Solar Systems Near and Far - ALMA View

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

The Big Questions

- Planets
  - How did the sun’s family of planets and minor bodies originate?
  - How did the solar system evolve to its current diverse state?
  - How did life begin and evolve on Earth, and has it evolved elsewhere in the solar system?
  - What are the characteristics of the solar system that lead to the origins of life?
- Astrophysics
  - What are the origin, evolution, and fate of the universe?
  - How do planets, stars, galaxies, and cosmic structure come into being?
  - When and how did the elements of life in the universe arise?
  - Is there life elsewhere?

The Not-Quite-So-Big Questions

- How common are planets around other stars, and what are their physical characteristics (orbit, mass, temperature, composition, etc.)?
- What are the current characteristics of the atmospheres, surfaces, and interiors of solar system bodies?
- How are these characteristics changing over time (past, present, and future)?

Three Examples

- Extrasolar giant planets (EGPs), direct and indirect detection
  - ALMA: high sensitivity and ability to detect many normal stars and take advantage of high-precision astrometry
  - ELTs: high sensitivity, extends volume of space for radial velocity studies and high-precision astrometry
- Giant planets in our own solar system
  - ALMA: high resolution and sensitivity, access to isolated transitions, wide bandwidths
  - ELTs: high spatial and spectral resolution, combined with sensitivity
- Icy bodies in our own solar system
  - ALMA: high resolution and sensitivity
  - ELTs: high spatial and spectral resolution, combined with sensitivity

Extrasolar Solar Systems

- Hundreds now known (344 as of this morning), via:
    - Radial velocity
    - Imaging
    - Astrometry
    - Photometry
    - Microlensing
    - Timing
- Many multiple planet systems (37 as of this morning)
- Surprising number very close in (migration?)
- Selection effects important

EGPs - ALMA Direct Detection

Expected flux density at 345 GHz:

$$F_{345} = 6 \text{ X } 10^{-2} \; T \frac{R_J^2}{D_{pc}^2} \quad [\mu\text{Jy}]$$

Distance (pc)	Jupiter	Gl229B	Proto-Jupiter
1	12	130	59000
5.7	.36	4.1	1820
10	.12	1.3	590
120	.0008	.009	4.1

Details in Butler, Wootten, & Brown 2003

EGPs - Direct Detection

- ALMA should be able to directly detect the thermal emission from proto-Jupiters out to the nearest star formation regions
- Nice complement to similar observations by the ELTs, which will probably be in the NIR, or dominated by reflectance

EGPs - ALMA Indirect Detection

Reflex motion of star:

$$\theta_r = \frac{m_p}{M_*} \frac{a_{AU}}{D_{pc}} \quad \text{[asec]}$$

Astrometric resolution of ALMA:

$$\Phi = \frac{\theta_{HPBW}}{\boxed{2\ SNR_*}}$$

This is the key!

Planet is detected at 345 GHz with 15 km baselines if:

$$SNR_* \geq 0.006 \left(\frac{M_*}{m_p} \frac{D_{pc}}{a_{AU}} \right)$$

EGPs - ALMA Indirect Detection

- Gliese's 3rd catalog of nearby stars and the Hipparcos catalog
- reject multiples and variables; those with unknown spectral class; those with dec > 40°
- use spectral class and subclass and luminosity class to determine T_{eff} and R
- Assume planet is in orbit at 5 AU
- Calculate for 3 planet masses: 5 X Jovian, Jovian, Neptunian
- Assume 10 minutes of integration

Catalog	5 X Jovian	Jovian	Neptunian
Gliese	200 (100)	120 (30)	30 (0)
Hipparcos	800	180	0

EGPs - Indirect Detection

- ALMA should be able to detect (or reject) the reflex motion due to EGPs for at least many 10's of systems, and potentially 100's
- Note that this takes a program of repeated observations over many years, since these orbits are of that order
- Complementary to both similar astrometric searches from ELTs, and to their radial velocity searches (which are most sensitive to planets close in and edge-on, both orthogonal to the astrometric searches)

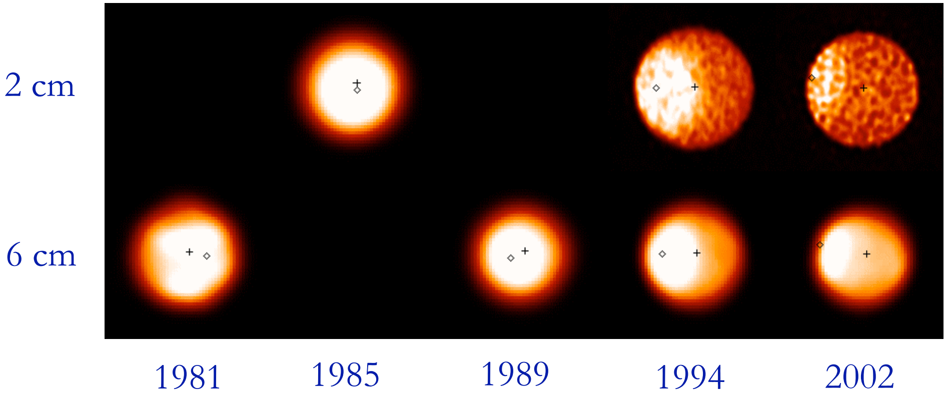
Atmospheres of Uranus and Neptune

- Understanding the current structure (temperature, composition, and dynamics) of the atmospheres of Uranus and Neptune, down to at least 10's of bars, is important for understanding how they formed
- Can only do this with a multiwavelength approach - centimeter for 10's to 1's of bars (EVLA then on to SKA), millimeter/submm for 1's of bars to 100's of mbars (ALMA) and OIR (ELTs) for 100's to 10's of mbars
- Currently limited in mm/submm and thermal IR by resolution and sensitivity
- No, they're not just calibrators

