VLA Observations of Solar System Bodies

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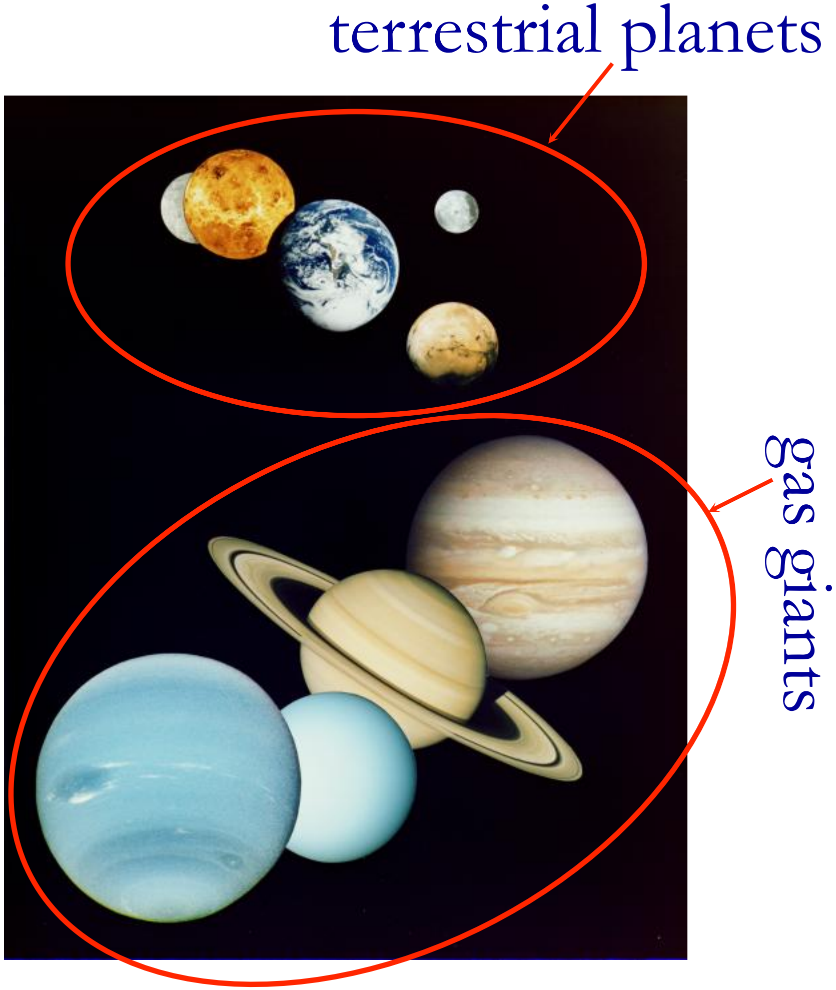
Introduction

Understanding our own solar system and its bodies is important for understanding planet formation in general. Using "radio" wavelengths (from meter to submm) is a powerful way of doing this, since unique information on the physical state of the surface, subsurface and atmospheres of objects in the solar system results from such observations.

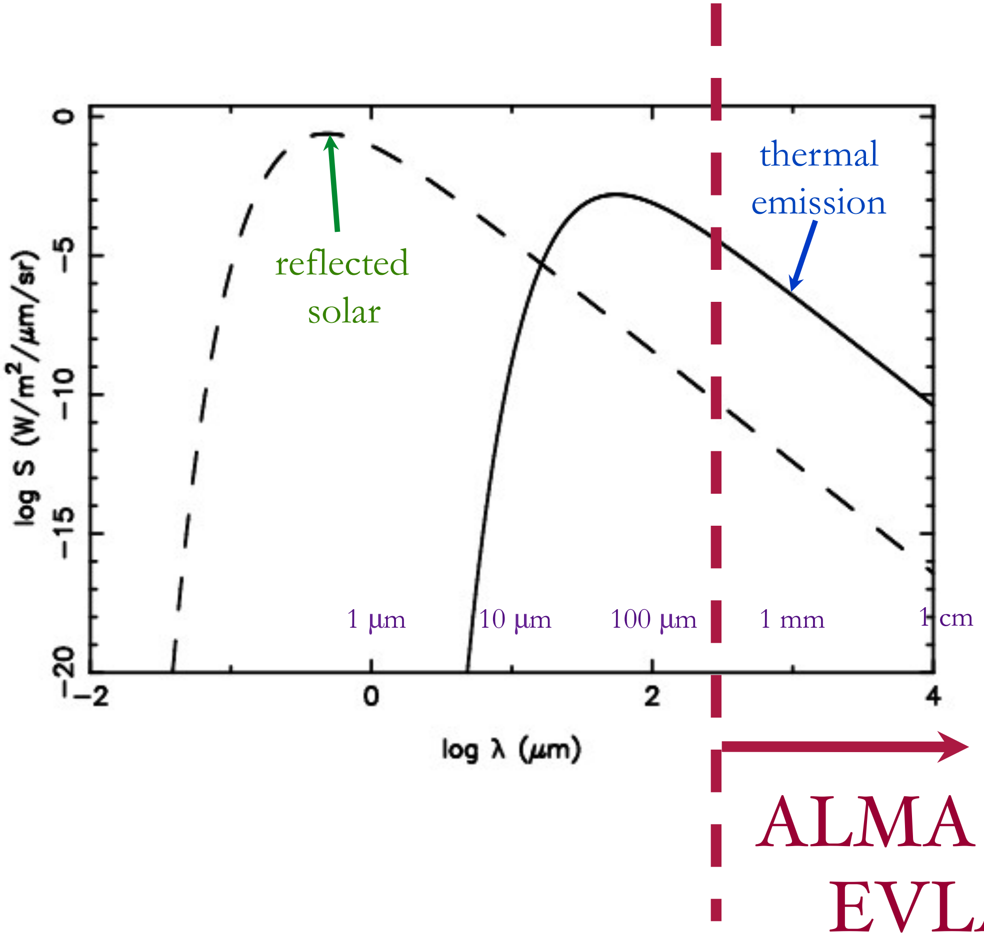


Why long wavelengths?

- Deep probe (depth ~10λ; ~mbars – 100's of bars)
- Relatively accurate diameters
- Accurate astrometry
- Potential to resolve bodies
- Simple spectroscopy (isolated transitions)
- Observe any time of day

Why long wavelengths?

