Current and Future Capabilities of the VLBA

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Outflows, Winds and Jets
NRAO-NAASC Workshop
2012 Mar 3

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

The VLBA stations

- Form a dedicated VLBI array
- Array dedicated in 1993
- Cover frequency range 310 MHz to 90 GHz
- 10 identical stations on U.S. territory:
  - Brewster WA, Hancock NH, Fort Davis TX, Kitt Peak AZ,
  - Los Alamos NM, Mauna Kea HI, North Liberty IA, Owens Valley CA,
  - Pie Town NM and Saint Croix, US Virgin Islands
- Each station has
  - 25-m Cassegrain antenna
  - Station building with maser, electronics, recorders
  - Weather station, GPS Rx, security camera
  - Staff of 2

Current antenna capabilities

- 310 MHz and 90 GHz in 10 select bands
  - Most bands use high sensitivity cryogenic receivers
  - Dual circular polarizations
  - Simultaneous operation at 2.4 and 8.4 GHz possible
  - Can change observing bands in seconds
- Relatively fast motion: 90 deg/min in Azimuth and 30 deg/min in Elevation
- Baseband data acquisition rate of 512 Mbps (and 2048 Mbps; see later slide)
  - 64 MHz bandwidth in two polarizations with 2 bits per sample
    - Via multiple 8 or 16 MHz sub-bands within a 512 MHz IF
  - Data is compatible with recordings made at most other VLBI antennas

- See the VLBA observational Status Summary for more details
  - http://www.vlba.nrao.edu/astro/obsstatus/current

VLBA correlator

- Socorro hosts the VLBA DiFX software correlator
  - DiFX has a global collaborative development team
  - It is now used at most VLBI processing centers
- 16-20 Mark5 units available for playback
- Can process data from 10 stations at a rate of 1500 Mbps
- Time resolution down to milliseconds (or less)
- Frequency resolution down to 2 Hz
- Some special features
  - Pulsar gating and binning
  - Simultaneous correlation at many positions
  - Extraction of calibration information (phase tones, Tsys)
  - Can dump high time resolution spectra for transient searching

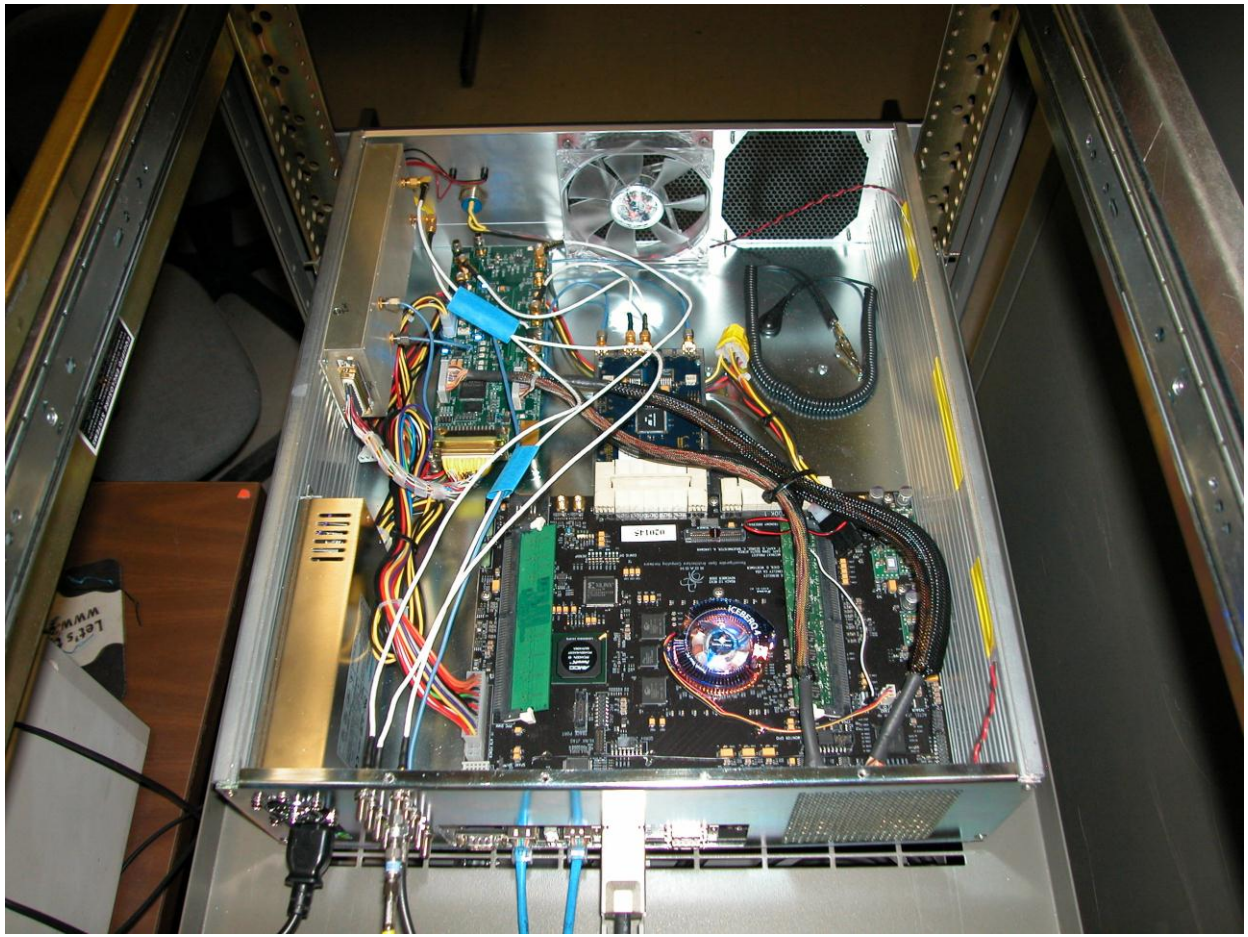
The key capabilities of the VLBA

- Long baselines yield high resolution
  - 5 mas at 1.5 GHz
  - 120 μas at 90 GHz → Highest resolution imaging in astronomy
  - Sensitive to brightness temperatures above about 10^5 K
- Instrumental stability and long baselines → astrometry
  - < 0.1 μ as achievable with minor effort, cooperative sources
  - 0.01 μ as demonstrated in some cases
    - Allows distance measurements at 1 kpc with 1% accuracy
- Identical 25-m antennas allow large field of view
  - 30' at 1.5 GHz
  - Can image hundreds of sources in one pointing
- Full time operations
  - Suitable for transient response, dynamic scheduling, multi-epoch obs…
- Rapid turnover to users: usually ~2 weeks
- Pulsar processing (gating and binning)

Bandwidth expansion project

- Goal: Increase the data rate from the VLBA from 512 Mbps to 2(4) Gbps
- Three major components, all developed collaboratively
  - New back-end electronics (collab. w/ Haystack)
    - Remove downconverters, samplers and formatter
    - Replace with FPGA-based hardware (from CASPER group)
  - New recorder (Haystack, Conduant Corp.)
    - Mark5C unit with 10 Gb input port
  - New correlator (Adam Deller and global collaboration)
    - Replace VLBA hardware correlator with DiFX software correlator
    - Complete as of Dec 2009
- Hardware is installed at all sites
- First science is underway!
- Memo series: https://science.nrao.edu/facilities/vlba/publications/memos/sensitivity-upgrade