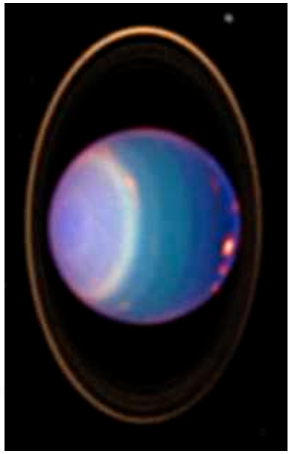
Atmosphere of Uranus

Voyager

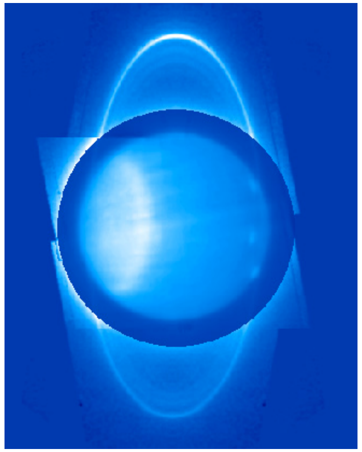
VLA



Hofstadter & Butler 2003



Karkoschka 2001

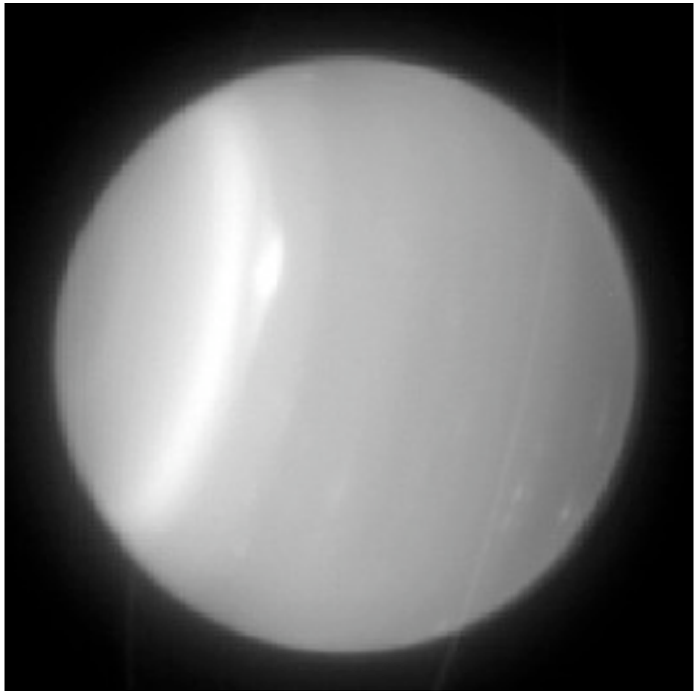


