# Observations of Solar System Bodies with the VLA and ALMA

Bryan Butler

National Radio Astronomy Observatory

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

NRAO

# Introduction

Unique information on the physical state of the surface and subsurface of objects in the solar system results from observations at "radio" wavelengths (from meter to submm wavelengths). Notably, these wavelengths probe to depths unseen at other wavelengths.

# Introduction

Specifically, information can be obtained on:

- spin/orbit state
- surface and subsurface properties
- atmospheric properties
- magnetospheric properties
- ring properties

Types of radiation:

- thermal emission
- reflected emission (radar or other)
- synchrotron or gyro-cyclotron emission
- occultations (natural or spacecraft)

# Telescopes

There are many radio-wavelength telescopes across the world that can do wonderful observations of solar system objects. I will concentrate here on what I consider to be the most powerful: the **Atacama Large Millimeter and Submillimeter Array** (ALMA, for submm-mm wavelengths); and the **Very Large Array** (VLA, for mm-m wavelengths). The reason to focus on these two is their combination of sensitivity and resolution, which is unmatched by other telescopes.

# ALMA

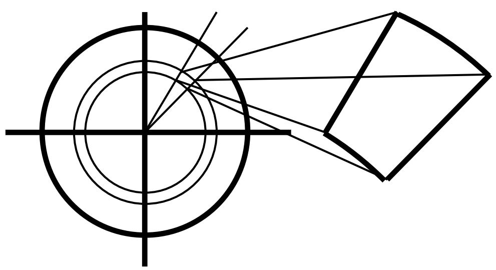
- Wavelengths from 350 μm to 3 mm.
- Large collecting area – 50 X 12-m dishes eventually (~35 currently available typically).
- Low-noise receivers.
- High Chilean Andes, so great submm-mm site.

# VLA

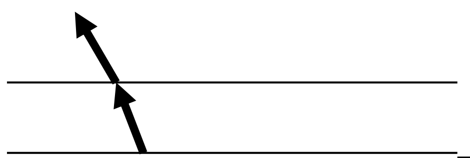
- Wavelengths from 6 mm to 4 m.
- Large collecting area – 27 X 25-m dishes.
- Low-noise receivers.
- Desert southwest, so great mm-cm site.

# Physics of solar system observations

$$S_\nu = \frac{2k}{\lambda^2}\frac{1}{D^2}\int_{beam} A(x,y)\, T_B^{pol}(x,y)\, dx\, dy$$



$$S_\nu = \frac{2k}{\lambda^2}\frac{2\pi R^2}{D^2}\int_{r=0}^{1} A(r)\, T_B^{pol}(r)\, r\, dr$$



$$T_B^{pol} = \left(1 - R^{pol}\right)\int_0^\infty k(z)\sec\theta_i\, T(z)\, e^{-\int_0^z k(z)\sec\theta_i\, dz}\, dz$$

$$R^{pol} = |\, r_{pol}\,|^2$$

$$r_s = \frac{\cos\theta_i - \sqrt{\varepsilon - \sin^2\theta_i}}{\cos\theta_i + \sqrt{\varepsilon - \sin^2\theta_i}}$$

$$r_p = \frac{-\varepsilon\cos\theta_i + \sqrt{\varepsilon - \sin^2\theta_i}}{\varepsilon\cos\theta_i + \sqrt{\varepsilon - \sin^2\theta_i}}$$

$$k = \frac{2\pi\nu}{c}\sqrt{\varepsilon}\,\tan\Delta$$

$$\varepsilon = \varepsilon_0\left(1 - \frac{3P\left(\varepsilon_0 - 1\right)}{P\left(\varepsilon_0 - 1\right) + 2\varepsilon_0 + 1}\right)$$

$$P = 1 - \varrho / \varrho_0$$

$$\frac{\partial}{\partial z}\left(K(z,T)\frac{\partial T}{\partial z}\right) = \rho(z)\, c_p(z,T)\frac{\partial T}{\partial t}$$

$$\left.\frac{\partial T}{\partial z}\right|_d = -\frac{J_0}{K_d}$$

$$\left(\frac{L_0}{4\pi D^2}\right)(1 - A_b)\sin^+\theta_i - J_0 = \varepsilon_{IR}\,\sigma_B\, T_s^4 - K_s\left.\frac{\partial T}{\partial z}\right|_s$$