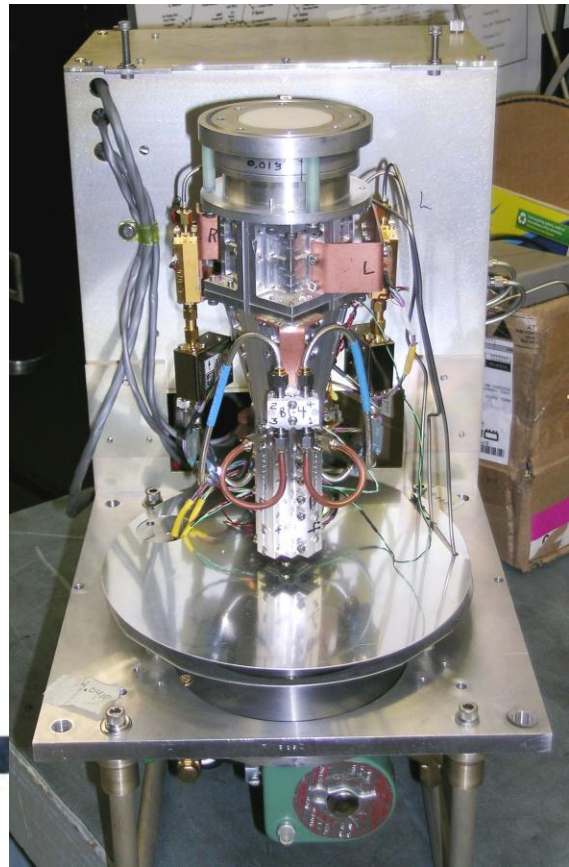
Bandwidth expansion hardware



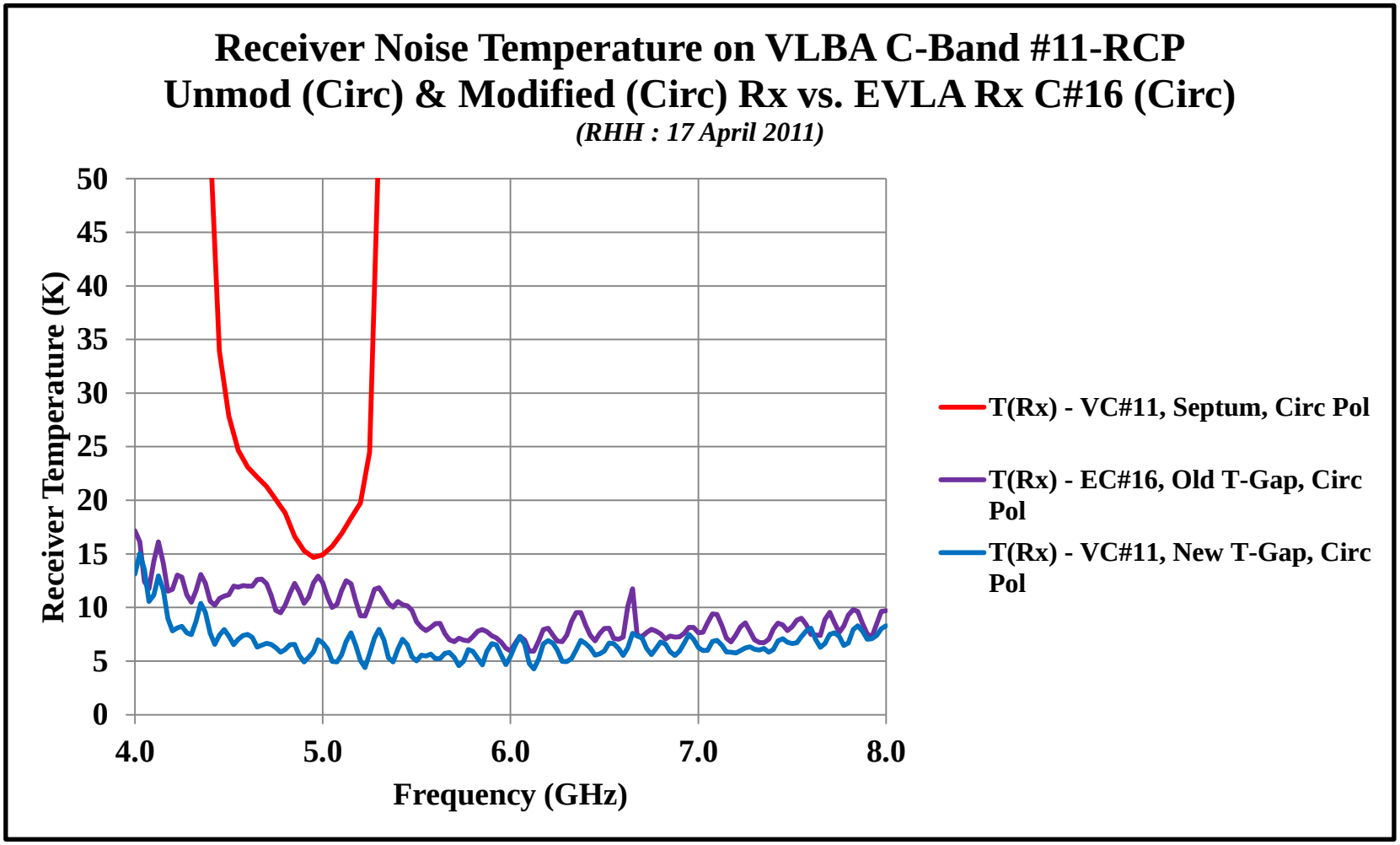
ROACH Digital Back End

C-band receiver upgrade

- Replace 4.5-5.1 GHz receivers with 4-7.9 GHz upgraded units
- Primary science goal: Astrometry of 6.7 GHz methanol line found in star forming regions to map the structure of the Milky Way
- This project will bring more of the VLBA to EVLA standards
- Upgraded down-converter will allow 2 IF pairs to attach to this receiver at widely separated frequencies
- Upgrade is in progress
  - Feed replacements done at 8 antennas
  - New receivers installed at 6 antennas
  - Rolling downtime of C-band receivers
    - Some observing impacted
- First science to begin ~May 2012
- Planned completion by August 2012



Performance of new C-band receiver

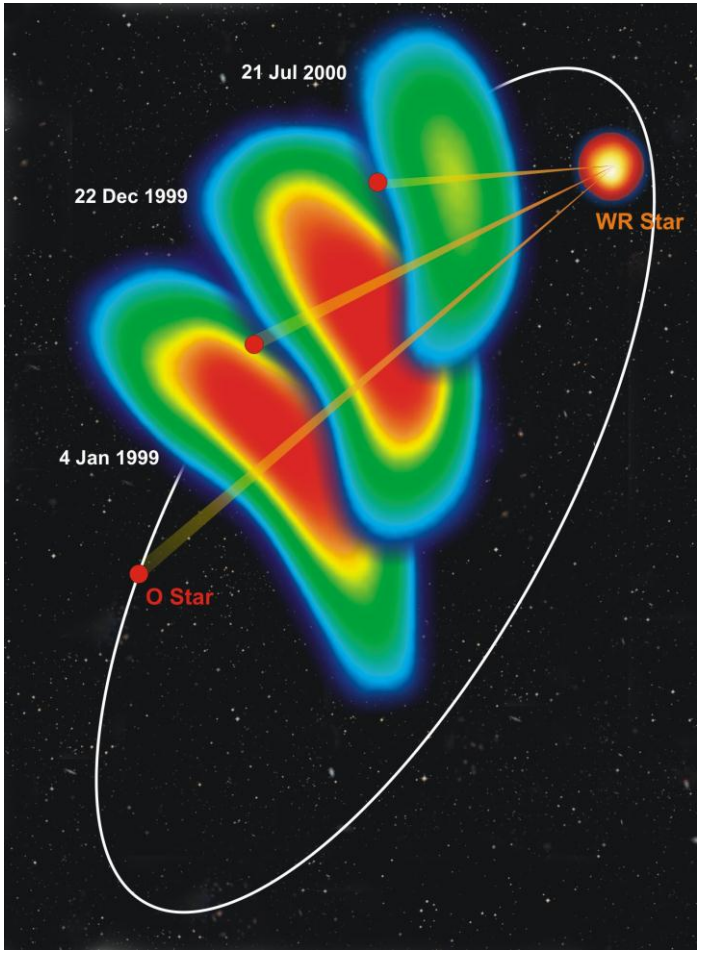


Performs even better than EVLA C-band receivers!

