Measurements to Constrain Uranus's Interior Structure

Credit: Quanta Magazine

Krista Soderlund

KISS Short Course:

What Do We Know About Uranus's Interior? Preparing for a Mission to Uranus

TEXAS Geosciences
The University of Texas at Austin
Jackson School of Geosciences
Institute for Geophysics

11 September 2023

Outline

- Techniques traditionally used to infer giant planet interior structure
  - Voyager 2 observations
  - Old data, new analyses
- New and emerging techniques
  - Lessons from Jupiter, Saturn, and exoplanets
- Knowledge gaps that limit our ability to interpret measurements

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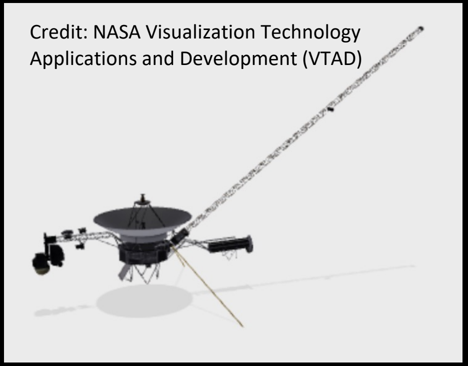
Traditional Techniques

- Voyager 2
  1) Imaging Science System (ISS)
  2) Ultraviolet Spectrometer (UVS)
  3) Infrared Interferometer Spectrometer (IRIS)
  4) Planetary Radio Astronomy Experiment (PRA)
  5) Photopolarimeter (PPS)
  6) Triaxial Fluxgate Magnetometer (MAG)
  7) Plasma Spectrometer (PLS)
  8) Low-Energy Charged Particles Experiment (LECP)
  9) Plasma Waves Experiment (PWS)
  10) Cosmic Ray Telescope (CRS)
  11) Radio Science System (RSS)


Credit: NASA Visualization Technology Applications and Development (VTAD)

Traditional Techniques

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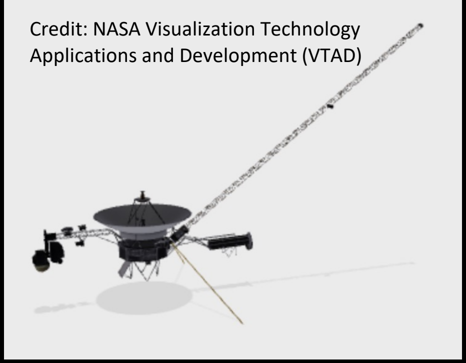
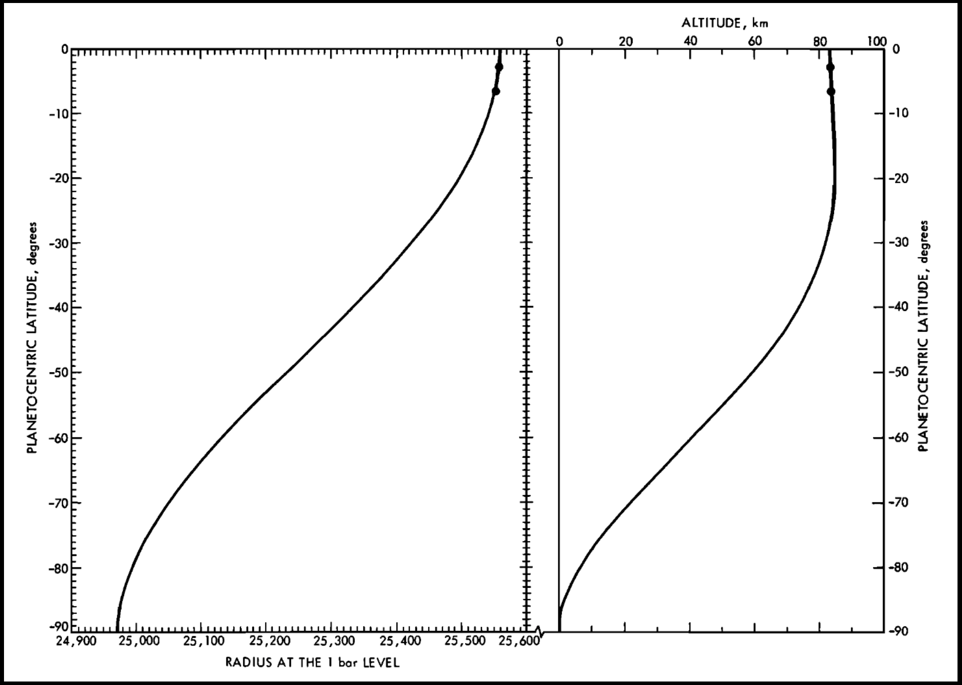


Physical Shape

- Voyager 2 at Uranus
  - Physical shape via radio occultations near the equator and extrapolated to the poles using gravity field data and zonal winds

Radio Science System



Credit: Lindal et al. 1987

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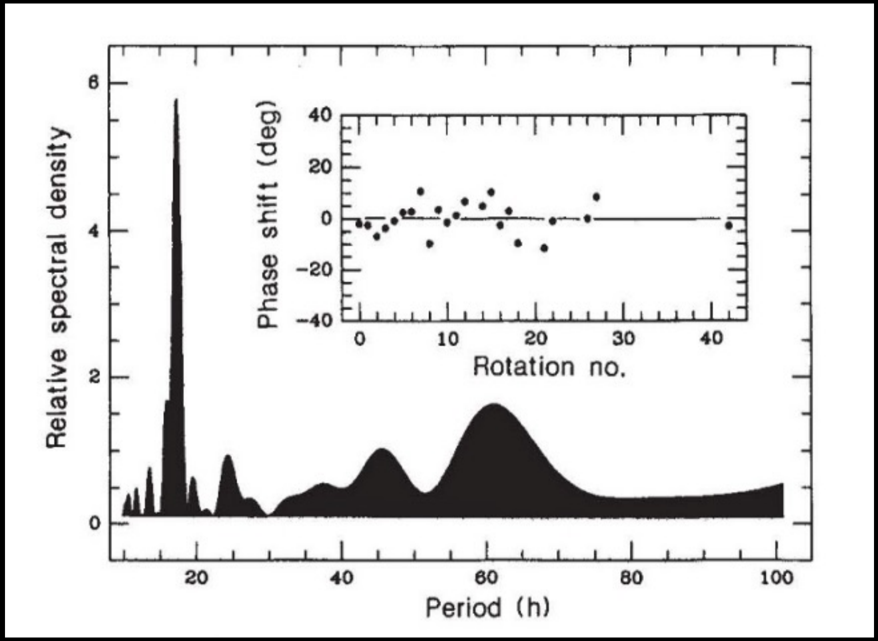
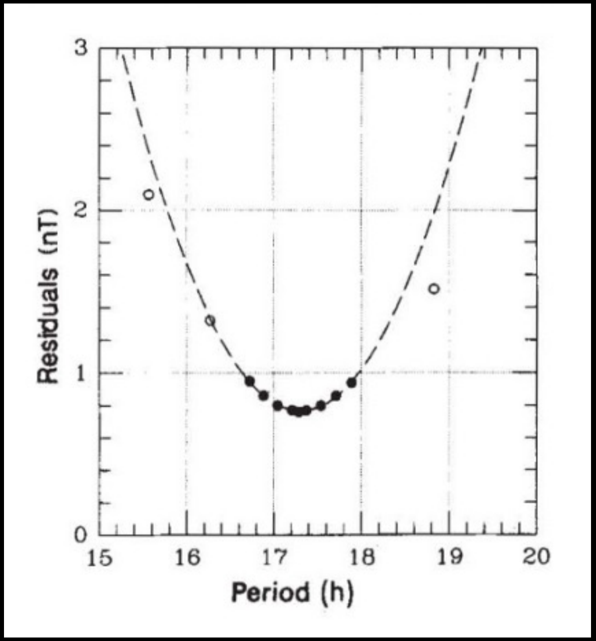
Rotation Period

- Voyager 2 at Uranus
  - Rotation period of 17.24 hours via radioastronomy and 17.29 hours via magnetometer observations

Planetary Radio Astronomy Experiment



Triaxial Fluxgate Magnetometer



Credit: Desch et al. 1986

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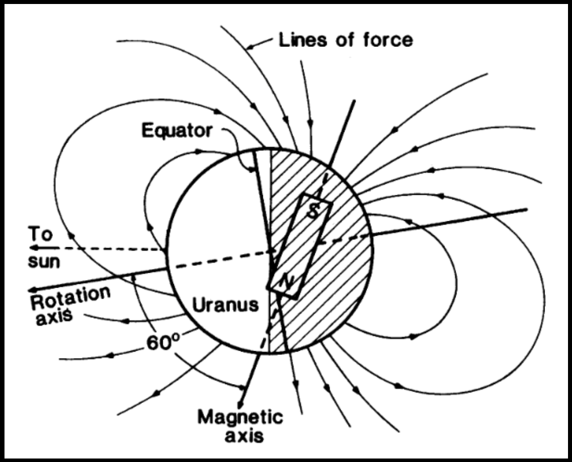
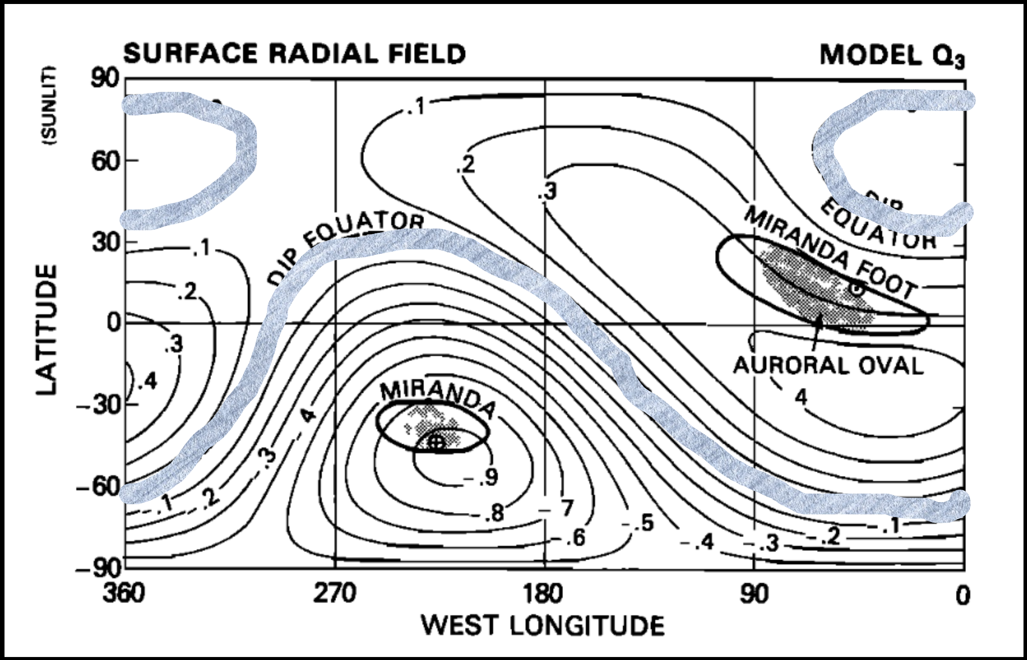
Intrinsic Magnetic Field

- Voyager 2 at Uranus
  - Magnetic field far from the planet can be approximated by an offset tilted dipole
  - Magnetic field has a large dipole tilt and unusually large quadrupole component

Triaxial Fluxgate Magnetometer



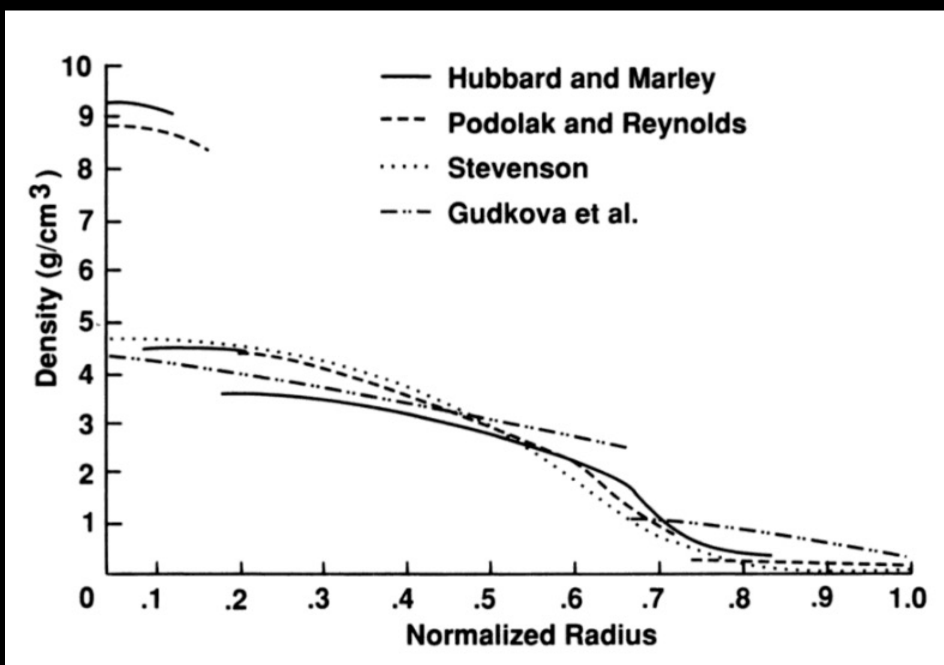


Credit: Ness et al. 1986

Credit: Connerney et al. 1987

Internal Structure

- Voyager 2 at Uranus
  - Internal structure models use gravitational moments to infer the density distribution within the planet
  - Even if the density profile is well determined, its implications for composition and temperature are not unique



Credit: Podolak et al. 1991

Radio science subsystem

TABLE I
Pressure Density Relation for Rock-Gas Mixtures

Pressure (Mbar)	Density (g cm^{-3})			
	Pure Ice	0.8 Rock 0.2 Gas	0.75 Rock 0.25 Gas	0.7 Rock 0.3 Gas
0.25	1.37	1.61	1.32	1.16
0.50	1.75	1.99	1.72	1.48
1.00	2.18	2.56	2.19	1.92
2.00	2.79	3.31	3.85	2.51
4.00	3.81	4.26	3.72	3.31
8.00	5.30	5.75	5.20	4.55

Credit: Podolak et al. 1991

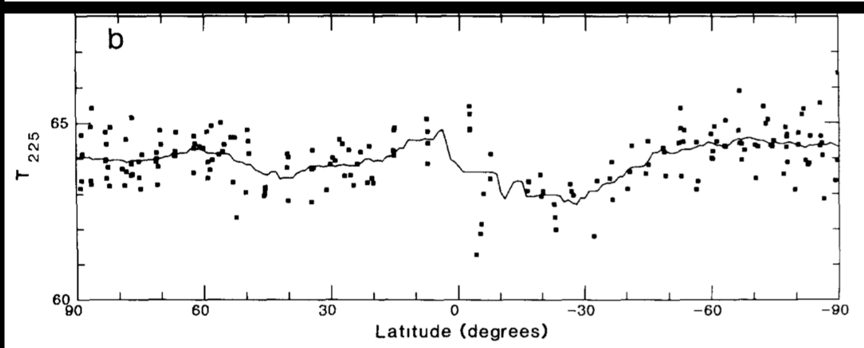
Energy Balance

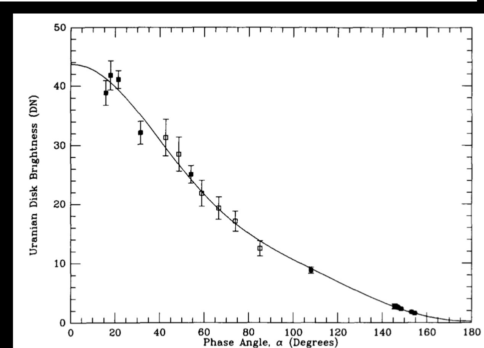
- Voyager 2 at Uranus
  - Energy balance (ratio of emitted thermal flux to the absorbed solar flux) suggests a relatively weak internal heat source
  - Nearly uniform latitudinal distribution of atmospheric temperatures

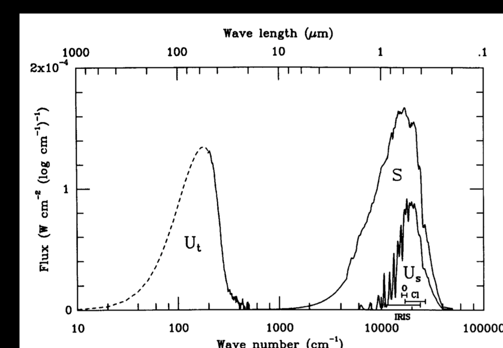
DETERMINATIONS OF THE ALBEDO AND ENERGY BALANCE OF URANUS

Reference	p	q	A	T_{eff}	Energy balance
Lockwood *et al.* (1983)	0.262 ± 0.008[a]	$1.50^{+0.14}_{-0.17}$	0.348 – 0.430	57.0 ± 2.5[b]	<1.24
Neff *et al.* (1985)	0.28 ± 0.02[a]	1.2	0.34 ± 0.02	58.6 ± 2.0[c]	<1.48
Pollack *et al.* (1986)[d]	0.253 ± 0.046	1.26 ± 0.11	0.319 ± 0.051	57.7 ± 2.0[e]	<1.27
This investigation[d]	0.215 ± 0.046	1.40 ± 0.14	0.300 ± 0.049	59.1 ± 0.3	<1.14