Spectrum of a body at 30 AU, albedo=0.1, emissivity=0.95



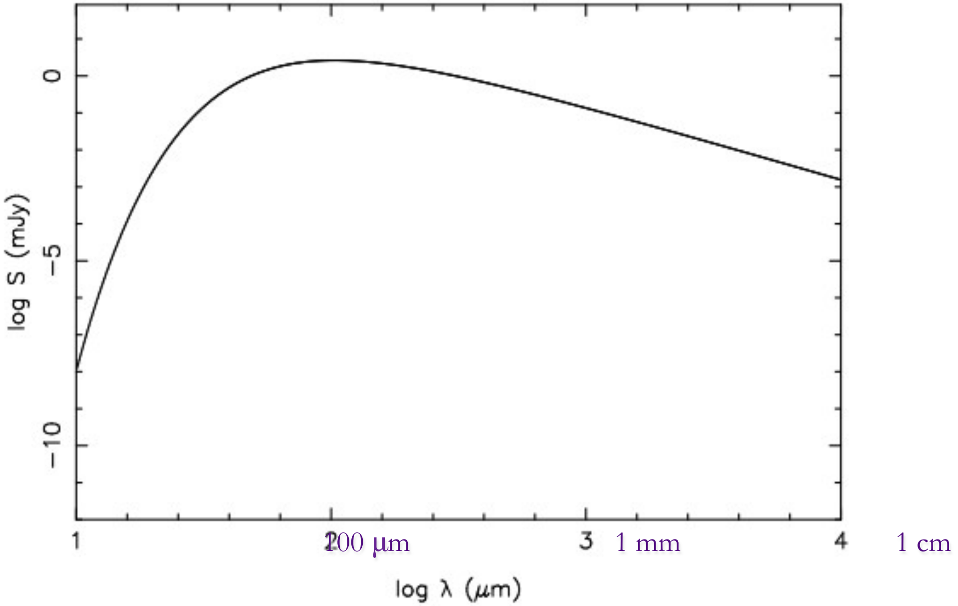
ALMA and EVLA

But, the emission is so weak!

Expected flux density for a body in thermal equilibrium is roughly:

$$F_\lambda \sim \frac{2k(T_b - T_{bg})}{\lambda^2}\frac{\pi R^2}{D^2} \qquad T_b = \varepsilon T_e \sim \varepsilon\kappa\left[\frac{F(1-A)}{\sigma}\right]^{1/4}$$

- 200 km diameter body at 35 AU (TNO) or 40 m diameter body at 0.02 AU (NEA)
- Need mJy to µJy sensitivity
- Beyond (or right at the edge of) capability of previous mm and cm telescopes



The EVLA Project – Improving the VLA

The VLA was the world's most powerful radio wavelength interferometer, but was designed and built in the 1960's/70's, and completed in 1980 - the dark ages relative to "modern" electronics! But the infrastructure (antennas, rails, buildings, etc…) are sound. The EVLA construction project modernized the VLA. The project concluded at the end of 2012 and we are now in regular VLA operations again.

Specifically, the EVLA project upgraded:

- Front Ends (feeds + Rx)
- LO/IF system
- Data transmission
- Correlator (WIDAR)
- Software

The main result for continuum observing is increased sensitivity (a few μJy in 1 hour at most frequencies).

VLA for our Solar System

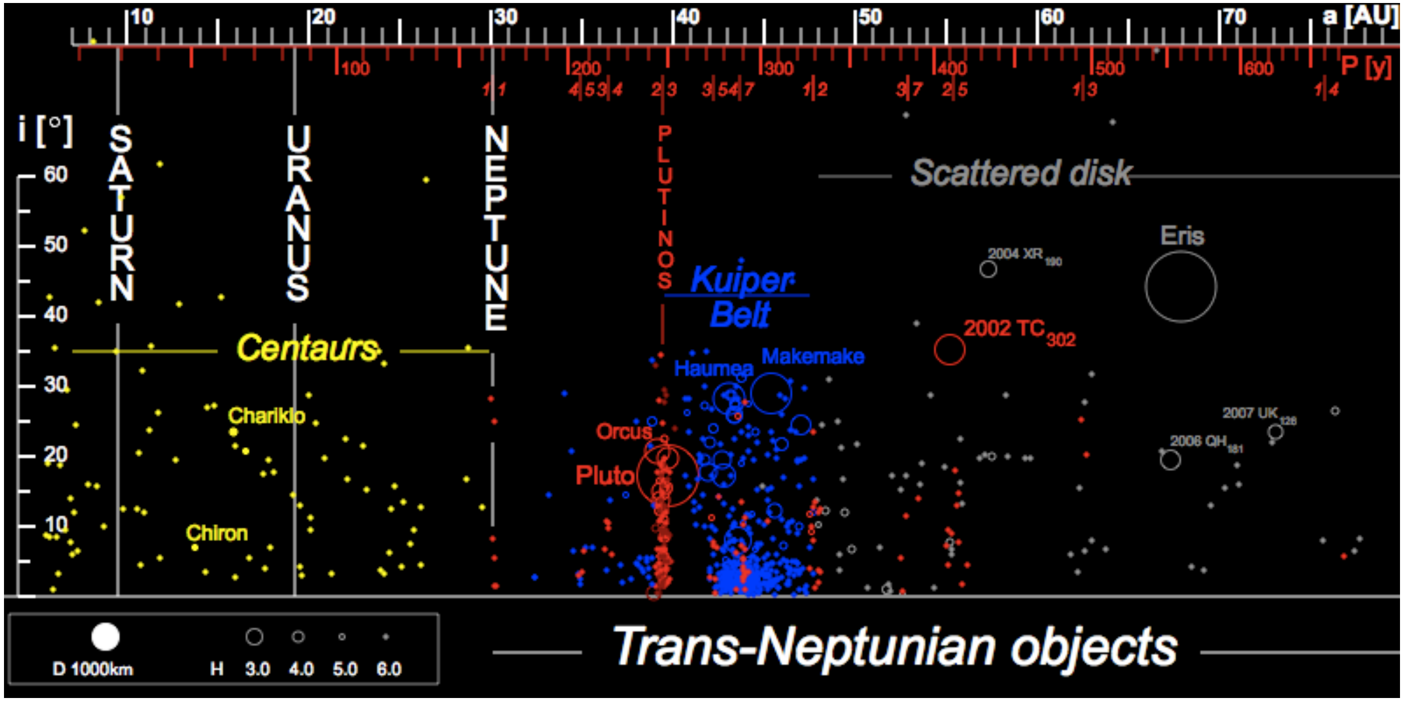
The VLA is a fantastic telescope for observing solar system bodies. Nearly every class of body, from largest to smallest, can be observed, yielding more information than was previously available.