Topical VLBA science

Imaging colliding winds

- Resolution
  - 80μas to 25 mas
    - In the galaxy (100pc-10kpc): 1 mas resolution is 0.1-10 AUs (even less than a stellar radius for nearby stars)
    - For nearby extragalactic (1-1000Mpc): 1 mas resolution is 1000 AU-5pc
  - E.g., WR140, colliding wind region in Wolf-Rayet binary star system

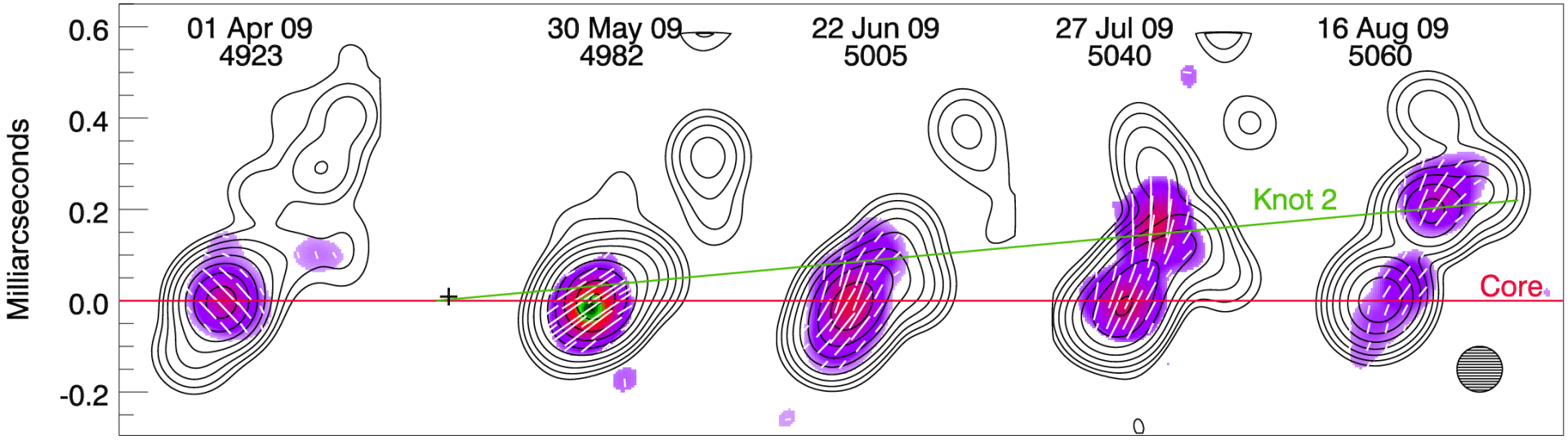


Dougherty et al. 2005

Comprehensive multi-waveband monitoring of γ-ray bright blazars

Marscher & Jorstad

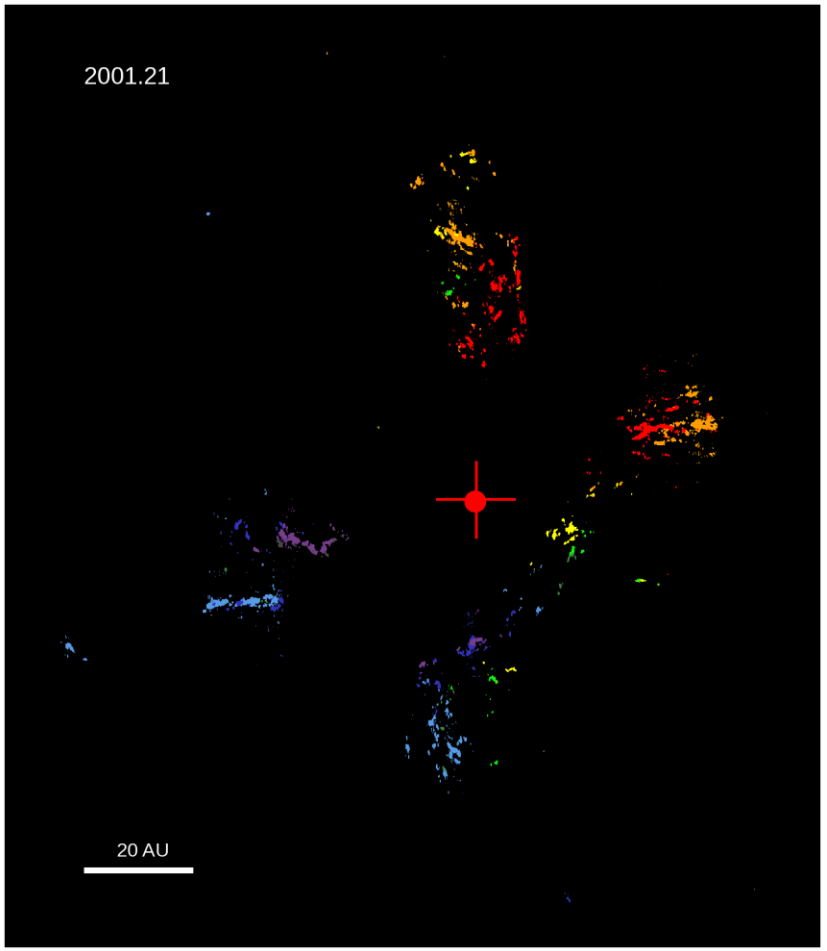
- Monthly observations at 43 GHz of FERMI detected blazars
- Goal: determine the source of γ radiation
- Results to date: γ-rays emitted when blobs are ejected
  - These "blobs" are likely shock waves



SiO maser emission from Orion Source I

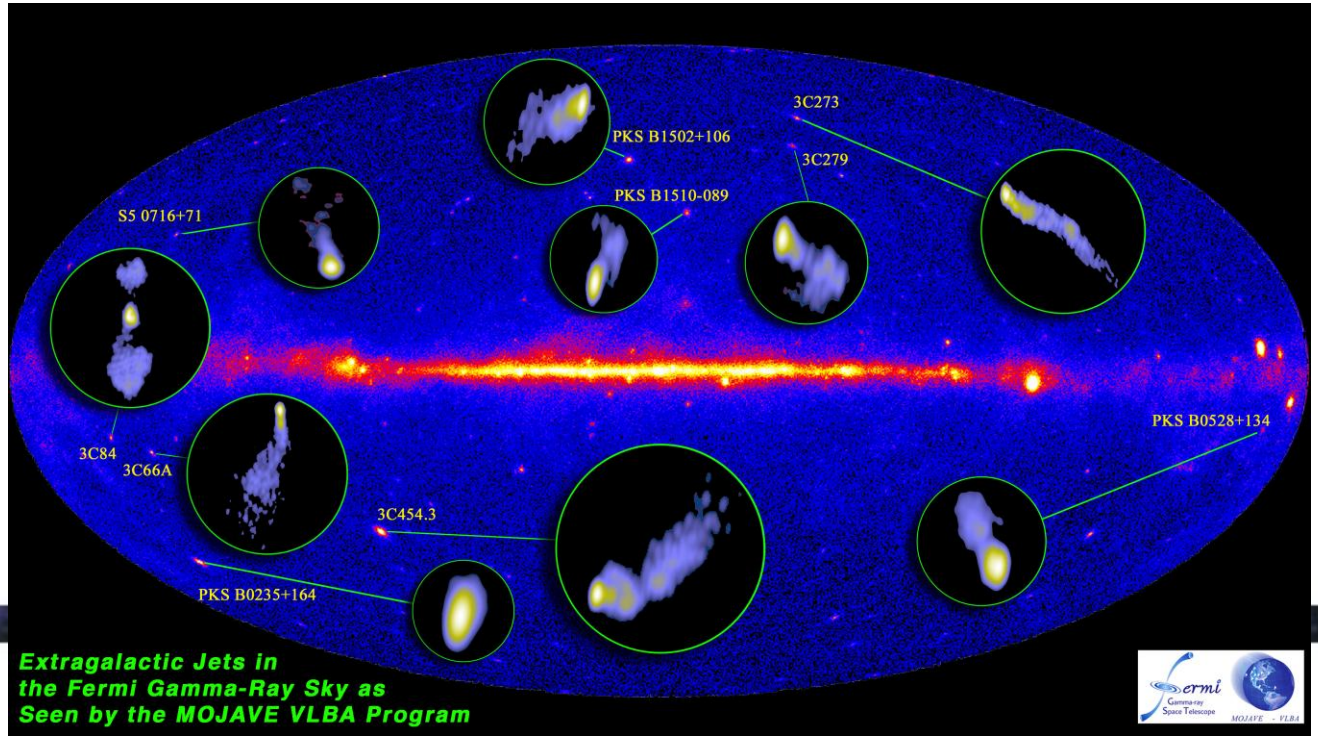
- Nearly edge-on massive (>8 Msun) YSO
- SiO J=1-0 maser emission @ 43 GHz
- 0.2 AU resolution (for D=414pc)
- Time evolution shows clear helical motion consistent with bipolar emission from rotating disk.
- Maser trajectories are thought to be shaped by magnetic fields.
- Supports disk-mediated accretion formation scenario