Infrared spectrometer and radiometer





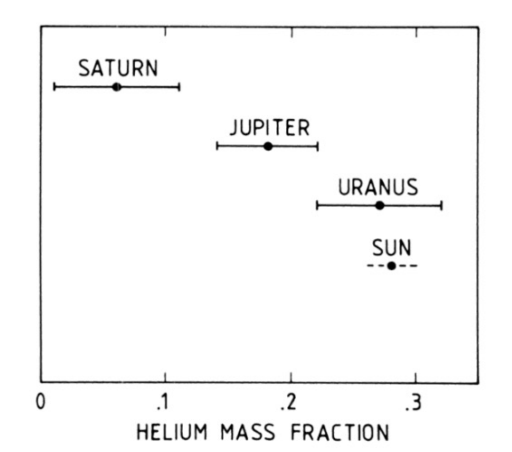


Credit: Pearl et al. 1990

Credit: Pearl et al. 1990

Atmospheric Composition

- Voyager 2 at Uranus
  - Observations covering the UV, visible, infrared, and radio wavelength regions imply that Uranus' atmosphere is enriched in heavy elements relative to solar composition
    - CH_4 /H_2 volume mixing ratio was enhanced ~24 times solar
    - NH_3/H_2 volume mixing ratio was depleted ~100-200 times solar
    - He mole fraction suggests helium differentiation has not occurred
    - H_2O/H_2 mixing ratio was estimated to be ~9%



Credit: Fegley et al. 1991

Infrared Interferometer Spectrometer & Ultraviolet Spectrometer

Molecule	Column Abundance[a] (cm am)	Volume Mixing Ratio[b]	Reference
NH_3	5	1.6×10^{-7}	Fink & Larson 1979
H_2S	30	1.0×10^{-6}	
C_2H_4	20	6.7×10^{-7}	
CH_3NH_2	10	3.3×10^{-7}	
CO	—	2×10^{-4}	Caldwell et al. 1981
CO	—	1×10^{-6}	de Bergh et al. 1985

Credit: Fegley et al. 1991

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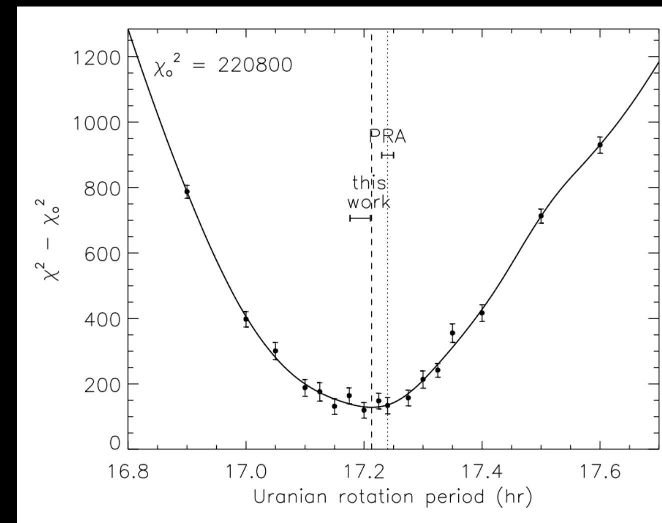
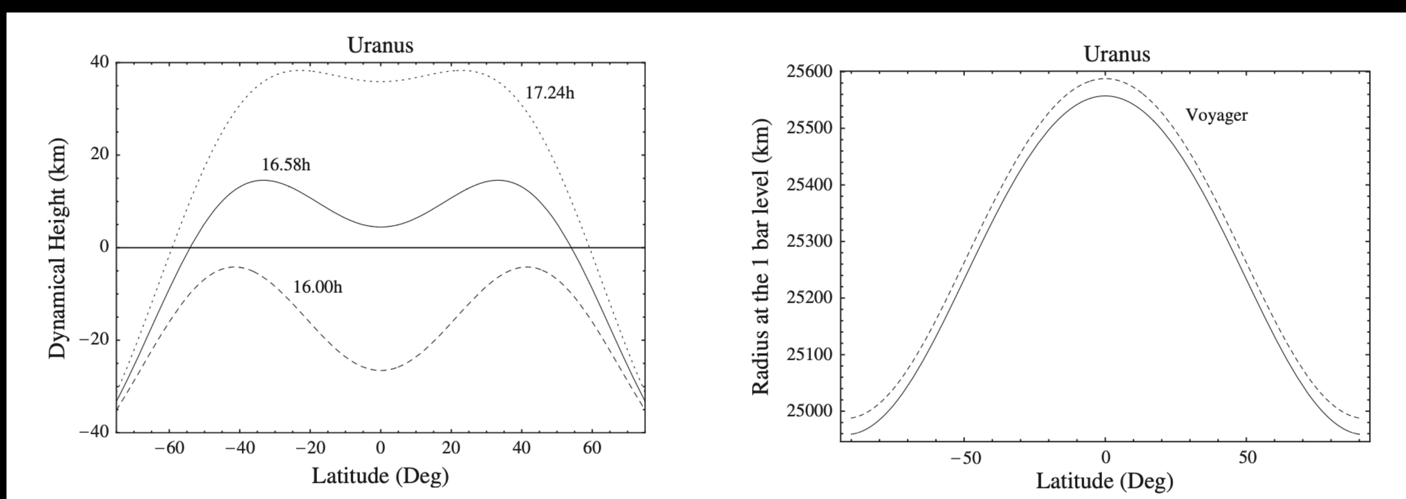
Shape and Rotation Period

- Minimization of dynamic heights of the 1 bar isosurfaces leads to rotation period of 16.58 hours
  - Slower than that estimated previously by radio occultations, magnetic field data, and UV spectrometer data of ~17.2 hours
  - Implications for gravity data interpretation and zonal flows



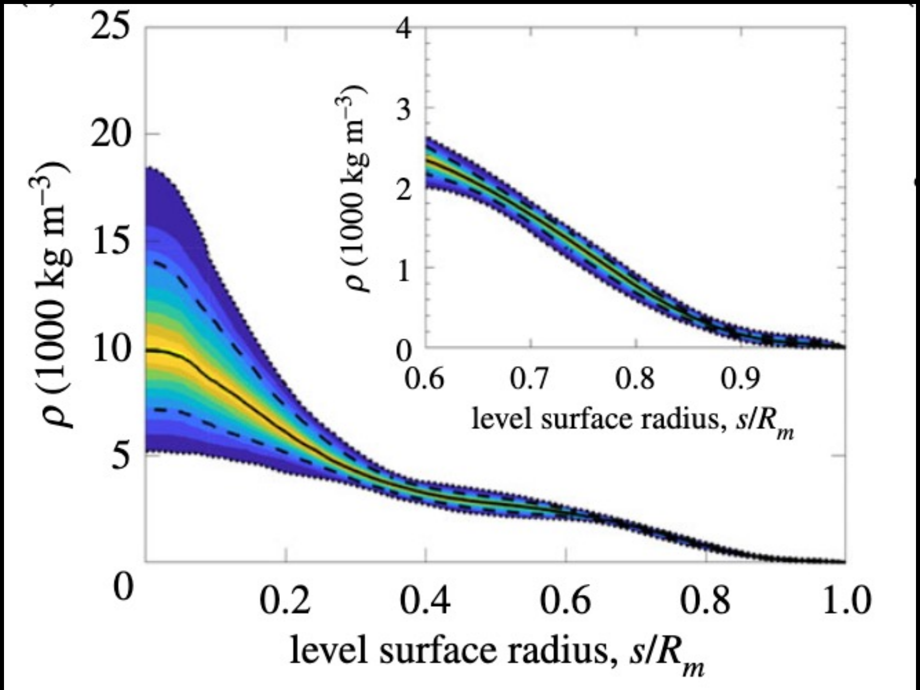


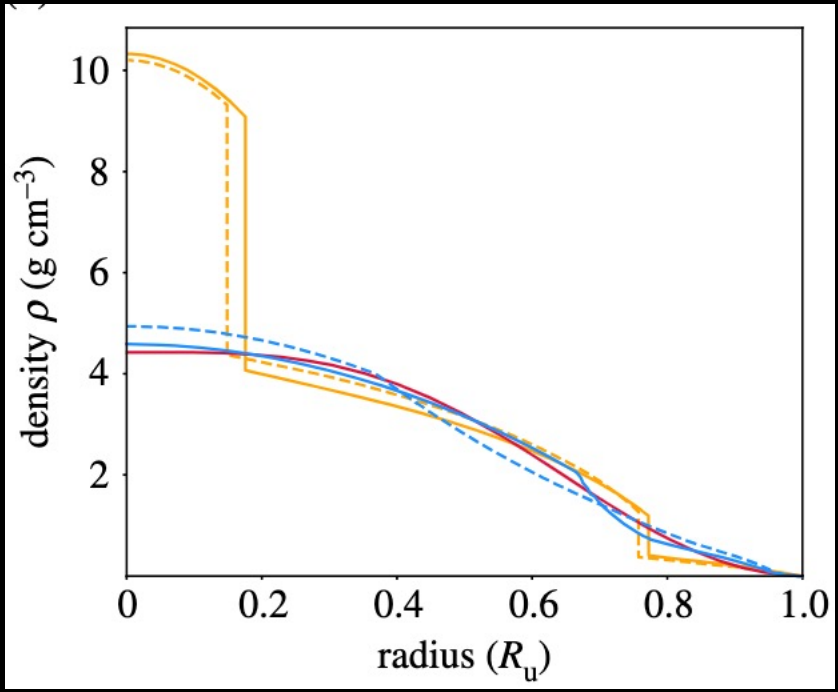
Credit: Helled et al. 2010

Credit: Herbert 2009

Internal Structure

- Composition-agnostic models of density distribution
- Moving away from three-layer models to continuous models with improved equations of state





Credit: Helled et al. 2020

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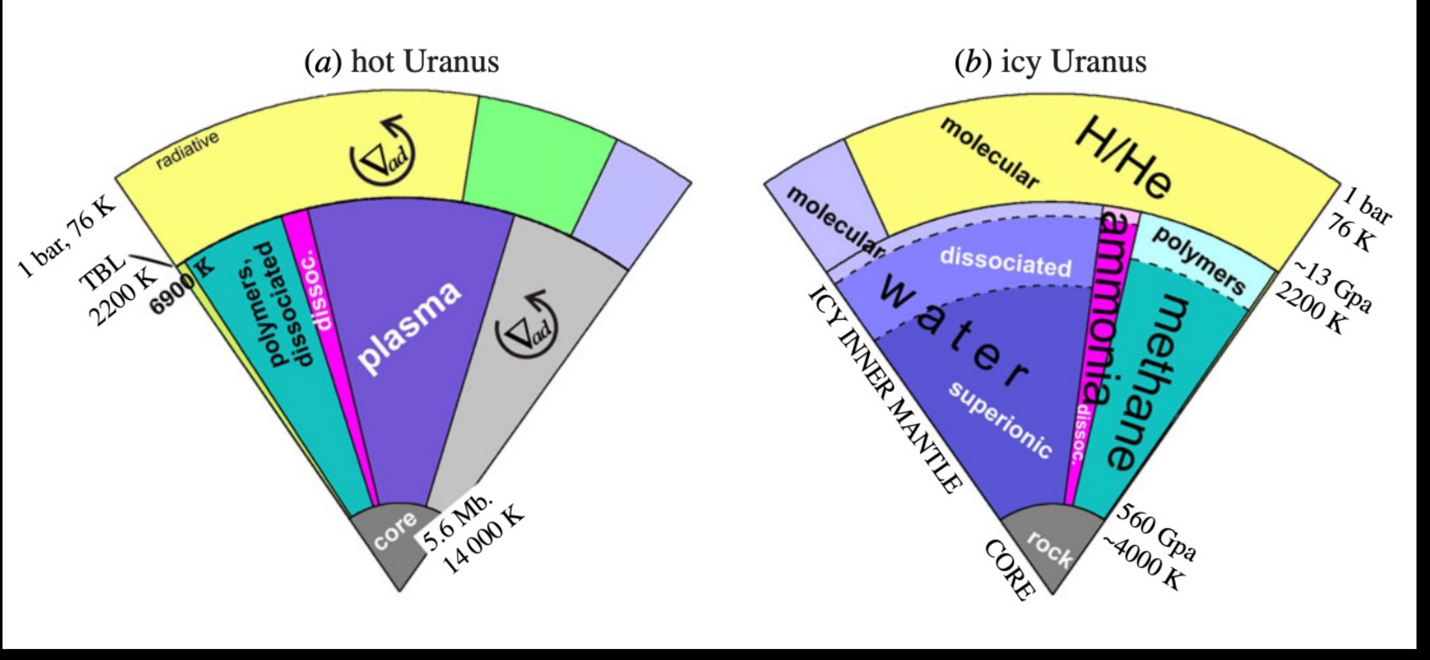
Internal Structure

- Composition-agnostic models of density distribution
- Moving away from three-layer models to continuous models with improved equations of state
- Moving towards models with non-adiabatic regions

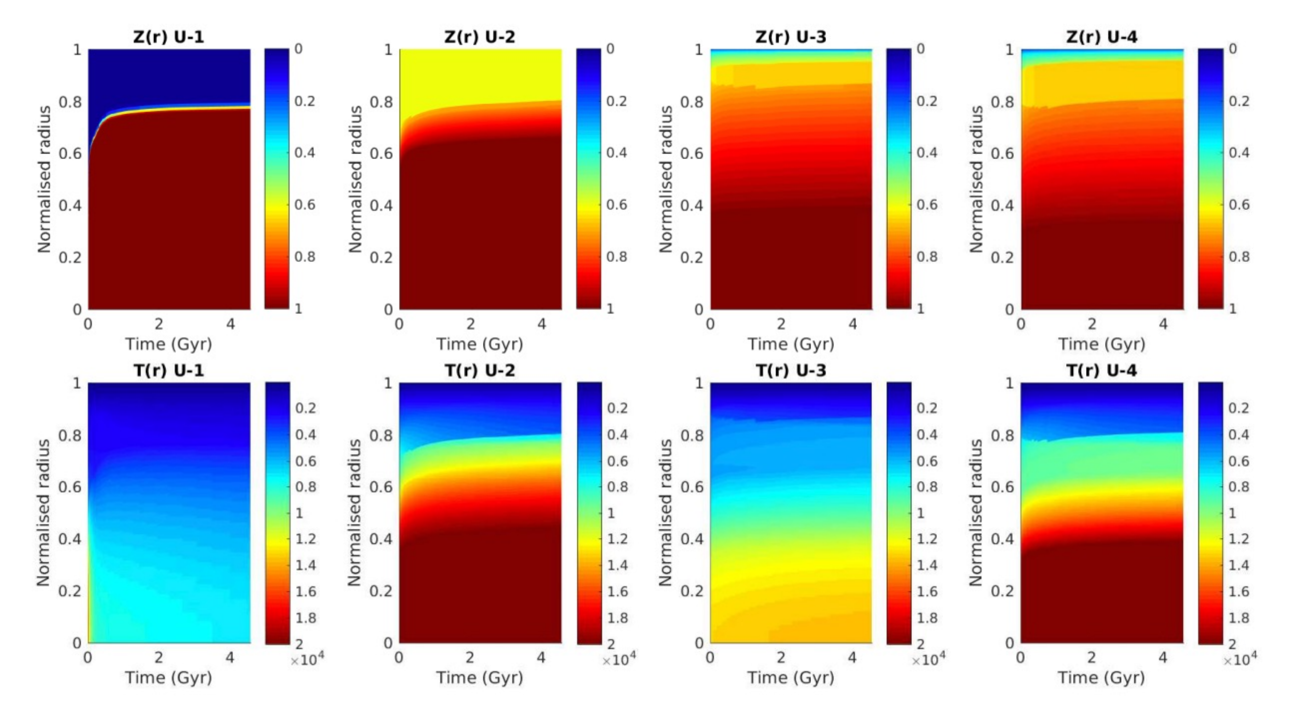


Credit: Nettelmann et al. 2016

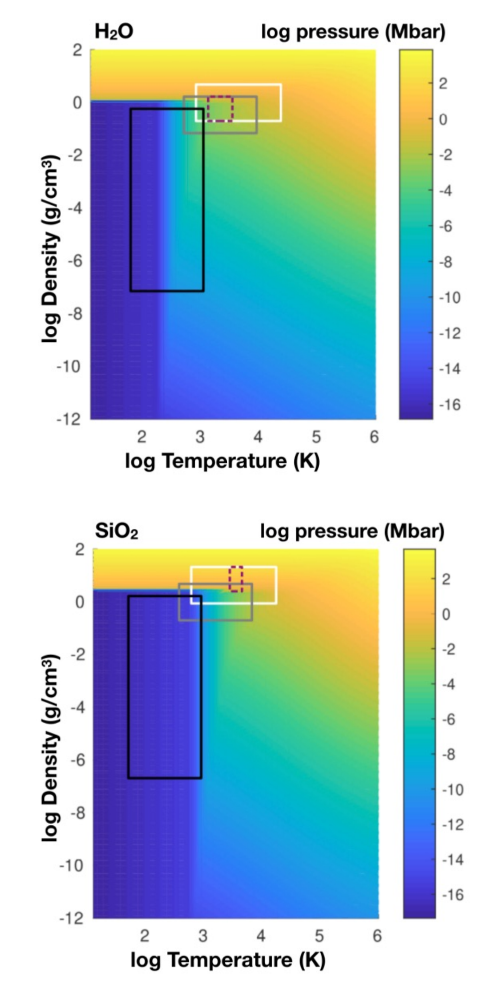
Credit: Bethkenhagen et al. 2017

Internal Structure

- Models with non-adiabatic regions, including their evolution over time
  - Mixtures of water and rock



