Next Generation VLA: Cradle of Life

Roberto Galván-Madrid

Instituto de Radioastronomía y Astrofísica (IRyA)
UNAM Campus Morelia, México

on behalf of the 'Cradle of Life' Science Working Group

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CRADLE OF LIFE

- 36 persons collaborated to the recently posted white paper.
- 2 coauthors from Mexico, but more interested.
- $\sim$ 25 faculty across Mexico that are direct users of present generation of radiointerferometers (8 in Morelia).

Next Generation Very Large Array Memo No. 6, Science Working Group 1: The Cradle of Life

Andrea Isella, Charles L. H. Hull, Arielle Moullet, Roberto Galván-Madrid, Doug Johnstone, Luca Ricci, John Tobin, Leonardo Testi, Maite Beltran, Joseph Lazio, Andrew Siemion, Hauyu Baobab Liu, Fujun Du, Karin I. Öberg, Ted Bergin, Paola Caselli, Tyler Bourke, Chris Carilli, Laura Perez, Bryan Butler, Imke de Pater, Chunhua Qi, Mark Hofstadter, Raphael Moreno, David Alexander, Jonathan Williams, Paul Goldsmith, Mark Wyatt, Laurent Loinard, James Di Francesco, David Wilner, Peter Schilke, Adam Ginsburg, Álvaro Sánchez-Monge, Qizhou Zhang, Henrik Beuther

(Submitted on 21 Oct 2015)

This paper discusses compelling science cases for a future long-baseline interferometer operating at millimeter and centimeter wavelengths, like the proposed Next Generation Vary Large Array (ngVLA). We report on the activities of the Cradle of Life science working group, which focused on the formation of low- and high-mass stars, the formation of planets and evolution of protoplanetary disks, the physical and compositional study of Solar System bodies, and the possible detection of radio signals from extraterrestrial civilizations. We propose 19 scientific projects based on the current specification of the ngVLA. Five of them are highlighted as possible Key Science Projects: (1) Resolving the density structure and dynamics of the youngest HII regions and high-mass protostellar jets, (2) Unveiling binary/multiple protostars at higher resolution, (3) Mapping planet formation regions in nearby disks on scales down to 1 AU, (4) Studying the formation of complex molecules, and (5) Deep atmospheric mapping of giant planets in the Solar System. For each of these projects, we discuss the scientific importance and feasibility. The results presented here should be considered as the beginning of a more in-depth analysis of the science enabled by such a facility, and are by no means complete or exhaustive.

Comments: 51 pages, 12 figures, 1 table. For more information visit this https URL
Subjects: **Solar and Stellar Astrophysics (astro-ph.SR)**; Earth and Planetary Astrophysics (astro-ph.EP); Astrophysics of Galaxies (astro-ph.GA); Instrumentation and Methods for Astrophysics (astro-ph.IM)
Cite as: **arXiv:1510.06444 [astro-ph.SR]**
(or **arXiv:1510.06444v1 [astro-ph.SR]** for this version)

KEY SCIENCE DRIVERS

- Formation of high-mass stars
- Formation of low-mass stars
- Formation of planets
- Structure of debris disks
- Chemistry of star and planet formation
- Solar system
- SETI

FORMATION OF HIGH-MASS STARS (AND CLUSTERS!)

- Free-free radio continuum is the best (sometimes the only) way of looking at the innermost regions of newly formed stars with $M_\star > 10\ M_\odot$.
- The most massive stars ($M_\star > 20\ M_\odot$) are believed to start ionizing their own accretion flow.

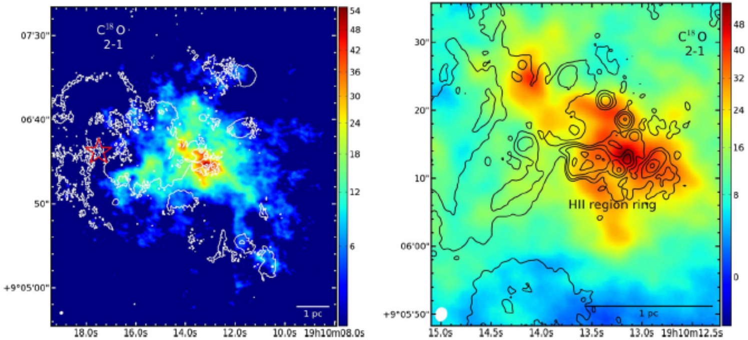


Fig: The W49A Galactic 'mini-starburst'. Colors show molecular gas (SMA+IRAM30m, Galván-Madrid+2013). Contours show the deeply embedded massive stars (VLA, De Pree+1997). Red star shows the part of the forming cluster visible in the NIR (Homeier & Alves 2005).