$$K(z,T) = A + BT^3(z)$$

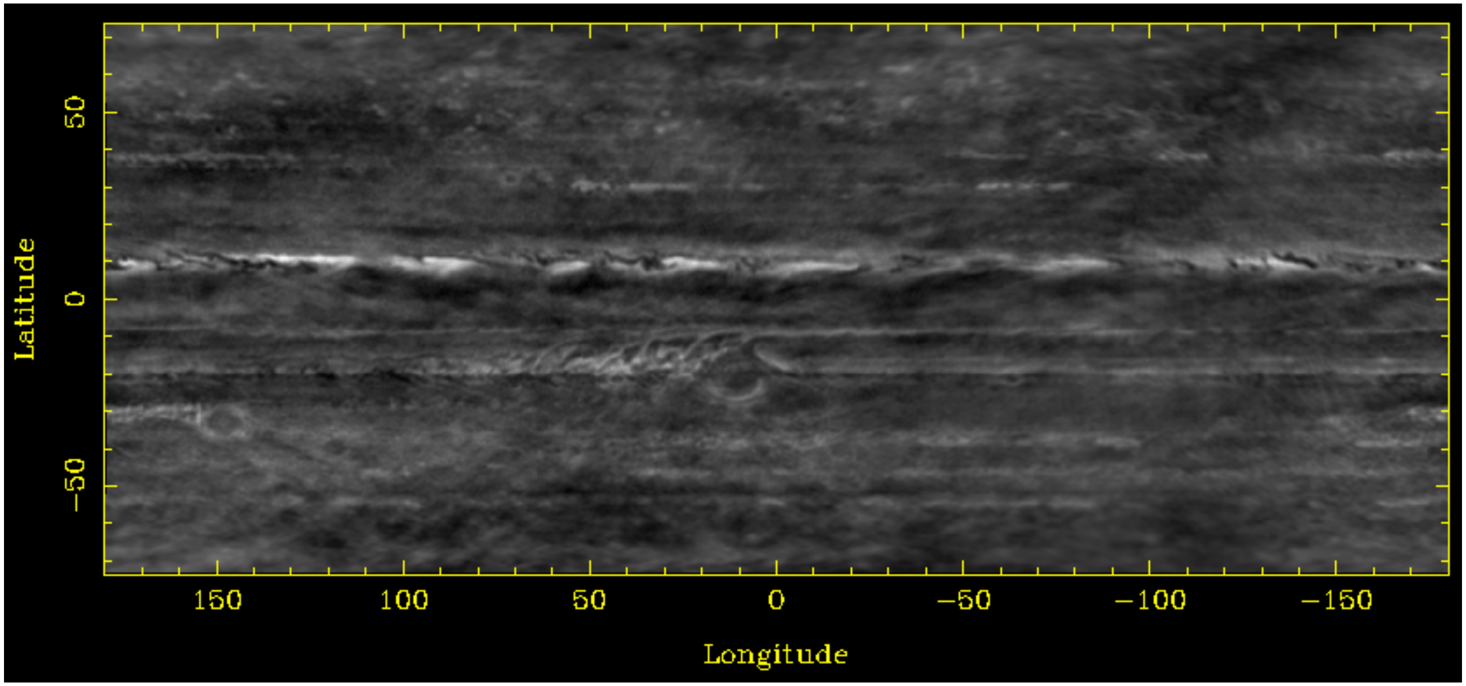
$$c_p(z,T) = T(z) / 2000$$

$$\ell_T = \sqrt{\frac{\omega\rho c_p}{2k}}$$

$$\ell_R = \frac{\lambda}{2\pi\sqrt{\varepsilon}\tan\Delta}$$

# VLA observations of Jupiter

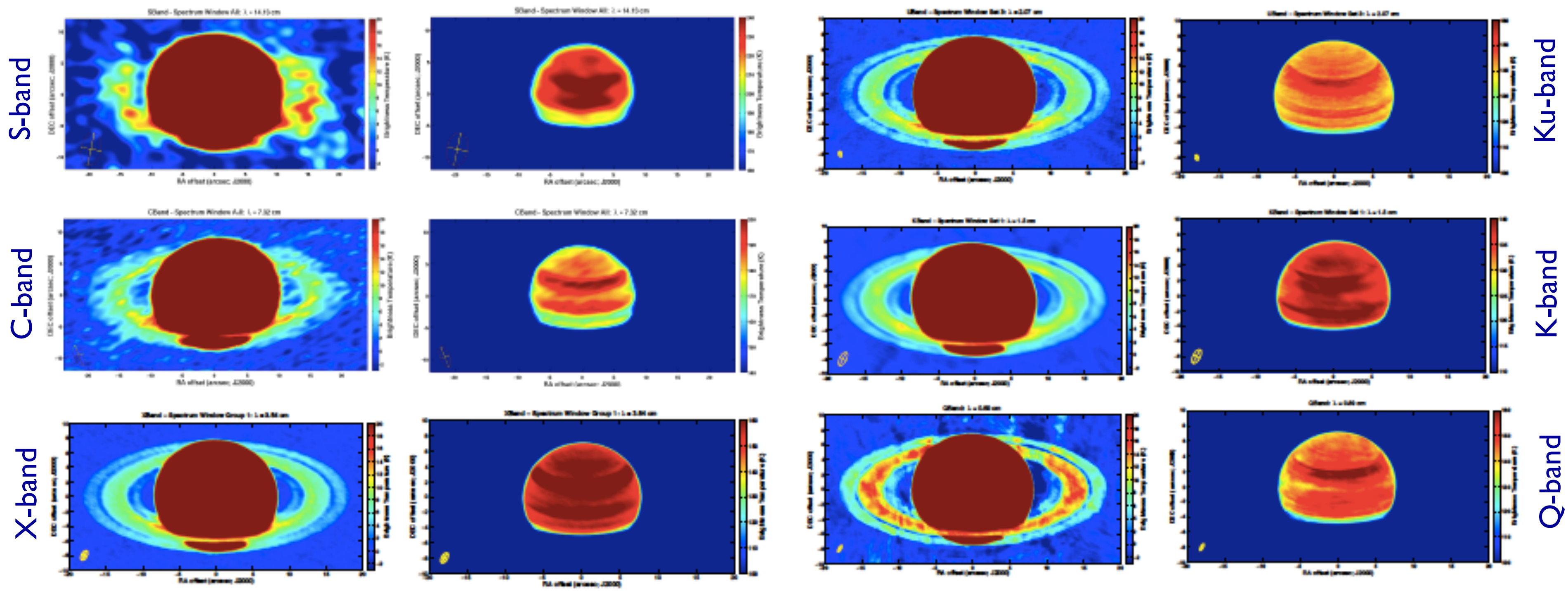
Jupiter rotates rapidly, but Bob Sault has developed a technique to "deproject" the visibilities (Sault+ 2006) into cartographic coordinates. In 2013 and 2014, two groups used this technique to make fantastic images of the planet, deriving abundances, temperature, and wind parameters.