- Matthews et al. 2010, ApJ, 708, 80



Monitoring of jets in active galactic nuclei with VLBA experiments (MOJAVE) *Lister et al.*

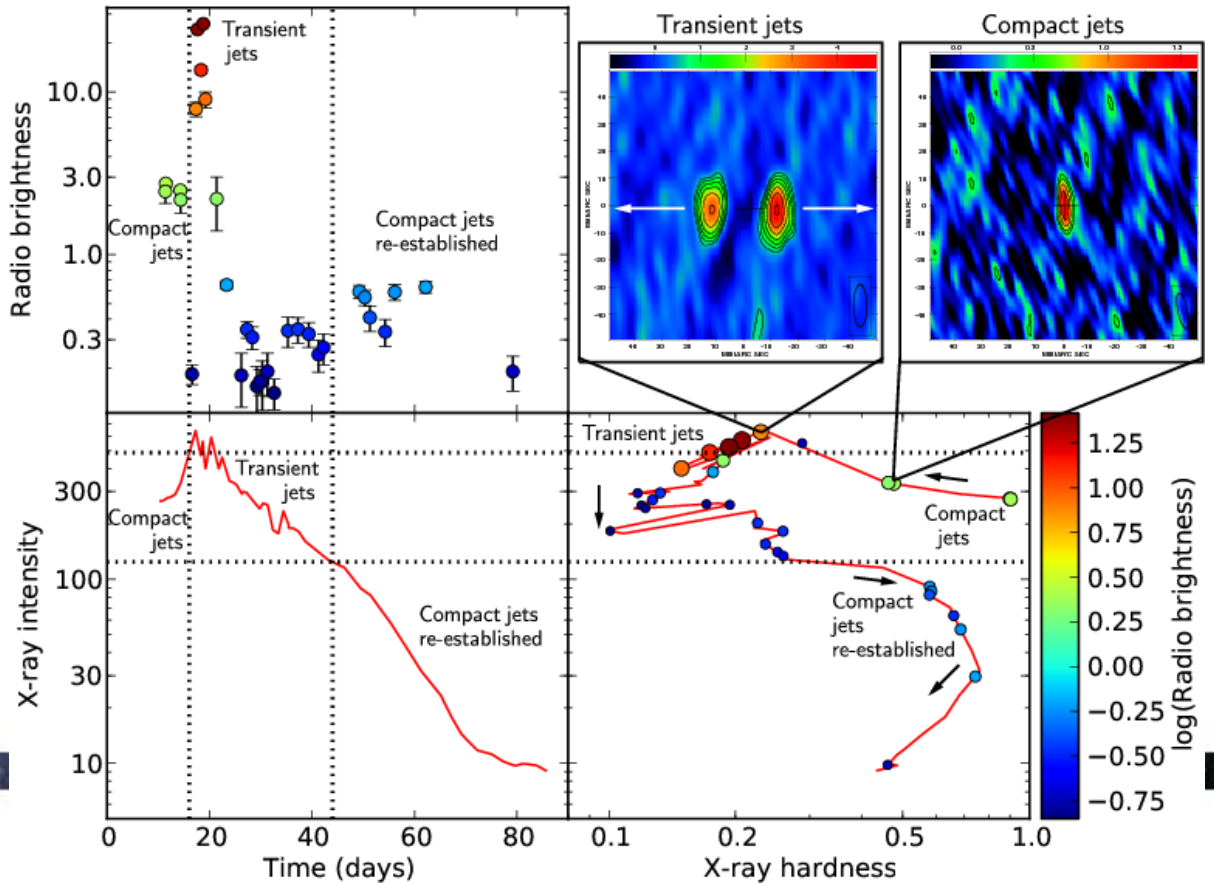
- Observations made at 15 GHz frequency
- A long term (already 20+ years) project to explore the variability of brightness and polarization in AGN jets on timescales of months to decades.
- Optical, x-ray and γ-ray observations are being made in parallel



Jet acceleration and collimation probe of transient X-ray binaries (JACPOT) *Miller-Jones et al.*

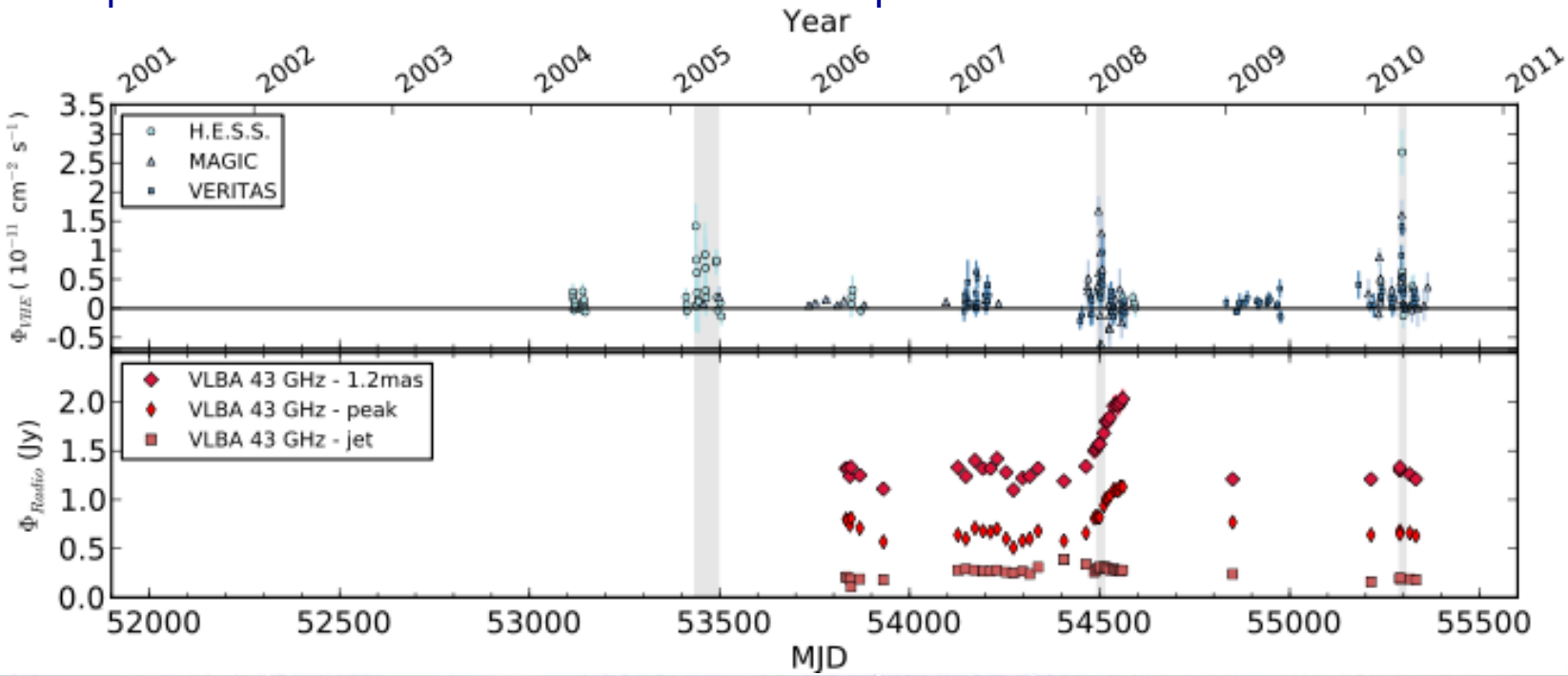
- Compare microquasar systems with white dwarf, neutron star and black hole companions
- Explore role of gravitational fields, magnetic fields and surface on jet formation

Black hole system candidate H1743-322 in outburst. VLBA images show jet transitioning from compact to relativistically moving knots