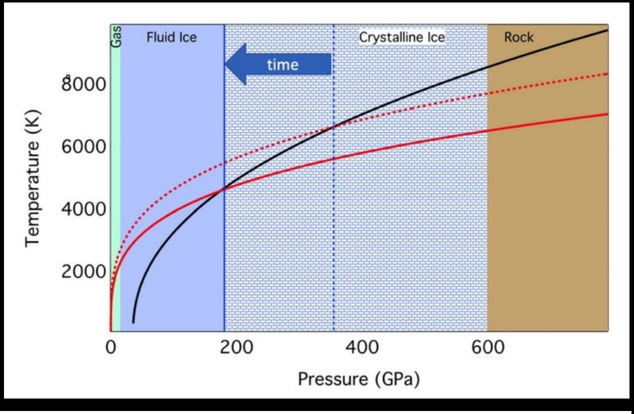
Credit: Vazan & Helled 2020

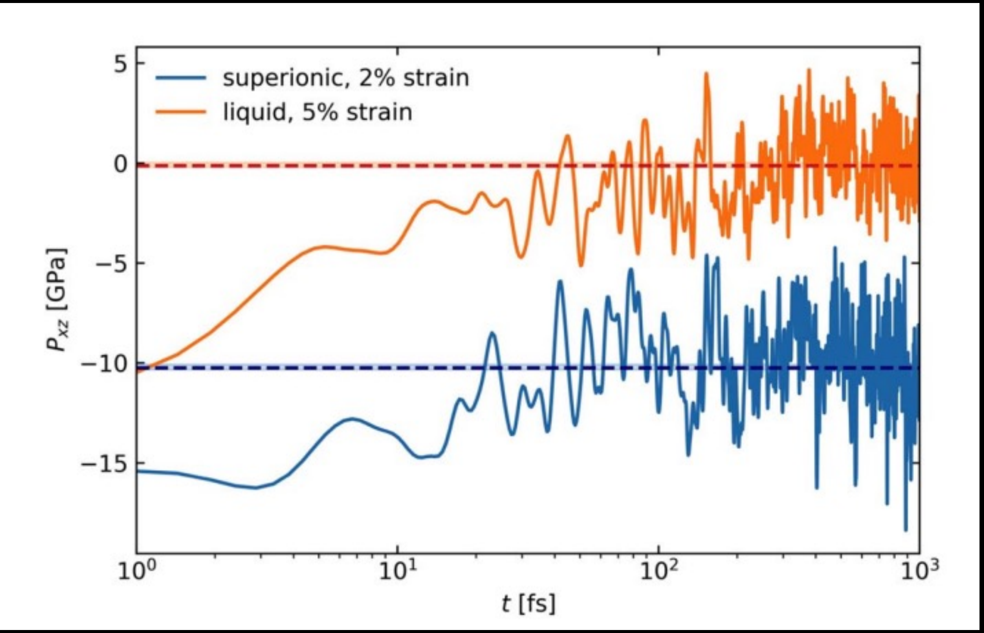


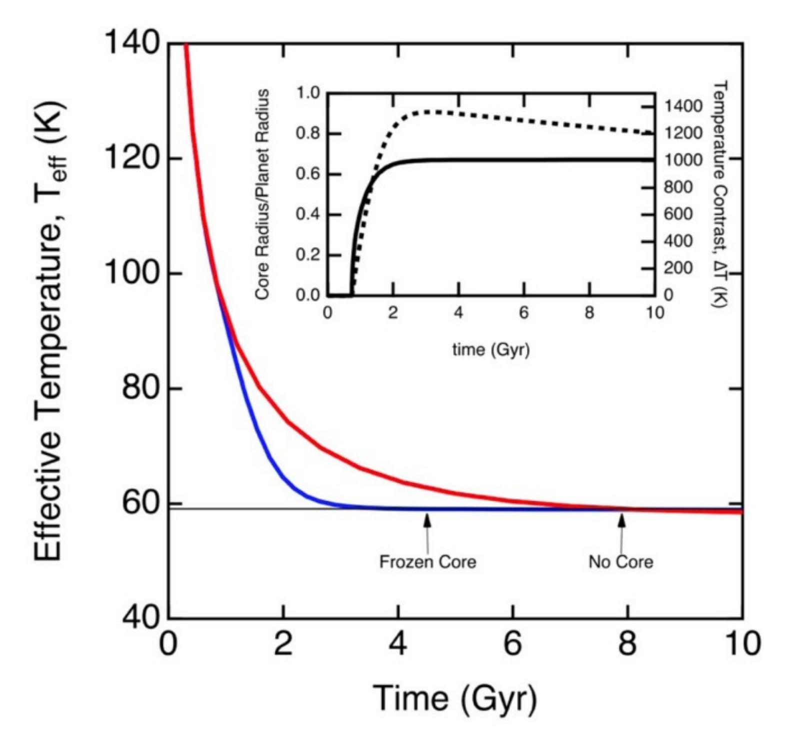
Credit: Vazan & Helled 2020

Internal Structure

- Models with non-adiabatic regions, including their evolution over time
  - Growing frozen core of superionic ice





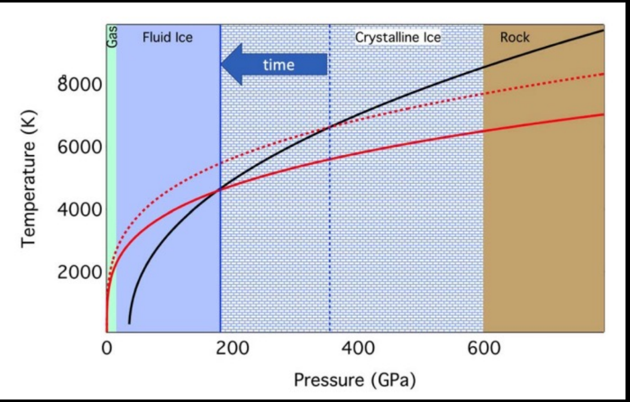


Credit: Stixrude et al. 2021

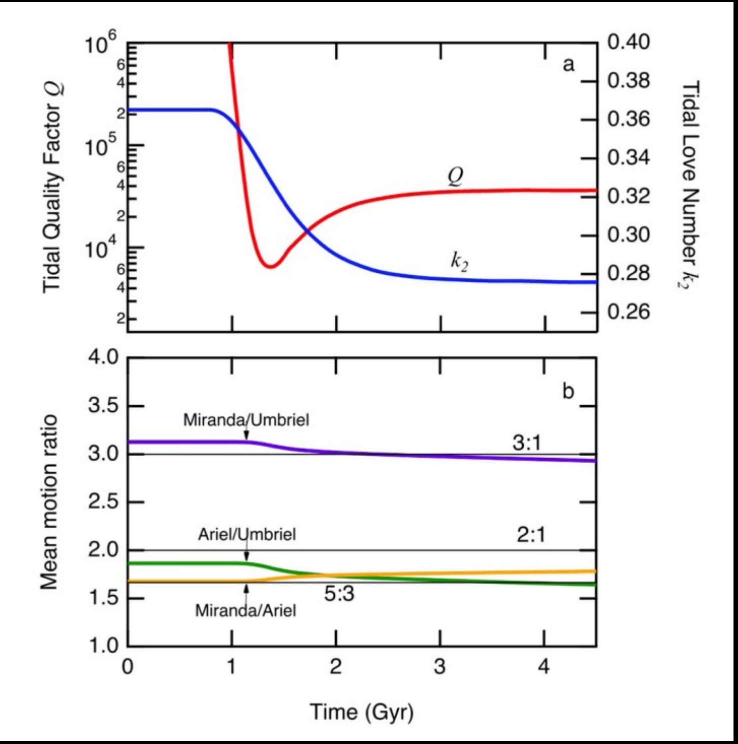
Credit: Stixrude et al. 2021

Satellite Orbits

- Models with non-adiabatic regions, including their evolution over time
  - Growing frozen core of superionic ice



- Predicts time-varying tidal dissipation that matches the requirements of the orbits of Miranda, Ariel, and Umbriel
  - Testable predictions include the tidal Love number of Uranus and the current recessional rates of its moons



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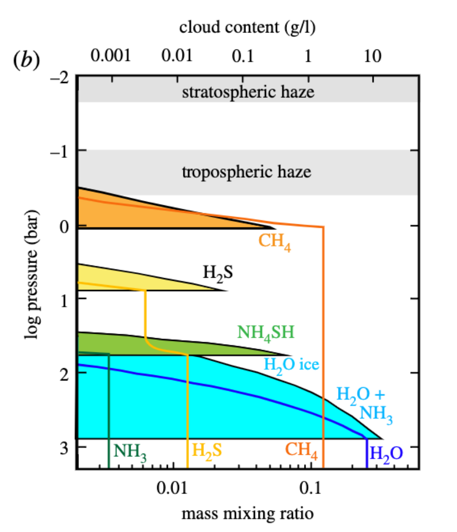
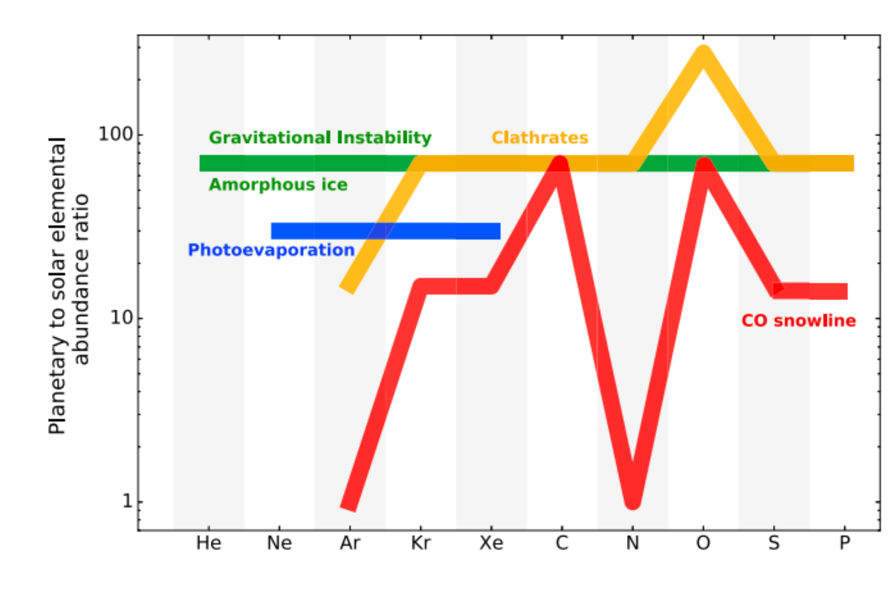
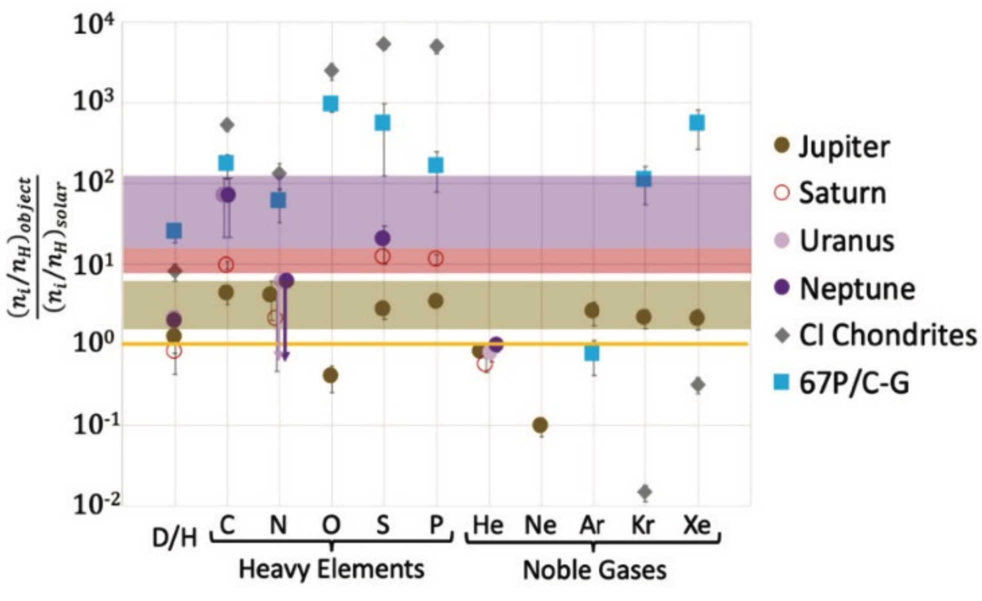
Atmospheric Composition

- Different formation scenarios have distinct predictions for enrichments in volatiles compared to solar abundances





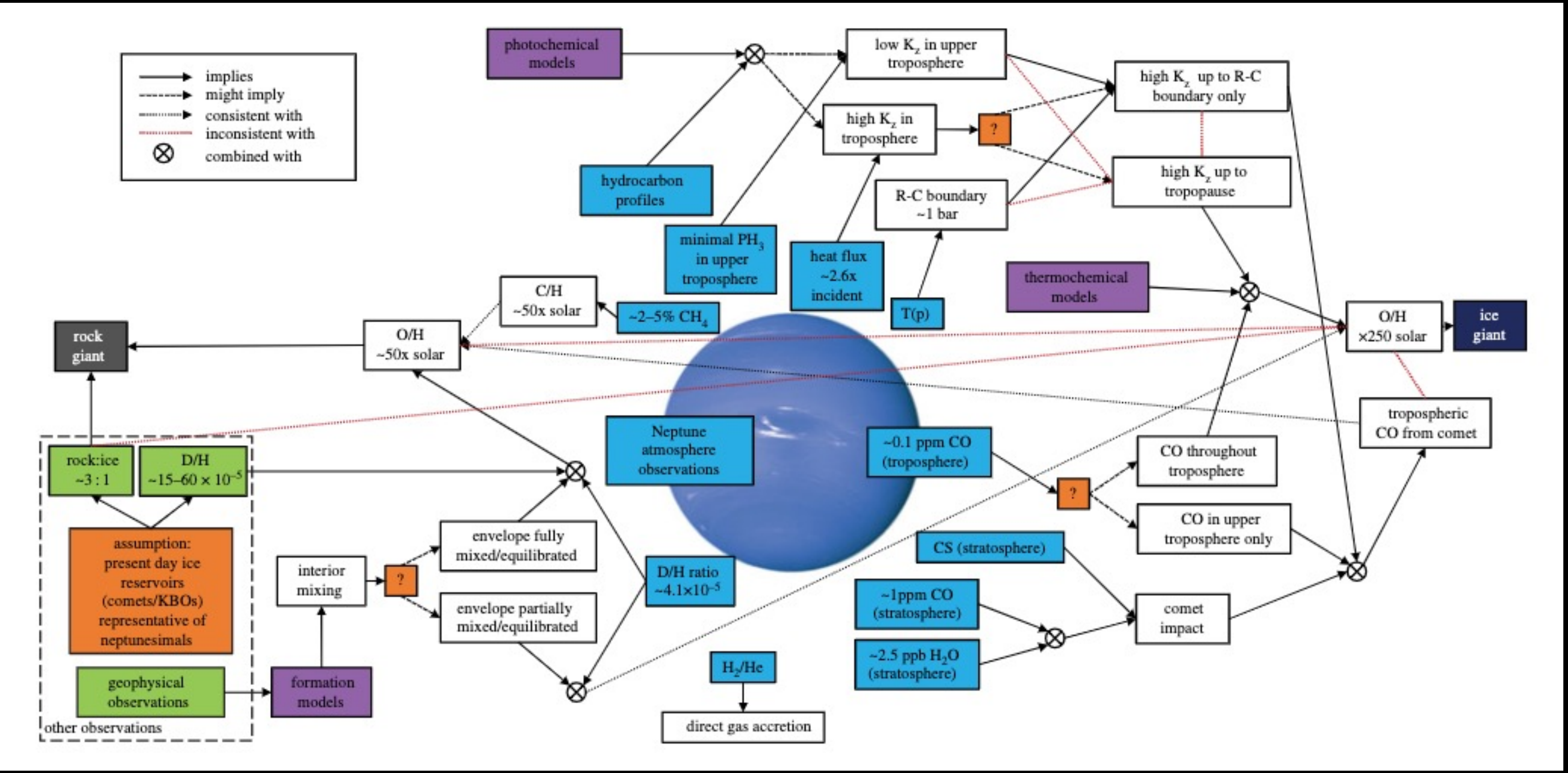


Credit: Mousis et al. 2018

Credit: Moses et al. 2020

Atmospheric Composition

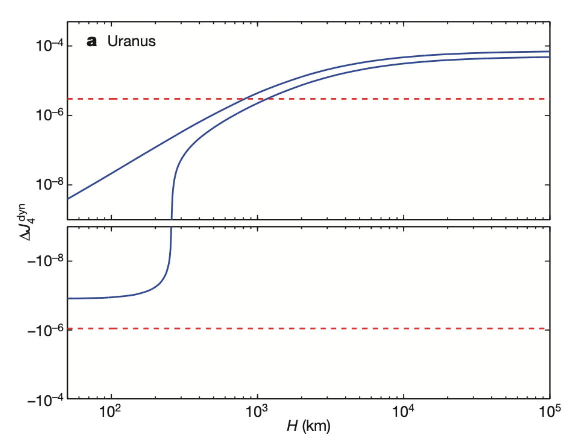
- Rock giant and ice giant scenarios with various degrees of interior mixing can fit the observed fundamental physical properties