de Pater+ 2016; Cosentino+ 2017

# VLA observations of Saturn

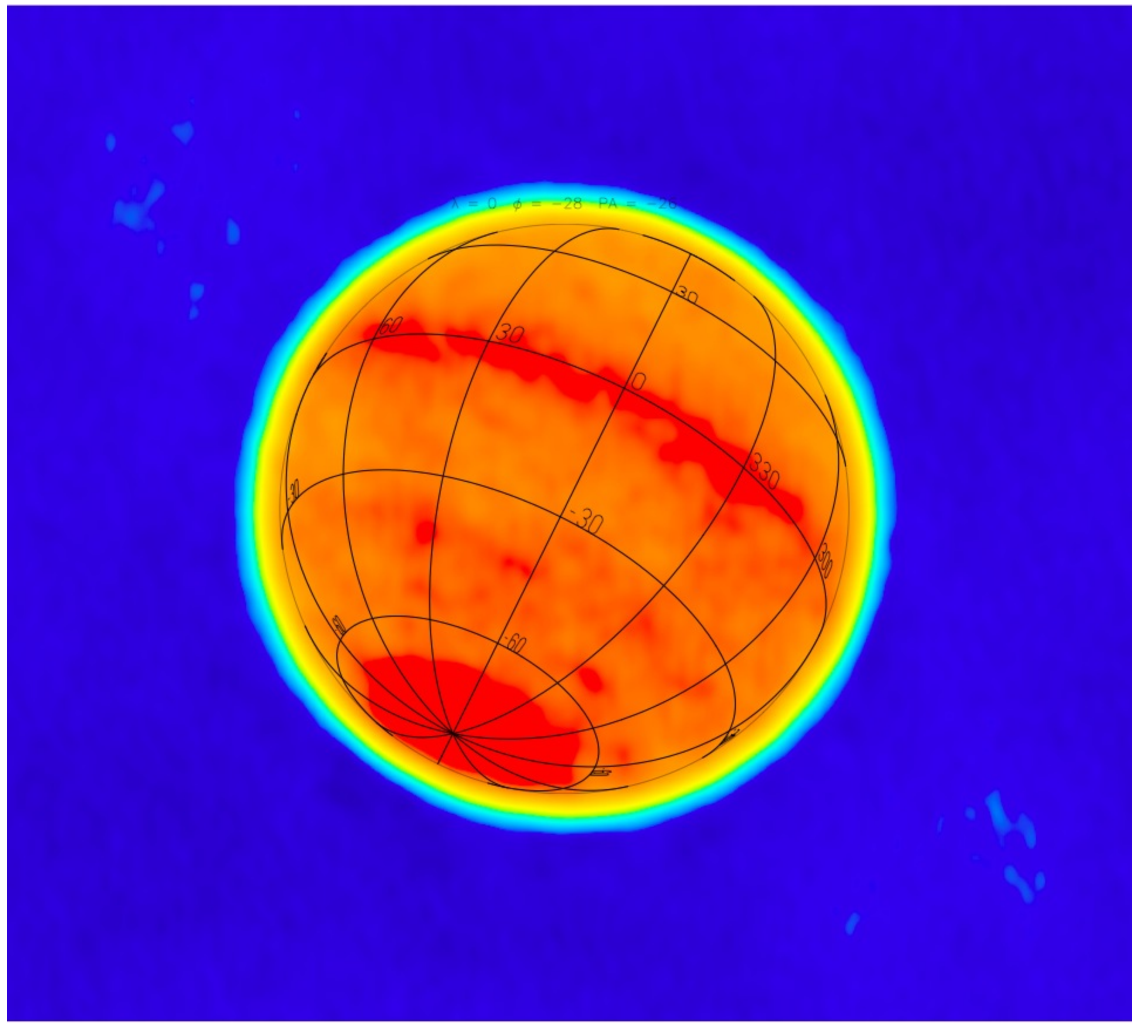
Observations of Saturn were taken in 2015, to determine ring and atmosphere properties.




**Zhang+ 2017**

# VLA observations of Neptune

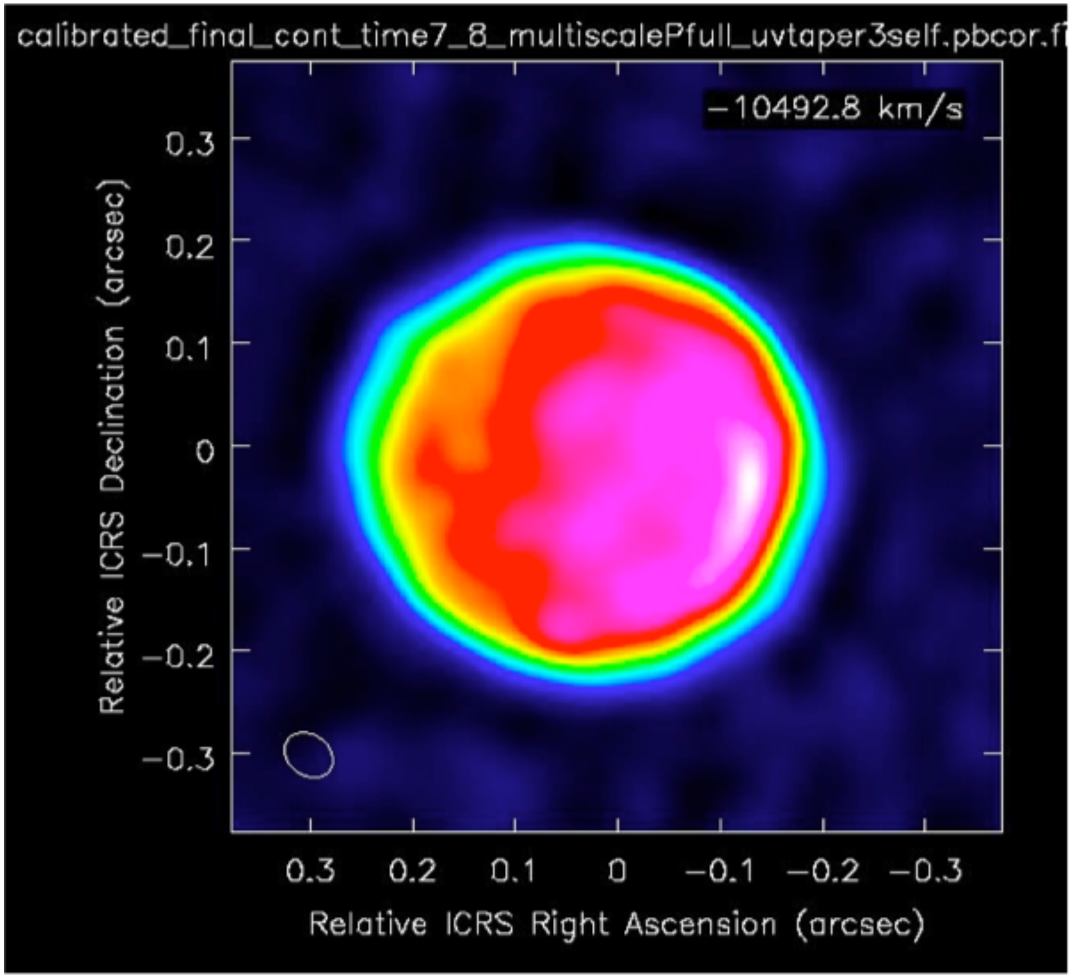
Observations of Neptune were taken in 2011. A combined image from two days is shown at right. More data has been taken (in 2016), which will have Bob Sault's deprojection technique applied.