M87 Very High Energy flare seen in multi-wavelength monitoring

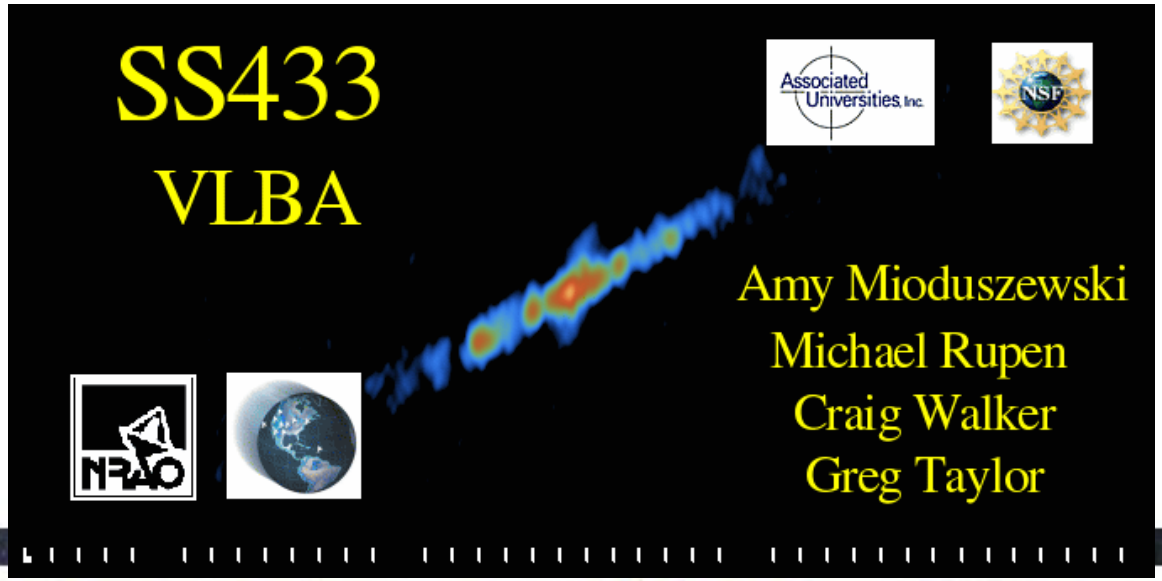
- Flares in 2008 and 2010 caught during VHE observing campaigns (HESS, Veritas, and MAGIC), and during VLBA monitoring campaigns.
- Changes in the jet at VLBI scales were seen in 2008 but not 2010.
- A third flare in 2005 was associated with X-ray flux changes in jet feature HST-1.
- No unique set of features describes the three flares reported.



Abramowski et al., 2012, ApJ, 746, 151

Precessing microquasar SS433

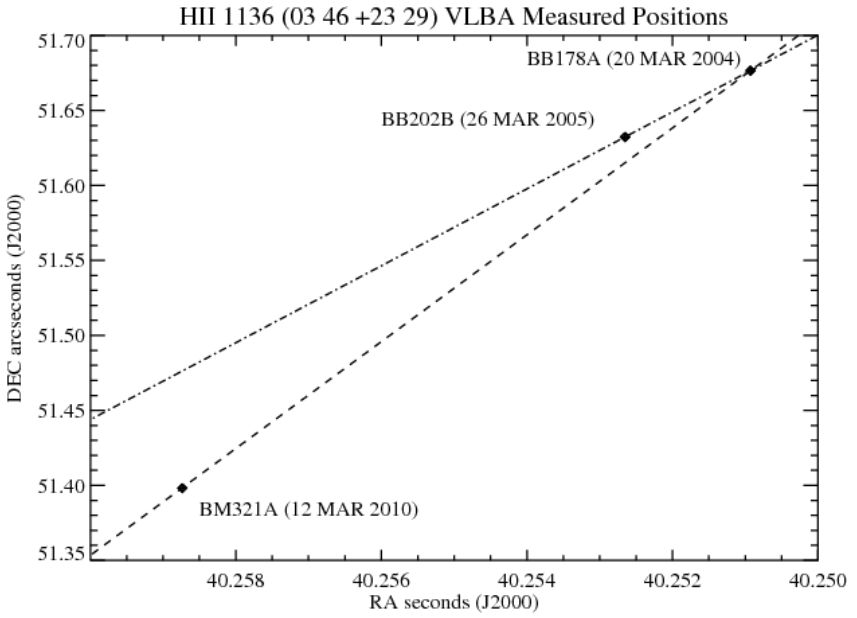
- BH or NS accreting matter from companion star
- The jet precesses with a 164 day period (movie spans ¼ cycle)
- VLBA observations at 15 GHz yield 3 AU resolution (at d=5 kpc)
- Jet material travelling at 0.26c
  - Contains baryons
  - Motions consistent with ballistic
- Movie: Mioduszweski et al. in prep.



Pleiades distance

Melis et al.

- Pleiades are a key system for understanding stars in open clusters
  - It is close and young
- Pleiades distance controversy:
  - Hipparcos measured 120 pc
  - Other methods yield ~133 pc
- Goal: use VLBA to determine geometric distance
  - VLA being used to identify cluster members that are bright enough
  - Early VLBA results have demonstrated the feasibility
    - Non-linear stellar motion hints at multiplicity



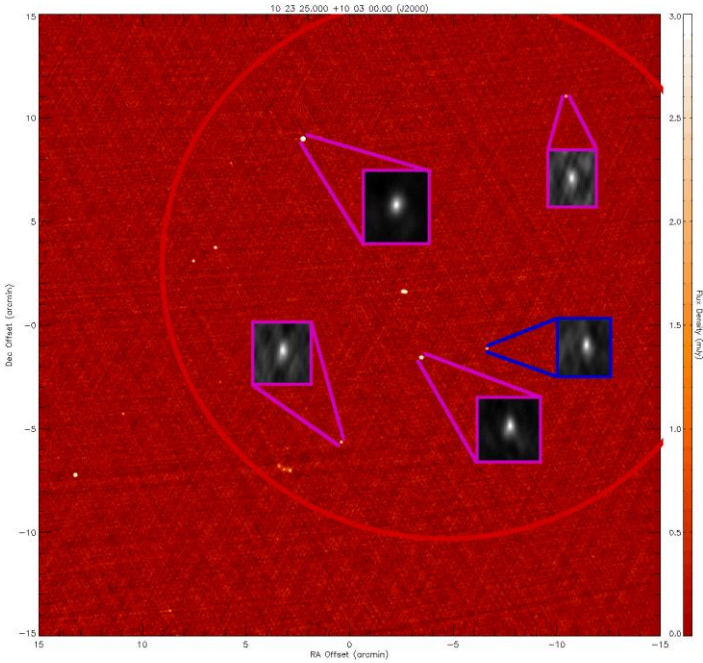
Resident Shared Risk Observing (Opportunities for you to contribute!)

- The VLBA is a very flexible instrument with many untapped possibilities
- A RSRO program is available to those wanting to help implement new capabilities
- As for EVLA RSRO there is a residency requirement (~2 months)
- RSRO astronomers get early access to new capabilities
- Some example projects:
  - Integration of phased EVLA into VLBA observations
  - Development of new correlator capabilities (Mark4 format output, on-the-fly calibration, new delay model options, …)
  - Single-dish observing capabilities
  - Implementation of "4-IF" modes
- Visit https://science.nrao.edu/facilities/vlba/observing/rsro for details

Additional VLBA Science Examples

PSRπ : pulsar astrometry

Adam Deller et al.

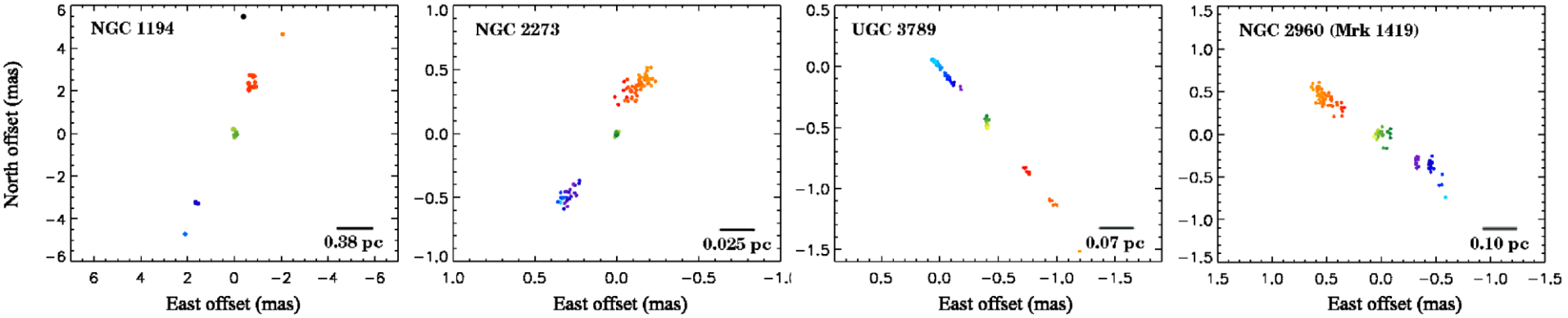


- Goal: 60 more parallax distances to pulsars
  - Proper motions come for free
- Luminosities can be calibrated
- Can connect pulsars with SNR or other objects
- Improve solar system to ICRF reference frame ties
- Used to better calibrate the Galactic electron density model
- Reduce covariances in pulsar timing array parameters
- Observing strategy
  - Use 1.5 GHz
  - Calibrate using background quasars in field of view
  - Make use of pulsar gating and multi-phase center correlation

Megamaser cosmology project

Braats, Kuo et al.