Of course the power of the VLA is when used in combination with other telescopes, notably ALMA (spacecraft as well, including landed missions, sample returns, and manned missions!).

I only have time for two examples – there are many more.

Trans-Neptunian Objects (TNOs)

- Bodies with orbital semi-major axes > Neptune; includes Pluto, Charon, large KBOs (Quaoar, Orcus, et al.), the scattered disk, Plutinos, Centaurs, etc.



Trans-Neptunian Objects (TNOs)

Orbits are well-constrained for most, but other fundamental properties are not. For instance:

- Sizes uncertain to at least 10's of percent, because they rely on thermal IR observations plus an albedo measurement, and additional thermal modelling, except for the largest few (note that this has changed in the past few years with the Herschel "TNO's are Cool" program, which has measured the sizes of some 10's of TNOs – but see later note)
- Surface composition limited by low-SNR spectra; only reliably done on the largest of the KBOs, others rely on broadband colors

The larger of these bodies can be easily detected by ALMA, and less easily detected by VLA. In fact, ALMA can detect most known TNOs with a modest amount of observing time.

TNOs – Pluto/Charon

Pluto has been detected and resolved from Charon already with the SMA (work of Mark Gurwell, Arielle Moullet and myself).

Measured flux densities:

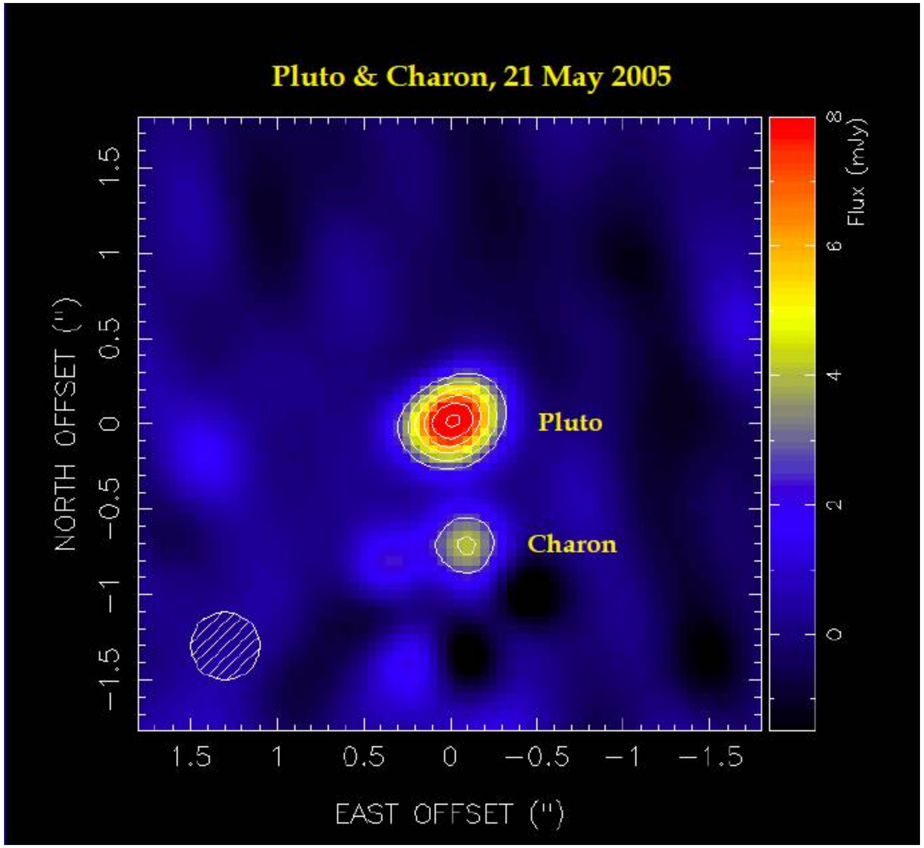
- Pluto – 9.8 ± 0.6 mJy
- Charon – 3.7 ± 0.6 mJy

Deduced brightness temperatures:

- Pluto – 37 ± 2.3 K
- Charon – 49 ± 8 K

Which tells us about surface composition…

VLA tells us about deeper conditions, and ALMA can do much better at these wavelengths because of the increased sensitivity.