FORMATION OF HIGH-MASS STARS (AND CLUSTERS!)

- The VLA has detected and mapped in the ionized pockets of gas around newly formed massive ($M_\star > 10\ M_\odot$) stars (UCHIIs, HCHIIs).
- A combination of continuum and RLs give density structure and dynamics.

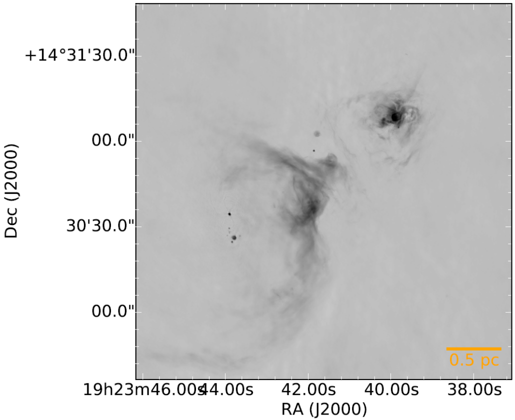


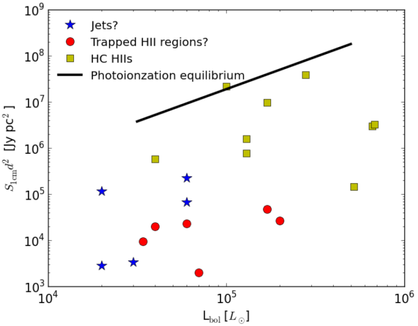
Fig: VLA view of the 'mini-starburst' Galactic region W51 (Ginsburg+, in prep.).

FORMATION OF HIGH-MASS STARS (AND CLUSTERS!)

… but:

What is the nature of those objects with $S_{\rm cm} \sim 10^2$ μJy and $r \sim 10^2$ AU at kpc distances ($r < 100$ mas)?.
So far only unresolved continuum detections.

- Gravitationally trapped HII regions (Keto 2003).
- HII regions 'quenched' by accretion (Walmsley 1995, Peters+2010).
- Objects in transition between shock-ionized jets and photo-ionized HII regions (Rodríguez 1997).
- Pure stellar winds (Panagia & Felli 1975).



FORMATION OF HIGH-MASS STARS (AND CLUSTERS!)

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These objects are:
- The only way of directly observing the late stages of accretion in the formation of stars $M_\star > 20\ M_\odot$.
- The only way of having a complete census of the upper end ($M_\star > 5\ M_\odot$) of the IMF.

FORMATION OF HIGH-MASS STARS (AND CLUSTERS!)

A $\times$10VLA could map these objects with a few to tens of resolution elements across with integrations < 1 hr in the continuum and ~ 10 hr in RLs.

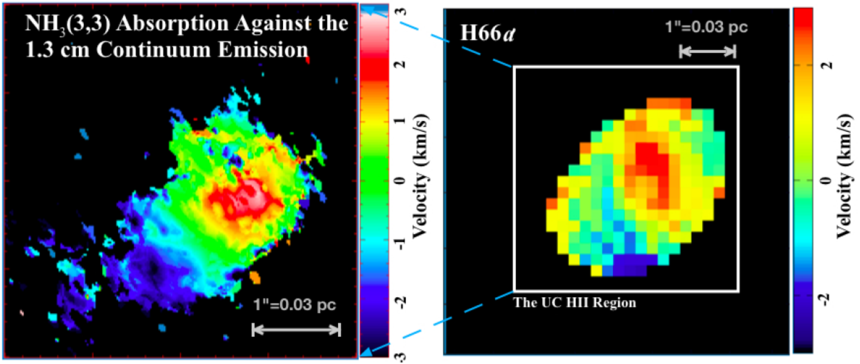


Fig: Resolved molecular+ionized accretion flow around a $M_\star \approx 200\ M_\odot$ aggregate of massive stars (Sollins+05). The ngVLA could perform such studies down to $M_\star \sim 10\ M_\odot$.