De Pater et al. 2002

HST & Keck

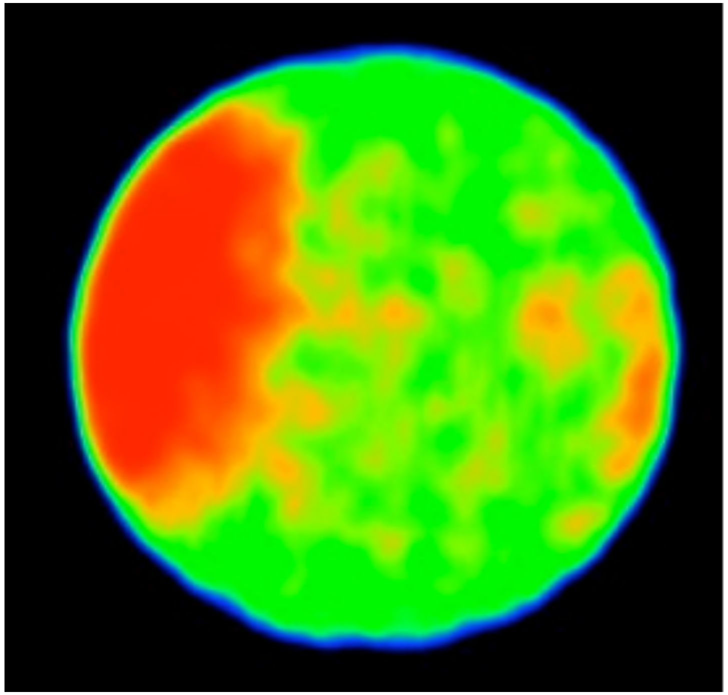
Atmosphere of Uranus

Keck 2μm



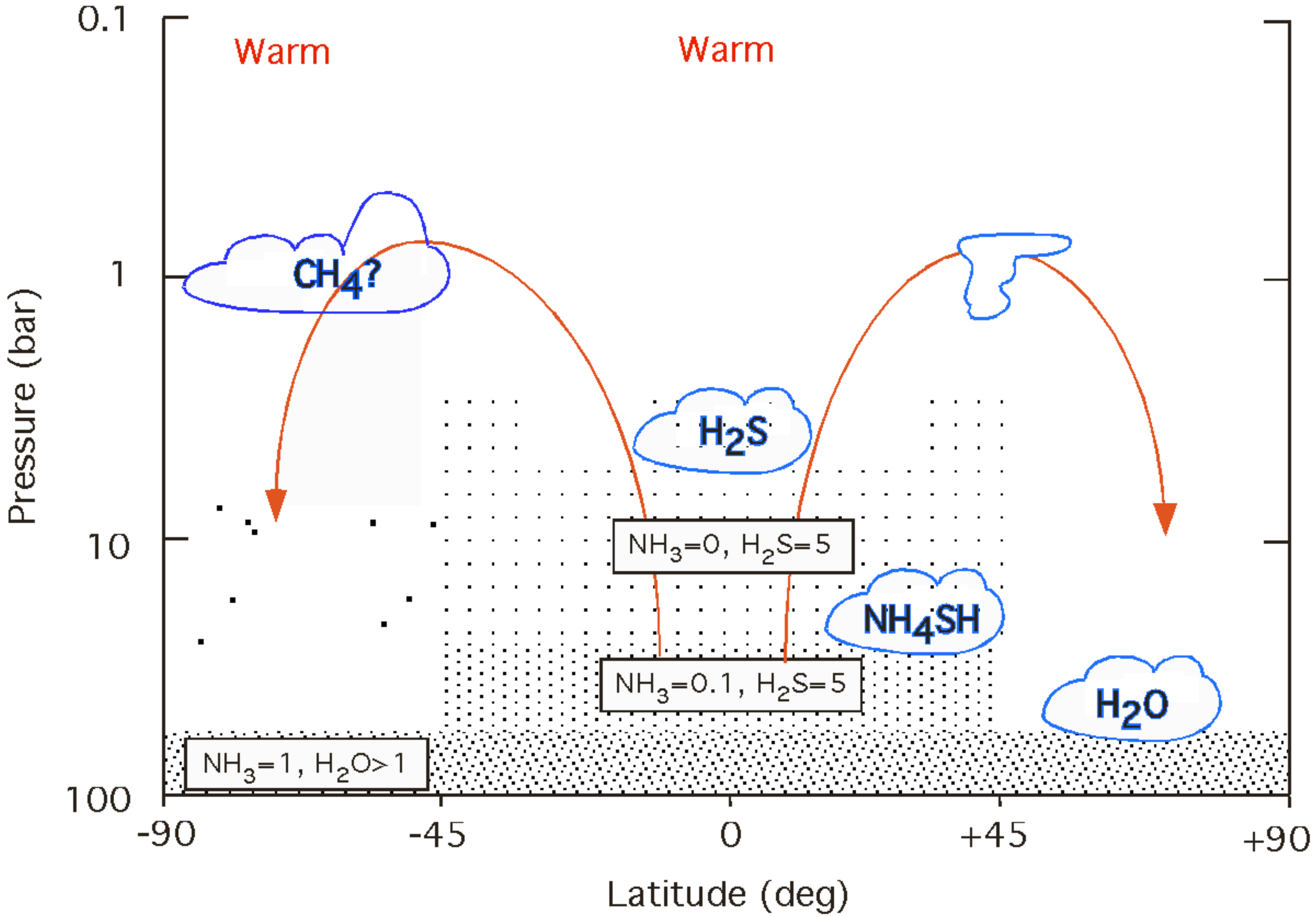
Hammel et al. 2004

VLA 2cm