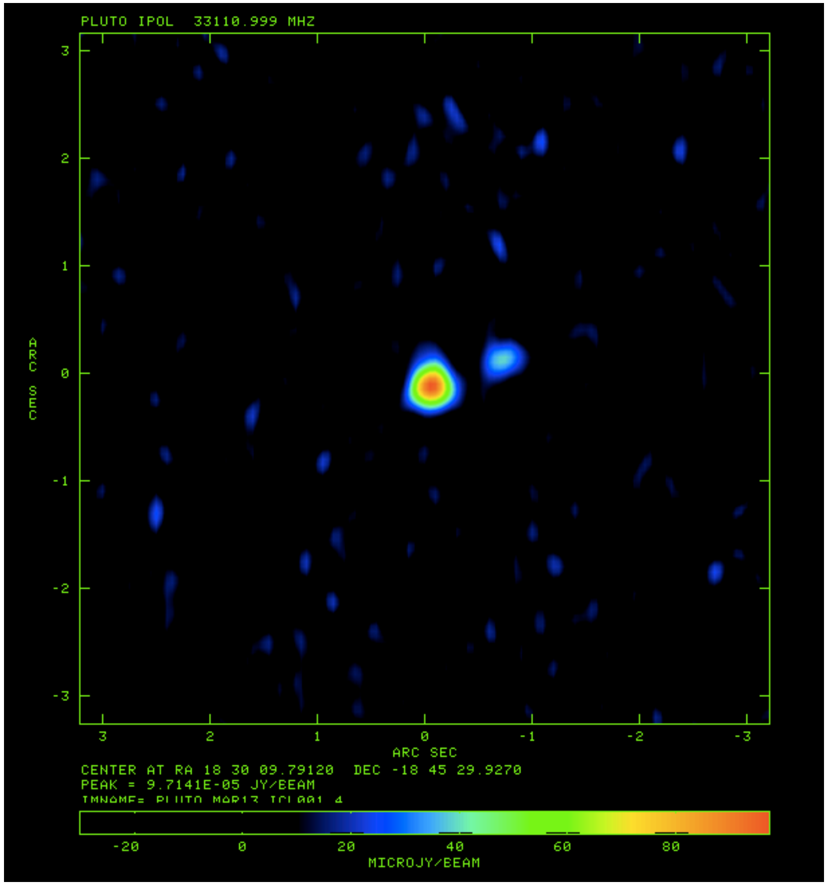


Gurwell et al. 2011

TNOs – Pluto/Charon

Pluto has also been detected and resolved from Charon with the VLA at 1 cm wavelength (work of myself, Mark Gurwell and Arielle Moullet).

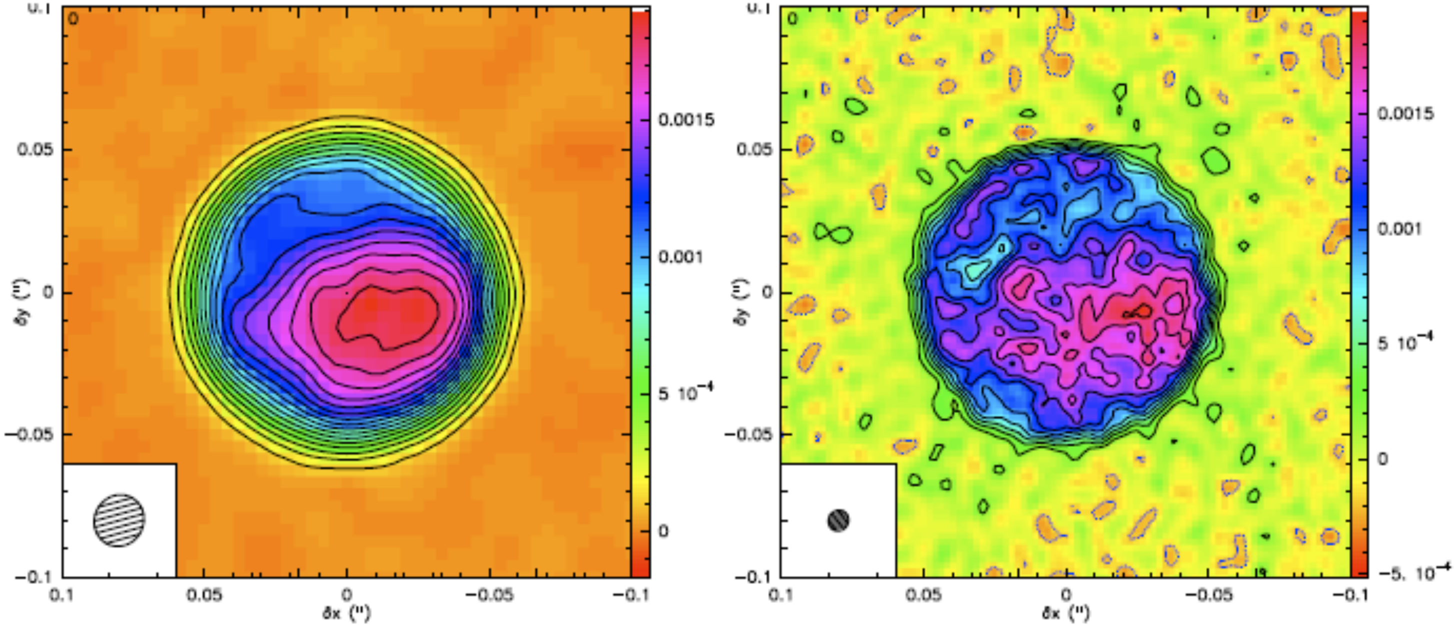
The measured brightness temperatures are consistent with the earlier SMA observations, but with much higher SNR (> 50).



Butler et al. 2011

What ALMA can do observing Pluto

ALMA will be able to make high-SNR resolved images of Pluto, and barely resolve Charon.

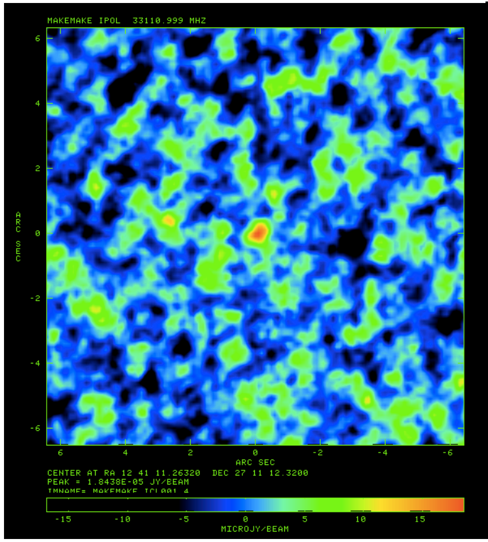


Simulation with 4 hours, 4 km baselines, 350 GHz (left), 850 GHz (right), from A. Moullet

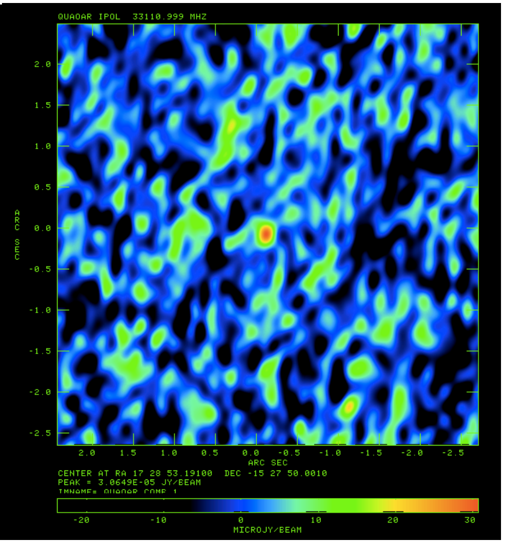
More TNOs with VLA

The VLA has also been used to observe the TNOs Makemake, Quaoar, and 2002 TC_{302}.