JETS IN LOW AND INTERMEDIATE MASS STARS

- Radio jets are the best way of looking at the innermost regions of low-mass ($M_\star \sim 0.1 - 5 M_\odot$) embedded (class 0/I) YSOs.
- Key element of theories of accretion in star formation, expected to launch at < 1 to few AU (need < 10 mas resolution).
- The VLA has mapped in continuum the brightest among them.
- Magnetic field mapped in 1 object and no kinematical mapping through RLs.

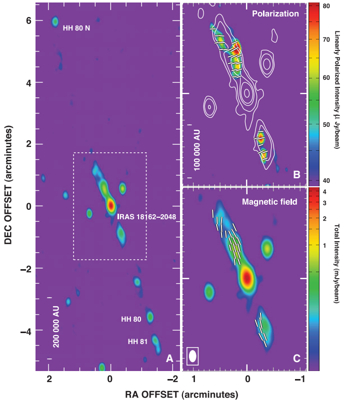


Fig: magnetic field mapped with the VLA in the jet of IRAS 18162 (Carrasco-González+2010).

JETS IN LOW AND INTERMEDIATE MASS STARS

- $\sim$ 10 mas angular resolution and $< \mu$Jy sensitivity is needed to perform resolved demographic studies of YSO radio jets of all masses and evolutionary stages.

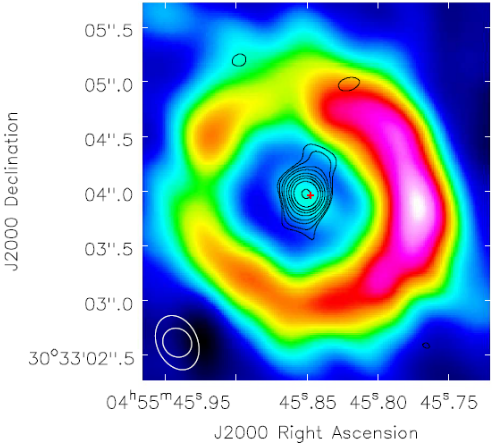


Fig: compact radio jet from the center of a transition disk in AB Aur (Rodríguez+2014).

MULTIPLICITY IN STAR FORMATION

- The multiplicity of protostars and young stars is poorly constrained.
- How and when stars are born in multiple systems is key to understand protostellar accretion and the evolution of young stars and their clusters/associations.

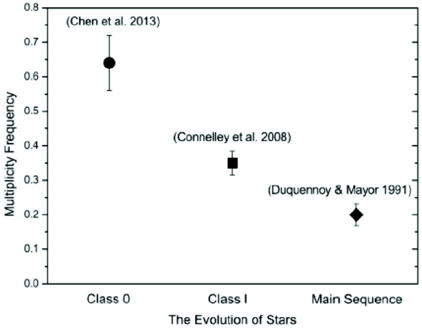


Fig. 4.— The multiplicity frequency declines through the protostellar phase because of the breakup of small multiple systems. From *Chen et al.* (2013).

Fig: Current estimates of YSO multiplicity are biased toward large (> 100 AU) separations.

MULTIPLICITY IN STAR FORMATION

- The disks+envelopes in class 0/I YSOs are optically thick at $r < 10$ AU even for the lowest frequency ALMA band (3 mm).
- Going to $\lambda \sim 1$ cm allows to peer through the dust down to $r \sim 1$ AU.
- $\times$10VLA sensitivity would allow to have noise $\sim$ K at 10 mas resolution with integrations of a few hours, expected $T_B \sim 10^2 - 10^3$ K.

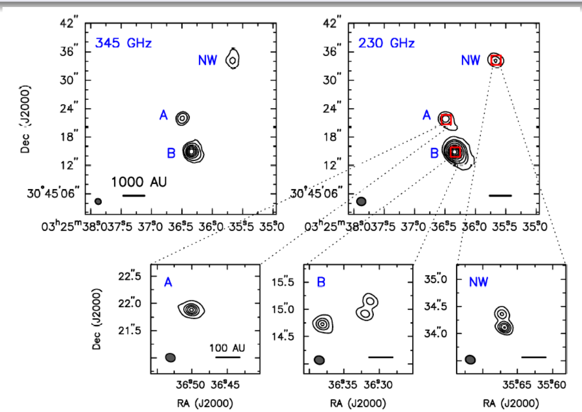
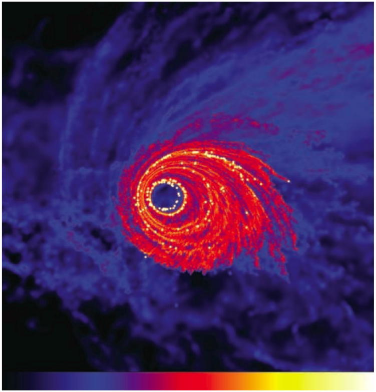


Fig: Multiplicity at $\sim$ 100 AU scales in protostars revealed by 0.1” VLA observations (Lee+2015).