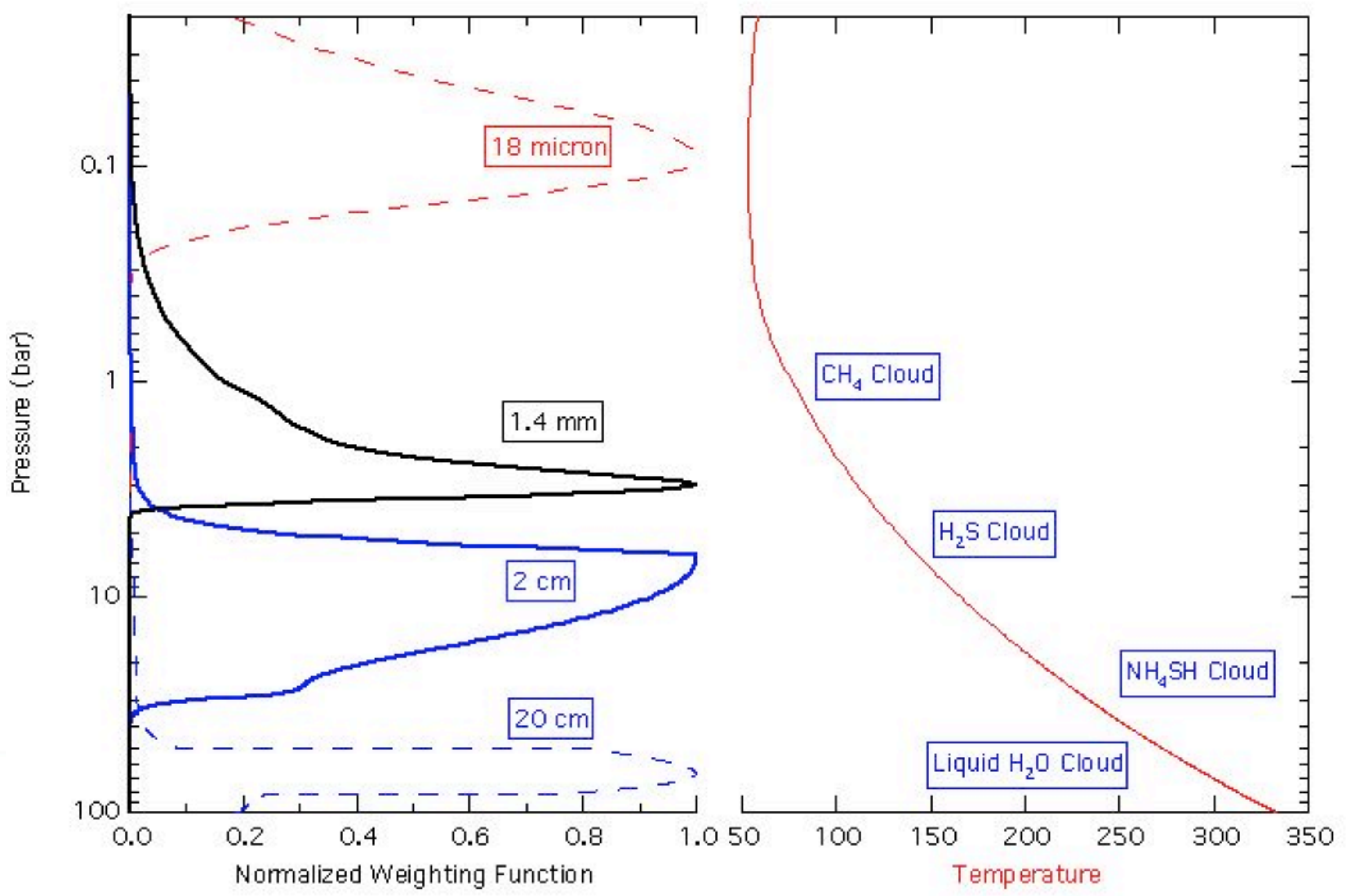


Hofstadter & Butler 2004

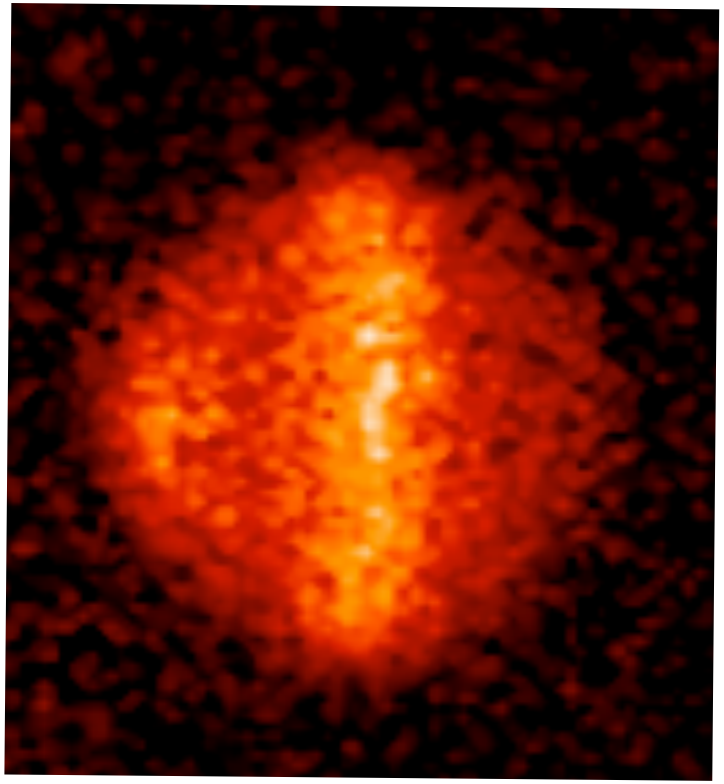
Emerging Picture

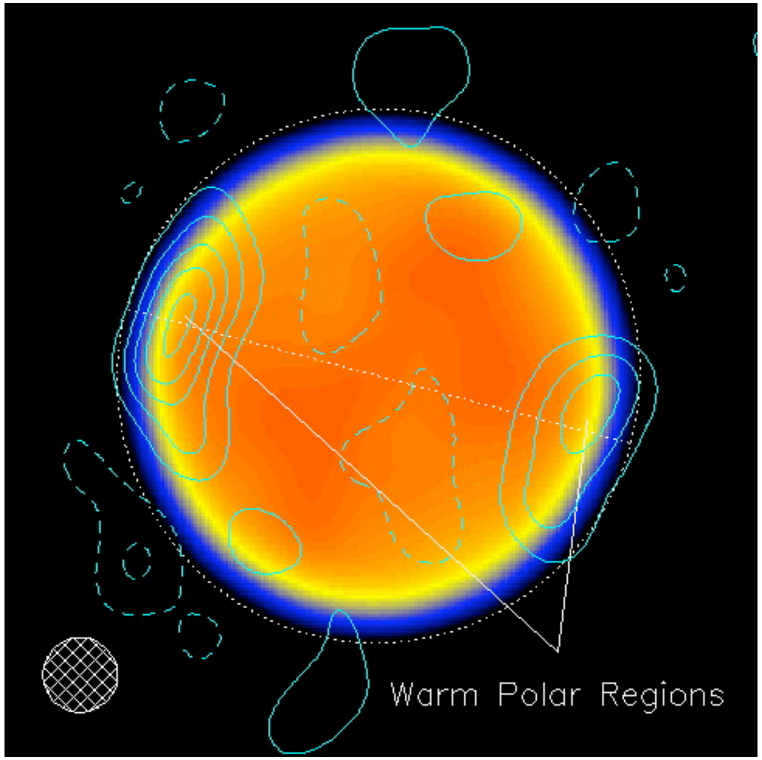


Weighting Functions