Noise is a few μJy on each – detections of ~5 sigma…



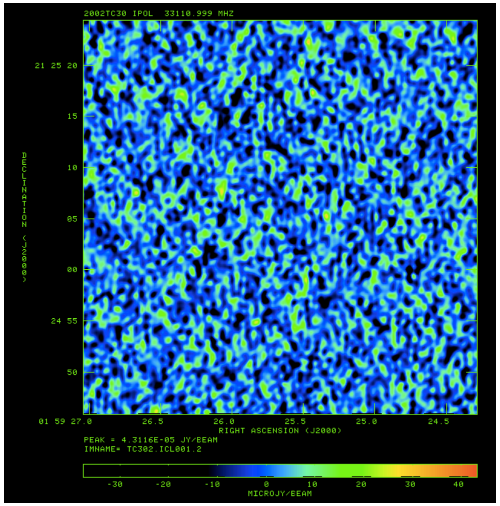
Makemake



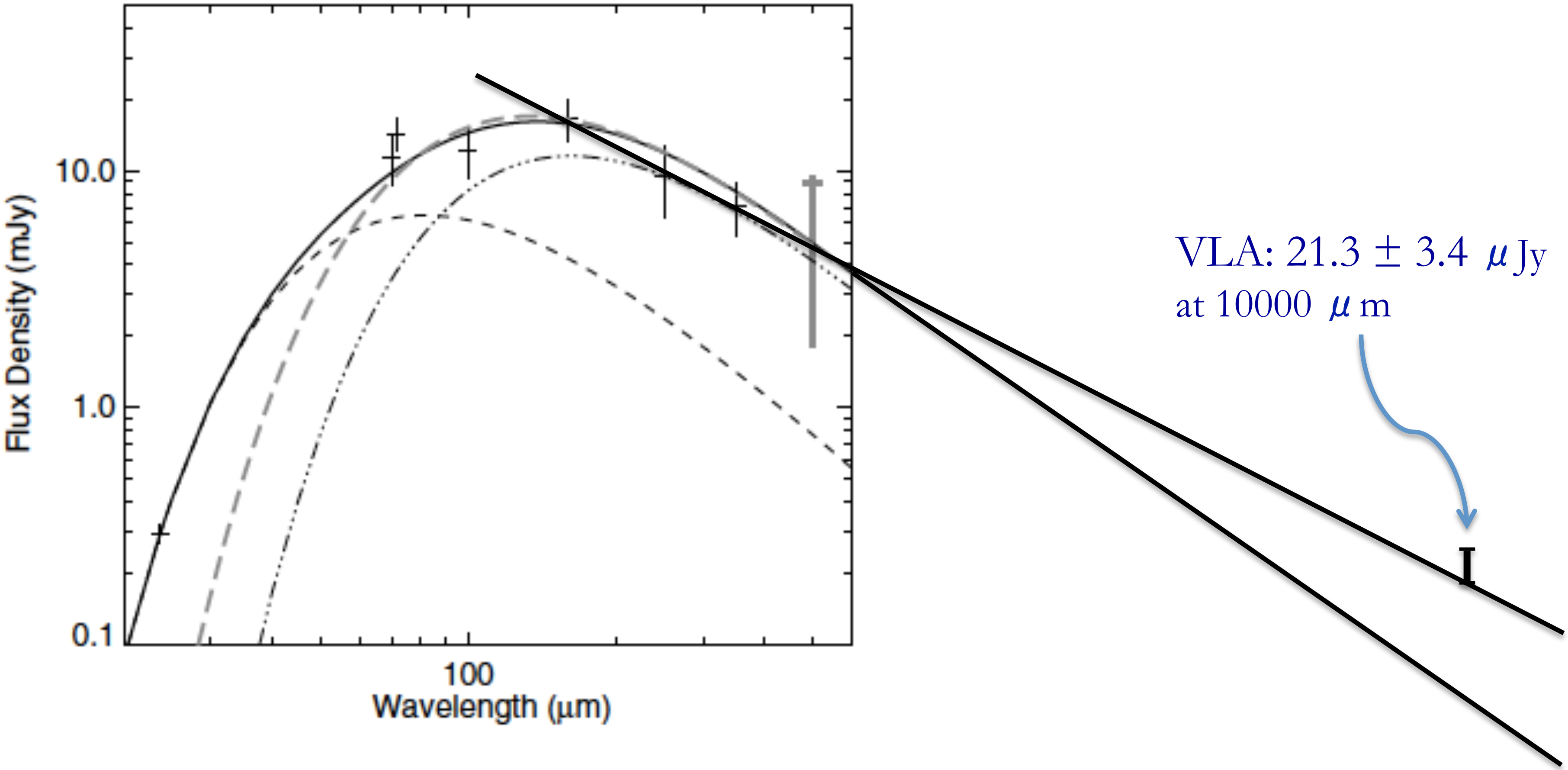
Quaoar

Butler et al. 2011

2002 TC_{302}



Makemake – why Herschel isn't enough



VLA: 21.3 ± 3.4 μJy
at 10000 μm

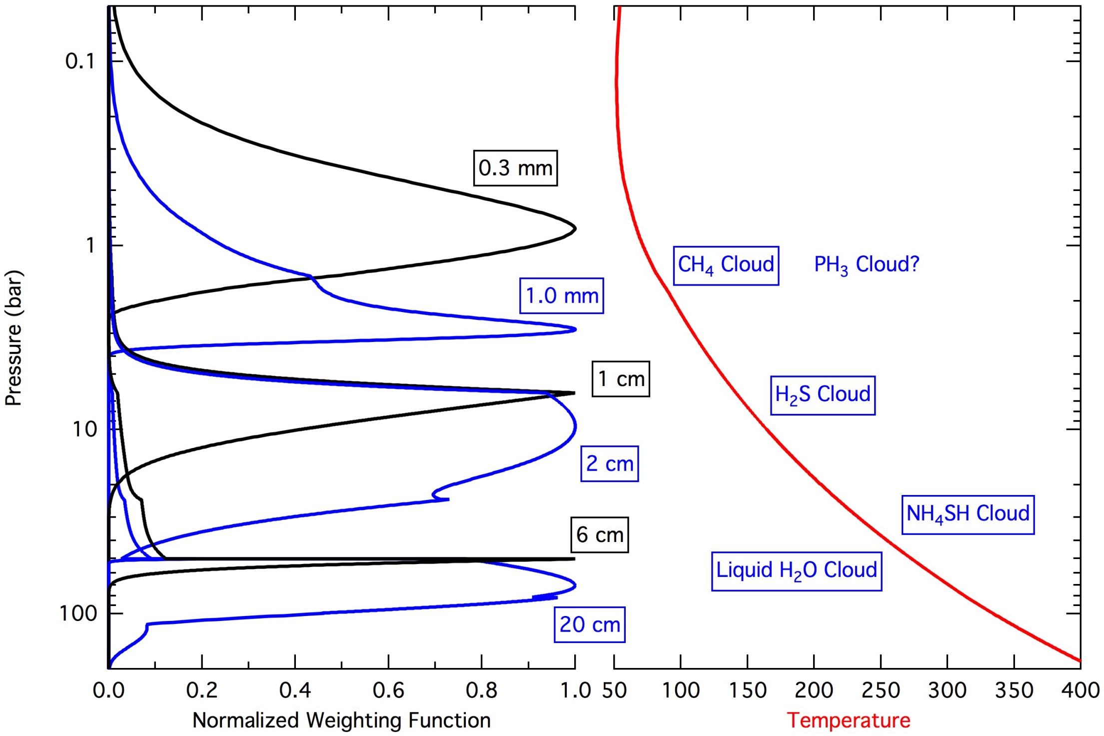
Modified from Lim et al. 2011

Uranus & Neptune

- Understanding the ice giant planets is becoming more and more apparent with the discovery of so many Kepler Ice Giant planets.
- We must understand not only the upper atmospheres, but also the lower atmospheres (down to 10's of bars) to fully qualify the properties of these bodies.
