics of supermassive black holes (BHs) in nearby galaxies. ALMA CO imaging has revealed dynamically cold, rotating, nuclear gas disks in a growing number of massive galaxies, providing ideal probes of their inner gravitational potentials and enabling highly precise direct BH mass determinations. Such precise BH mass measurements are needed to anchor the sparsely populated high-mass end of the BH mass-host galaxy correlations. The ngVLA is capable of extremely high spatial resolution imaging of the ^{12}CO(1-0) transition for nearby galaxies. Furthermore with its high emission-line sensitivity, the ngVLA can produce benchmark BH mass measurements out to a larger distances. We discuss lessons learned from gas-dynamical modeling of recent ALMA data sets and also compare ALMA and ngVLA simulations of CO disks. The ngVLA will expand on ALMA's revolutionary capability to probe cold molecular gas rotation within the gravitational influence of BHs.

Kristina Nyland (NRC fellow, resident at NRL)

Pallavi Patil (UVA/NRAO), Dipanjan Mukherjee (University of Torino), Mark Lacy (NRAO), Isabella Prandoni (INAF), Jeremy Harwood (University of Hertfordshire), Amy Kimball (NRAO), Katherine Alatalo (StSci), Geoffrey Bicknell (ANU), Bjorn Emonts (NRAO), Sibasish Laha (UCSD), W. Peter Maksym (Harvard-Smithsonian CfA), Jenny Greene (Princeton), Tracy Clarke (NRL), Namir Kassim (NRL), Mark Sargent (University of Sussex), Eric Perlman (Florida Institute of Technology)

Topic: Galaxy Evolution

Parsec-scale Observations of Jets in the ngVLA Era: From Physics to Feedback

Super massive black hole-galaxy co-evolution is believed to operate via energetic feedback from active galactic nuclei (AGN), influencing galaxy evolution through the regulation of galaxy star formation rates and efficiencies. The conventional wisdom is that AGN feedback operates via two distinct modes: 1) the radiative or quasar mode, in which winds launched by the accretion disk quench star formation (SF) through the removal of a galaxy's star-forming reservoir, and 2) the jet or "maintenance" mode, in which large-scale (10-1000 kpc) jets influence SF through the inhibition of cooling flows in the intracluster medium. However, evidence continues to mount that jetted AGN may also have a significant impact on interstellar medium (ISM) through jet-ISM interactions on sub-galactic (pc to kpc) scales, motivating the need for high-resolution studies probing jet formation and acceleration and characterizing their feedback effects. With an emphasis on the essential role of continental-scale baselines for imaging galactic nuclei on milliarcsecond scales, I describe how the unique capabilities of the next-generation Very Large Array will enable new advancements in our understanding of jet launching and feedback physics necessary for placing the role of jet-ISM feedback on galaxy growth and evolution in context.

Laura Lenkic (University of Maryland, College Park)

Alberto D. Bolatto (University of Maryland, College Park)

Topic: Galaxy Evolution

Constraints on the Molecular Gas Mass Density Evolution over Cosmic Time from Serendipitous CO Detections in PHIBSS2