Filling the Thermal IR/mm/submm Gap



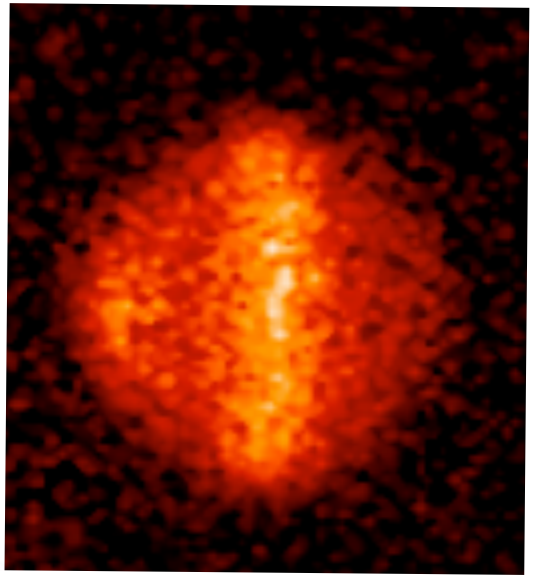


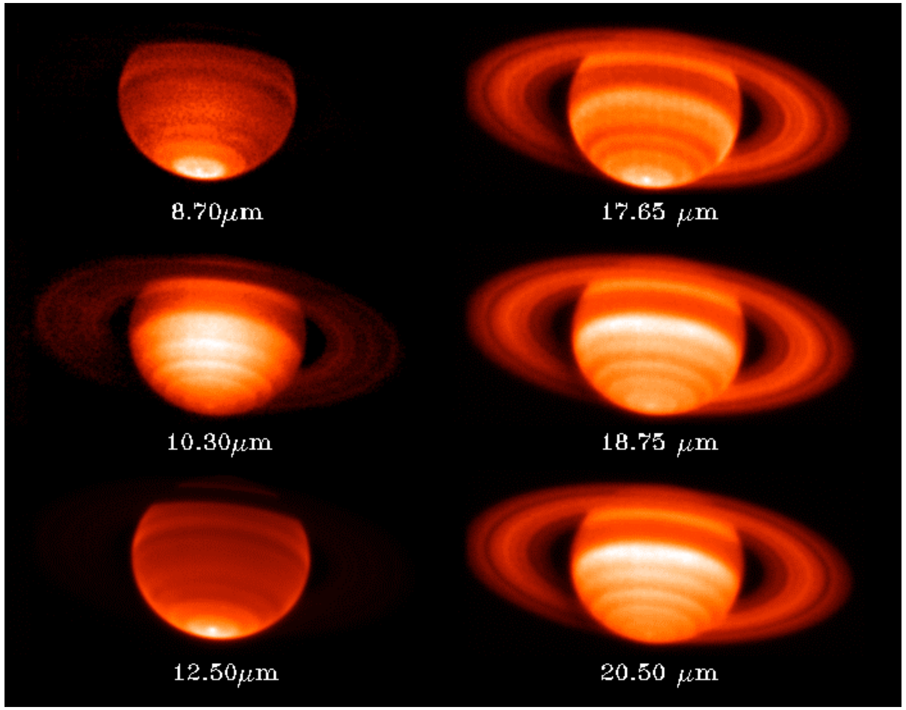
VLT/VISIR 18.7 µm
Orton et al.

SMA 1.4 mm
Hofstadter et al.