**Butler+ 2013**

# ALMA observations of Ceres

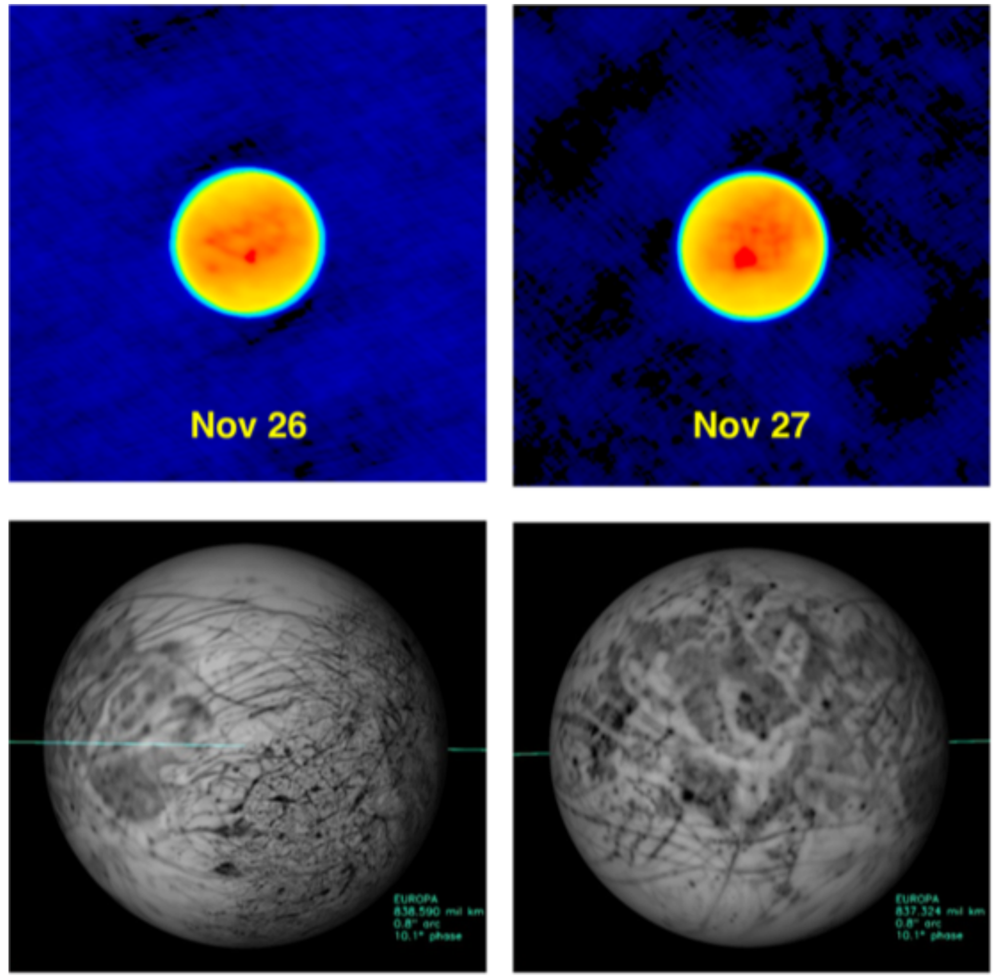
ALMA is observing Ceres in Band 6 over a complete Ceres orbit (~3 years) to look for the signature of subsurface water ice.




Li+ 2016

# ALMA observations of Europa

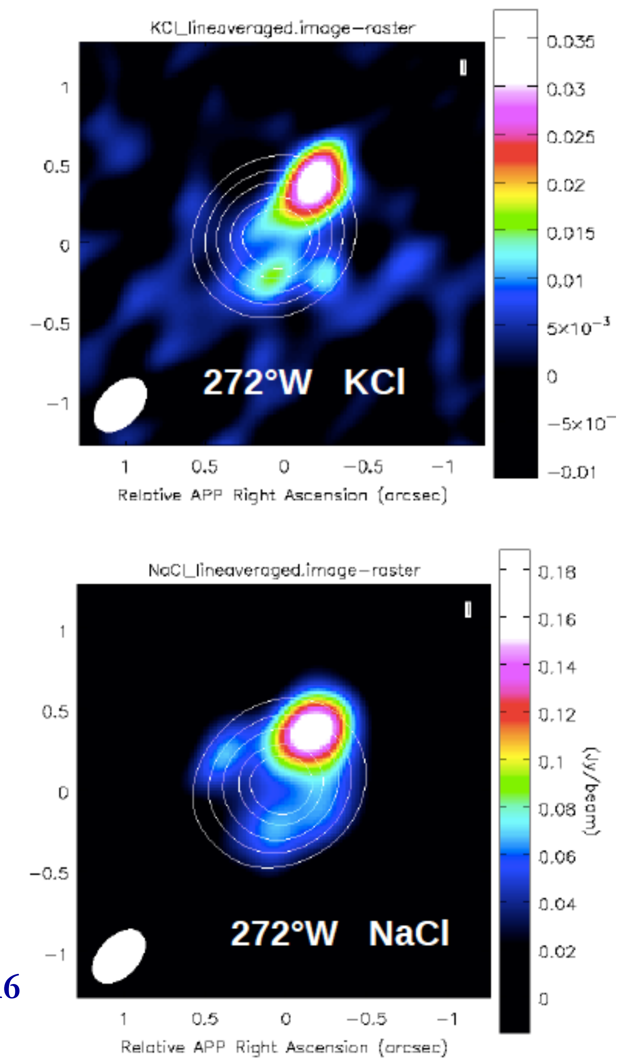
Europa was observed in Band 6 in 2015, to try to correlate thermal signatures with features seen at other wavelengths (mainly optical and IR); notably to correlate with surface chemical composition.




