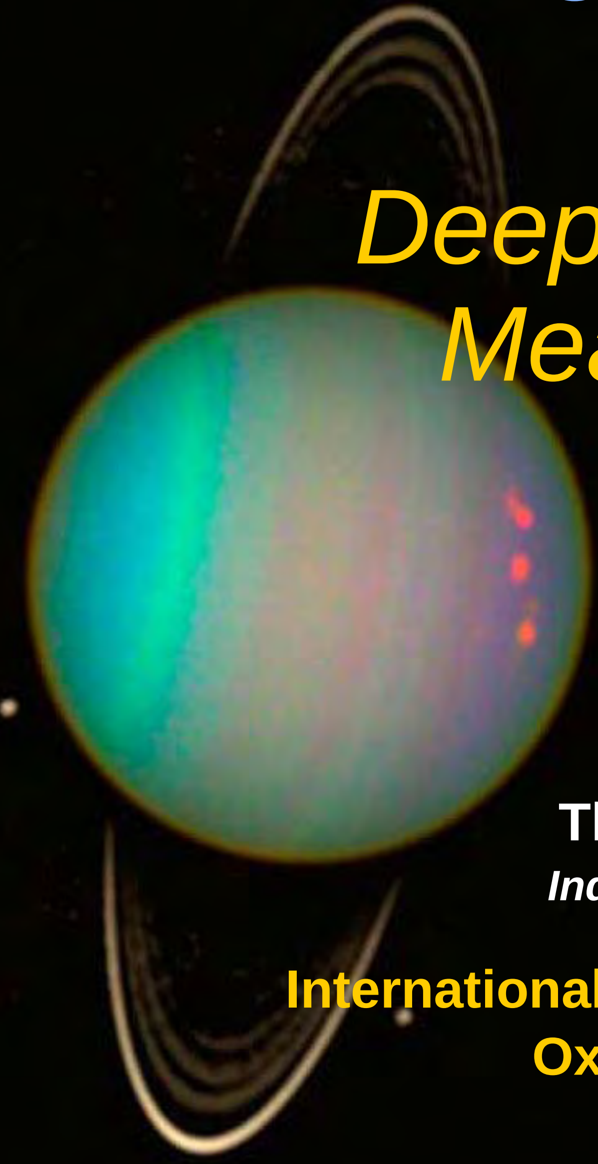
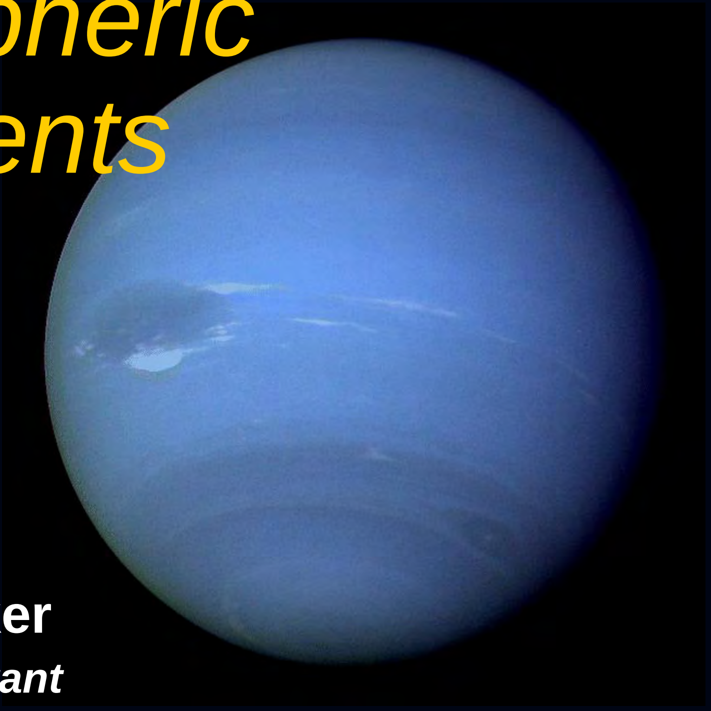
Challenges and Options *for* *Deep Atmospheric Measurements*





Thomas R. Spilker
Independent Consultant

International Planetary Probe Workshop
Oxford, England, UK

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Topics Addressed

- Challenges
  - Pressure
  - Temperature
  - Telecommunications
  - Distances and time constraints
- Options
  - Custom electronics components packaging
  - High-temperature electronics
  - Phase-change thermal materials
  - Low radio frequency
  - High transmitter power
  - Large receiving antenna
  - Multiple probes
  - *Staged* probe

Challenges of Pressure

- Natural result of going deep
  - Pressure increases with depth
  - Most of a giant planet’s mass is at thousands to millions of bars
  - Upper regions of the atmosphere are not like the interior
  - Tropospheric chemistry, structure, & dynamics can be diagnostic of the interior

- Sensitivities
  - Atmosphere sampling by mass spectrometers
    - Must exhaust samples to very low-pressure sinks
  - Electronic components, especially chips
    - Standard packaging can have problems above ~20 bars
  - Structures (pressure vessels, etc)
    - Can include some instrument components

Challenges of Temperature

- Natural result of going deep
  - Below the tropopause, temperature increases with depth
  - *Lapse rate*: derivative of temperature with altitude
    - Even planets with very cold tropopauses can be very hot at depth
  - Uranus & Neptune aren't too bad in this regard
    - 100-bar-level temperatures thought to be ~300-350 K
    - But … going much deeper it can get toasty
- Sensitivities
  - Electronic components
    - Semiconductor devices
    - Fundamental components: wiring insulation, solder etc.
  - Polymers
    - Used in a wide variety of space-qualified components
  - Instruments
    - Sensors

Challenges of Telecommunications

Fundamental Telecommunications Problem

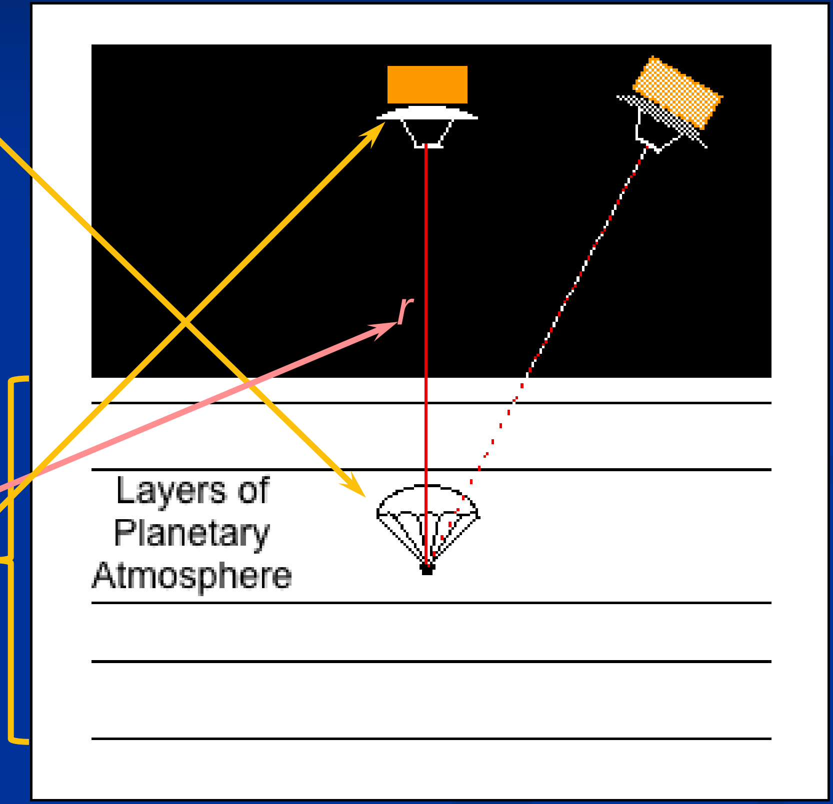
A probe at some level in a planet's atmosphere