The Improvement of the ELTs

With the ELTs, resolution (in terms of linear scale on the planet) in the thermal IR on Uranus and Neptune will be similar to what we can get on Saturn now (ALMA improvement similar):



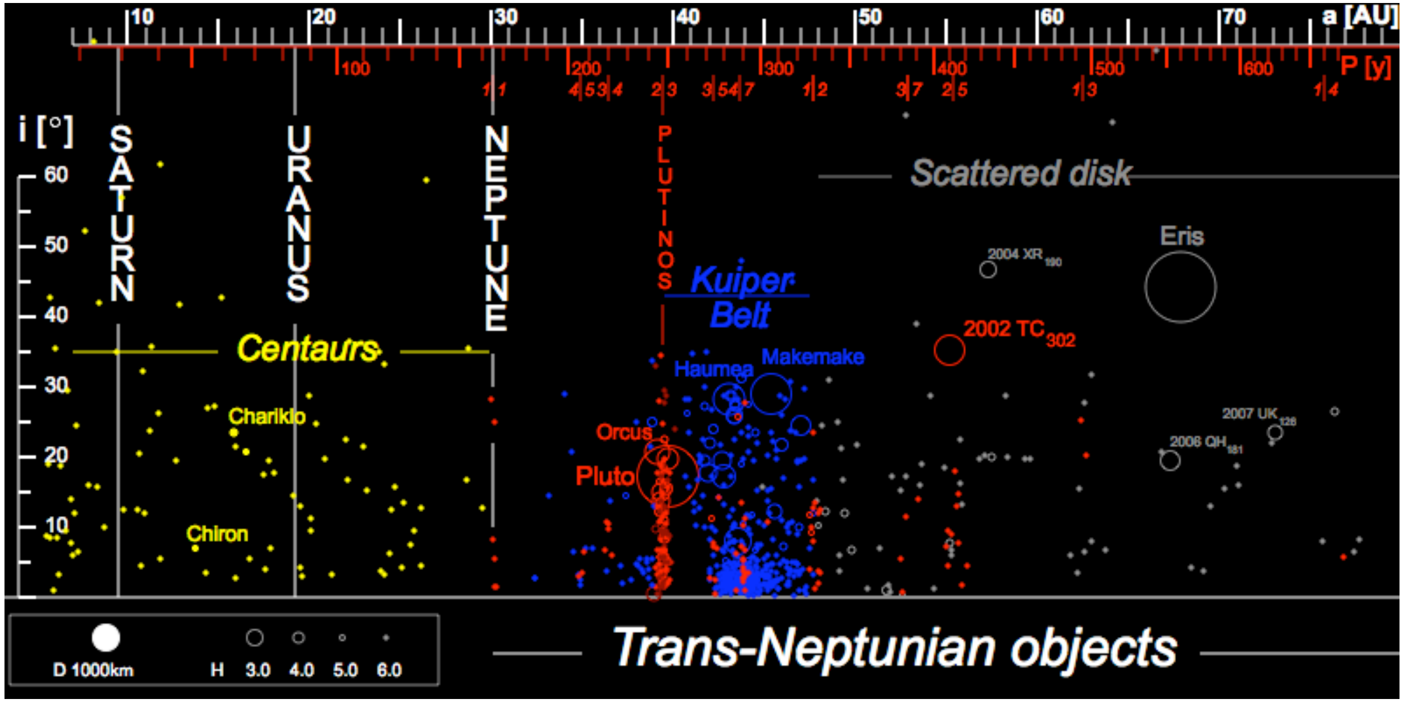


Atmospheres of Uranus and Neptune

- ALMA and the ELTs will allow us to complete the altitude coverage from 10's of millibars to 10's of bars in Uranus and Neptune at high resolution and sensitivity, thus allowing us to complete the picture of temperature, composition, and dynamics in this important pressure region
- This gives clues as to the formation history of these important ice giants

Trans-Neptunian Objects (TNOs)

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



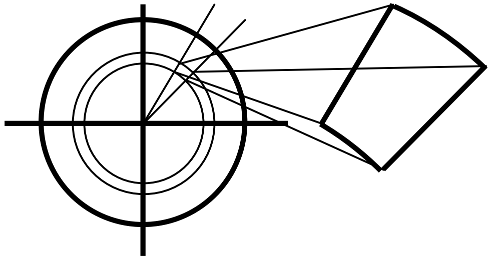
Trans-Neptunian Objects (TNOs)

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

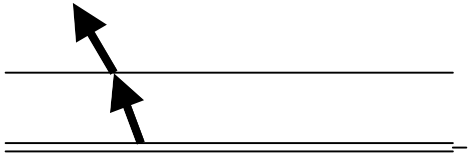
- Sizes uncertain to at least 10's of percent, because they rely on thermal IR observations plus an albedo measurement, and additional thermal modelling, except for the largest few
- Surface composition limited by low-SNR spectra; only reliably done on the largest of the KBOs, others rely on broadband colors