- Understanding the similarities and differences between Uranus and Neptune currently is important in understanding their formation and evolution, and forms an important part of the study of these two bodies.

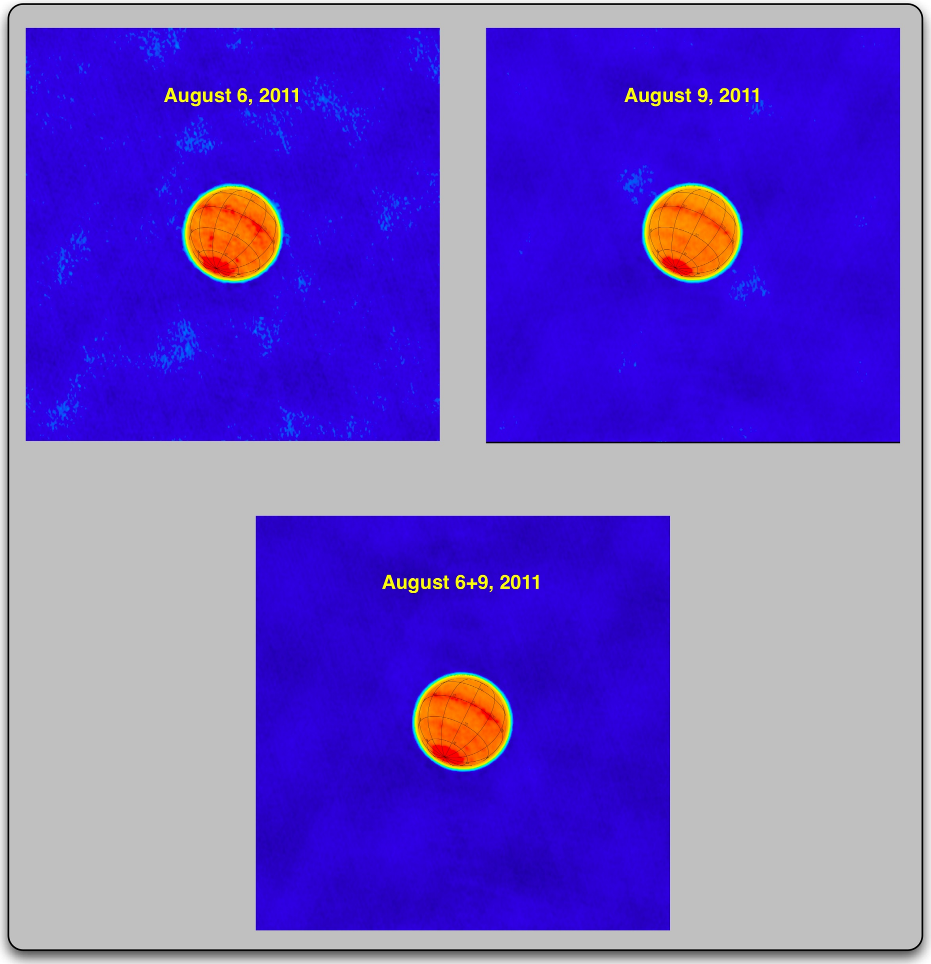
Radio wavelength weighting functions

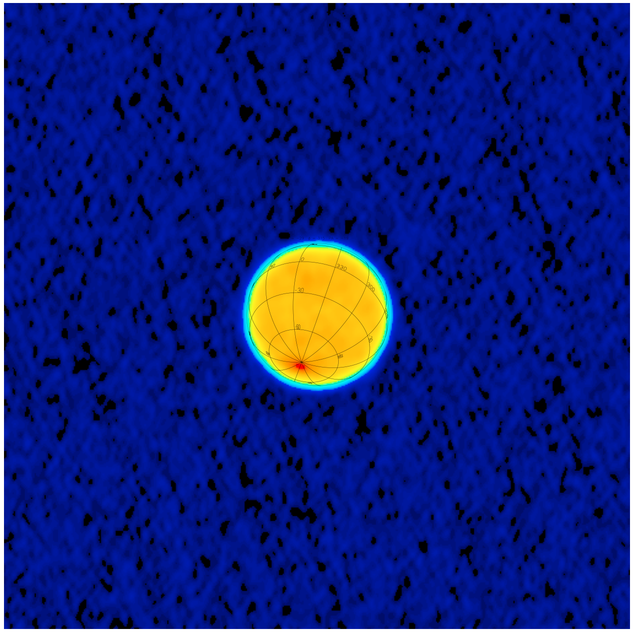
Radio wavelengths probe the atmospheres of the giant planets from a few tenths of a bar to 10's of bars



VLA observations of Neptune

Images from VLA data at 1 cm (August, 2011).