…must send a given volume of data in a given time

…through the intervening atmosphere, and possibly other non-vacuum media

…over some distance *r*

…to a receiving station of given performance



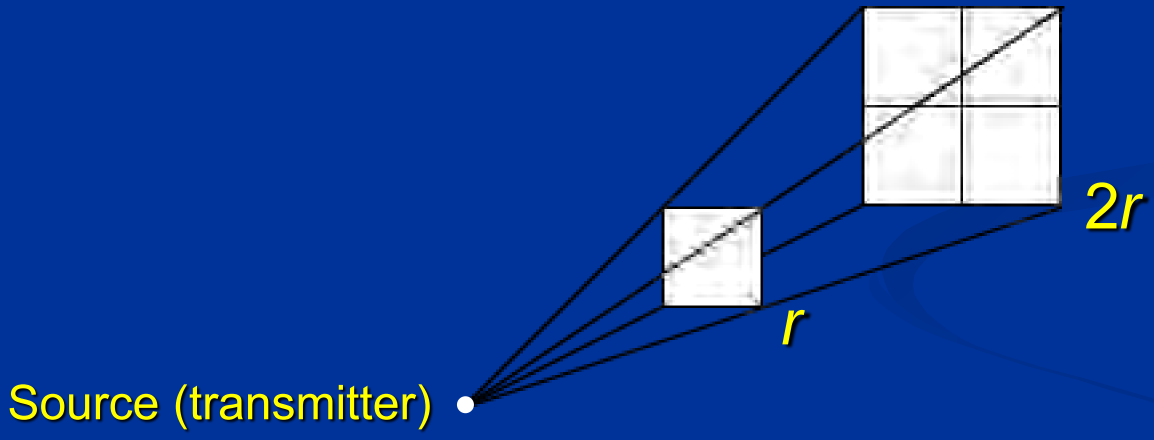
Power required is important!

The atmosphere can absorb some (or most!) of that power

Behavior of Telecommunications Systems

Inverse-Square Law

- A given amount of signal power distributed over a given area yields a signal *intensity*, W/m^2.
- As a signal propagates, that area is proportional to r^2.

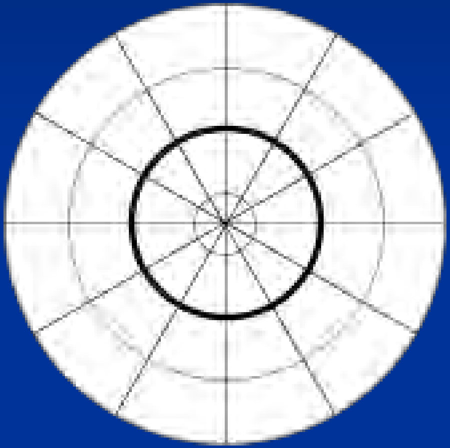


The signal power available to a receiver is proportional to the receiving antenna's *aperture* (area) times the incoming signal's intensity, so for a given antenna, proportional to 1/r^2.

Behavior of Telecommunications Systems

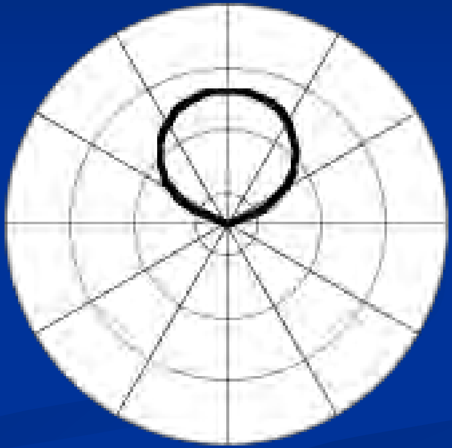
Gain

“Isotropic Radiator” (a fiction)

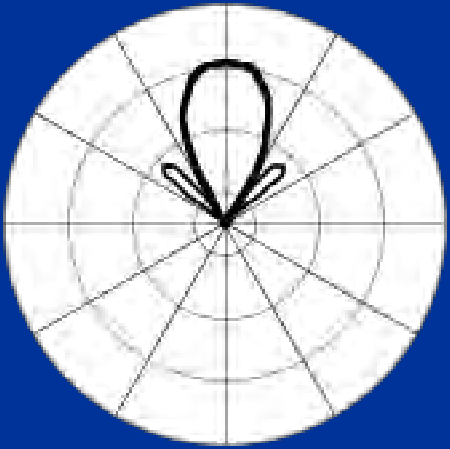


Gain is the ratio of an antenna’s on-axis emitted signal intensity to that of an isotropic radiator driven by the same total power

“Low Gain” antenna

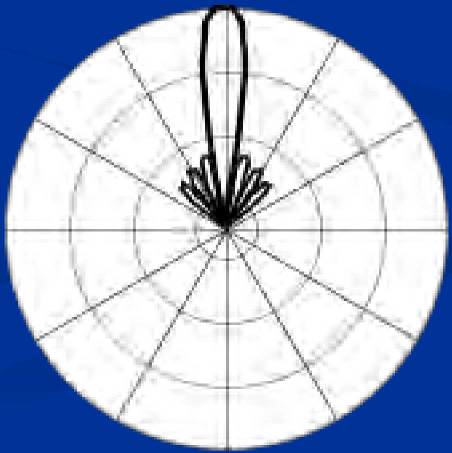


“Medium Gain” antenna



But … the higher the gain, the narrower the beam, so the more accurately you must point

“High Gain” antenna



Behavior of Telecommunications Systems

Gain

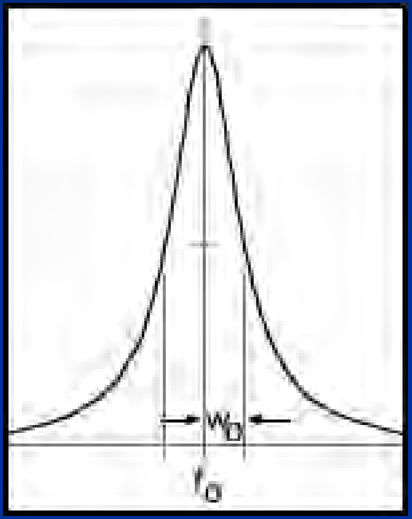
For a given antenna aperture, gain and beamwidth are *not* independent of wavelength (frequency)

$$G = C\left(\pi \frac{D}{\lambda}\right)^2$$

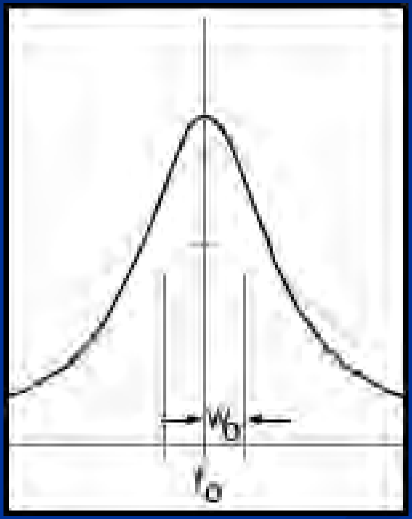
If you go to a longer wavelength (lower frequency), to maintain the same gain and beamwidth the antenna diameter must get proportionately larger!