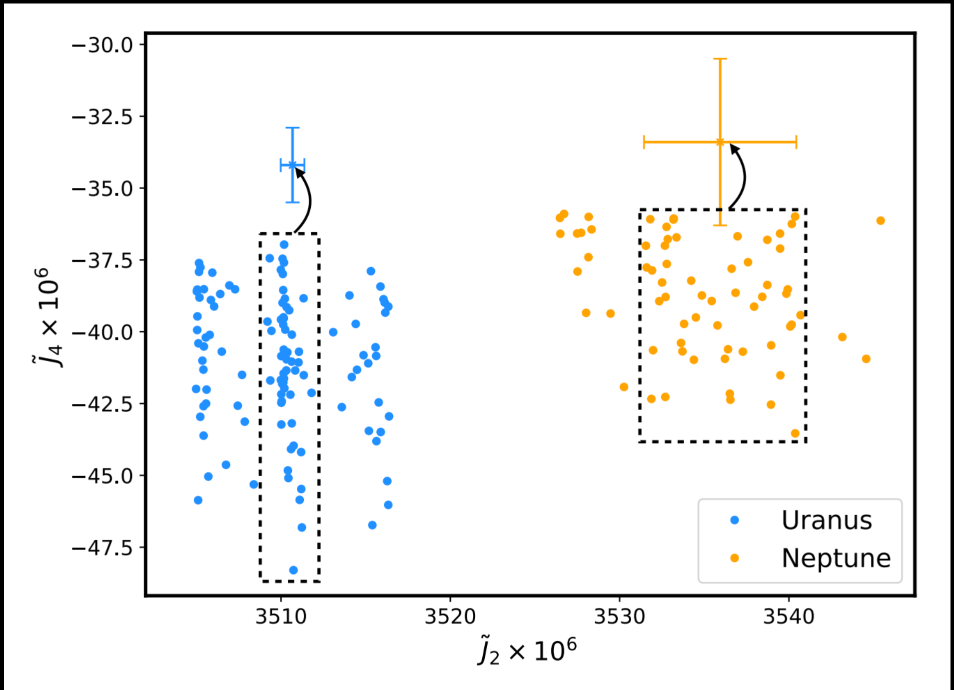


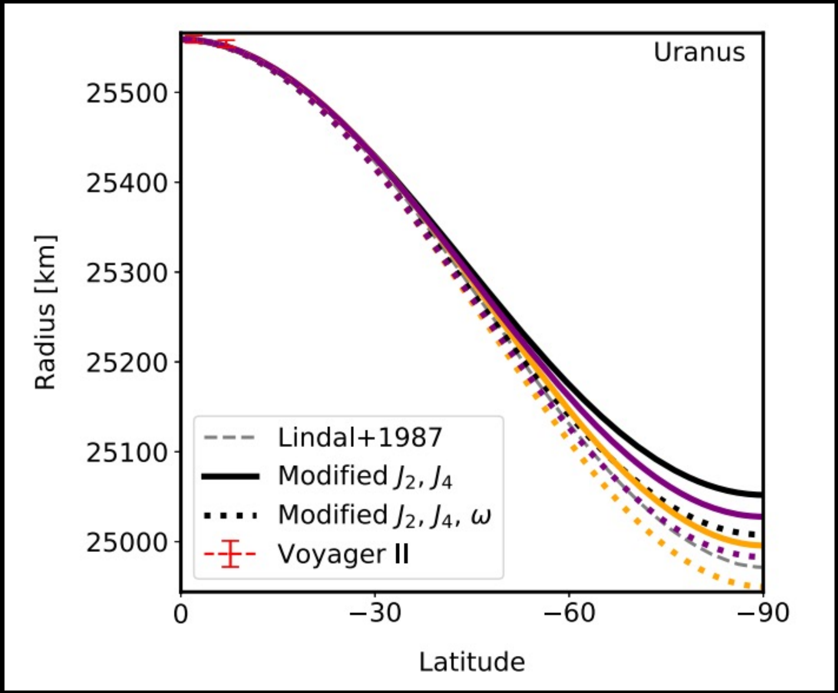
Credit: Teanby et al. 2020

Zonal Wind Depth

- Zonal winds likely confined to outer 2-3% of the planet using gravity, shape, and rotation rate measurements





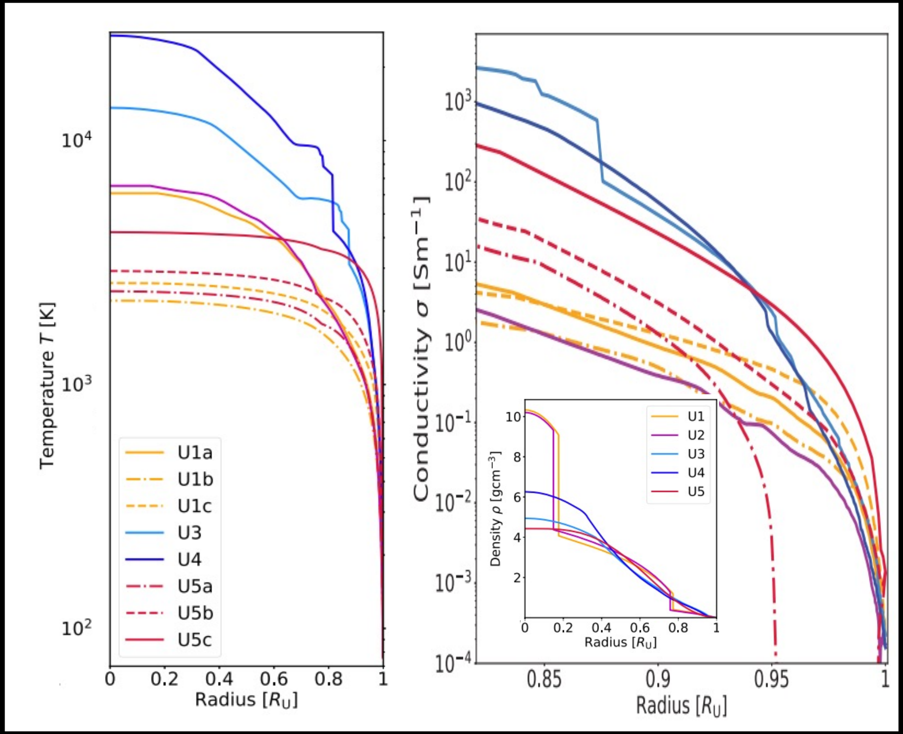


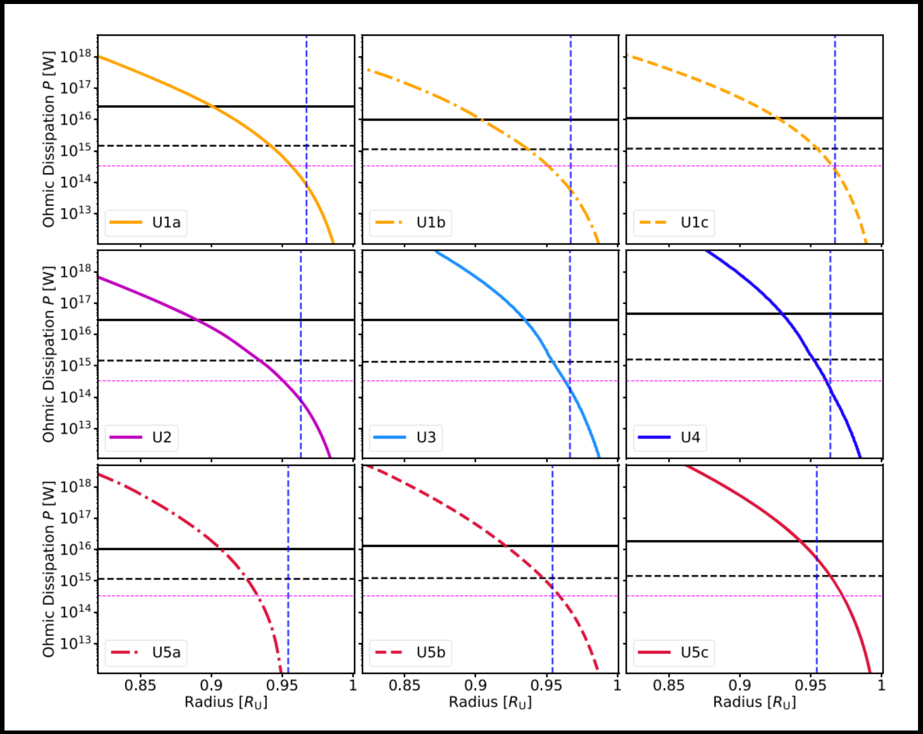
Credit: Soyuer et al. 2023

Credit: Kaspi et al. 2013

Zonal Wind Depth

- Zonal winds likely confined to relatively shallow outer region of the planet using estimates of Ohmic dissipation and electrical conductivity measurements
  - Detectable magnetic field perturbation (Soyuer et al. 2021)?



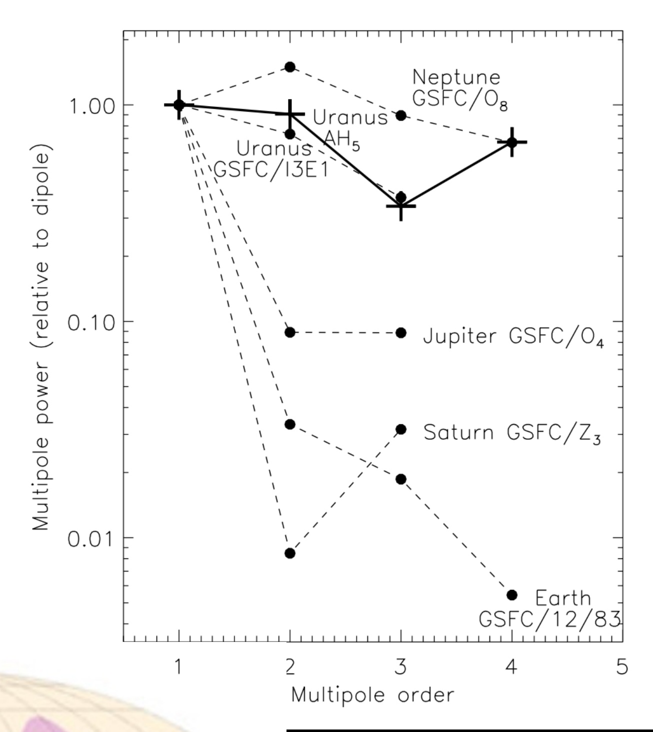


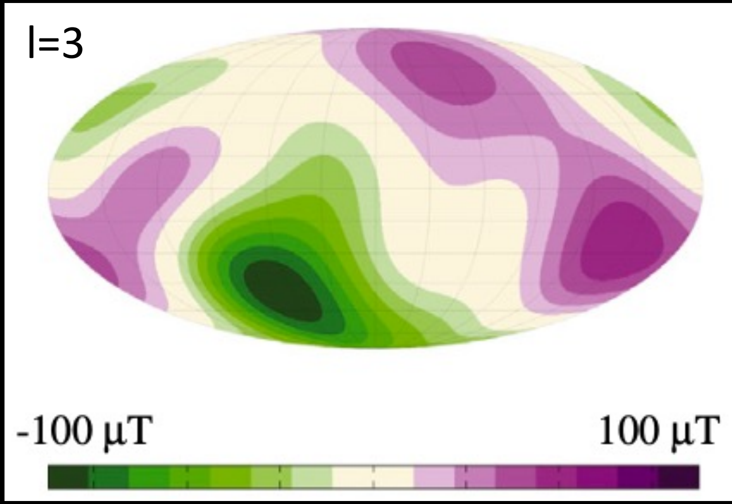
Credit: Kaspi et al. 2013

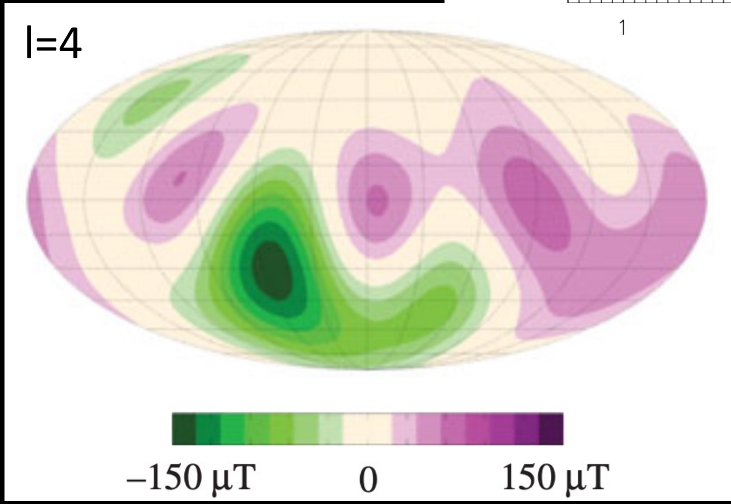
Credit: Soyuer et al. 2020

Magnetic Field

- Auroras at the magnetic field line footprints serve as additional constraints to determine the higher multipole moments of the intrinsic dynamo