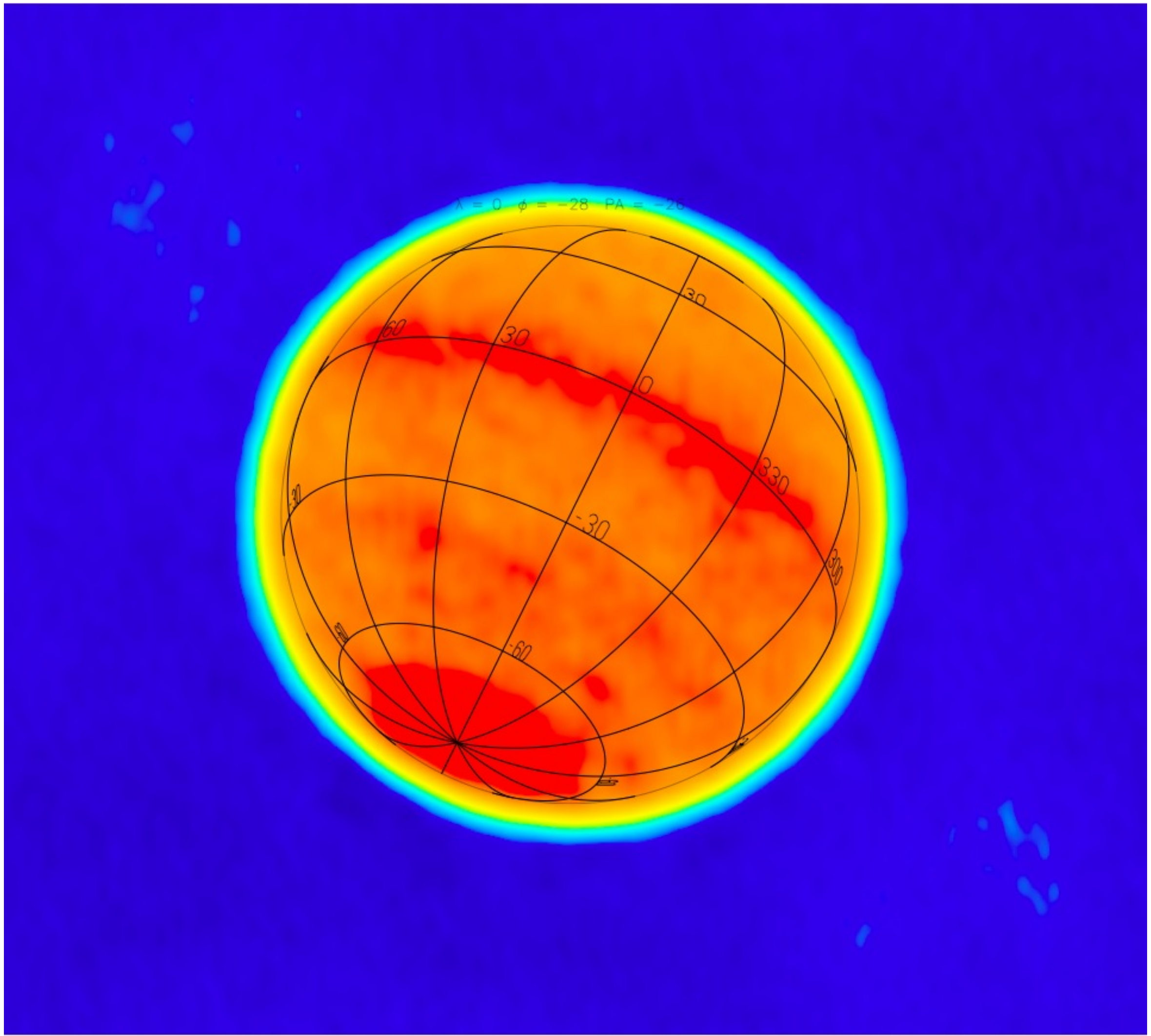




This is older VLA data from 22 GHz taken by us in 2006; demonstrating how much more sensitive the VLA is after its upgrade.