STAR FORMATION AROUND THE GALACTIC CENTER

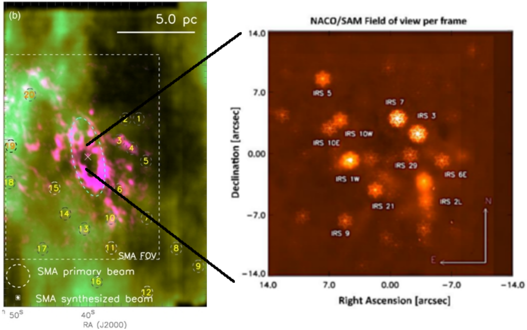
- Is star formation in the extreme environment of the inner 2-4 pc from the Galactic Center possible, and if yes, different from SF in the Galactic disk?
- 10 mas (80 AU) resolution can resolve cirmustellar disks/jets around Sgr A*.
- Coverage from few GHz to 50-100 GHz is needed to disentangle dust from free-free.



Simulation of SF around a supermassive black hole of $M_{\rm BH} = 3 \times 10^6\ M_\odot$ (Bonnel+Rice2008)

STAR FORMATION AROUND THE GALACTIC CENTER

- NGVLA can detect dust disks and radio jets in objects with masses down to T-Tauri.
- Proper motions of young stars can be observed and 3D orbits calculated, similar to what is done with stars using VLT and Keck.
- Objects in the inner arcsec like the G2 cloud ($S_{7\text{mm}} \sim 1\ \mu$Jy before synchrotron bow shock takes over) could be imaged and proper motions followed.



Left: Dense (green) and denser (magenta) molecular gas in the Circumnuclear Disk (CND) around Sgr A* (Liu+2013). Right: young massive stars in the inner parsec (Sánchez-Bermúdez+2014)

PLANET FORMATION

- Possibly the main driver for MW science.
- Previous generation of submm interferometers with resolution $\sim 0.3''$ (15 to 40 AU for nearest objects) was mostly sensitive to optically-thin dust emission.

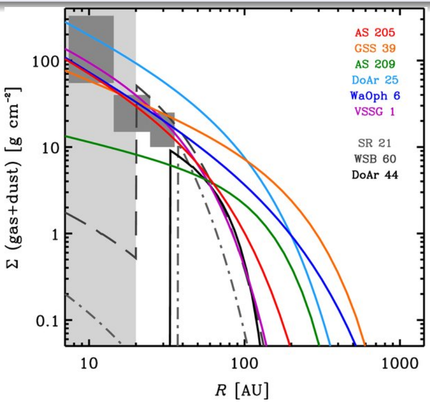


Fig: Surface density profiles for protoplanetary disks in the sample of Andrews+09. The SMA resolution roughly corresponds to $\tau = 1$ at 1 mm.

PLANET FORMATION

- ALMA with long baselines (resolution down to $\sim$ 25 mas, or 3.5 AU) is providing astonishing images of disks with signatures of planet formation.

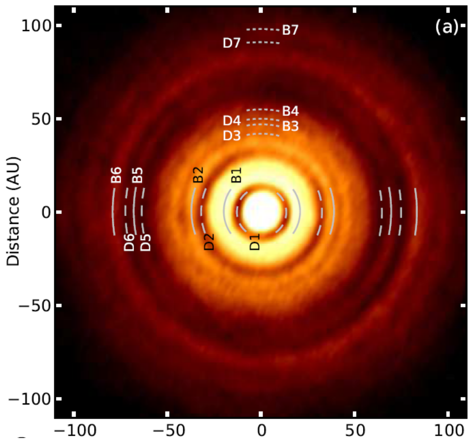


Fig: Deprojected ALMA 1 mm (B6+B7) image of the HL Tau disk (ALMA Partnership 2015).