An Aside on Surface Physics

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



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



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

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

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

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

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

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

$P = 1 - \rho / \rho_0$

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

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

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

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

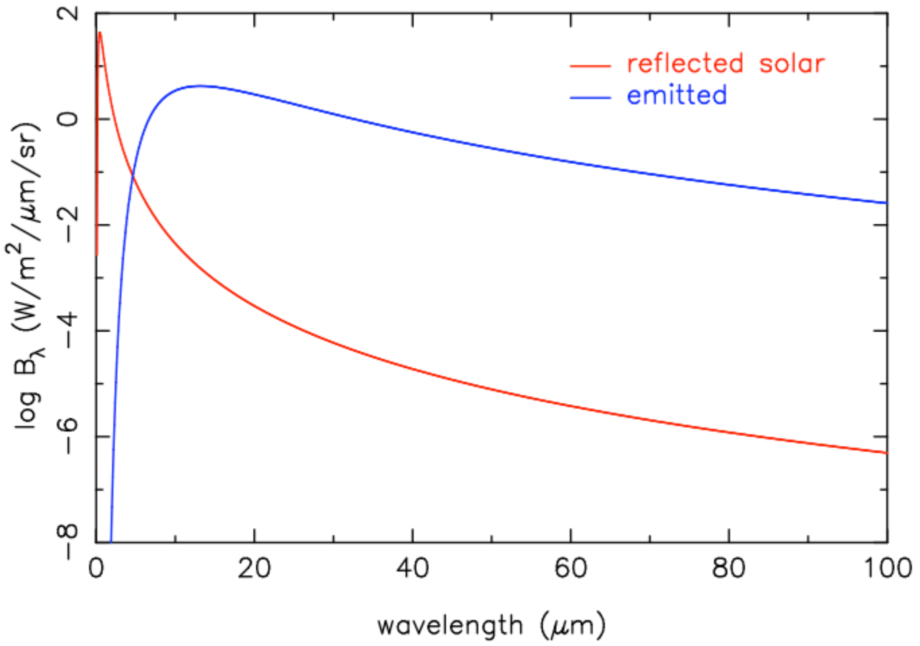
$$c_p(z,T) = T(z)\,/\,2000$$

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

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

A Reminder

- Optical and near-IR measure reflected solar radiation.
- Thermal-IR and longer measure emitted radiation



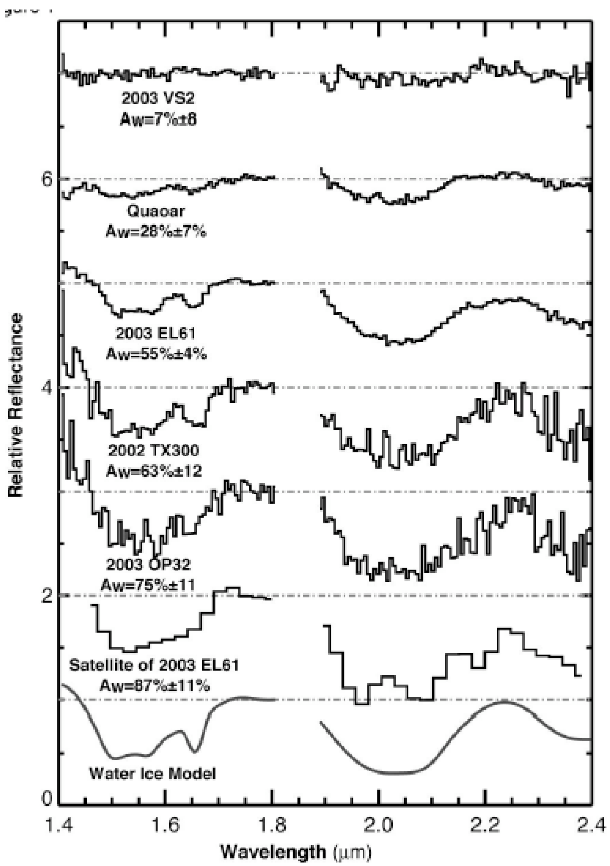
TNO Sizes from ALMA

- ALMA will be fantastic for determining sizes of TNOs
- Expected flux density:

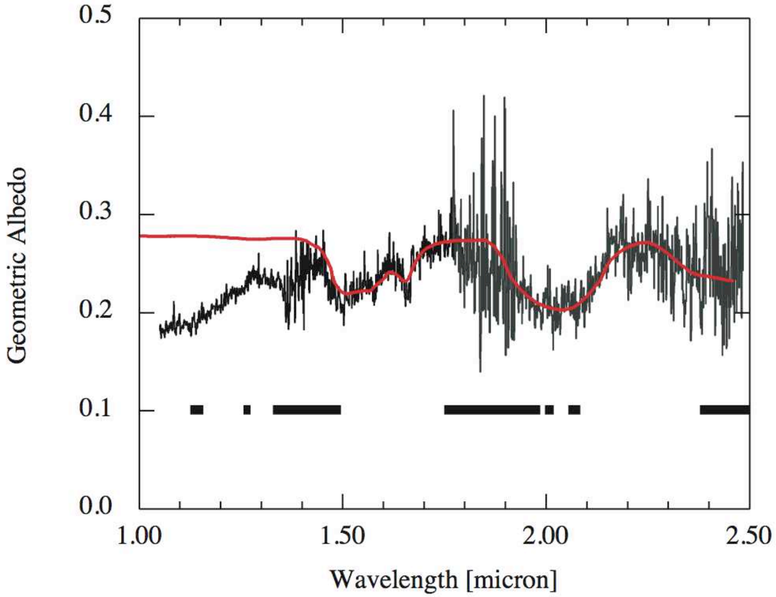
$$F_{345} = 0.6 \; T_b \, \frac{R_{km}^2}{D_{AU}^2} \quad [\mu\mathrm{Jy}]$$