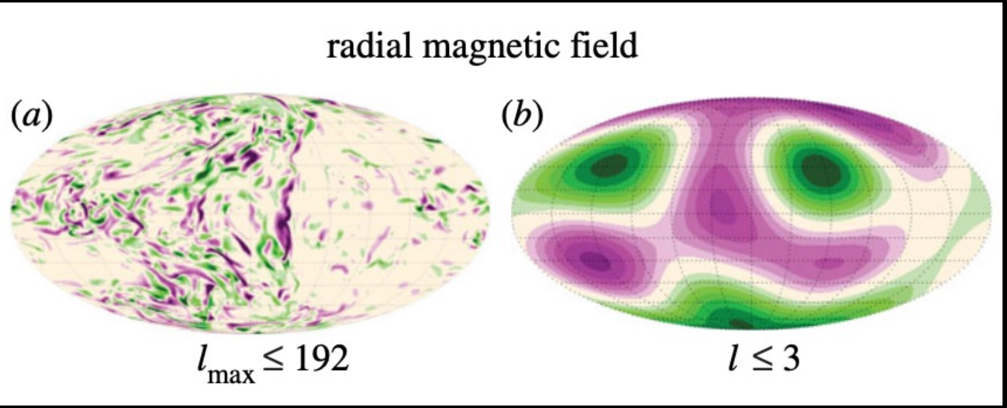


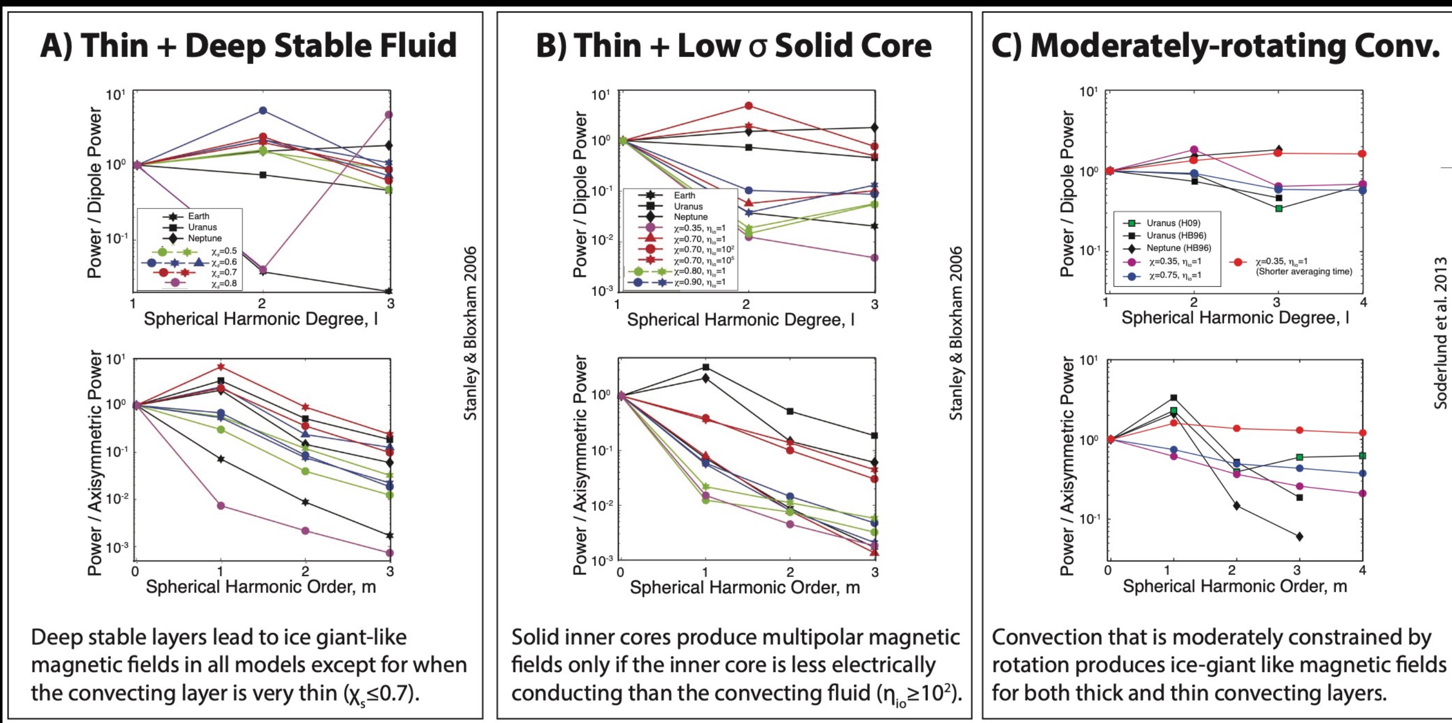
Credit: Soderlund et al. 2013; Soderlund & Stanley 2020

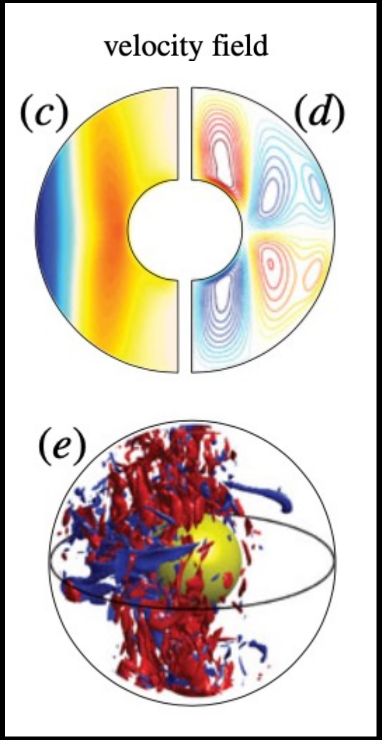
Credit: Herbert 2009

Magnetic Field

- Dynamo models test hypotheses for both internal structure and dynamics







Credit: Soderlund & Stanley 2020

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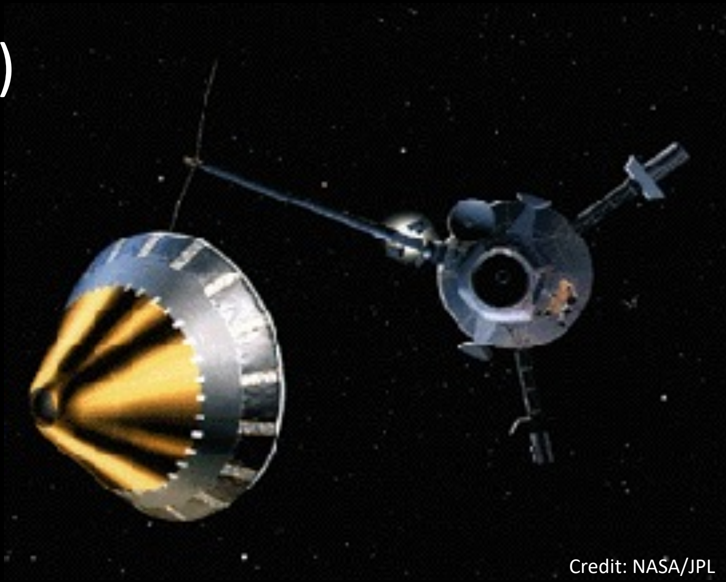
Lessons from the Galileo Probe

- Galileo Probe
  1) Atmospheric Structure Instrument (ASI)
  2) Energetic Particle Detector (EPI)
  3) Lightning/Radio-Emission Detector (LRD)
  4) Helium Abundance Detector (HAD)
  5) Nephelometer (NEP)
  6) Net Flux Radiometer (NFR)
  7) Neutral Mass Spectrometer (NMS)
  8) Doppler Wind Experiment (DWE)
  9) Radio Scintillation Experiment



Credit: NASA/JPL

Lessons from the Galileo Probe

- Galileo Probe at Jupiter
  1) Atmospheric Structure Instrument (ASI)
  2) Energetic Particle Detector (EPI)
  3) Lightning/Radio-Emission Detector (LRD)
  4) **Helium Abundance Detector (HAD)**
  5) Nephelometer (NEP)
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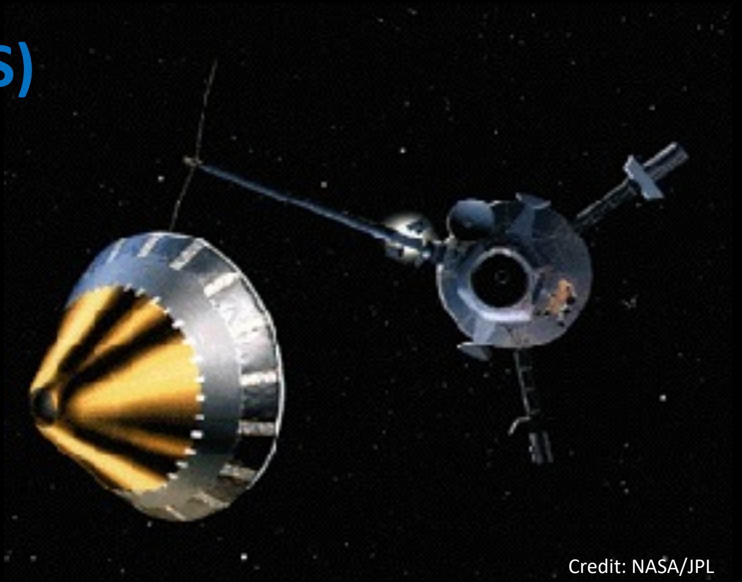
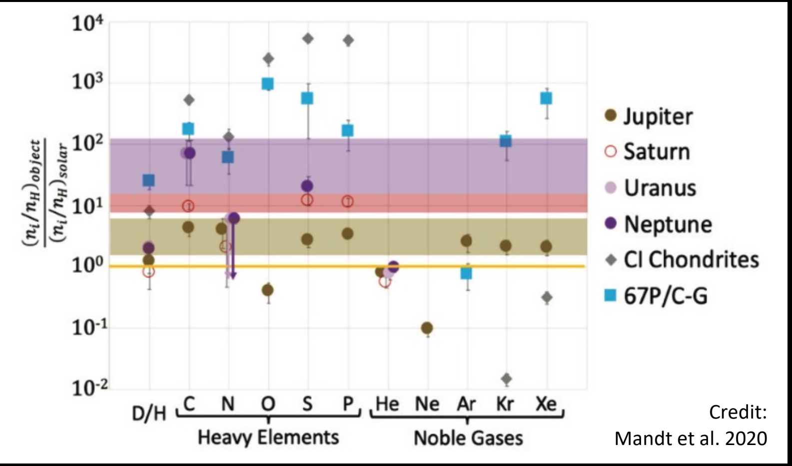


Credit: NASA/JPL

Atmospheric Composition

- Elemental abundances and isotopic ratios can be compared to solar values to test origin and evolution hypotheses

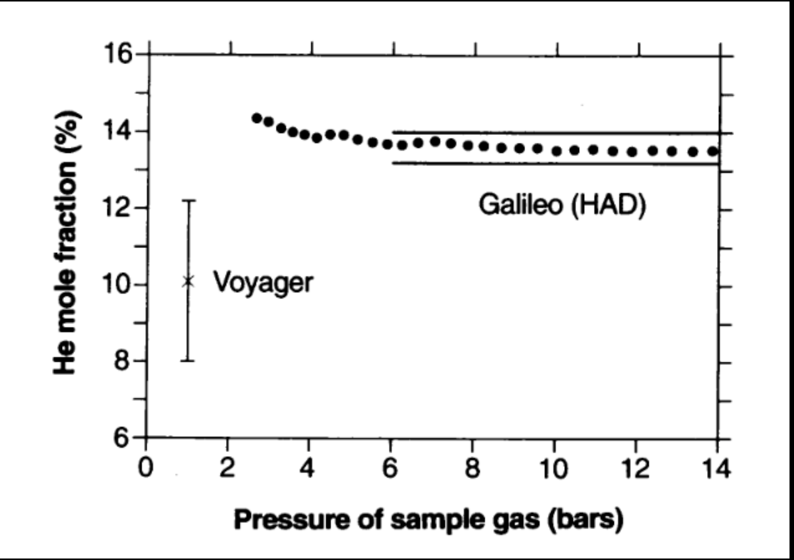


Quadrupole mass spectrometer

Species	Jovian atmosphere	Ratio to solar value	Prior results
^{4}He	0.156 ± 0.006	0.80	0.11
^{20}Ne	$(2.3 \pm 0.25) \times 10^{-5}$	0.10	
^{36}Ar	$(1.0 \pm 0.4) \times 10^{-5}$	1.6	
^{84}Kr	$\leq (8.5 \pm 4) \times 10^{-9}$	≤ 5	
^{132}Xe	$\leq (5 \pm 2.5) \times 10^{-9}$	≤ 50	
CH_4	$(2.1 \pm 0.15) \times 10^{-3}$	2.9	2.2×10^{-3}
H_2O	$\leq (3.7 \pm 0.35) \times 10^{-4}$	≤ 0.2	
NH_3	$\leq (3.5 \pm 0.3) \times 10^{-3}$	≤ 16	2.5×10^{-4}
H_2S	$(7.7 \pm 0.5) \times 10^{-5}$	2.2	
D/H	$(5 \pm 2) \times 10^{-5}$		$(2.0, 3.6) \times 10^{-5}$
$^{3}He/^{4}He$	$(1.1 \pm 0.1) \times 10^{-4}$		
$^{13}C/^{12}C$	0.0108 ± 0.0005	1.0	

Credit: Niemann et al. 1996

Helium Abundance Interferometer

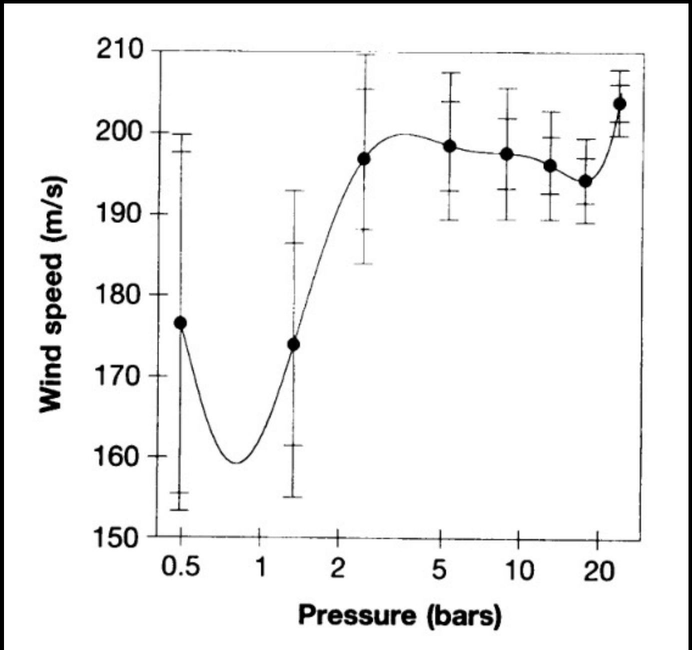


Credit: von Zahn & Hunten 1996

Zonal Winds

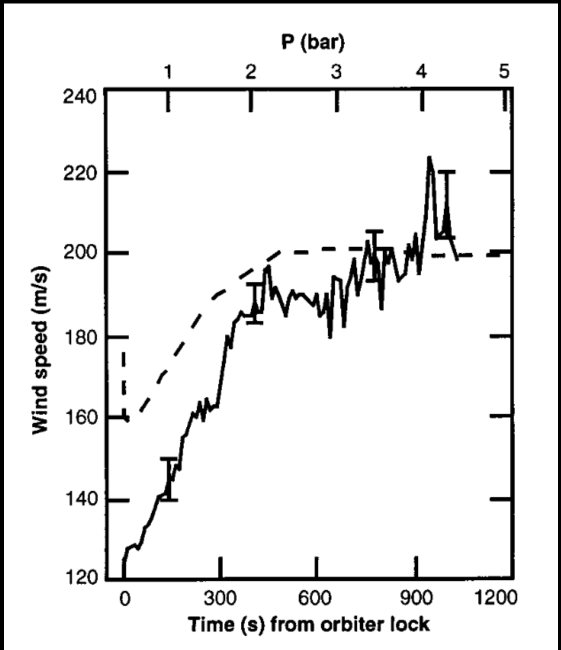
- Deep winds were identified via Doppler effects in the probe relay carrier frequency and at Earth-based radio observatories
- Sustained speeds of ~200 m/s to 24 bars

Doppler Wind Experiment



Credit: Atkinson et al. 1996

Very Large Array (ground-based)



Credit: Folkner et al. 1996

Lessons from Juno

- Juno
  1) Gravity/radio science system (Gravity Science)
  2) Six-wavelength microwave radiometer for atmospheric sounding and composition (MWR)
  3) Vector magnetometer (MAG)
  4) Plasma and energetic particle detectors (JADE and JEDI)
  5) Radio/plasma wave experiment (Waves)
  6) Ultraviolet imager/spectrometer (UVS)
  7) Infrared imager/spectrometer (JIRAM)
  8) Visible color imager (JunoCam)
  9) Stellar reference unit (SRU)

Credit: NASA/JPL

Lessons from Juno

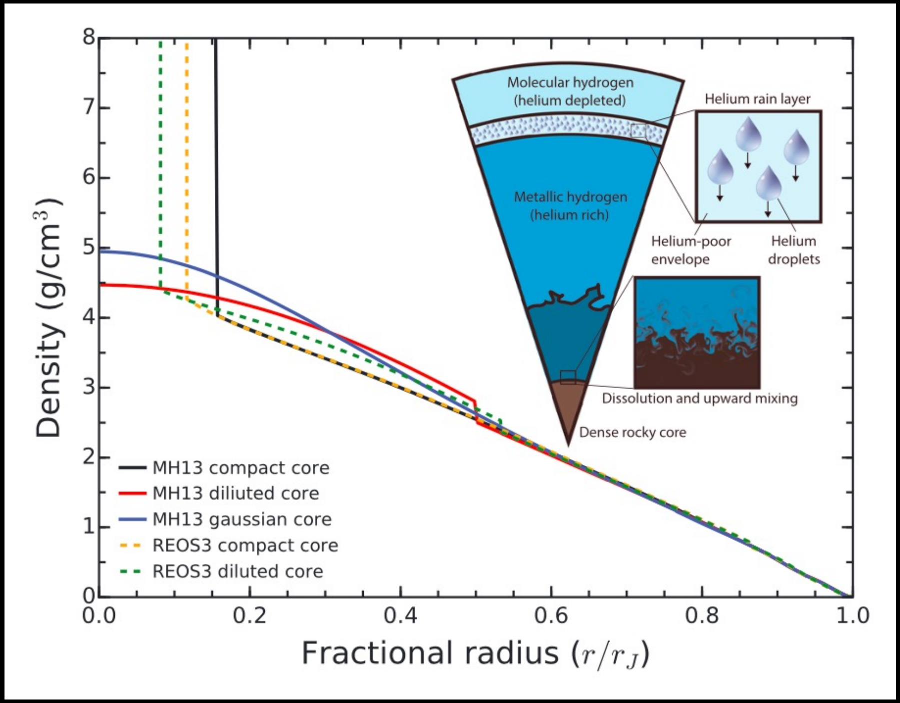
- Juno at Jupiter
  1) **Gravity/radio science system (Gravity Science)**
  2) **Six-wavelength microwave radiometer for atmospheric sounding and composition (MWR)**
  3) **Vector magnetometer (MAG)**
  4) Plasma and energetic particle detectors (JADE and JEDI)
  5) Radio/plasma wave experiment (Waves)
  6) Ultraviolet imager/spectrometer (UVS)
  7) Infrared imager/spectrometer (JIRAM)
  8) Visible color imager (JunoCam)
  9) Stellar reference unit (SRU)