**Trumbo, Brown, & Butler 2017**

# ALMA observations of Io

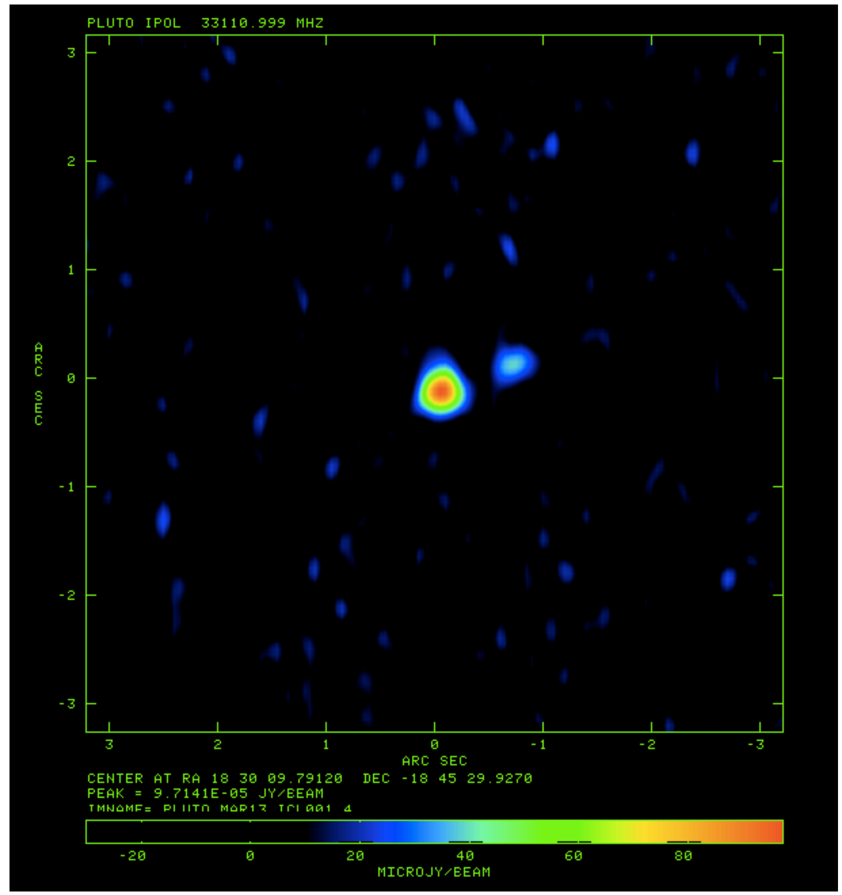
ALMA was used in 2015 to observe Io in continuum and in spectral lines – notably KCl and NaCl. Luckily, two volcanic eruptions were caught in the act!




Moullet+ 2016

# VLA Observations of Pluto/Charon

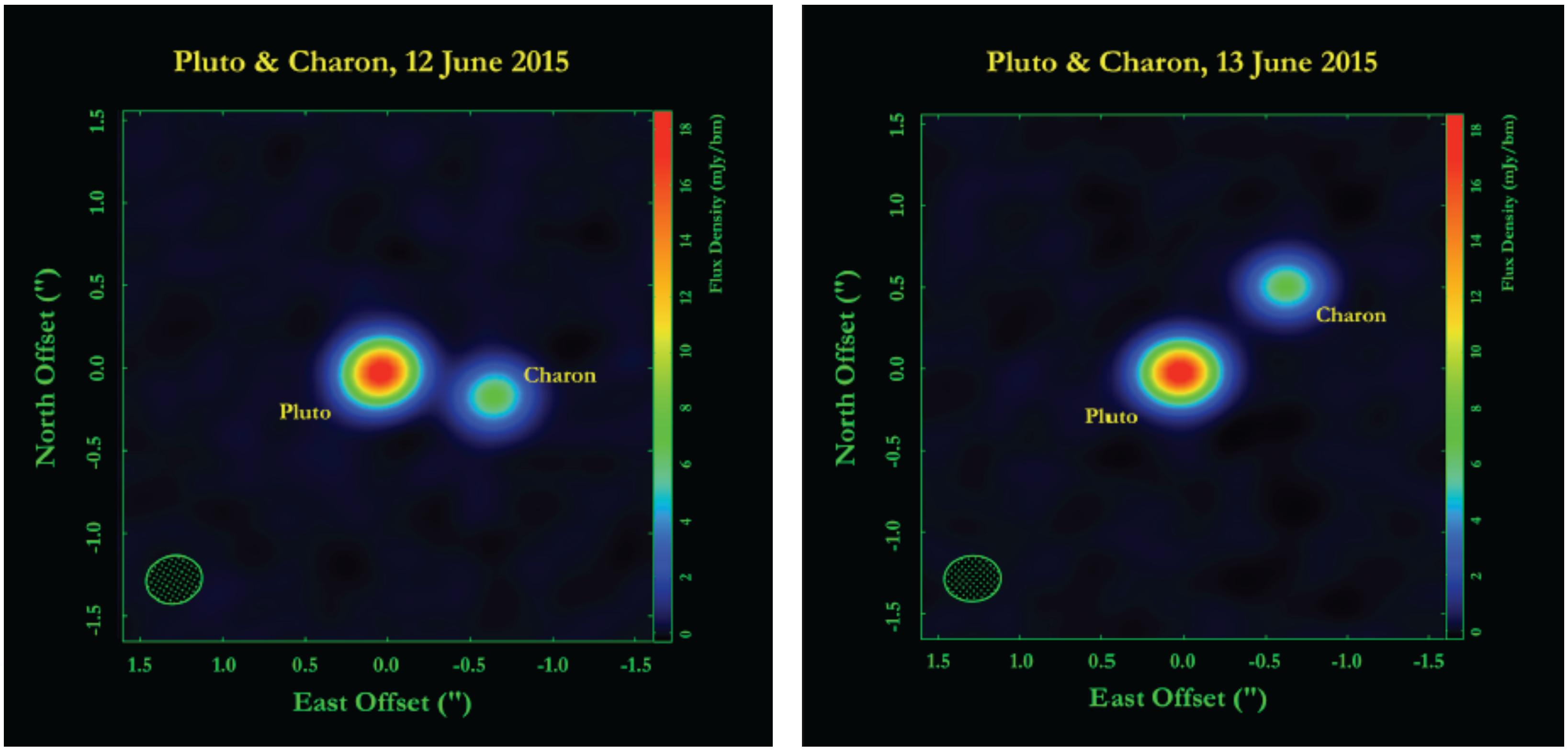
Pluto and Charon were observed at the VLA at Ka-band in 2011. Measured brightness temperatures are lower than what was expected; almost certainly an expression of depressed emissivity.