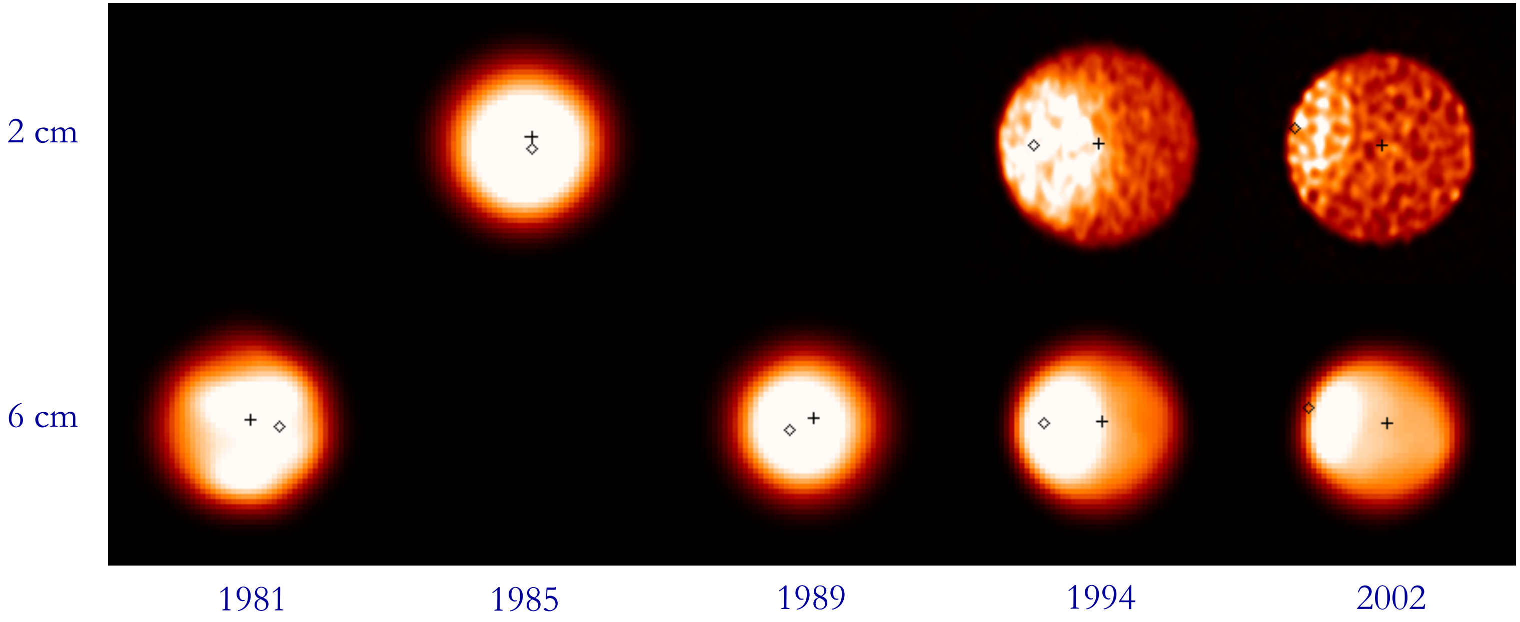
VLA observations of Neptune

The combined image, enlarged. Note brightness enhancements at the south pole, equator, and mid-southern latitudes. South polar enhancements have been seen before at both radio and thermal infrared wavelengths (Martin et al. 2008; Hesman et al. 2009; Orton et al. 2012), but equatorial and mid-latitude enhancements have not been seen before.



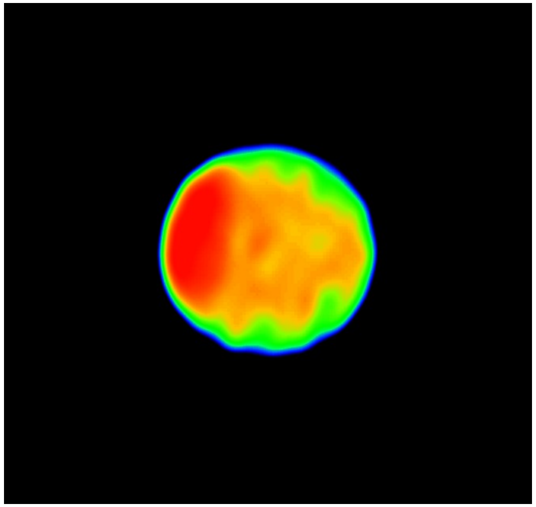
VLA observations of Uranus

We've been observing Uranus with the VLA since the early-1980's, and with the SMA for the past 5 years or so. These observations are a fantastic probe of structure in depth, location, and time.

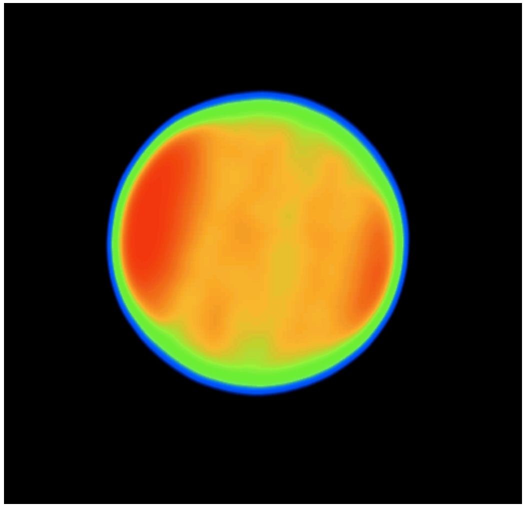


Hofstadter & Butler 2003

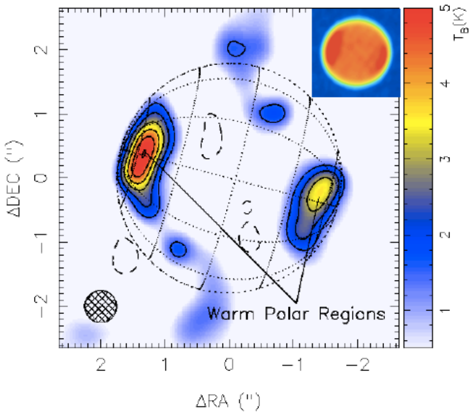
VLA observations of Uranus



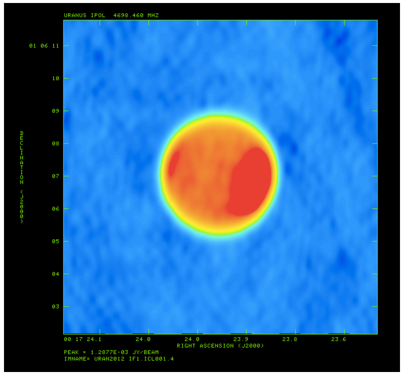
2003 6 cm



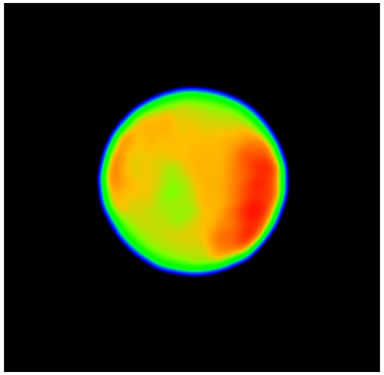
2005 1.3 cm



2006 1.4 mm (residual)



2012 6 cm



2012 2 cm

We'd like to use ALMA to constrain H_2S and PH_3 abundances and structure.

Summary

- The VLA is a revolutionary telescope for solar system observations
- Its power is only fully realized when used with other high-resolution, high-sensitivity telescopes (notably ALMA)
- Such observations can be used to constrain the properties of every class of solar system body, from the smallest (NEAs, TNOs, etc.) to the largest (giant planets and even the Sun) and everything between
- Properties from those as simple as size (and hence potentially density), to orbits, to surface/subsurface and atmospheric compositions and temperatures, to wind characteristics can be constrained, and observations over time can yield clues as to longer-term climate conditions