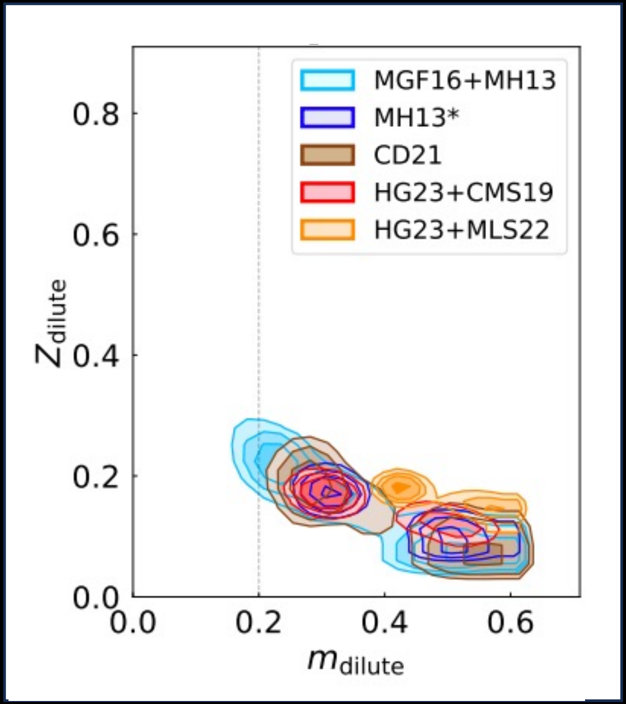
Credit: NASA/JPL

Dilute Core

- Low-order, even gravitational moments (J_2–J_8) suggest a dilute core
    - Extent of dilute core and its mass of heavy elements depends on the equation of state

Gravity/radio science system



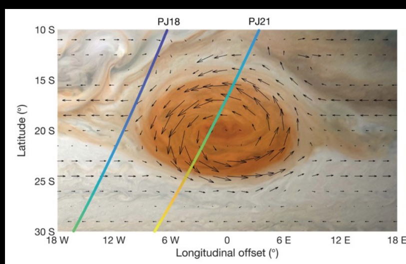


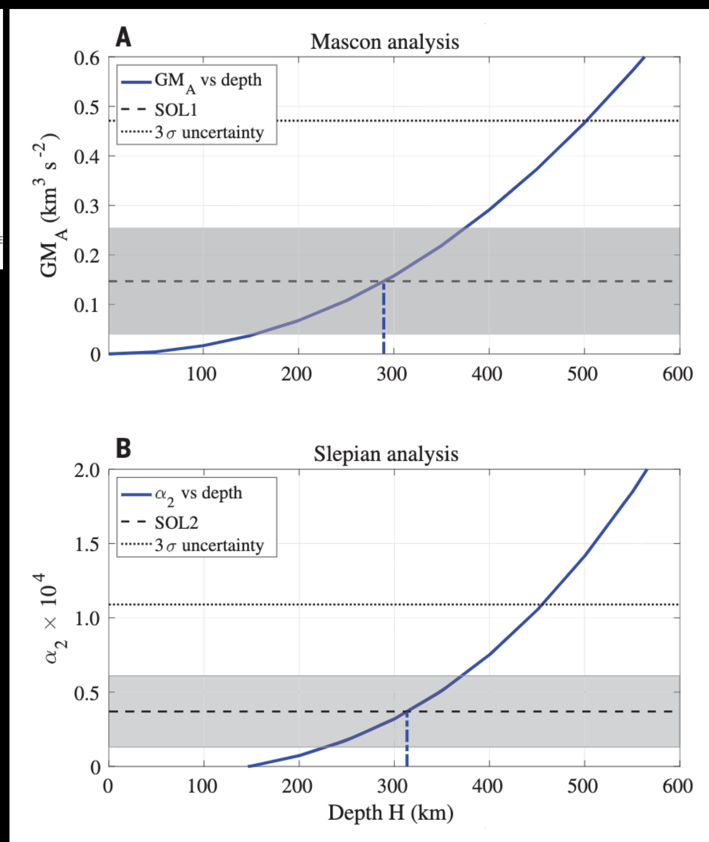
Credit: Wahl et al. 2017

Credit: Howard et al. 2023

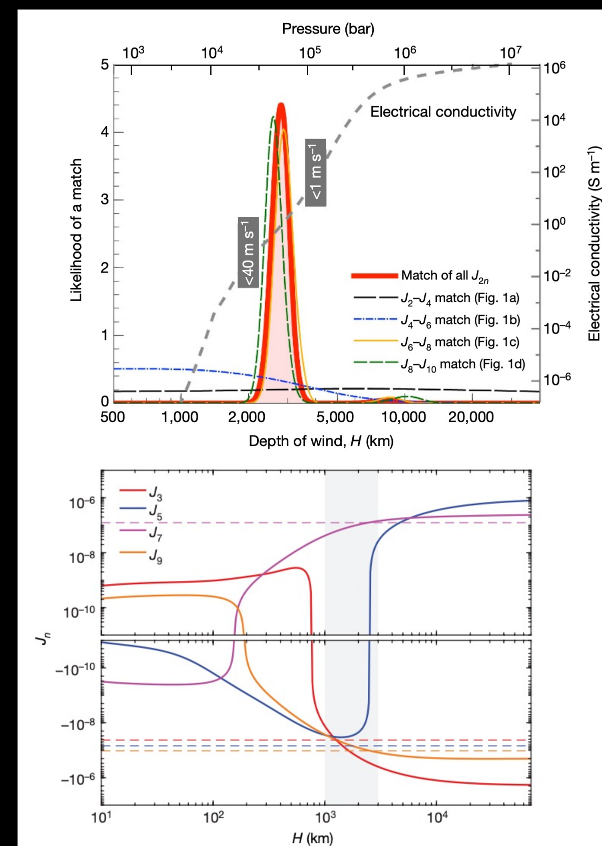
Atmospheric Dynamics

- Gravitational data can assess the depth of vortices, such as the Great Red Spot, as well of the zonal winds





Gravity/radio science system

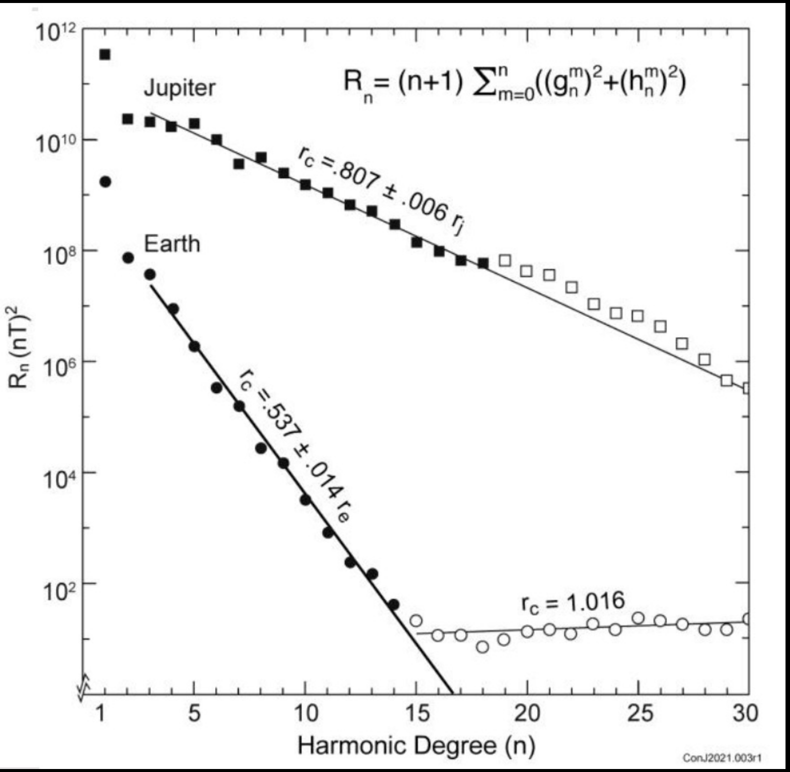


Credit: Parisi et al. 2021

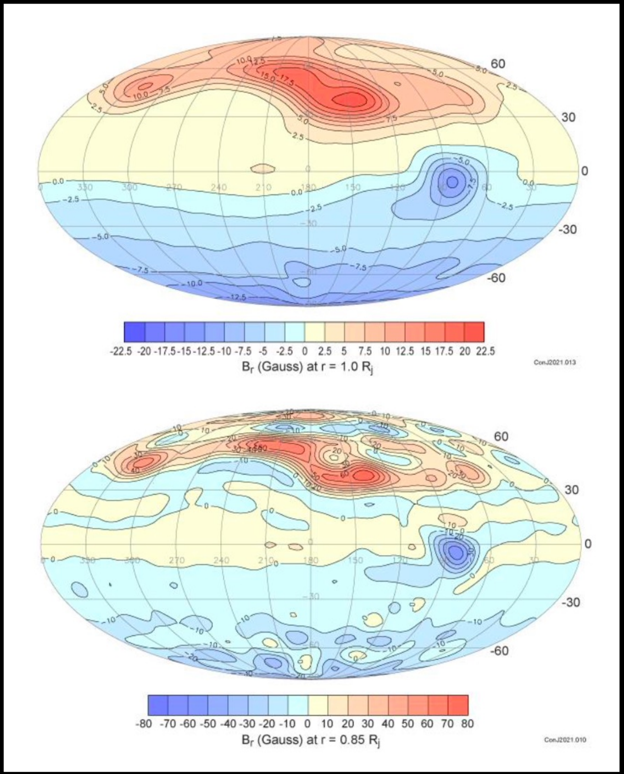
Credit: Guillot et al. 2018; Kaspi et al. 2018

Magnetic Field

- Magnetic field model out to spherical harmonic degree 18!
  - Know Jupiter's intrinsic magnetic field to higher spatial resolution than Earth's



Vector magnetometer

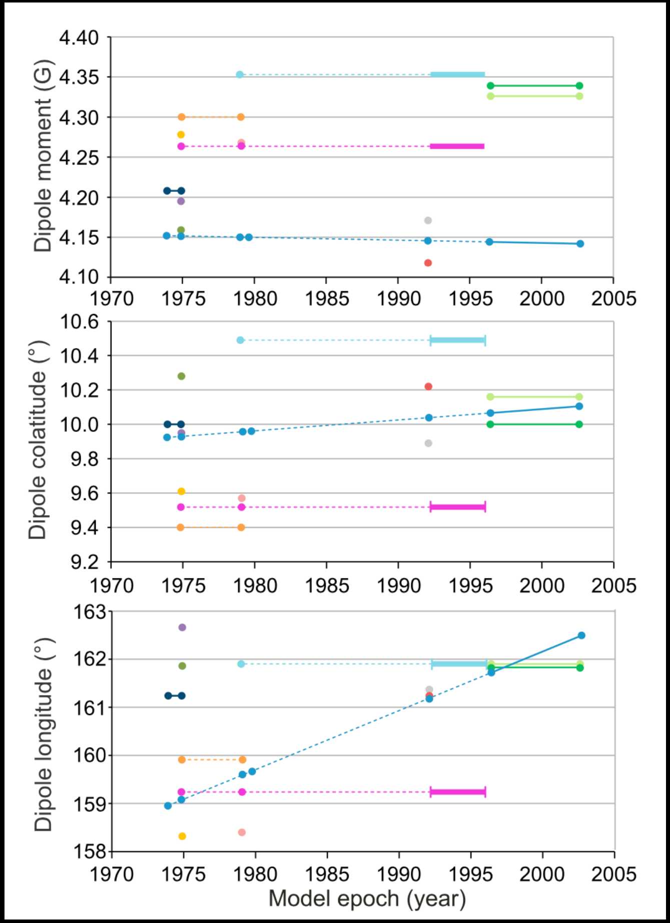


Credit: Connerney et al. 2021

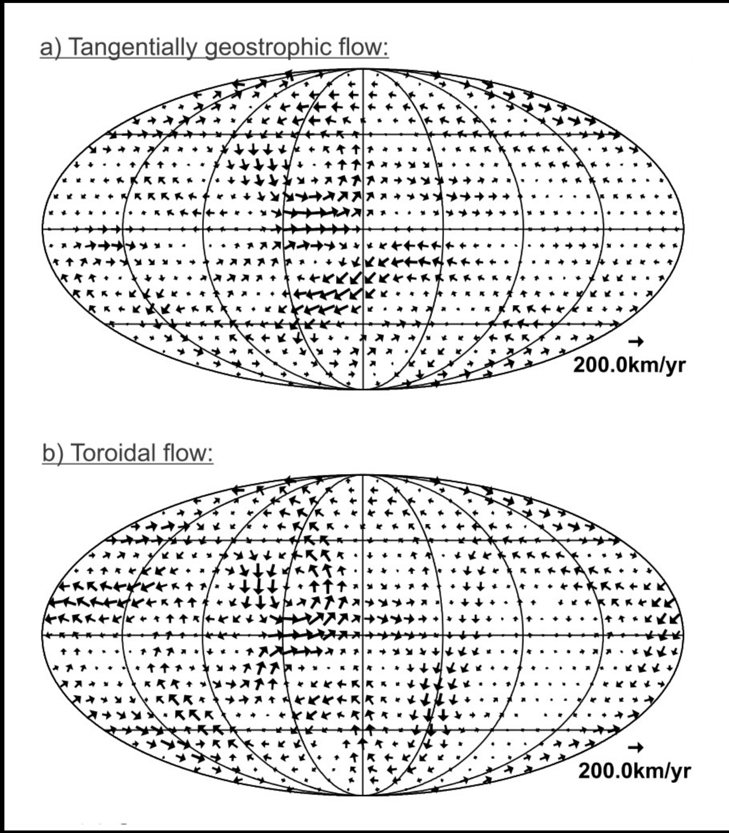
Credit: Connerney et al. 2021

Magnetic Field

- Magnetic field evolution over time can be used to infer flow speeds and directors in the interior



Vector magnetometer



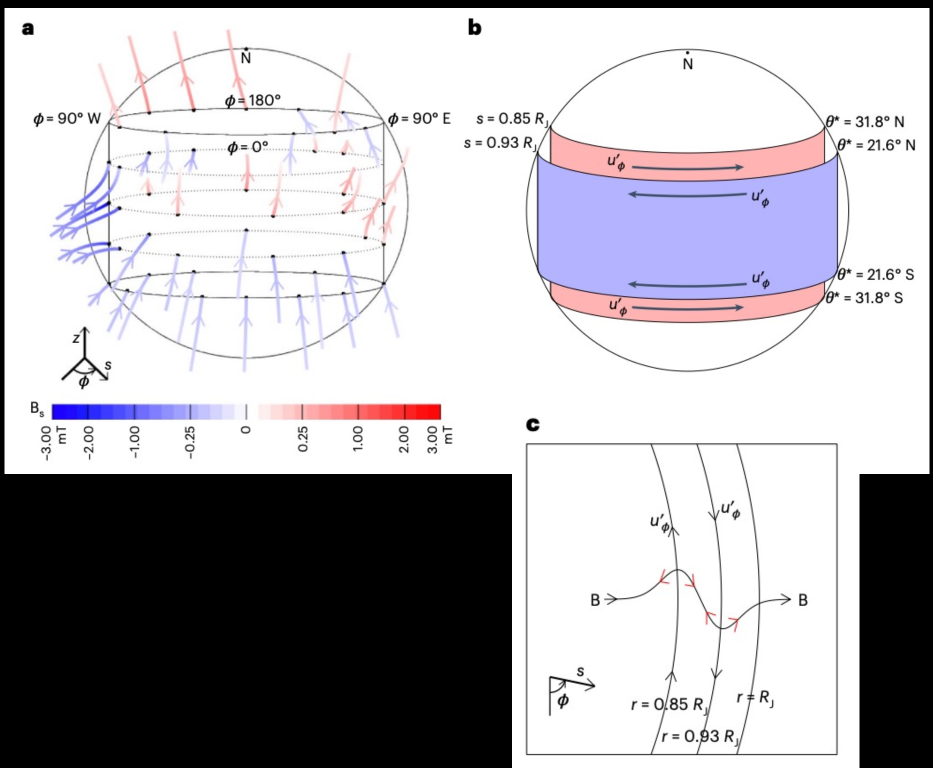
Credit: Connerney et al. 2021

Credit: Ridley & Holme et al. 2015

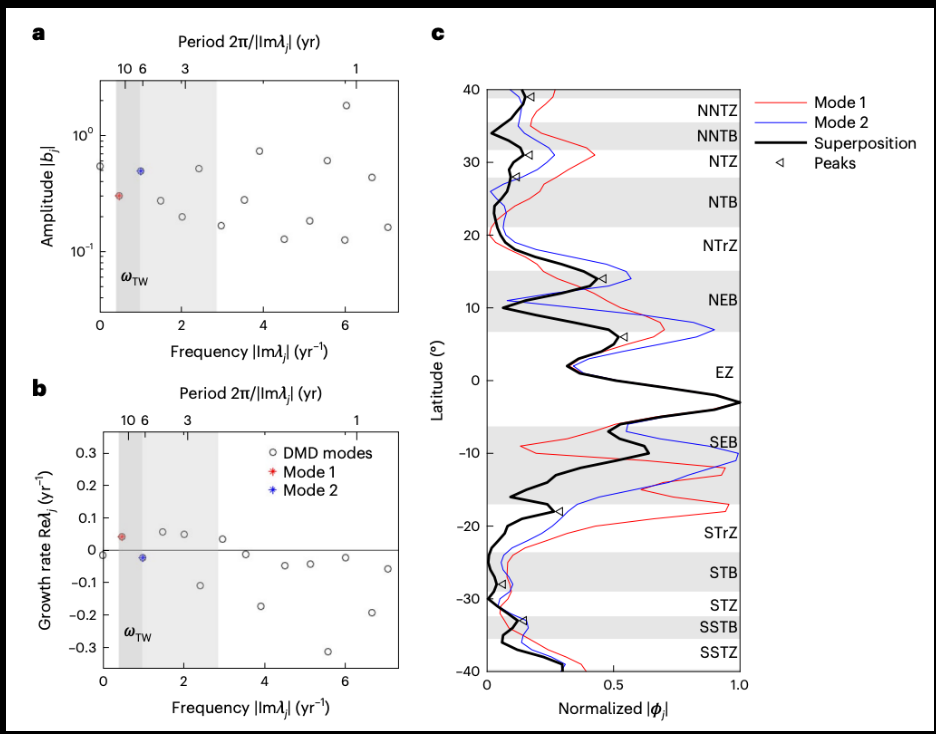
Magnetic Field

- Magnetic torsional oscillations arising from the dynamo region could modulate the heat transport and be responsible for variability of tropospheric banding