- Goal: Measure Hubble constant
  - Determine geometric distance to AGNs hosting water maser disk through orbit modeling high velocity maser motions
  - Couple to redshift determined from systemic maser velocity
- Goal: Measure black hole masses precisely
- First results from galaxies within the Hubble flow suggest H_0=69±11 km/s

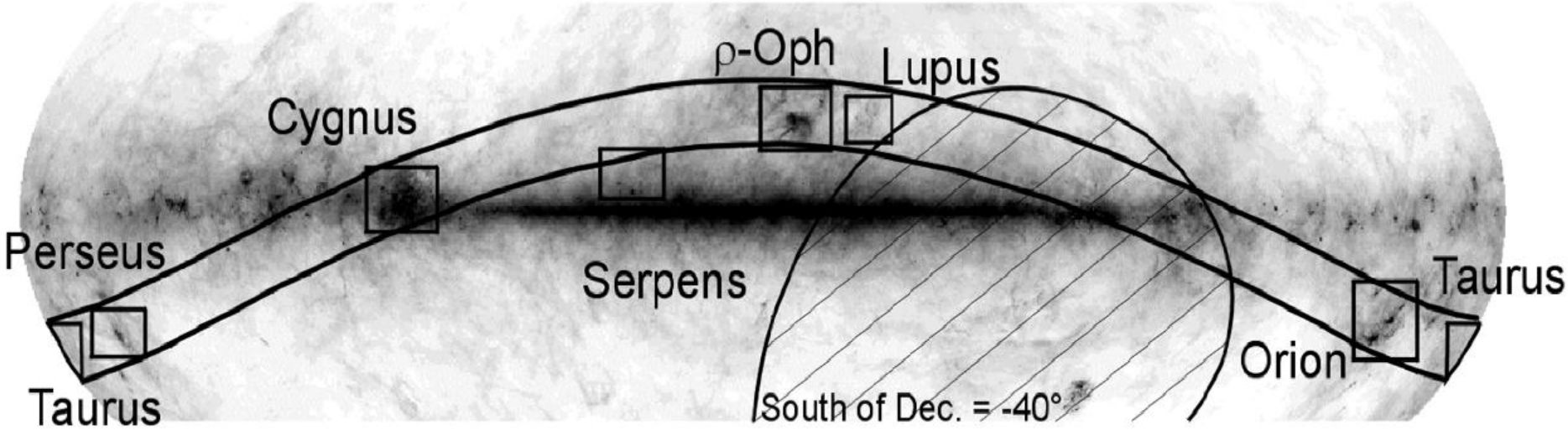


4 example maser spot maps

Gould's belt distance survey

Loinard et al.

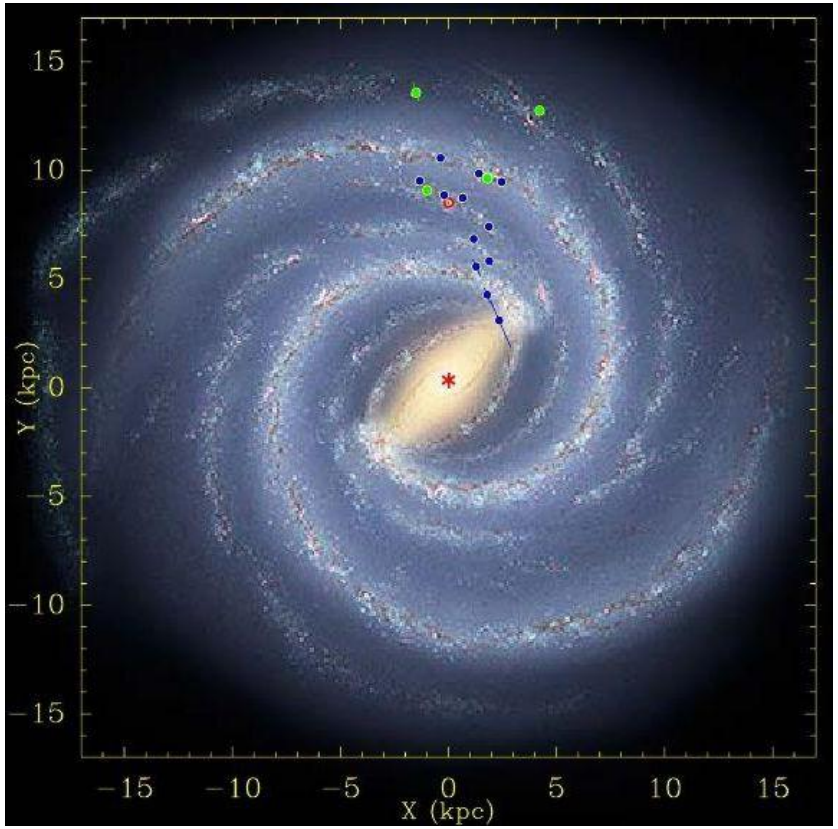
- Goal: determine distances to nearby star-forming regions
  - Perform parallax astrometry on young radio bright stars
  - EVLA being used to identify suitable stars
- Results from studies of the Taurus star forming region are already mapping the three dimensional structure of the region
- The unexpectedly close distance to Orion determined through this project has brought star forming models into accord



Bar and spiral structure legacy survey (BeSSeL)

Reid et al.

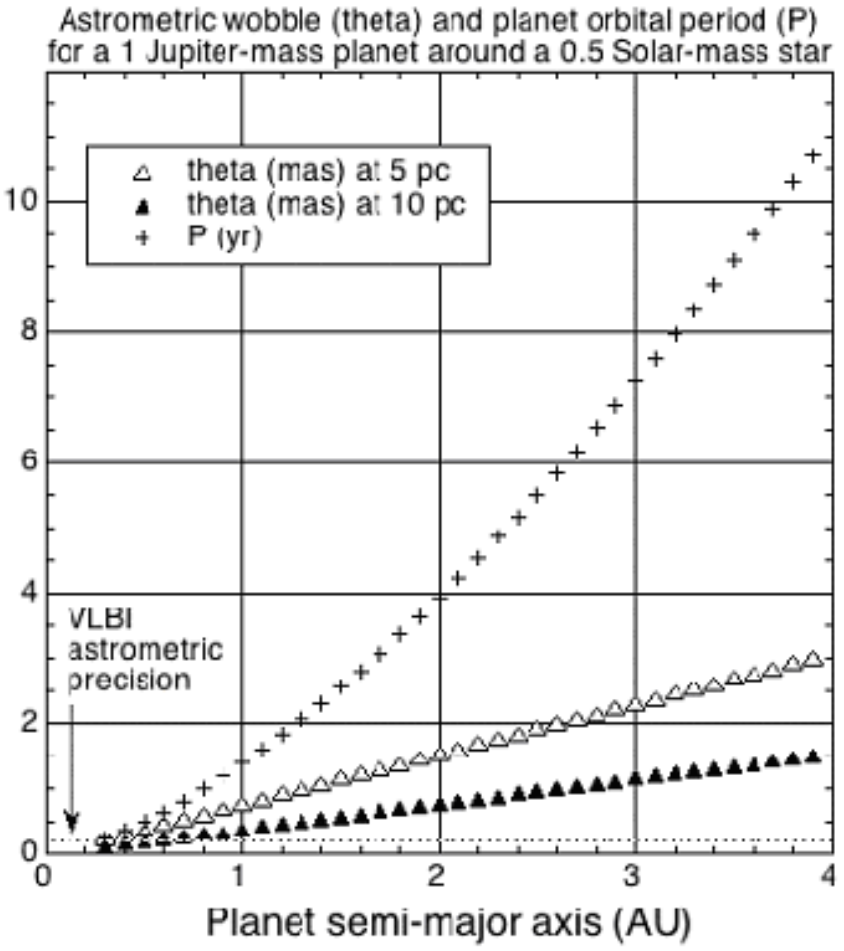
- Goal: determine structure and kinematics of the Milky Way Galaxy
- Perform astrometry on masers in star forming regions
  - Water masers at 22 GHz
  - Methanol at 11 and (soon) 6.7 GHz
- Early results have improved measurements of the distance to the Galactic Center and rotational velocity
  - $R_0 = 8.4 \pm 0.6$ kpc
  - $\Theta_0 = 254 \pm 16$ km/s