The star formation rate density of the Universe is known to peak around z ~ 1–2 and has declined to the present day. The fundamental physical processes shaping this evolution, however, remain uncertain. Constraints on the molecular gas mass density evolution are particularly relevant to understanding these processes because this gas is the immediate fuel for star formation. Most studies rely on blind CO searches in deep fields, which require hundreds of hours of telescope time and then use those detections to construct the CO luminosity function over the sampled cosmological volume. We instead use a new hybrid method by taking advantage of existing data from the *Plateau de Bure High-z Blue Sequence Survey 2* (PHIBSS2) program. The observations targeted normal star-forming main sequence galaxies at the cosmic peak of star formation, selected from the 3D-HST/CANDELS fields. We do a systematic search in the data for serendipitous "secondary" sources and use these to measure the CO luminosity function for a variety of CO transitions and redshift ranges. With these data, we derive the molecular gas mass density evolution over the redshift range z ~ 0.3 – 4, and find that our result is consistent with previous observations. We also add constraints on CO luminosity functions for previously unexplored transitions and redshift ranges such as CO(3–2) at z ~ 1.5, CO(4–3) at z ~ 2.2, and CO(5–4) at z ~ 3.3. Our method can be a powerful new way of measuring the CO luminosity function and molecular gas mass density over cosmic time by leveraging existing data as well as broader bandwidth and higher sensitivity data from future facilities such as the ngVLA. Finally, we will present new 0.15'' (1–1.5 kpc) resolution HST observations of six rare local ($z \sim 0.1$) galaxies observed to have turbulent, clumpy disks, making them much more similar to high-z main sequence galaxies than they are to other local ones. The angular resolution allows us to study star forming clumps on scales that are not achievable at the peak of cosmic star formation, and future instruments like the ngVLA will greatly improve our ability to do this.

Hiddo Algera (Leiden University)

Dieuwertje van der Vlugt (Leiden University)
Jacqueline Hodge (Leiden University)

Topic: Galaxy Evolution

A Multi-Frequency View on the Faint Star-forming Radio Population

The radio window offers a dust-unbiased and high-resolution view of the high-redshift galaxy population. In the faint regime ($S_{3\ GHz} \lesssim 100$ μJy), this population is strongly dominated by star-forming galaxies, which show radio emission consistent with the well-studied far-infrared-radio correlation. Historically, such faint star-forming sources have predominantly been studied at low radio frequencies, where their emission is dominated by non-thermal synchrotron radiation. However, the higher frequencies ($\nu \gtrsim 30$ GHz, rest-frame) offer an additional and potentially superior tracer of star formation: thermal free-free emission (FFE). With the ngVLA this high-frequency window will be studied in great detail, but even the current VLA is already able to probe this regime at high redshift. Through the combination of various deep VLA datasets over the COSMOS and GOODS-North fields, we study the spectrum of the faint radio population at four frequencies (1.4, 3, 10 and 34 GHz). The 3 and 10 GHz data in particular reach depths of ~0.5 and ~0.4 μJy/beam, respectively, allowing the additional exploration of the average radio spectrum of the nanoJansky population through a multi-frequency stacking analysis. We present initial results on the isolation of FFE for the faint radio population and investigate its potential as a high-redshift star formation rate tracer.

Jim Condon (NRAO)

Allison Matthews (University of Virginia)
Eric Murphy (NRAO)

Topic: Galaxy Evolution

Tracing the Star Formation History of the Universe via Free-free Emission

Ultraviolet (UV) and far-infrared (FIR) data indicate that the comoving star-formation rate density peaked at cosmic noon ($z\sim2$) and that > 95% of all stellar mass assembly has occurred since $z\sim4$. However, most UV emission is absorbed in dusty star-forming galaxies (SFGs). Cold dust illuminated by older stars contaminates the FIR emission of low-luminosity SFGs, and existing FIR images can detect only the most luminous galaxies beyond cosmic noon. The radio continuum luminosities of SFGs are proportional to their recent star-formation rates, unbiased by dust or older stars. The confusion-limited 1.3 GHz MeerKAT DEEP2 image is sensitive enough to trace the evolution of most SFGs via their synchrotron emission, but inverse-Compton scattering off the cosmic microwave background may suppress synchrotron radiation at high redshifts. Only an ngVLA Band 3 (16 GHz) confusion-limited image with $\theta\sim6''$ resolution will be able to detect the $S \geq 60$ nJy free-free emission tracing the star formation history of all galaxies that produced > 85% of the stellar mass in the universe today.

Jeremy Darling (University of Colorado)

Topics: Cosmology and Fundamental Physics

Cosmological and Extragalactic Science Cases for Incompatible Versions of the ngVLA

We present three science cases and their associated radio array requirements:

(1) Extragalactic proper motions enable measurements of the secular extragalactic parallax, transverse peculiar velocities of galaxies, the evolution of the baryon acoustic oscillation, and the primordial gravitational wave background. This science requires 8000 km baselines and 50,000 sq. m collecting area (10x the VLBA) at 8 GHz.