PLANET FORMATION

- But the terrestrial planet-forming region ($r < 10$ AU) is opaque at all ALMA bands.
- For relatively massive disks like HL Tau even most of the disk is optically thick.

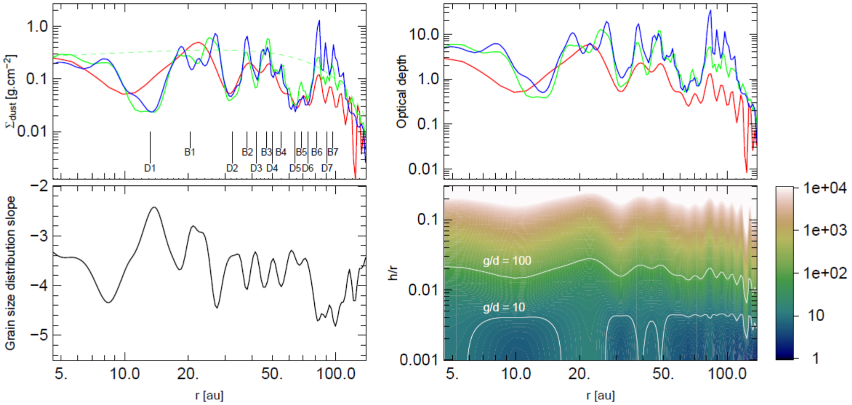


Fig: Results from radiative transfer modelling of the ALMA LBC maps of HL Tau (Pinte+15). Top-right panel shows that the disk is optically thick for $r < 50$ AU even at 3 mm (red line).

PLANET FORMATION

For the brightest disks such as HL Tau, the current VLA with integrations $\sim$ 15 hrs illustrates the need for a ngVLA to perform such studies in all disks:
- The entire disk is imaged in optically-thin dust emission.
- Unveiling grain growth across disk.
- Access to terrestrial-planet forming region ($r < 10$ AU.)

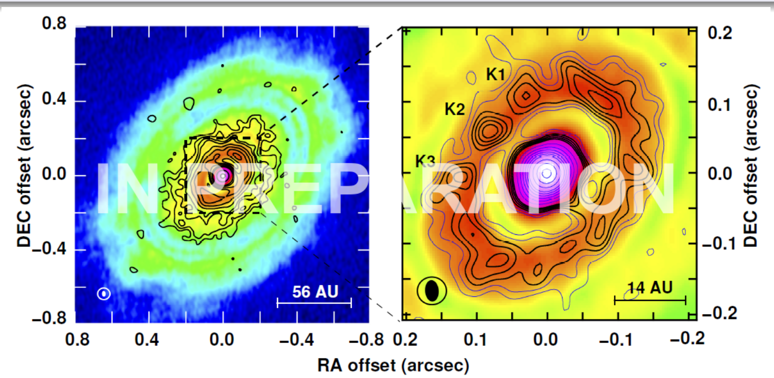


Fig: Deep (noise $\sim$ 3.5 to 7 μJy) VLA 7 mm images at resolutions of 10 (left) and 6 AU (right) of the HL Tau disk. Carrasco-González, Henning, Chandler et al., in prep.

DEBRIS DISKS

- Faint. Challenging for detection and imaging.
- ALMA is starting to do detailed mapping.
- The longer λ of the ngVLA gives a more direct probe of cm-sized bodies and collisional models.

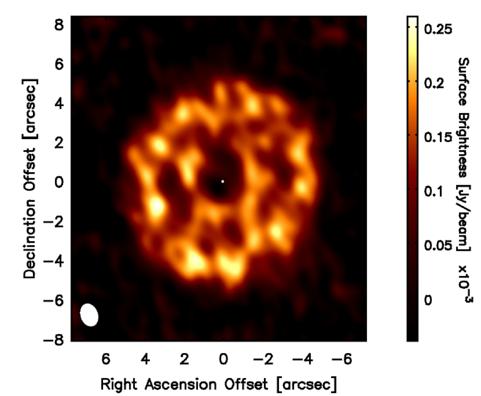


Fig: ALMA map at 1.3 mm of the debris disk HD 107146 (Ricci+2015).

CHEMISTRY OF STAR AND PLANET FORMATION

- Complex organic (including prebiotic) molecules are the building blocks of life.
- Warm sources are more easily detected in the submm, but line blending is a killer.
- For cold sources, $\lambda \sim 0.5$ to 1 cm may be ideal.