Behavior of Absorbing Species

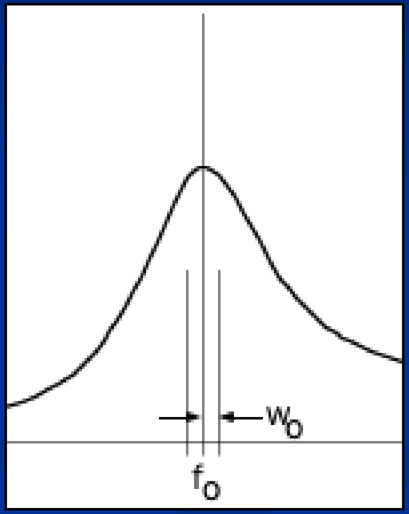
Absorption/Emission Lines & Line Shapes



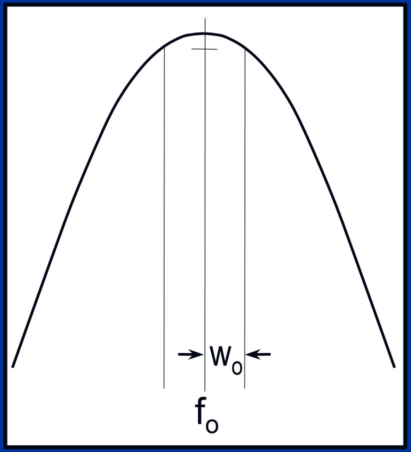
Unbroadened



Mildly Broadened



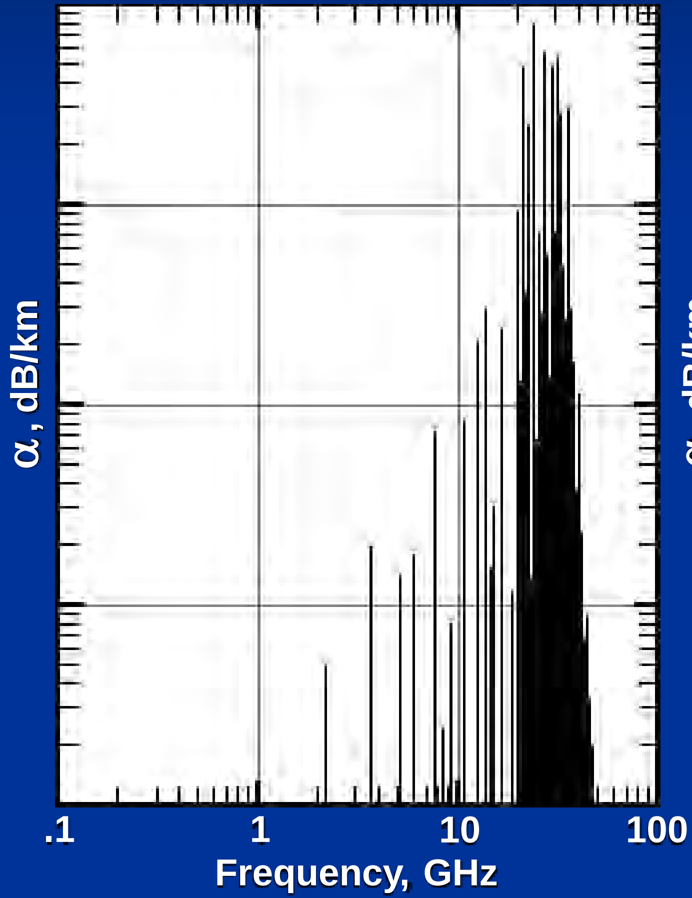
Moderately Broadened



Behavior of Absorbing Species

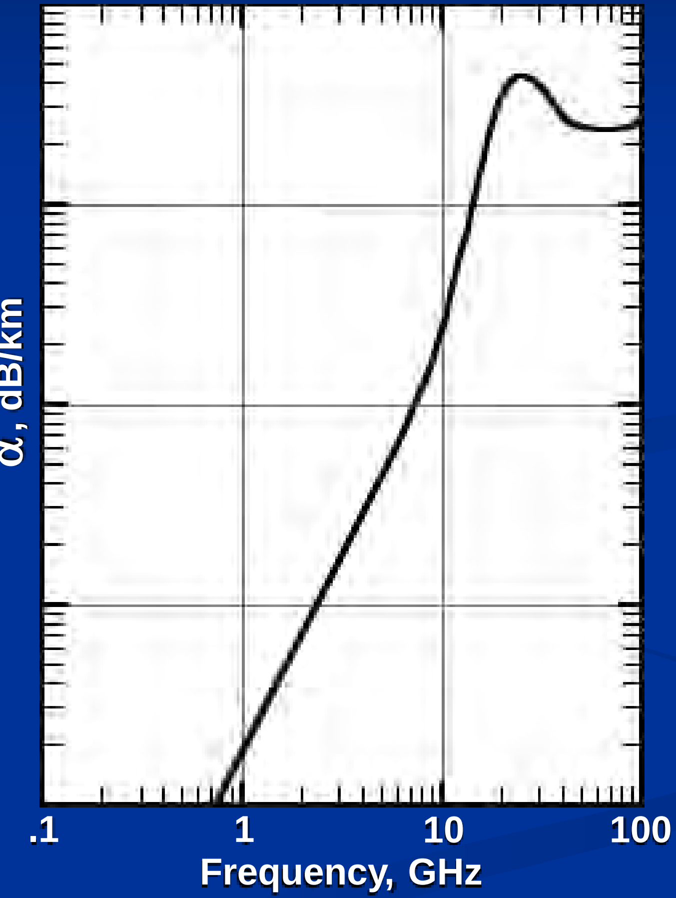
Broadened Absorption Lines and Absorption Spectra