The radio-interferometric planet search (RIPL)

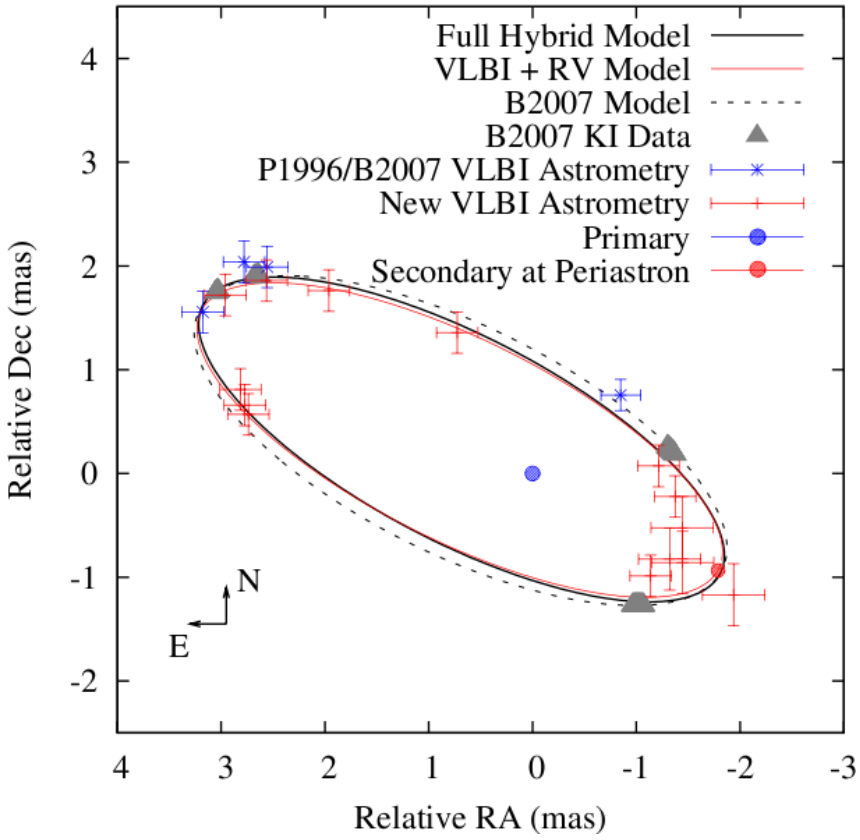
Bower et al.

- Goal: search for planets around M-dwarf stars
  - Via astrometric reflex
  - Sensitive to sub-Jupiter masses with long periods
  - Complementary to radial velocity methods



Mass, distance, and radio structure of V773 Tau A

- Multi-epoch VLBA astrometric observations trace out 51-day orbit and determine distance (133+-2 pc).
- Mass measurements of the binary members determined: 1.55 and 1.29 Msun.
- Magnetospheric activity inferred from increased brightness of both stars at periastron.
- Fit residuals show acceleration consistent with a 26-yr hierarchical orbit around 2.4 Msun star V773 B.



Torres et al. 2012, ApJ, 747, 18

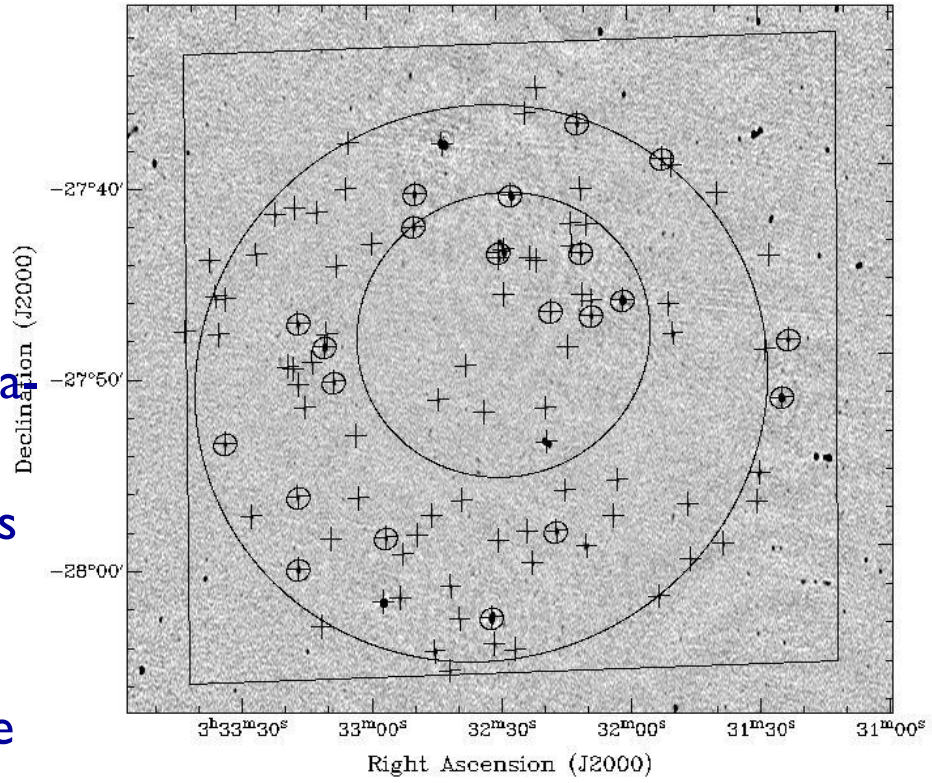
V-FASTR: Fast transient detection with the VLBA

- VLBA DiFX Software Correlator has been augmented with a transient detection pipeline
  - Looks for "Lorimer" type events
  - Commensally searches all projects correlated in Socorro
  - Short term (~2ms) accumulated spectra sent to processor
  - Data are reordered, flattened, and searched for dispersed pulses
- Machine-learning algorithms exploited (Thompson et al., 2011, ApJ, 735, 98)
  - 10 separated antennas used as coincidence detectors
  - Artificial pulses injected constantly to assess/set thresholds
- Pulsar test datasets prove the concept (Wayth et al., 2011, ApJ, 735, 97)
  - Regular pulses from PSR B0329+54 detected
  - Giant pulses from the Crab Pulsar detected

NRAO

Wide-field VLBA Observations of the Chandra Deep Field South

- VLBI fields of view are notoriously narrow
- A new wide-field technique allows for 10s or 100s of sources to be simultaneously studied with the VLBA
- This technique was used to target extra-galactic sources within the CDS
- Results were used to classify sources as AGN or star bursts
- With this advance VLBI can be used effectively alongside deep surveys made with other instruments



Middelberg et al., 2011, A&A 526, 74

VLBA Astrometry of Cassini at Saturn

- 8 measurements of the position of Cassini were made between 2006 and 2009; each measurement was accurate to ~0.3 mas (2 km) relative to the quasar reference frame (ICRF).
- This new data is contributing to the new DE422 planetary ephemeris. Ongoing observations will ultimately reduce uncertainty in Saturn's position by a factor of about 3 as more of Saturn's orbit is probed.
- This will have implications for spacecraft navigation, solar system dynamics, relativity research, pulsar timing, and frame ties connecting the solar system to the ICRF.