(2) A formaldehyde deep field provides a mass-limited survey of molecular gas across the history of star formation and galaxy evolution (z = 0–7). This requires a 100 km array with at least 0.1 K brightness temperature sensitivity at 2–10 GHz (10x the VLA collecting area).

(3) The cosmological acceleration can be measured directly by monitoring the drift of molecular absorption lines over time. This is "light bucket" science that needs to maximize collecting area while minimizing atmospheric and array-based spectroscopic systematics. Measuring $\dot{z}$ would best be done with a compact large-area array at 40 or 100 GHz.

The arrays required by these science goals are mutually incompatible. The reference design ngVLA that includes long baselines may be a reasonable compromise for extragalactic proper motions and a formaldehyde deep field, but it may not be capable of the parts-per-trillion precision needed to measure the redshift drift.

James Braatz (NRAO)

Dominic Pesce (Harvard-Smithsonian CfA)
James Condon (NRAO)
Mark Reid (Harvard-Smithsonian CfA)

Topic: Cosmology and Fundamental Physics

H_2O Megamaser Cosmology with the ngVLA

As a complement to observations of the Cosmic Microwave Background, a measurement of the Hubble Constant at $z < 0.5$ provides a powerful test of LCDM cosmology and constrains the equation of state of dark energy. Observations of circumnuclear water vapor megamasers at 22 GHz in nearby active galaxies can be used to measure distances to the host galaxies, geometrically, and thereby provide a direct, one step measurement of the Hubble Constant, independent of standard candles. Observations of megamasers with present-day instrumentation are expected to reach a ~4% H_0 measurement. A long-term goal of the observational cosmology community is to attain a one percent measurement of H_0 in agreement across several independent methods to minimize the systematics. We will discuss the opportunity to reach a ~1% H_0 measurement using the megamaser method by taking advantage of the sensitivity at 22 GHz afforded by the ngVLA.

Katherine de Kleer (Caltech/MIT)

Topic: Planetary Systems

Frontiers in Planetary System Astrophysics with Next-Generation Radio Facilities

Observational facilities that have come online in the past decade have enabled significant advances in our understanding of planetary systems, including both our own Solar System and systems around other stars. Millimeter observations with ALMA in particular have provided truly unprecedented views into these worlds and their environments. In the upcoming decade, continuing upgrades to ALMA, and radio facilities such as the ngVLA, have the potential to capitalize on this momentum and play a central role in pushing the frontiers in planetary system science. This talk will provide a brief review of recent scientific milestones in this field and will discuss the potential high-impact science enabled by next-generation cm/mm observatories within the broader context of planetary studies, highlighting specific technical requirements and opportunities to leverage multi-wavelength and multi-facility programs.

Nicole Lloyd-Ronning (Los Alamos National Lab; University of New Mexico, LA)

Topic: Multi-messenger Astronomy and Astrophysics

Message Received: Radio Observations in the Multi-messenger Era

With the advent of gravitational wave detections from compact object mergers and the increasing number of cosmic neutrino detections (including the first potential association of a high energy neutrino with a blazar jet), we now can truly utilize multiple channels with which to observe and understand our universe. Our understanding will not be complete, however, without a coherent view of all of these "messages" - photons, neutrinos, cosmic rays, and gravitational waves. Radio observations are not only an important piece of this puzzle, but absolutely essential if we hope to truly decipher the physics behind a number of astrophysical sources - especially black holes/compact objects at all scales and their progenitors. In this talk, I will discuss how radio/mm observations from an ngVLA - particularly when coordinated with observations at other wavelengths - will enlighten our understanding of astrophysical objects that are multi-messenger in nature.