Line spectrum



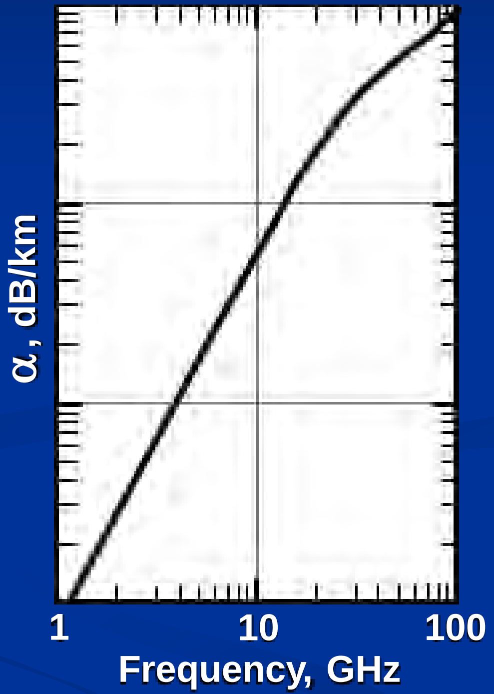
Few mb NH_3

Pressure broadened



+ ~1 bar H_2 + He

Near-Debye

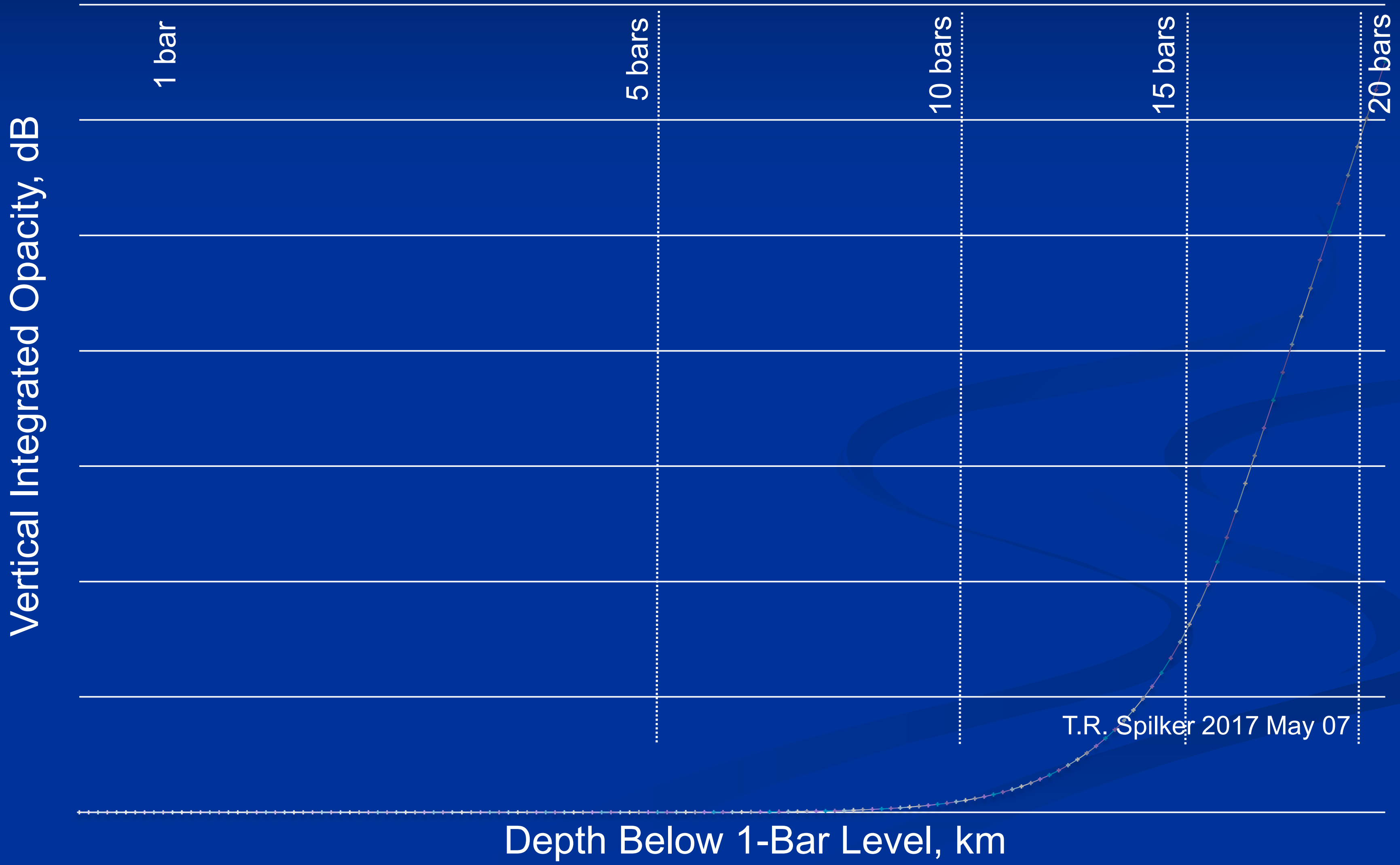


+ 50-100 bars H_2 + He

Behavior of Absorbing Species

Example: Uranus Integrated Vertical Opacity vs. Depth

“Maximum NH3” model by Mike Wong; stressing case for data relay



T.R. Spilker 2017 May 07

Telecom Signal Attenuation by Scattering

- What is scattering?
  - Propagation direction of part of the signal is diverted so it doesn't reach the receiving antenna
  - Reduces the overall intensity of the signal (*attenuation*)
- What can cause scattering?
  - Inhomogeneities (such as turbulence) in the atmosphere
  - Particulates: "rain", "snow"
    - The larger the particles (the closer to the signal wavelength) the greater the scattering
    - The higher the concentration of particles the greater the scattering
- Deep scattering at Uranus and Neptune
  - Possible minor scattering by shallow NH_4SH and NH_3 or H_2S clouds
  - Possibly significant water snow upon penetrating the top of the cloud, and significant rain below the 273 K temperature level

Challenges of Distances and Time Constraints

Strong Coupling of Orbital Dynamics, Aerodynamics, & Telecom

How long does it take to get *deep*?

How long can a relay spacecraft stay in positions allowing data relay?

What telecom geometries can system designs allow?

Challenges of Distances and Time Constraints

Atmospheric Scale Height

Scale Height: vertical distance over which the atmospheric pressure changes by a factor of *e* or 1/*e*

$$P(z) = P_0 e^{-\frac{z - z_0}{H}}$$ with $$H = \frac{RT}{Mg}$$

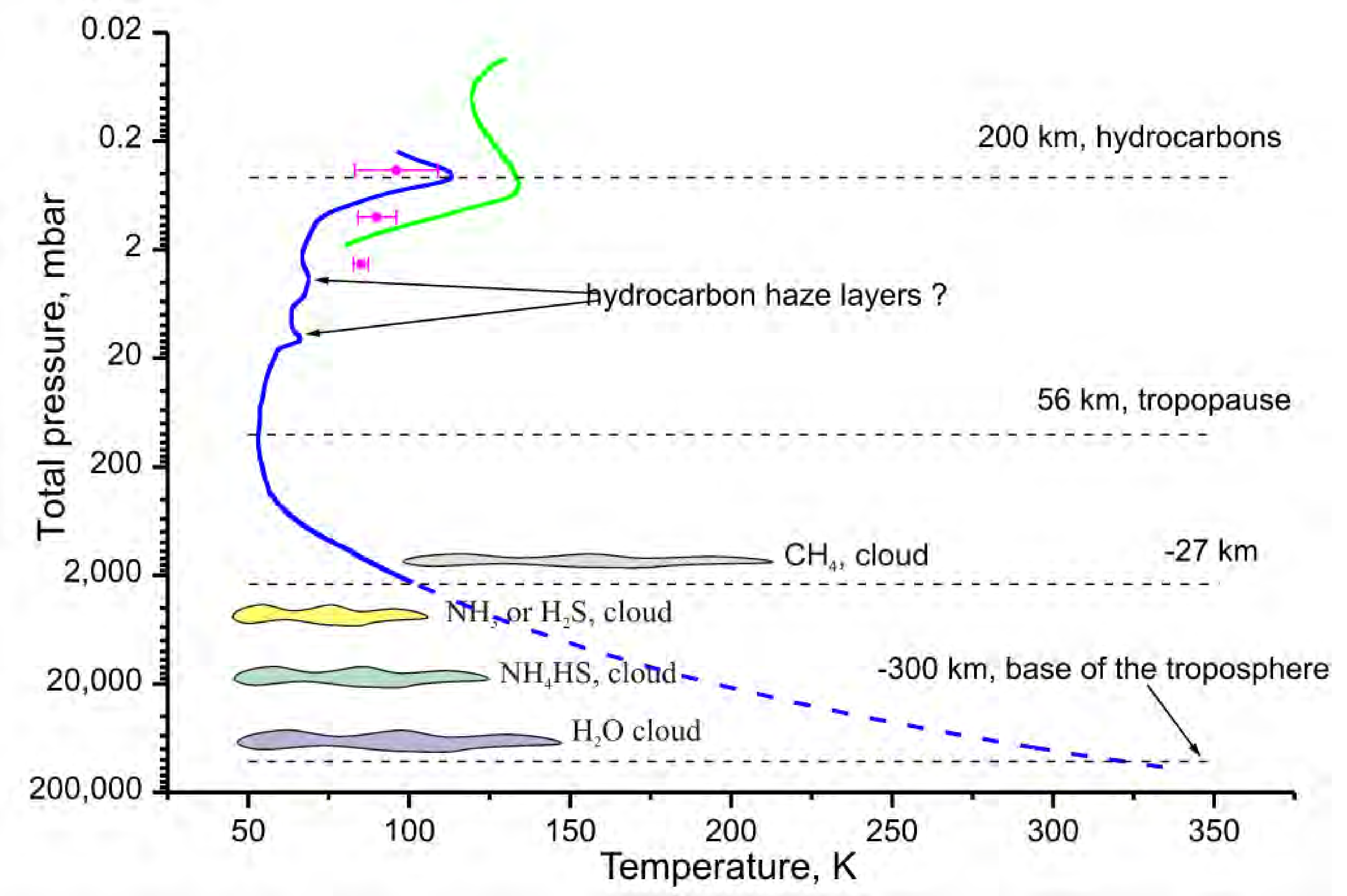
Valid for isothermal atmospheres; for non-isothermal atmospheres you must use the differential form