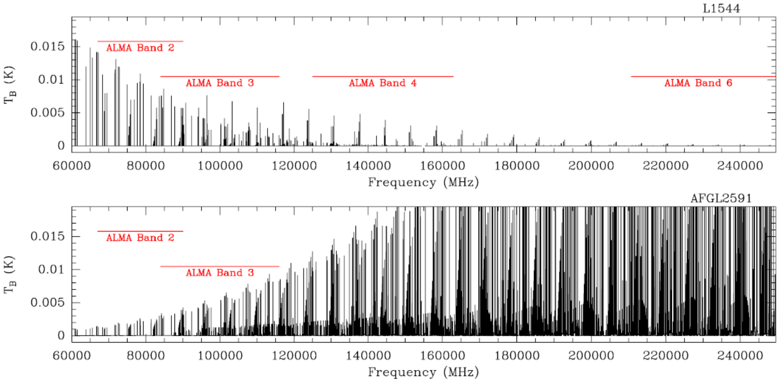


Fig: Simulations of the spectrum of Glycine (NH_2CH_2COOH) for a pre-stellar core (top) and a hot molecular core (bottom). Jiménez-Serra+2014.

CHEMISTRY OF STAR AND PLANET FORMATION

- But detecting simple (and complex!) organic molecules in protoplanetary disks is challenging.
- ALMA is enabling the detection of molecules such as CH_3CN, HCN, HC_3N in disks, showing that the rich organic chemistry of the Solar Nebula was not unique.
- A $\times$10VLA telescope would enable detection of low-E levels of CH_3CN to probe their formation, and T mapping through the $\sim$ 23 GHz NH_3 lines.

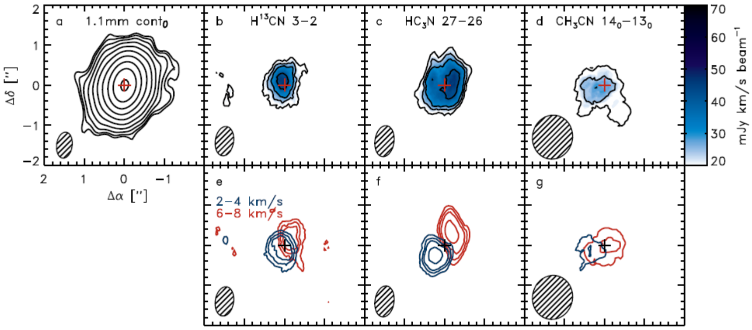


Fig: ALMA mapping of cyanides in the MWC 480 protoplanetary disk. Öberg+2015.

SOLAR SYSTEM: DEEP ATMOSPHERIC MAPPING

- Unknown whether clouds and storms in giant planets extend deep in atmosphere.
- cm observations can probe to tens of bars in Saturn, Uranus, and Neptune (IR and optical only probe to 1 bar).
- ngVLA angular resolution allows to image small-scale atmospheric structures (disk sizes of Uranus and Neptune are 3.6" and 2.2").
- High sensitivity for instantaneous imaging required because rotation periods $\sim$ 10 hr.

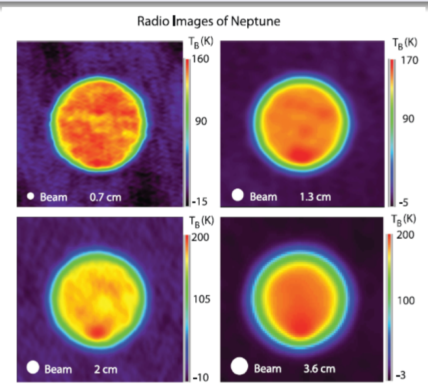


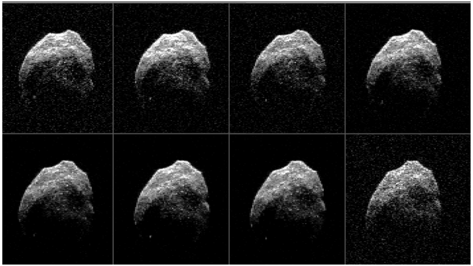
Fig: VLA mapping of Neptune. de Pater+2014.