Ryan Lynch (Green Bank Observatory)

Megan Decesar (Lafayette College)
Scott Ransom (NRAO)
Shami Chatterjee (Cornell University)
James Cordes (Cornell University)
Paul Demorest (NRAO)
David Kaplan (University of Wisconsin-Milwaukee)
Michael Lam (West Virginia University)
Joseph Lazio (NASA/JPL)
Maura McLaughlin (West Virginia University)
Xavier Siemens (University of Wisconsin-Milwaukee)

Topic: Multi-Messenger Astronomy and Astrophysics

The ngVLA as a Precision Pulsar Timing Instrument for NANOGrav

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) Physics Frontiers Center runs a long-term millisecond pulsar (MSP) timing program with the goal of detecting and characterizing nHz-frequency gravitational waves (GWs), the most likely sources of which are a GW background (GWB) from a population of coalescing supermassive binary black holes (SMBBHs), and individual, nearby SMBBHs. These detections will open a new window on the GW spectrum, complementing the higher-frequency LIGO detections. NANOGrav currently uses the Arecibo and Green Bank telescopes to time 76 MSPs with the sub-microsecond timing precision necessary to detect small, correlated variations in pulse arrival times caused by GWs. We have also begun timing several pulsars with the VLA, demonstrating the utility of phased arrays for precision pulsar timing, and have developed a plan to use the ngVLA for future NANOGrav timing observations. We expect to observe ~200 MSPs with the ngVLA; this significant increase in MSP number will result from a combination of more sensitive pulsar surveys (e.g. with FAST) and the increased sensitivity of the ngVLA, making it feasible to time some known, fainter pulsars with good precision. Indeed, a key benefit of the ngVLA is its increased sensitivity, relative to current instruments, at frequencies typically used for pulsar timing, as these higher frequencies mitigate the corrupting effects of the interstellar medium. Our requirements for the ngVLA include: a wide bandwidth (using observing ands of 1-4 or 2-8 GHz) for robust dispersion measure determination; sub-array capability; 10-20 observing hours per week; and good sky coverage to allow the best possible spatial distribution of, thus maximizing our GW sensitivity. We note that by the time the ngVLA is in use, the GWB and likely one or more individual GW-emitting SMBBHs will have been detected; additionally, several synergistic facilities for space-based GW detection and electromagnetic follow-up will be in operation. Thus, the ngVLA will be vital to NANOGrav's transition from a focus on detection to that of extracting exotic physics and other interesting science from low-frequency GW sources, especially through multi-messenger observations of individual SMBBHs.

Laura Blecha (University of Florida)

Joseph Lazio (Jet Propulsion Laboratory/Caltech)
Sarah Burke-Spolaor (West Virginia University, Center for Gravitational Waves & Cosmology)

Topic: Multi-messenger Astronomy and Astrophysics

Supermassive Black Hole Pairs and Binaries: Multi-Messenger Astrophysics and Long Baselines with the Next-Generation Very Large Array

Dual (<~ 10 kpc separation) and binary (<~ 10 pc separation) supermassive black holes (SMBHs) are formed during the merger of two galaxies. Their formation and evolution is controlled by interactions with their environment and, at close separations, the emission of gravitational waves. Accordingly, the occupation fraction of dual SMBHs in galaxy merger products is central to our understanding of galaxy and SMBH evolution, and determining the rate of dual active galactic nuclei (AGN) in galaxy mergers will advance our understanding of merger-induced SMBH fueling and growth. The rate of gravitational wave-driven SMBH mergers is critical to the predictions for gravitational wave signals that will be detected by pulsar timing arrays (such as the North American Nanohertz Observatory for Gravitational Waves [NANOGrav]) and future space-based laser interferometers (LISA). A related prediction is that AGN can appear offset significantly from the host galaxy due to gravitational wave "kicks" during the merger of an asymmetric SMBH binary. We review the current status and likely 2030s landscape for SMBH pairs and binaries, with a particular focus on the role that the ngVLA can play.

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The NANOGrav project receives support from NSF Physics Frontier Center award number 1430284.