$$\frac{d}{dz} P(z) = -\frac{P_0}{H(z)} e^{-\frac{z - z_0}{H(z)}}$$

…and integrate over altitude because H varies with temperature and thus with altitude.

Challenges of Distances and Time Constraints

Atmospheric Scale Height



Challenges of Distances and Time Constraints

Atmospheric Drag

Drag equation:

$$F_D = \frac{C_D}{2} A \rho V^2$$

Terminal Velocity:

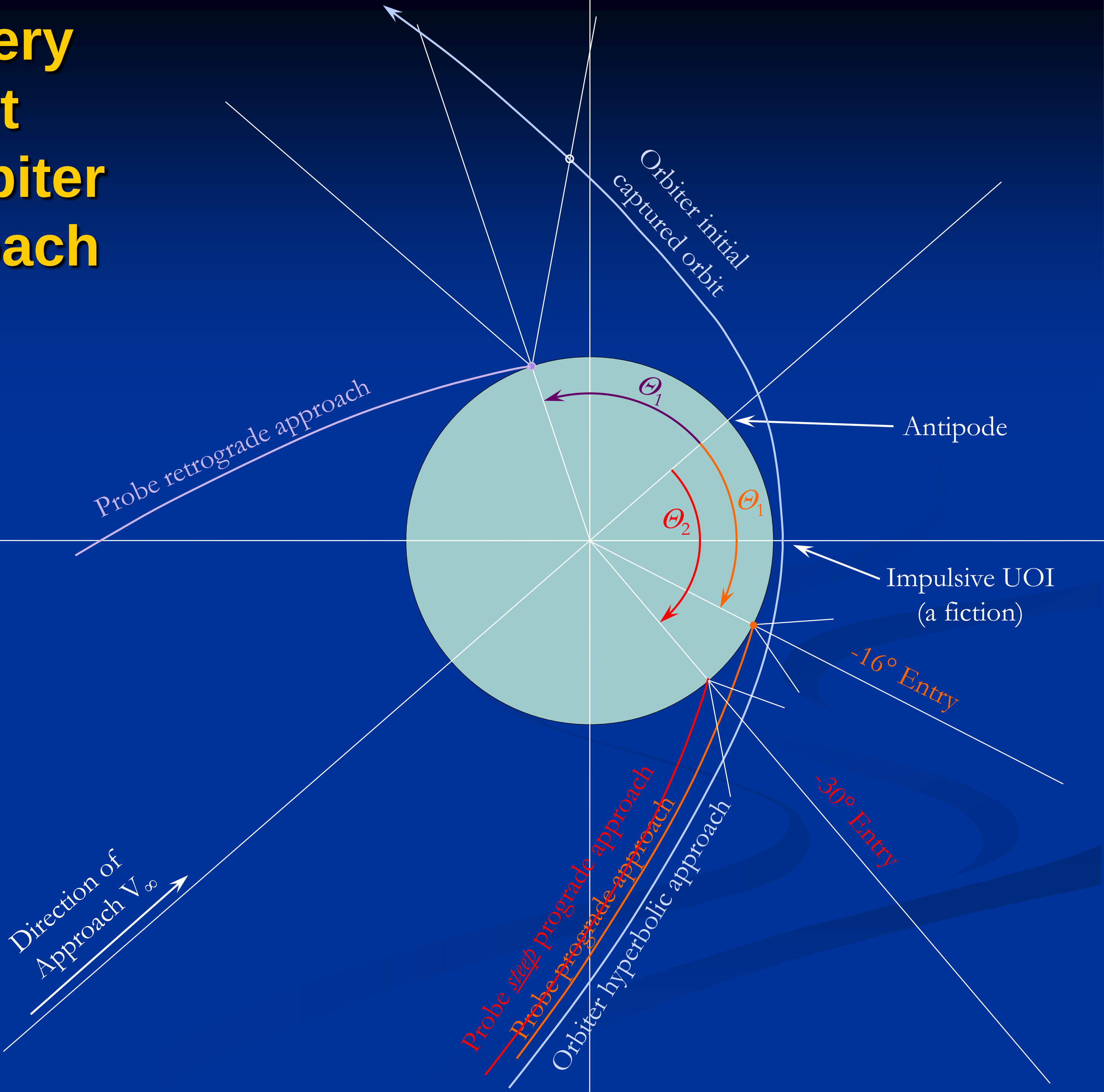
$$Mg = \frac{C_D}{2} A \rho V_{term}^2 \rightarrow V = \sqrt{\frac{2Mg}{C_D A \rho}}$$

$C_D A$ can't be too large and *M* can't be too small

But if *V* is large at 100 bars, it is *huge* shallow, possibly supersonic. This can cause measurement problems.

Descent times from the tropopause to the 100-bar level, for historical probe sizes & shapes & even relatively small parachutes, can be greater than 2 hours. *How long do we have?*