**Butler+ 2014**

# ALMA Observations of Pluto/Charon

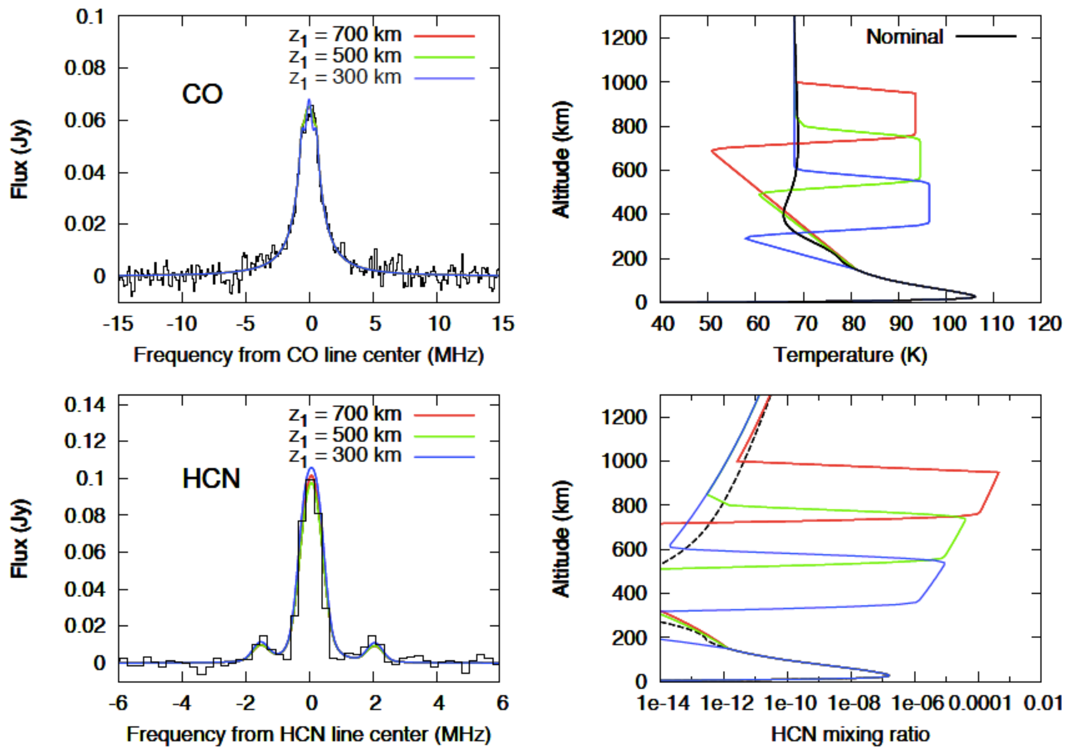
Pluto and Charon were observed with ALMA in 2015. A similar depression in emissivity was seen.




Butler+ 2015

# ALMA Observations of Pluto/Charon

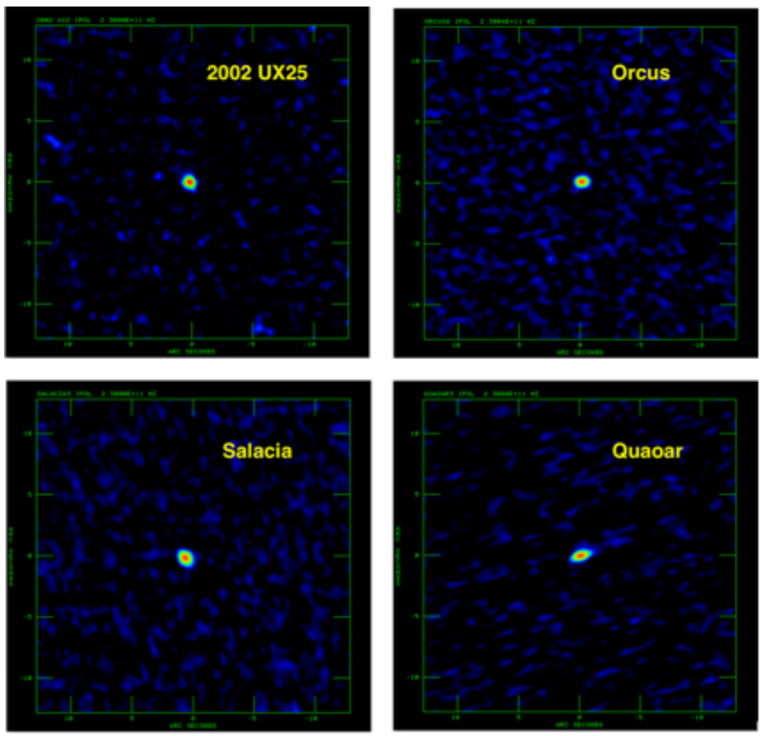
In that same observation we also observed spectral lines of CO and HCN, detecting them clearly for the first time.