Vector magnetometer + 5 μm ground-based observations



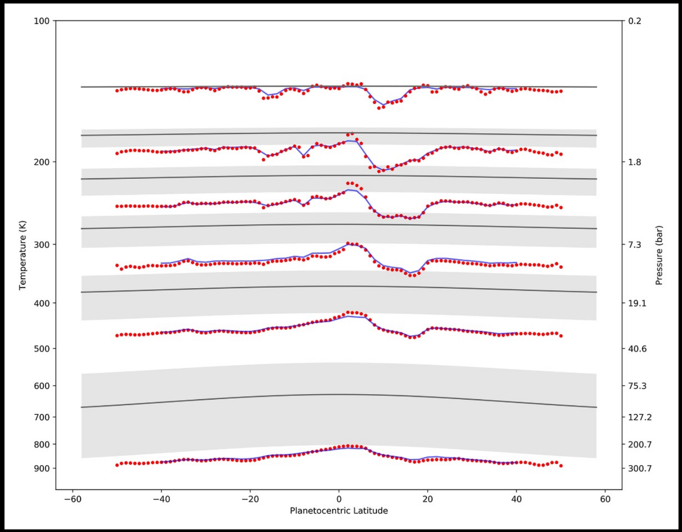
Credit: Hori et al. 2023



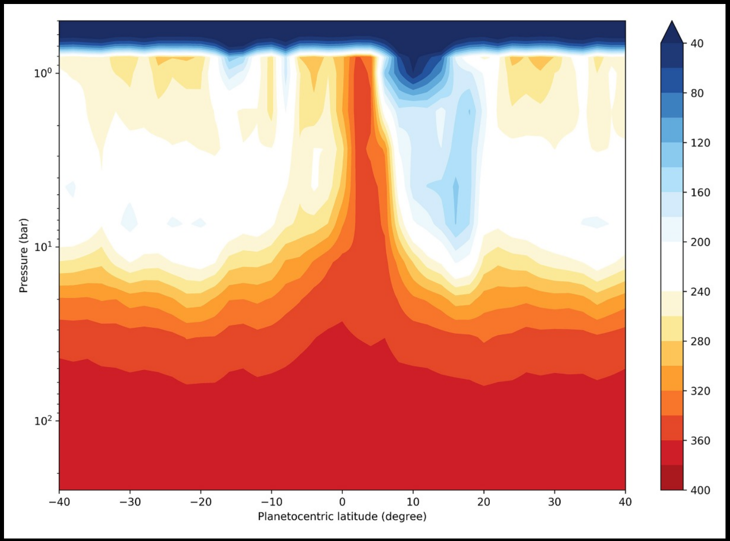
Credit: Hori et al. 2023

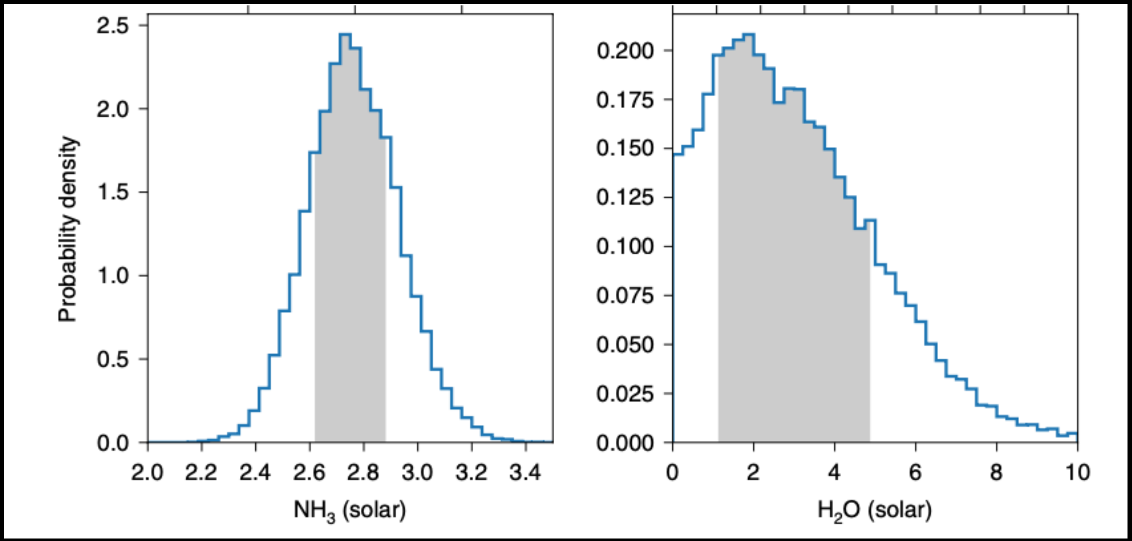
Deep Atmosphere Structure

- Microwave radiometer measured thermal emission from ~1 to >300 bars
  - Map of ammonia abundance and estimates of water abundance



Microwave Radiometer



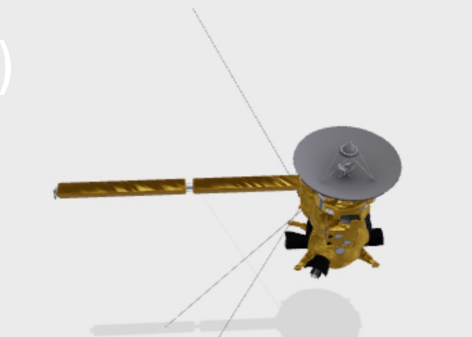


Credit: Li et al. 2017

Credit: Li et al. 2020

Lessons from Cassini

- Cassini
  1) Composite Infrared Spectrometer (CIRS)
  2) Imaging Science Subsystem (ISS)
  3) Ultraviolet Imaging Spectrograph (UVIS)
  4) Visible and Infrared Mapping Spectrometer (VIMS)
  5) Cassini Plasma Spectrometer (CAPS)
  6) Cosmic Dust Analyzer (CDA)
  7) Ion and Neutral Mass Spectrometer (INMS)
  8) Magnetometer (MAG)
  9) Magnetospheric Imaging Instrument (MIMI)
  10) Radio and Plasma Wave Science (RPWS)
  11) Radar
  12) Radio Science Subsystem (RSS)



Credit: NASA Visualization Technology Applications and Development (VTAD)

Lessons from Cassini

- Cassini at Jupiter
  1) **Composite Infrared Spectrometer (CIRS)**
  2) Imaging Science Subsystem (ISS)
  3) Ultraviolet Imaging Spectrograph (UVIS)
  4) **Visible and Infrared Mapping Spectrometer (VIMS)**
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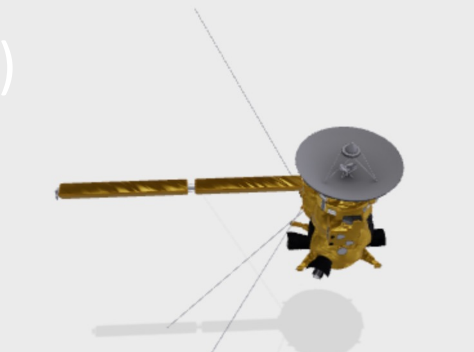
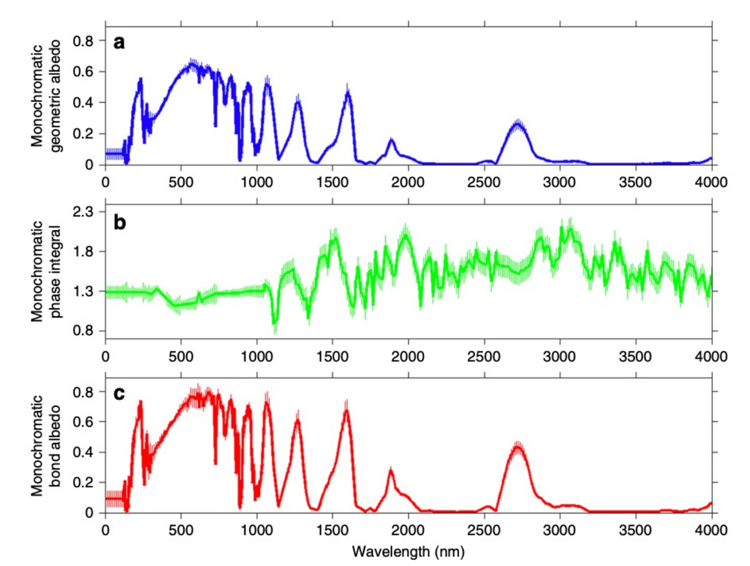

Credit: NASA Visualization Technology Applications and Development (VTAD)

Energy Balance

- Jupiter’s internal heat is significantly larger than the previous best results (5.4 W m^{-2}) based on Pioneer and Voyager observations

Table 1 Jupiter's radiant energies and internal heat

Parameter	Power
Reflected solar radiation	6.693 ± 0.160 W m^{-2}
Absorbed solar radiation	6.613 ± 0.160 W m^{-2}
Emitted thermal radiation	14.098 ± 0.031 W m^{-2}
Internal heat	7.485 ± 0.163 W m^{-2}



- Saturn’s emitted power also appears to be time-variable

Composite Infrared Spectrometer (CIRS)

	Global Average	NH Average	SH Average
Emitted power (W/m^2)	4.952	4.573	5.331
Standard deviation (W/m^2)	±0.035	±0.014	±0.058
Effective temperature (K)	96.67	94.77	98.47
Standard deviation (K)	±0.17	±0.07	±0.27

	Pioneer 11	Voyager 1	Cassini
Time	September 1979	November 1980	May 2009
Solar longitude (°)	353.6	8.6	357.4
Emitted power (W/m^2)	4.91	4.614	4.9108
Uncertainty (W/m^2)	±0.50	±0.075	±0.0048
Effective temperature (K)	96.5	95.00	96.470
Uncertainty (K)	±2.5	±0.4	±0.023

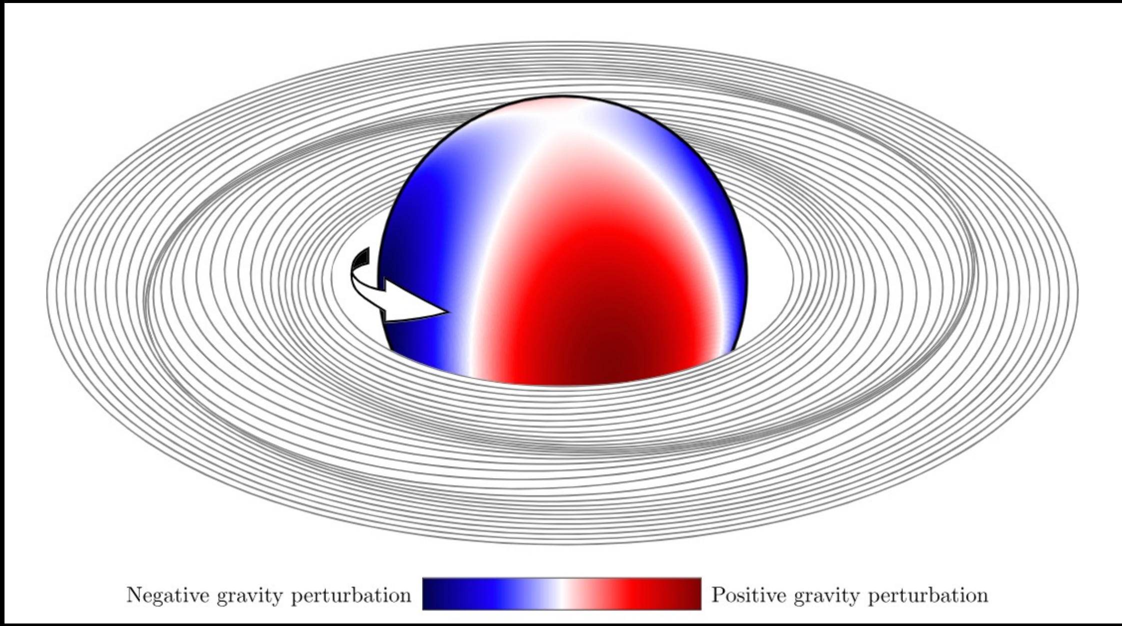
Credit: Li et al. 2018

Credit: Li et al. 2010

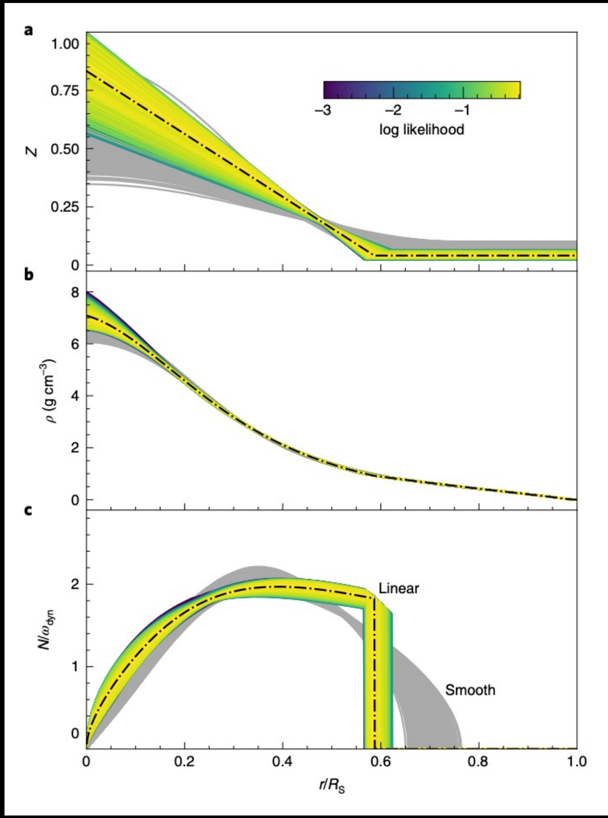
Ring Seismology

- Gravity couples normal mode oscillations to the orbits of ring particles
  - Stably stratified region near Saturn's center that extends to approximately 60% of the radius