Probe Delivery And Support From an Orbiter Upon Approach



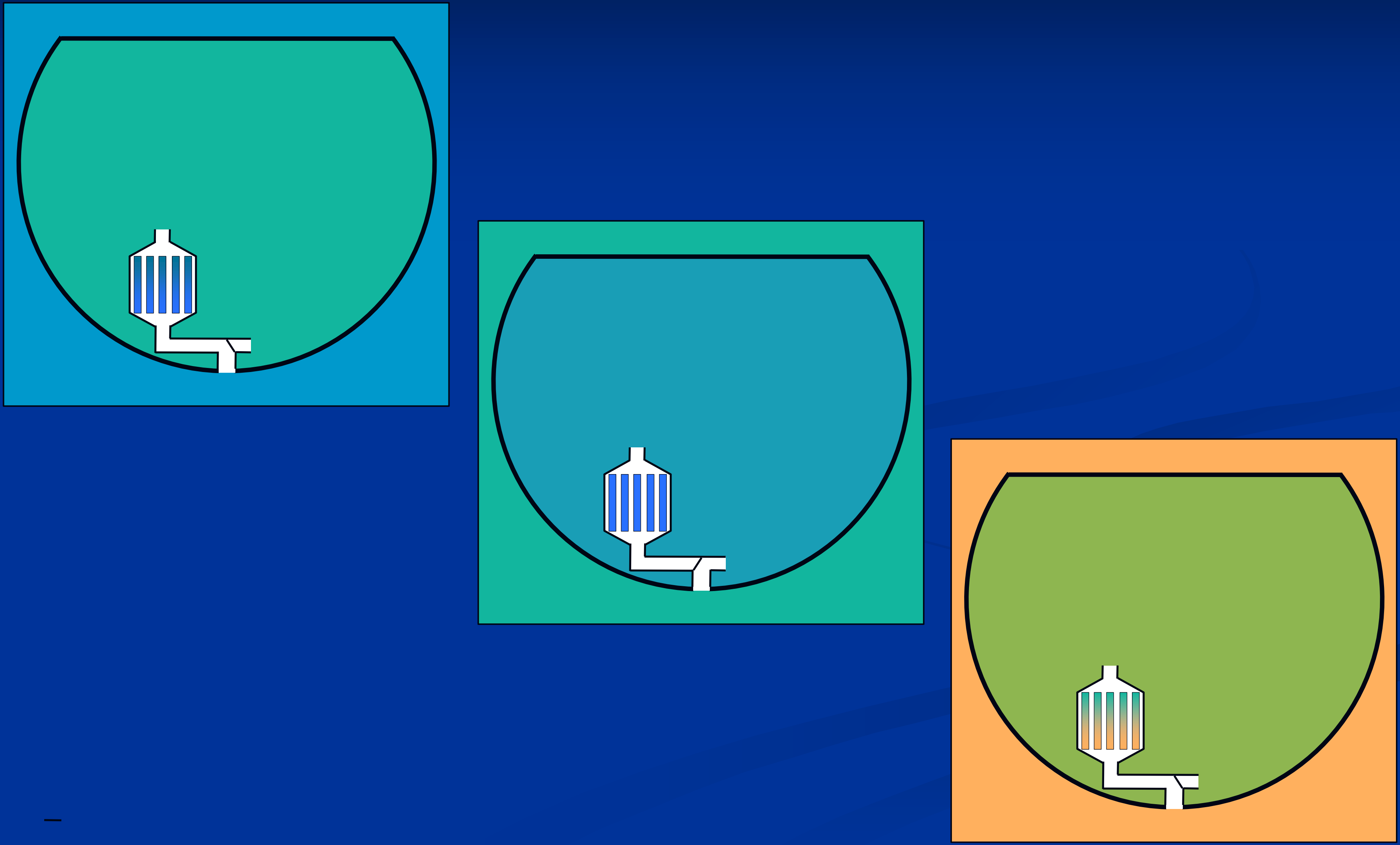
Options for Handling Pressure

- Global pressure vessels
  - Keep sensitive components at lower pressures
    - Must have penetrations: signals, and in some cases, samples
  - Not all components can be inside
    - Thermometers, composition instrument samplers, radio antennas
  - Can also aid with thermal control
- Component hardening
  - Custom packaging for chips
    - Must exhaust samples to very low-pressure sinks
  - Local pressure vessels
    - Standard packaging can have problems above ~20 bars

Options for Handling Extreme Temperatures

- Protect components from temperature extremes
  - Isolate with insulating materials
    - Duration of exposure becomes important
  - Control temperatures
    - Heaters
    - Thermal sinks
    - Phase change materials
  - Not usually a technology development
- Develop components less sensitive to temperatures
  - Electronic components
  - Polymers
  - Often involves technology development

Options for Handling Extreme Temperatures

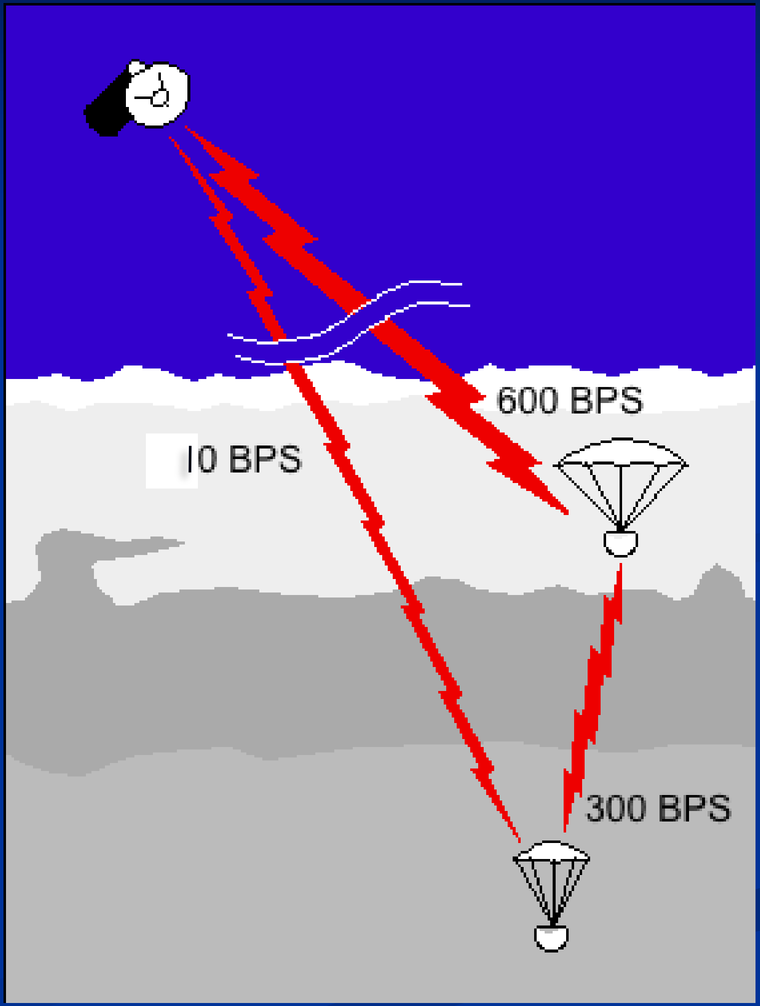


Options for Handling High Atmospheric Opacity

- Low-frequency radio
  - Decreased atmospheric opacity
  - Maintaining antenna gain & beamwidth requires larger antenna
    - Wind shear sufficient?
- High transmitted power
  - Requires larger batteries
  - Very high opacity requires impractical power levels
- Large Receiving Antenna
  - Adds mass to relay spacecraft
  - If larger than a launch vehicle fairing, must be deployable