Lellouch+ 2016

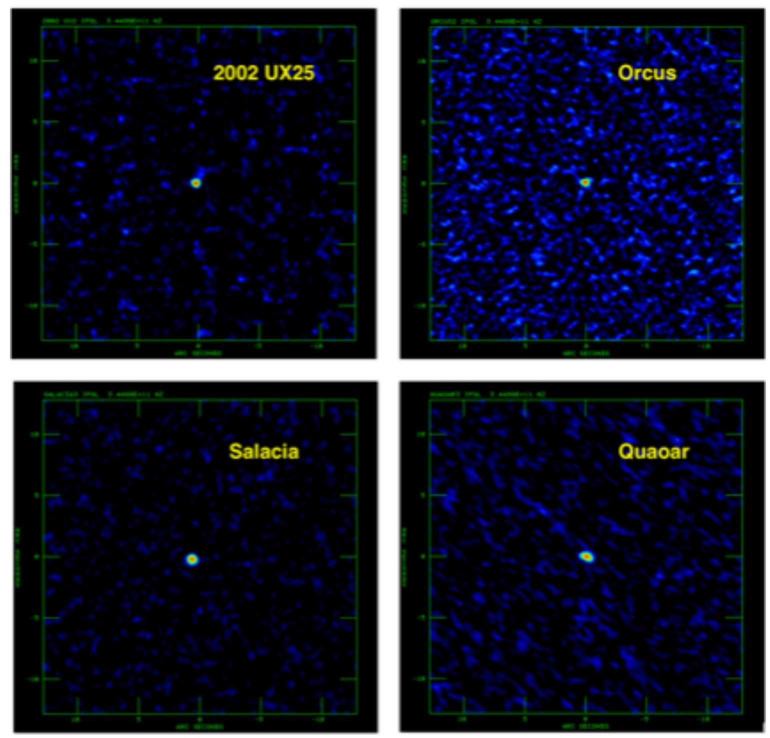
# ALMA Observations of Four KBOs

Orcus, Quaoar, Salacia, and 2002 UX25 were observed with ALMA in Bands 6 and 7 in 2013 and 2014.  Emissivity depression also seen for these four KBOs.



Band 6 = 1300 μm

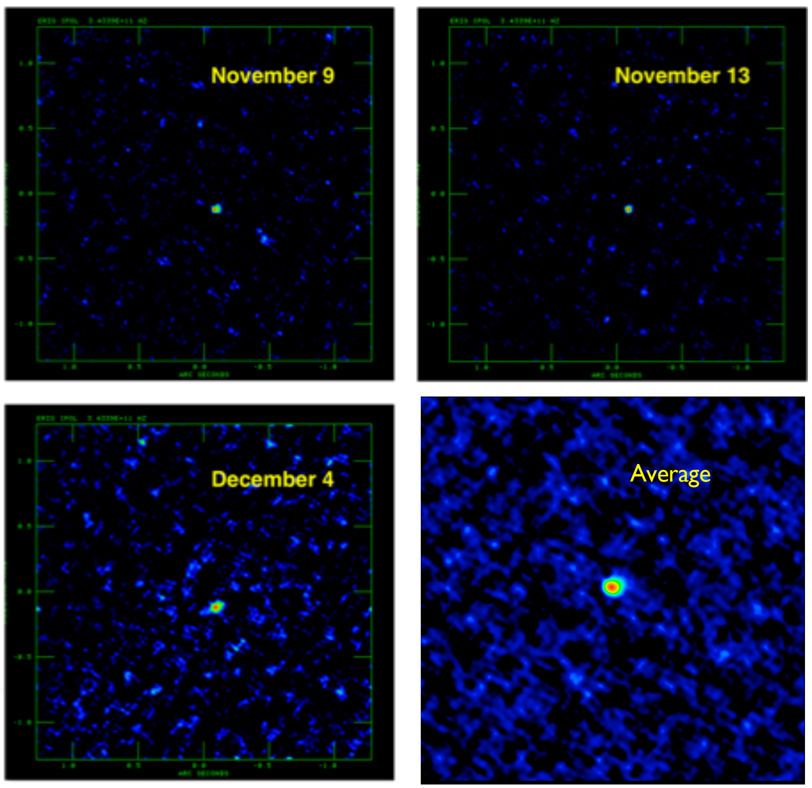
Brown & Butler 2017



Band 7 = 800 μm

# ALMA Observations of Eris/Dysnomia

Eris-Dysnomia observed three times in November, December 2015, at 800 μm, for astrometry.

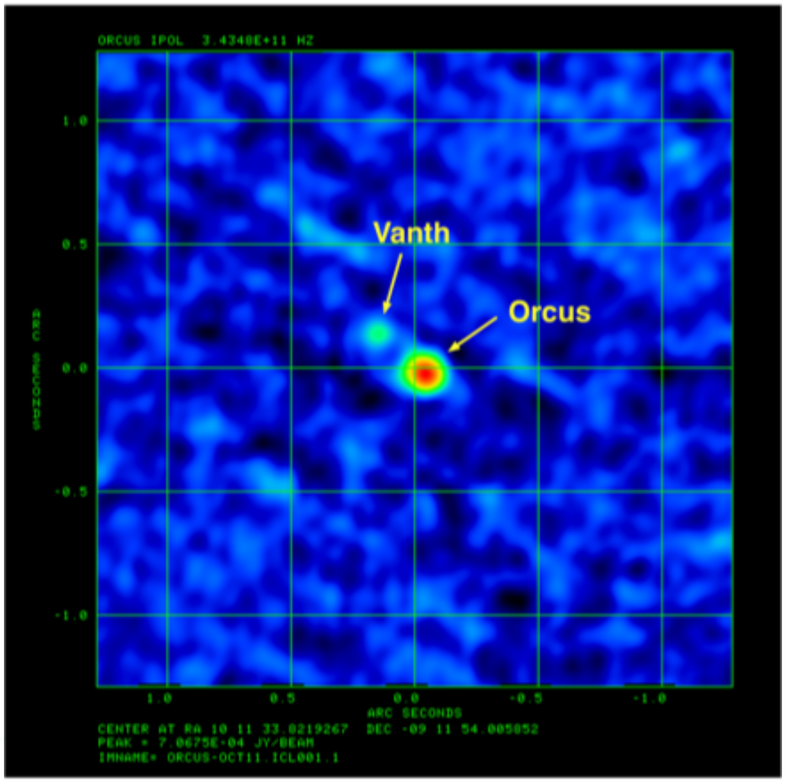



Brown & Butler 2017

- No clear Dysnomia detection in individual observations; even after co-adding with orbital shifts.
- Eris weaker than expected (like other four).