SOLAR SYSTEM: THE NGVLA AS A RADAR

- The ngVLA could be used as the receiver for bistatic radar observations.
- Sensitivity would expand volume over which potentially dangerous asteroids are probed.

NEWS | NOVEMBER 3, 2015

Radar Images Provide New Details on Halloween Asteroid



Asteroid 2015 TB145 is depicted in eight individual radar images collected on Oct. 31, 2015 between 5:55 a.m. PDT (8:55 a.m. EDT) and 6:08 a.m. PDT (9:08 a.m. EDT). Image Credit: NASA/JPL-Caltech/GSSR/NRAO/AUI/NSF

Fig: Radar mapping of asteroid 2015 TB145. DSS-14 at Goldstone was used as transmitted and GBT as receiver.

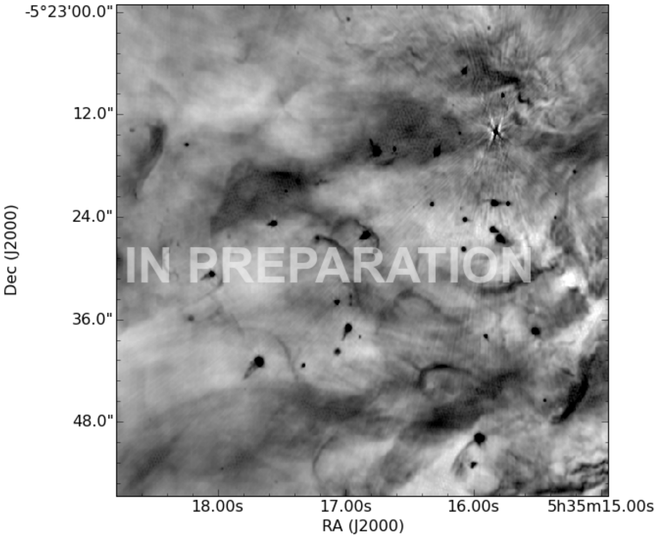


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Image courtesy of Jan Forbrich

Table 2: Technical requirements of the ngVLA "Cradle of Life" science cases

(1) Science case	(2)	(3) Frequency (GHz)	(4) Sensitivity (μJy bm^{-1})	(5) Angular res. (mas)	(6) Max. Ang. Scale ($''$)	(7) Vel. res. (km/sec)
§ 2.1 **HII regions & high-mass jets**	cont	10–50	1-10	5–20	5	—
§ 2.1 **HII regions & high-mass jets**	line	40–100	1	20	5	1
§ 2.2 Infall via spectral line absorption	line	18–40	100 K	20	10	1
§ 2.3 Polarization in star-cluster-forming cores	cont	40–50	—	5–100	5	—
§ 2.4 Star formation in the galactic center	cont	20–70	0.1	10–20	2	—
§ 3.1 **Binary/multiple protostars**	cont	10–30	1–10 K	20	< 1	—
§ 3.2 Dust polarization	cont	20–50	1	100–3000	< 5	—
§ 3.3 Structure of protostellar jets	cont	4–30	0.5	20–150	10	—
§ 4.1 **Mapping planet formation**	cont	10-50	1 K	1–10	<5	—
§ 4.2 **Probing dust/pebble distribution in disks**	cont	10–50	1 K	1–50	<5	—
§ 5.1 Complex molecules in hot cores	line	18–50	0.15 K	20–100	<5	0.1–0.5
§ 5.2 **Chemistry (NH_3) of planet-forming regions**	line	10–40	1K	20–5000	<5	0.1-1
§ 6.1 Debris disks	cont	10–100	0.1	1000–5000	50	—
§ 7.1 **Deep atmospheric mapping**	cont	1–50	—	<0.5	50	—
§ 7.2 (Sub)surface thermal emission	cont	10–50	—	<0.05	8	—
§ 7.3 (Sub)surface structure using bistatic radar	cont	2–8	—	<0.05	1	—
§ 7.4 Comet chemistry	line	22–24	—	<0.5	300	<0.2
§ 7.5 Planetary rings	cont	10–50	—	—	120	—
§ 7.6 Jupiter synchrotron emission	cont	10–50	—	—	200	—
§ 8.1 SETI	line	5–100	$>5\times$ JVLA	—	0.5 deg^2 FOV	0.1 Hz

Table 2: Technical requirements for each of the ngVLA science cases presented by the "Cradle of Life" working group. Key Science Projects (KSPs) are in bold.