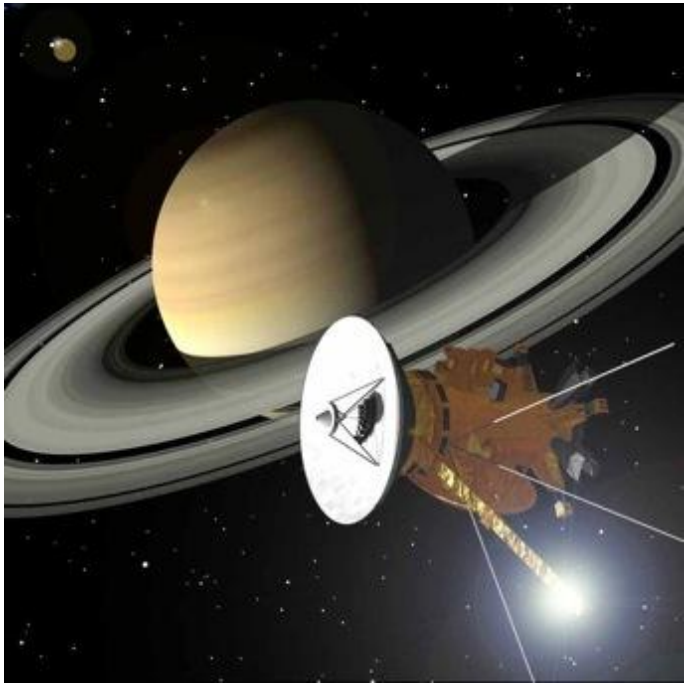


Image: NASA

Jones et al., 2011, ApJ, 141, 29

Backup Material

- Frequency bands and sensitivity
- Daily USNO observations
- The HSA and global VLBI
- Important VLBA links

Frequency bands and sensitivity

λ(cm)	ν(GHz)	σ(μJy/beam) in 4 hrs at 2Gbps
90 cm	0.312 - 0.342	277*
50 cm	0.596 - 0.626	782*
21 cm	1.35 - 1.75	13-14
13 cm	2.15 - 2.35	14
6 cm	4.6 - 5.1	13
6 cm (upgrade)	4.1 - 7.9	8
4 cm	8.0 - 8.8	13
2 cm	12.0 - 15.4	24
1 cm	21.7 - 24.1	18-22
7 mm	41.0 - 45.0	66
3 mm	80.0 - 90.0	316†

- Maximum bandwidth 256 MHz with two polarizations - available Feb 2012 proposal deadline
- More later about:
  - Increasing sensitivity by adding more/larger telescopes to the array
  - Sensitivity upgrade
  - C-band upgrade

* Narrower bandwidths

† 8 stations

Daily UT1-UTC observations

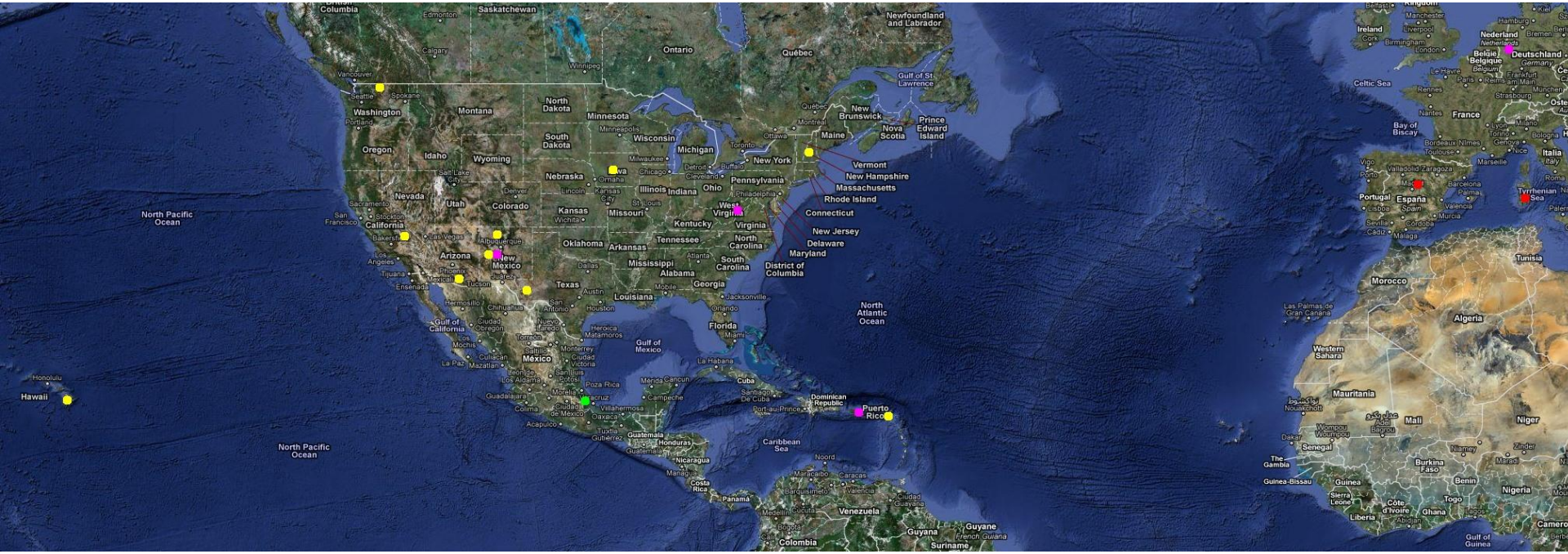
- US Naval Observatory is contributing to VLBA operations in exchange for daily ~1 hour observations using 2 VLBA antennas: Mauna Kea and Pie Town
- High speed network links have been installed at these two sites
  - MK and PT to Washington D.C. at ~250 Mbps
- Daily ~1 hour observations to begin soon
- VLBA science to face potential interruptions
  - Users have been contacted with tips to reduce impact on observing

High Sensitivity Array

- HSA = VLBA + Phased EVLA + GBT + Arecibo + Effelsberg
- 1-hr integration at 1.7 GHz gives S_{rms} = 5 μJy/beam with 512 Mbps recording rate
- Phased EVLA will be provided by the EVLA's WIDAR correlator
  - Has not been available since the VLA correlator shutdown on Jan 11, 2010
- Phased EVLA originally not due to be implemented until 2013, but RSRO program has made it likely that this will be complete earlier
  - Adam Deller & Joe Lazio demonstrated phased array recording
  - Lots of little issues to be addressed before scientific use can begin

- 2 Gbps operation at most/all HSA antennas hoped during CY 2012

The High Sensitivity Array on the map



Yellow: VLBA antennas

Pink: Other current HSA members: VLA, GBT, Arecibo, Effelsberg

Red: Other antennas under some consideration: Yebes, Sardinia

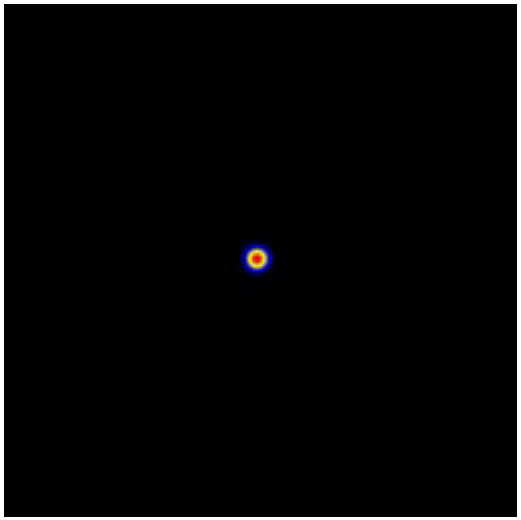
Global VLBI

- Add telescopes from the European VLBI Network (EVN) to the VLBA.
- The EVN has many large sensitive telescopes adding them increases the sensitivity as well as improving *uv* coverage (e.g., EVN has many more short baselines so can be more sensitive to larger structures.)

Important Links

- NRAO Help Desk
  https://help.nrao.edu
- VLBA Observational Status Summary
  http://www.vlba.nrao.edu/astro/obstatus/current/
- EVN Sensitivity Calculator
  http://www.evlbi.org/cgi-bin/EVNcalc
- Proposal Submission Tool
  my.nrao.edu
- SCHED – observation preparation software
  http://www.aoc.nrao.edu/software/sched/index.html
- AIPS – data reduction software
  http://www.aips.nrao.edu/index.shtml
- 13th Synthesis Imaging Workshop (registration opened Feb 1)
  http://www.aoc.nrao.edu/events/synthesis/2012/

SN1993J in M81



10 mas

36,000 AU

Bartel et al. 2000