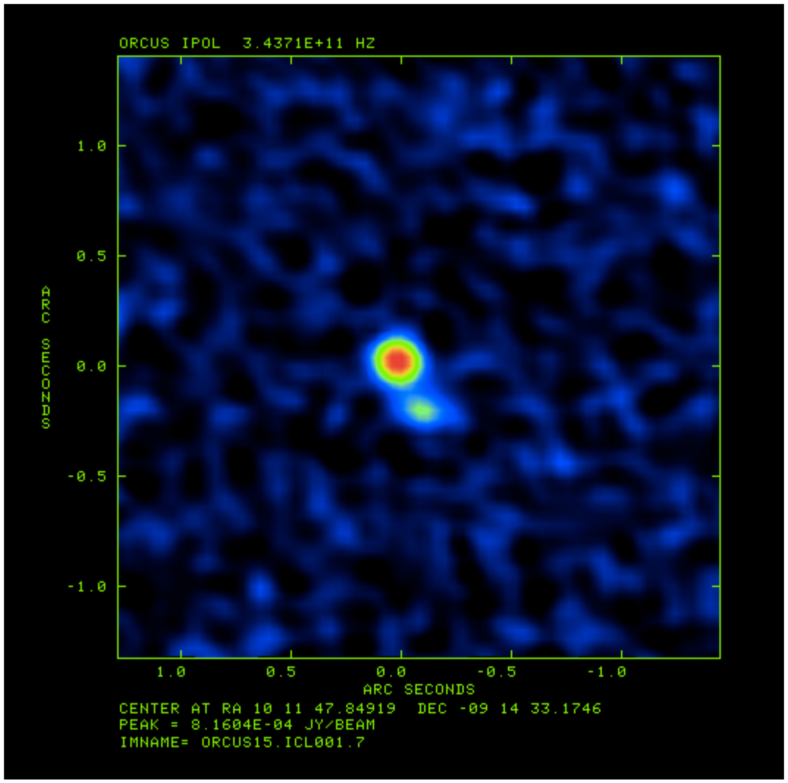
# ALMA Observations of Orcus/Vanth

The Orcus/Vanth system is being observed currently, for astrometry and diameters.  Emissivity depression seen (again).




October 11, 2016

Brown & Butler 2017

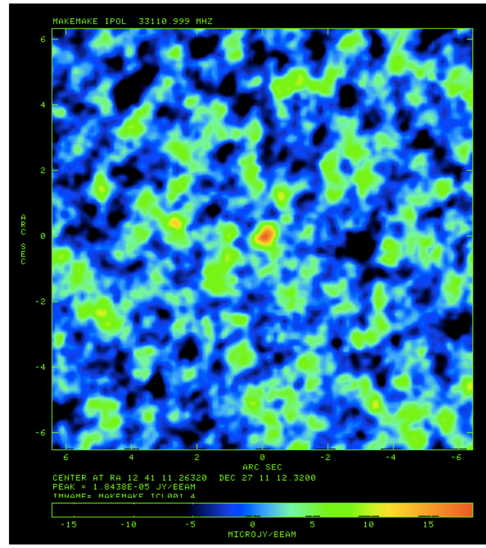



October 15, 2016

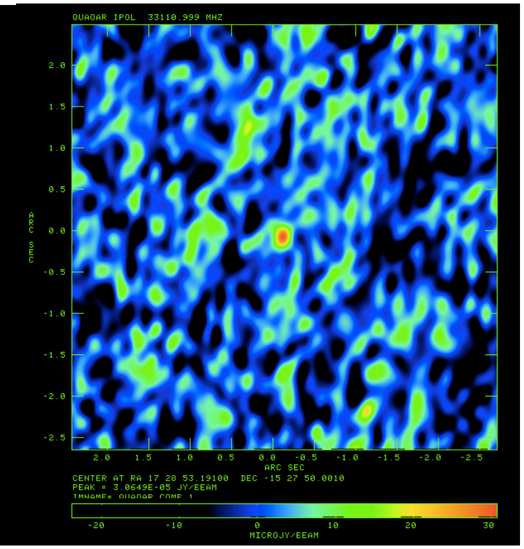
# VLA Observations of KBOs

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

Makemake and Quaoar clearly detected; 2002 $TC_{302}$ not.

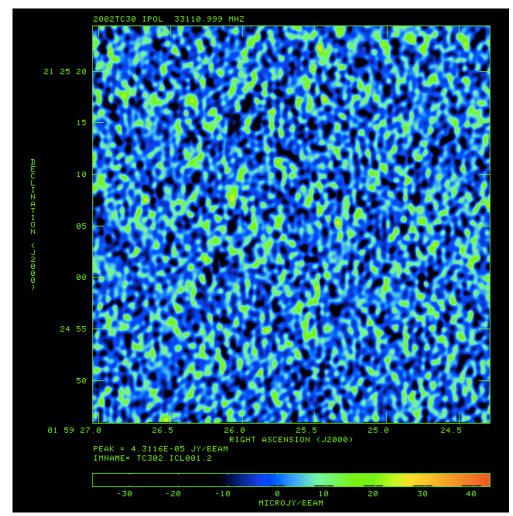


Makemake



Quaoar

**Butler+ 2011**



2002 $TC_{302}$

# Conclusions

- Radio wavelength observations of solar system bodies yield unique information about them.
- VLA and ALMA are already making fantastic contributions in many areas of planetary science, from the atmospheres of the giant planets to the surfaces and subsurfaces of small icy bodies, and will continue to do so in the coming years.