Options for Handling High Atmospheric Opacity

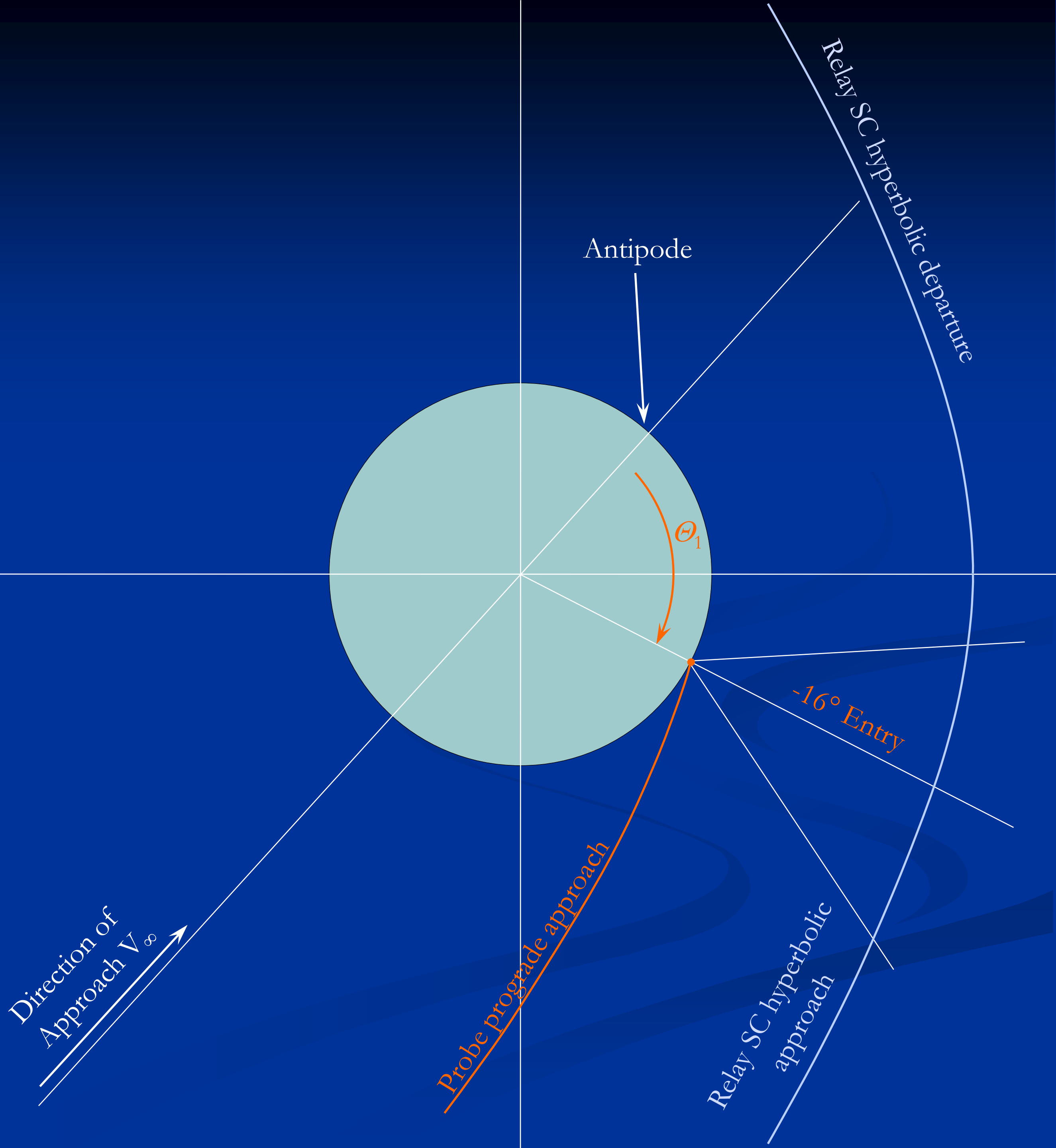
- Multiple descent modules
  - Deep probe relays through shallow
    - Separates opacity vs range
  - Separate entries?
    - Can give deep probe a “head start”
    - Difficult to orchestrate trajectories!
- *Staged Probe*
  - Entry in one entry vehicle
  - Very different ballistic coefficients
  - Can “tune” separation level
- Low-frequency radio
  - Both elements deploy long half-dipole antennas (wires)
  - Requires lateral separation
    - Wind shear sufficient?



Options for Handling Distance & Time Constraints

- Probe delivery from orbit
  - More flexibility in entry location, relay SC overflight geometry
    - If periapsis is low, not a lot better than delivery from approach
- Probe delivery from a flyby mission
  - More flexibility in relay SC periapsis radius

Probe Delivery And Support From a Flyby Mission



Options for Handling Distance & Time Constraints

- Probe delivery from orbit
  - More flexibility in entry location, relay SC overflight geometry
    - If periapsis is low, not a lot better than delivery from approach
  - More mass into orbit —> more orbit inser’n propellant, less sci payload
- Probe delivery from a flyby mission
  - More flexibility in relay SC periapsis radius
  - Can tune angular rates of RSC pass & planetary rotation
- Probe delivery from orbit, larger periapsis radius
  - Retains greater flexibility in entry location, relay SC overflight geometry
  - Similar to flyby RSC scenario: can tune angular rates
- Dedicated small RSC (CubeSat?) on flyby trajectory
  - Receives probe data directly, relays to orbiter
  - Uses flyby RSC trajectory; can tune angular rates
  - MarCO CubeSats demonstrated feasibility of this CubeSat architecture
  - More complex system architecture — increases total mission cost

Important Technologies

- Critical Technologies
  - Instruments robust to high inertial loads
    - Level depends on entry trajectory specifics
  - High-performance TPS materials
    - Materials available in US
    - With some development, materials available in Europe might be space-qualified (testing under appropriate conditions?)
    - Availability must be maintained

- Greatly Enhancing Technologies
  - Radioisotope heater units
    - Reduces probe battery mass
    - Reduces orbiter divert maneuver ΔV (thus propellant mass)
  - Low-mass survey composition instruments (e.g., mass spec)
    - Significant effect on probe total mass
    - “Front-end” (inlets, valves, enrichment cells) currently is most massive subsystem

Questions?

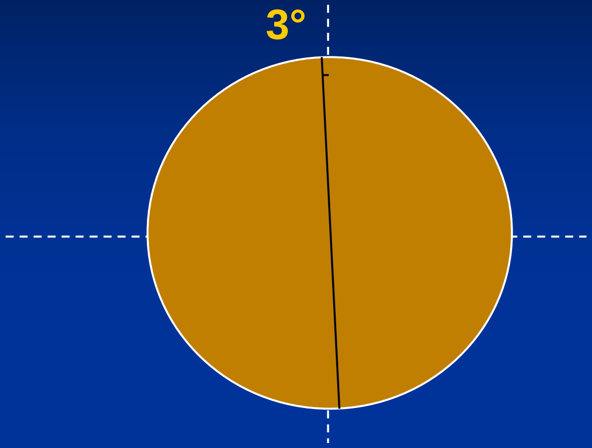
Bulk Characteristics of the Giant Planets

Characteristic Planet	Mass (Earth masses)	Equatorial radius (km)	Mean mass density (gm/cm^3)
Jupiter	317	71490	1.32
Saturn	95	60330	0.68
Uranus	14.5	25500	1.27
Neptune	17.1	24770	1.64

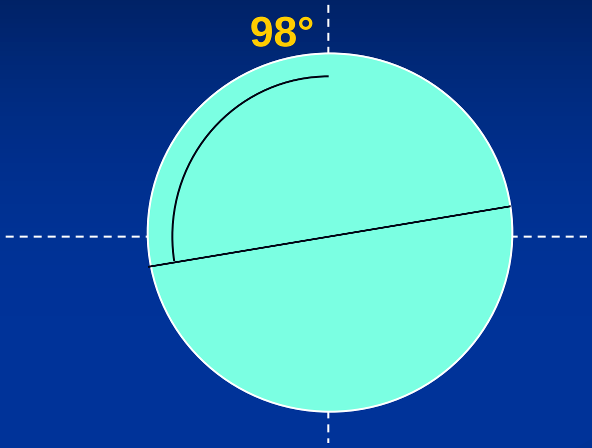
Bulk Characteristics of the Giant Planets

Characteristic / Planet	Atmospheric Helium Abundance	Icy Element Abundance (x Solar)	Tropopause Temperature (K)
Jupiter	11-12%	3-6	110
Saturn	13±5%	5-10?	90
Uranus	18%?	20-50?	50
Neptune	18%?	20-50?	50