Visible and Infrared Mapping Spectrometer & Radio Science Subsystem



Credit: Mankovich 2019

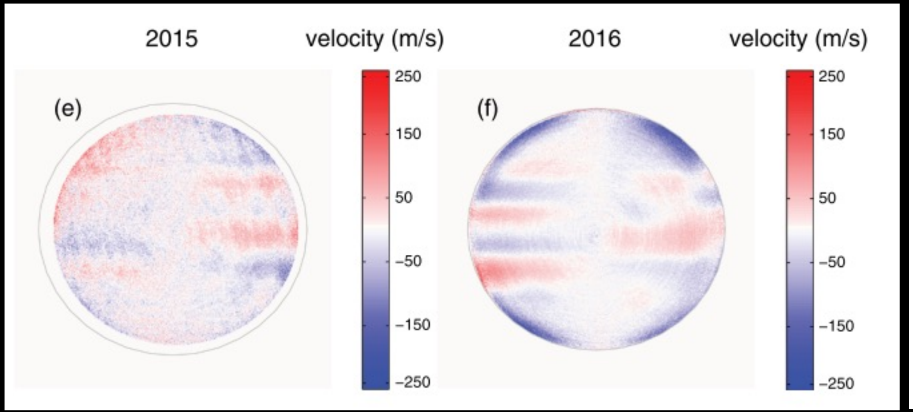


Credit: Mankovich & Fuller 2021

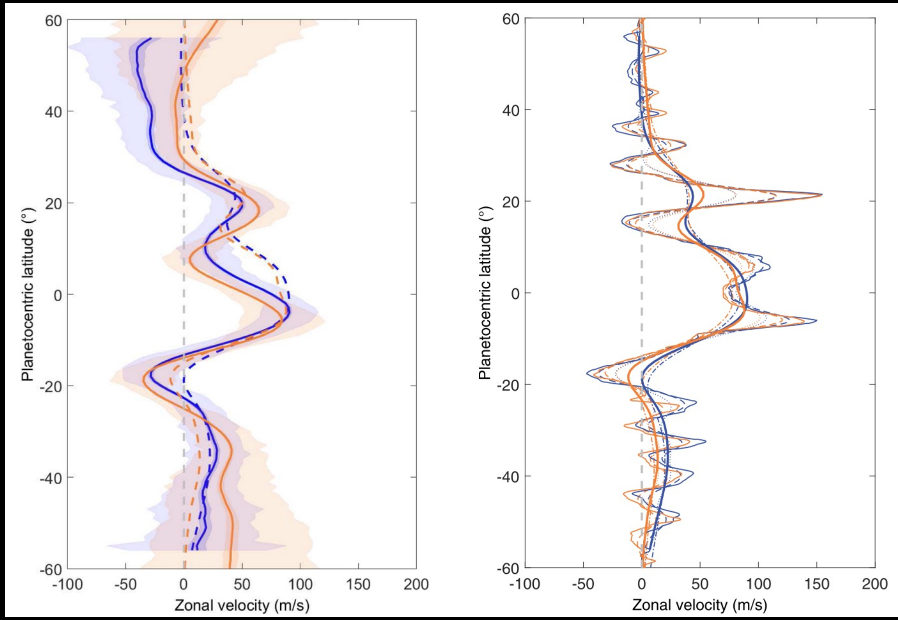
Doppler Imaging of Jupiter

- Doppler spectrometry for giant planets is inspired by helioseismology to probe deep internal structures
  - Detection of global oscillation modes, whose properties are a function of the internal density profile
  - Monitors the position of a spectral line that probes an atmospheric level where the amplitude of acoustic modes is maximum

Doppler spectro-imager JOVIAL-JIVE



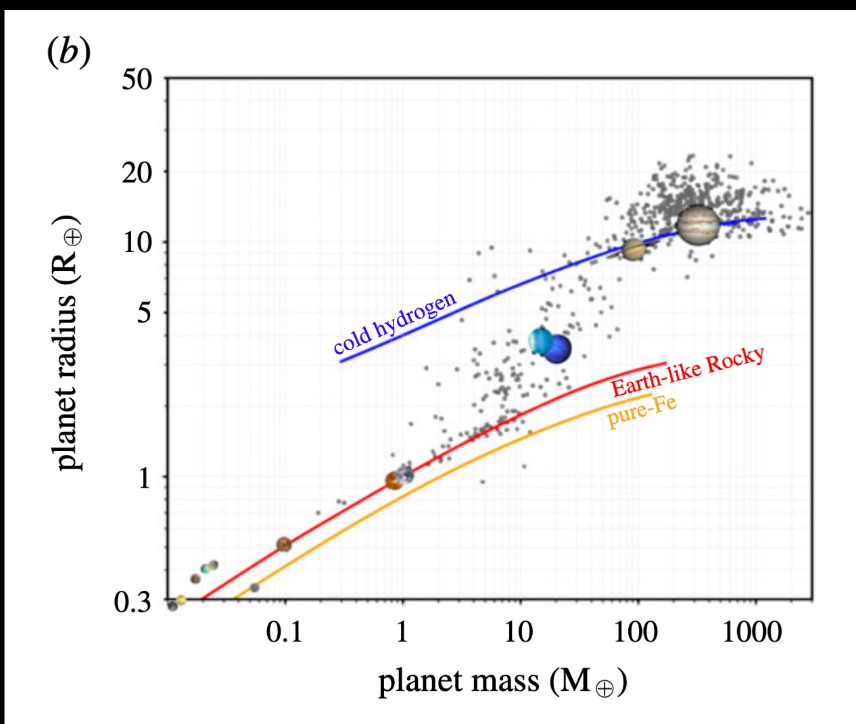
Credit: Gonçalves et al. 2019



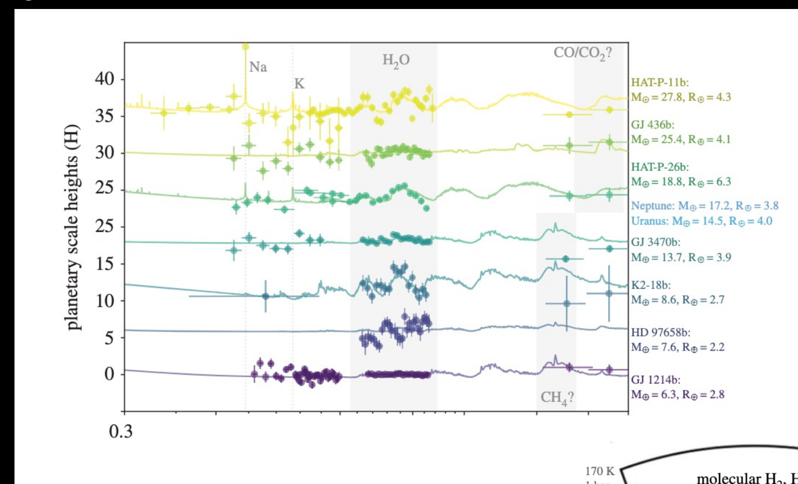
Credit: Gonçalves et al. 2019

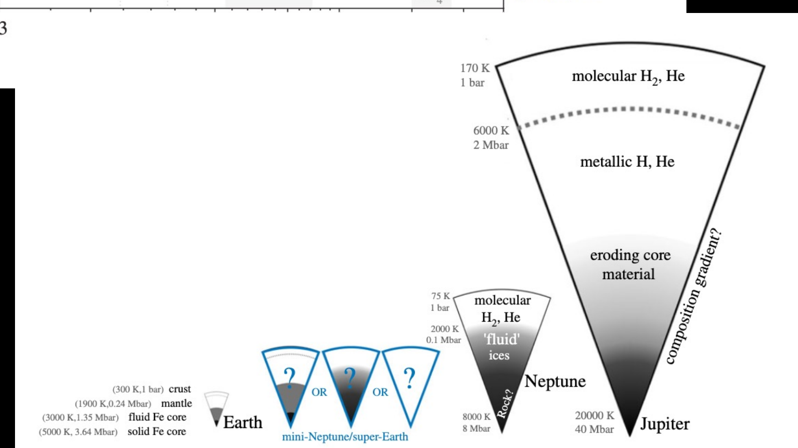
Lessons from Exoplanets

- Uranus and Neptune offer a direct link between gas giants and terrestrial planets / icy moons of our solar system and exoplanetary systems



Credit: Wakeford & Dalba 2020

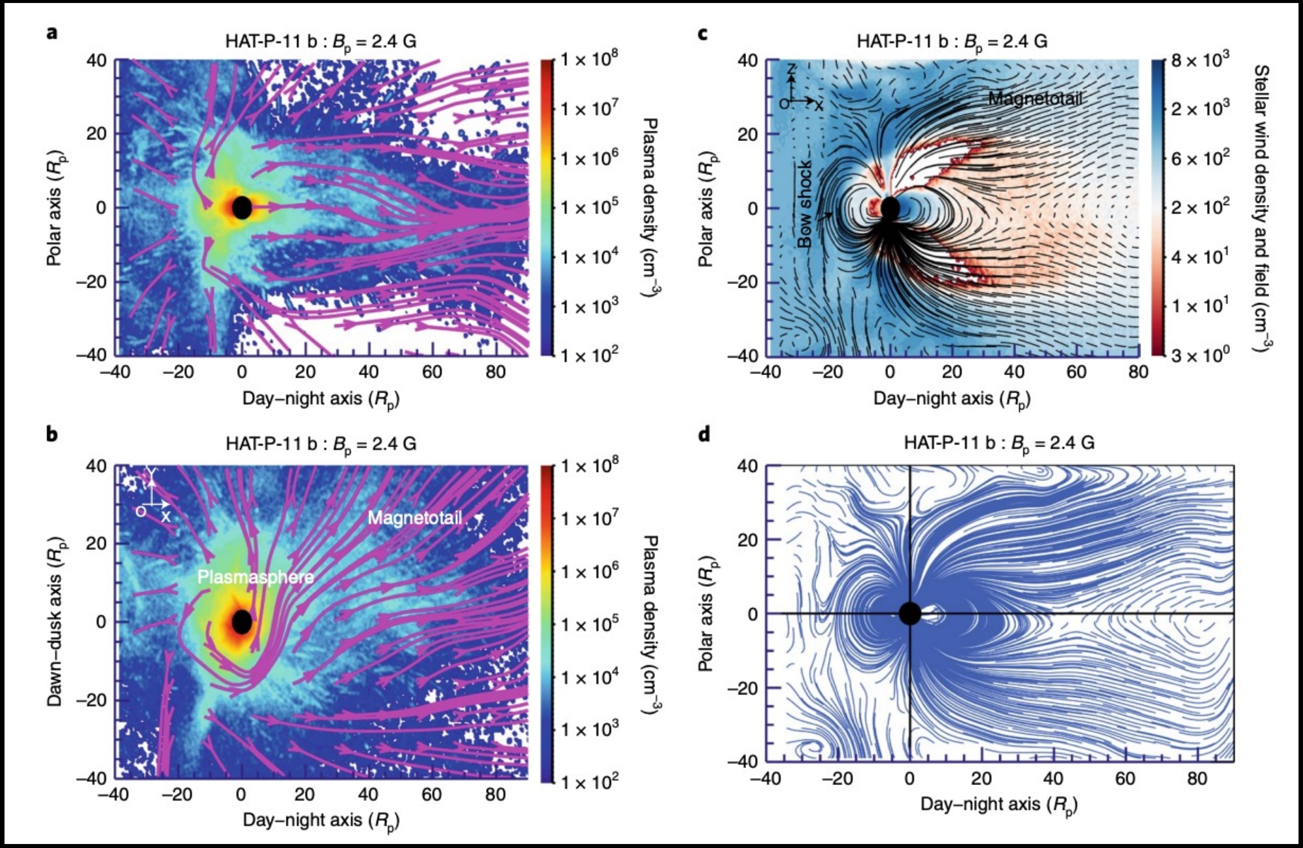




Credit: Wakeford & Dalba 2020

Lessons from Exoplanets

- HST ultraviolet observations indicate strong magnetization and metal-poor atmosphere for a Neptune-sized exoplanet



Credit: Ben-Jaffel et al. 2022

Outline

- Techniques traditionally used to infer giant planet interior structure
  - Voyager 2 observations
  - Old data, new analyses
- New and emerging techniques
  - Lessons from Jupiter, Saturn, and exoplanets
- Knowledge gaps that limit our ability to interpret measurements

Uranus Orbiter and Probe

- Uranus Orbiter and Probe
  1) Magnetometer
  2) Narrow angle camera
  3) Wide angle camera
  4) Thermal IR camera
  5) Visible-Near IR imaging spectrometer
  6) Fields and particle suite
  7) Radio science and ultrastable oscillator

  8) Atmospheric structure instrument
  9) Mass spectrometer
  10) Ultrastable oscillator
  11) Ortho-para hydrogen sensor

Credit: NASA/JPL

Uranus Orbiter and Probe

	Science Objective	Measurement	Nominal Instrument	Mission Functional Requirement
Atmospheres	**A1. How does atmospheric circulation function, from interior to thermosphere, in an ice giant?**	A. Cloud top zonal and 2D winds, waves to ~10 m/s resolution	NAC, imaging at 50 km/pixel	Repeated views of same features over timescales of minutes to hours
		B. *In situ* vertical wind profile to 10–20 m/s resolution	USO (probe), 10 measurements per scale height	Probe to 5 bars
		C. Resolved composition, disequilibrium species mapping (to P < 3 bars): CH_4, H_2S, H_3^+, C_2H_2, C_2H_6, etc., hydrogen ortho/para fraction to mixing ratio ±20%	Vis/NIR, 1000 km/pixel	
			TIR, ~1000 km horizontal spatial resolution	
			MS (probe)	Probe to 5 bars, 10 bars preferred
			Ortho/para sensor (probe)	Probe to 5 bars
		D. Depth of atmospheric winds (gravity moments)	Radio Science, gravity passes	Polar and equatorial passes, distances of 1.1 R_u
	A2. What is the 3D atmospheric structure in the weather layer?	A. Cloud tomography and aerosols	Vis/NIR imaging spectra at 500–1000 km/pixel	Repeated views of same features over timescales of hours
			WAC or NAC imaging at 500–1000 km/pixel	Repeated views of same features over minutes to hours
		B. Vertical temperature profile to ±1K	ASI (probe), 4 measurements per scale height	Probe to 5 bars
			Ortho/para sensor (probe)	Probe to 5 bars
			Radio Sci + UltraStable Oscillator, occultations	Atmospheric occultations
		C. Global temperature variations in troposphere, stratosphere, thermosphere	TIR, 500-1000 km/px mapping	Global coverage, repeated views
			Vis/NIR spectra at 500–1000 km/pixel	
	A3/I1. When, where, and how did Uranus form, and how did it evolve both thermally and spatially, including migration?	A. Noble gas (& isotopes of He, Xe) abundances to ± 5%	MS (probe)	Probe to 5 bars
		B. Elemental (& isotopes of H, C, S, N & O (stretch goal)) abundances, lower bounds on CH_4, H_2S, NH_3, H_2O, and the variation with depth	MS (probe)	Probe to 5 bars, 10 bars preferred
		C. Global distribution of atmospheric composition	*Same as A1.C above*	
Interiors		D. Global energy balance (Bond albedo and thermal emission) to 1%	TIR, 1000 km/pixel	Repeat orbiter ~yearly to determine variability
			Vis/NIR spectra at 500-1000 km/pixel	Repeat ~yearly to determine variability
	I2. What is the bulk composition and its depth dependence?	A. Gravity field to at least J_8, uncertainties on J_2-J_6	Radio Science + UltraStable Oscillator, gravity passes	
	I3. Does Uranus have discrete layers or fuzzy core, and can this be tied to its formation and tilt?	A. Gravity field to at least J_8, uncertainties on J_2-J_6	*Same as I2.A above*	Polar passes, distances of 1.1 R_u require validation of safe passage inward of rings
		B. Ring oscillations	NAC imaging of rings (<1 km/pix)	
			Radio Sci + UltraStable Oscillator, occultations	
	I4. What is the true rotation rate of Uranus, does it rotate uniformly, and how deep are the winds?	A. Internal magnetic field structure	MAG, 0.1 to 20,000 nT, 1-second cadence	Many close passes
		B. Planet shape and gravity to J_8	Radio Sci + UltraStable Oscillator, occultations	
		C. Gravity field to J_8	*Same as I2.A above*	
Magnetospheres	**M1. What dynamo process produces Uranus's complex magnetic field?**	A. Internal magnetic field structure	*Same as I4.A above*	Close passes
	M2. What are the plasma sources & dynamics of Uranus's magnetosphere and how does it interact with the solar wind?	A. Particles & fields over range of space (distance, longitude, latitude, local time) and time (spin, solar wind variability)	Fields & Particles package	Multiple passes
	M3. How does the magnetosphere interact with Uranus' upper atmosphere and satellite surfaces?	A. Energetic particle fluxes at satellite orbital ranges	Fields & Particles package	
		B. Plasma/energetic particle fluxes over Uranus polar regions	Fields & Particles package	Polar passes

Uranus Orbiter and Probe

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Strategic Supporting Activities (OWL)

- *What processes influence the structure, evolution, and dynamics of giant planet interiors?*
  - Laboratory measurements and numerical simulations of high-pressure, high temperature equations of state, chemical reaction rates, and transport properties (i.e., viscosity, thermal and electrical conductivity, diffusion coefficients)
  - Numerical and analytical models of dynamic processes in the atmosphere, interior and magnetosphere of giant planets
  - Continued data analysis from past missions and development of new observational techniques (e.g., ring seismology, Doppler imaging)
  - Long-term monitoring of atmospheric dynamics, waves and oscillations, auroras, and impacts
  - Create a census of a large population of young planets recently formed, of the composition of giant exoplanet atmospheres, of magnetospheric activity in exoplanets, and of mass-radius relations of sub-Neptunes with radio and telescopic observations