- 100 km TNO at 40 AU and 40 K ~ 0.13 mJy
- Uncertainty in R^2 linear in uncertainty in brightness temperature (and emissivity only uncertain to a few %)

TNO Surface Composition from ELTs



Brown et al. 2007



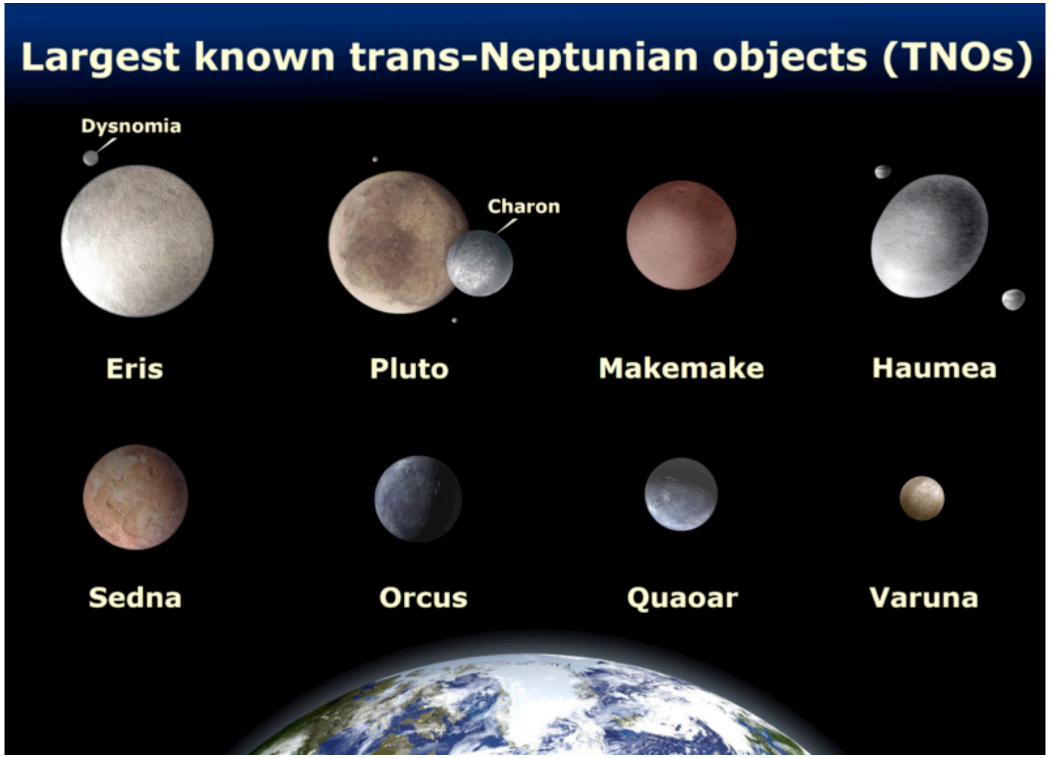
Jewitt & Luu 2004

TNO Surface Composition

- ELTs will be able to extend this to the smaller bodies because of their sensitivity
- Spectral light curves could be obtained for the larger bodies, providing evidence of surface heterogeneity (similar to Pluto)
- The combination of ALMA and ELTs will determine temperatures as well as compositions

The Largest TNOs

- The largest TNOs will actually be resolved by both ALMA and the ELTs (apparent sizes of order 10’s of masec)



TNOs

- ALMA and the ELTs will allow characterization of these important (and potentially pristine) objects beyond simple dynamical parameters
- Sizes will be well determined allowing a more accurate census of mass distribution in the outer solar system
- Compositions will be determined for a much larger population (of smaller bodies) than currently accessible, providing important constraints on composition of the forming solar system in this important region
- (And I haven't even touched on comets or the other icy bodies!)

Summary

- It is clear that ALMA and the ELTs would provide stunning new results for a broad range of solar system studies, including
- EGP direct and indirect detection
- Characterization of the atmospheres of the icy giant planets, Uranus and Neptune
- Physical characterization of the small icy bodies in the outer solar system
- AND MUCH MORE!

Important Points for Solar System

- ALMA
  - Sensitivity and resolution key
  - Band 1 important to get deeper into the subsurfaces (and to complement EVLA for southern sources)
  - Polarization important
- ELTs
  - Sensitivity and resolution key
  - Thermal IR extremely important
- Both
  - Observations of planetary systems (known and exploratory) should be coordinated