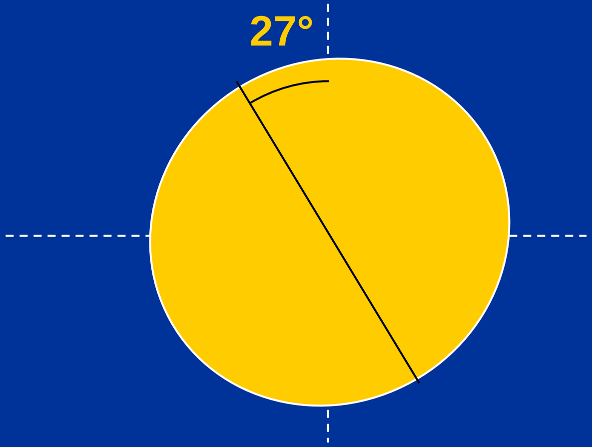
Obliquities of the Giant Planets



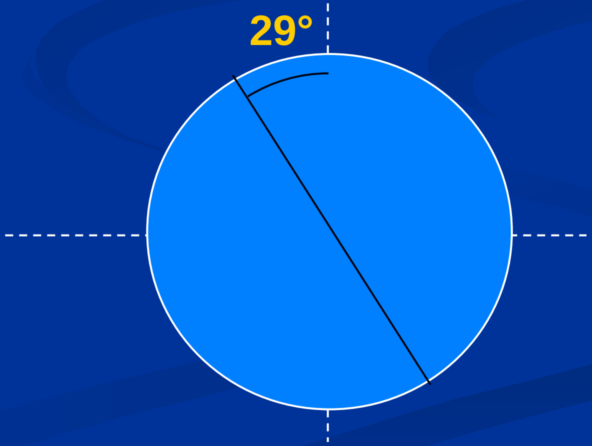
Jupiter



Uranus



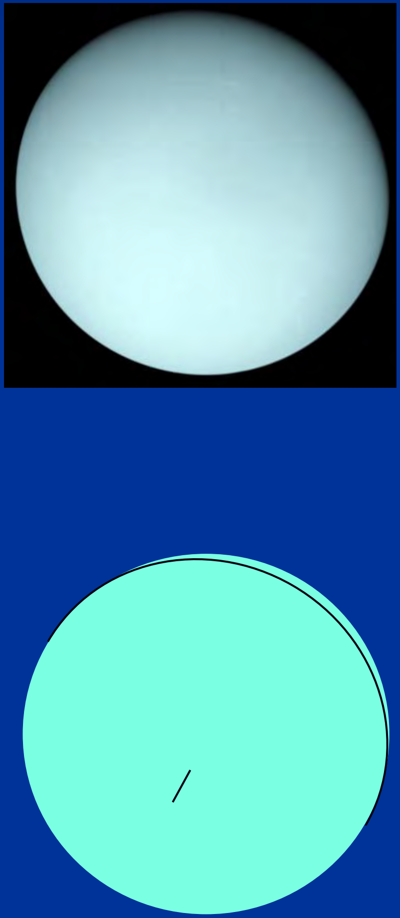
Saturn



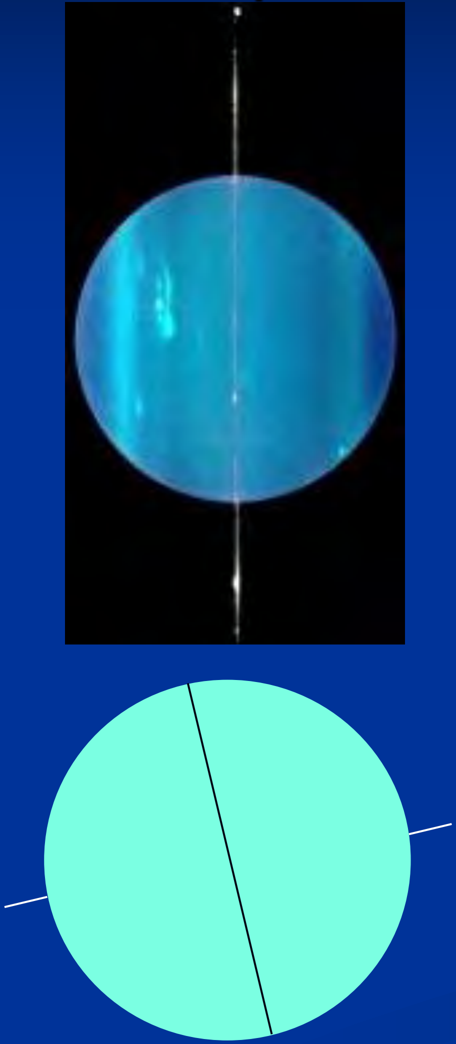
Neptune

Uranus Heliocentric Views With Time

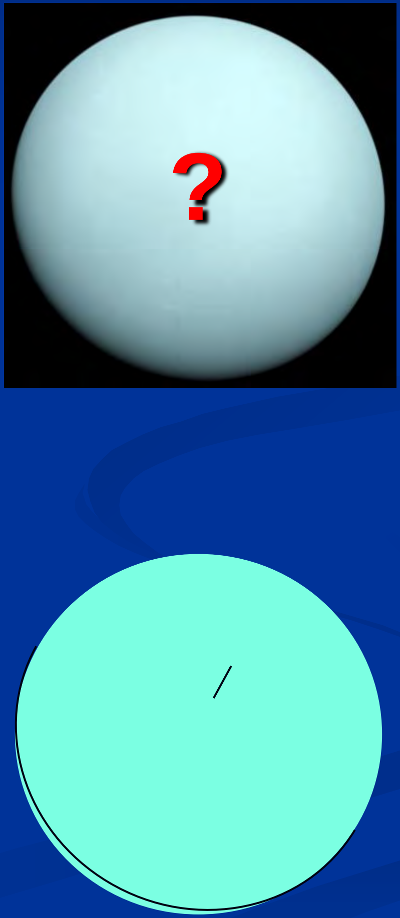
1986: *Voyager 2* View



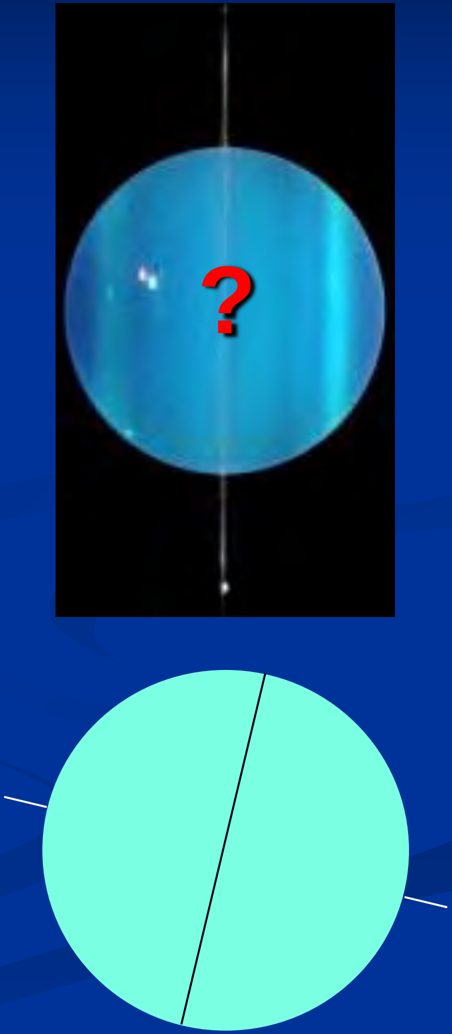
2007: Equinox



2028



2049: Equinox



Organization