APCosPA-Planet2 RESCEU Summer School: Takayama, 26 August 2016

Interiors and atmospheres of giant planets: Present status and perspectives with JUNO and JOVIAL

Tristan Guillot (OCA, Nice)

Thx: François-Xavier Schmider, Ivan Gonçalves, Fran Bagenal

Outline

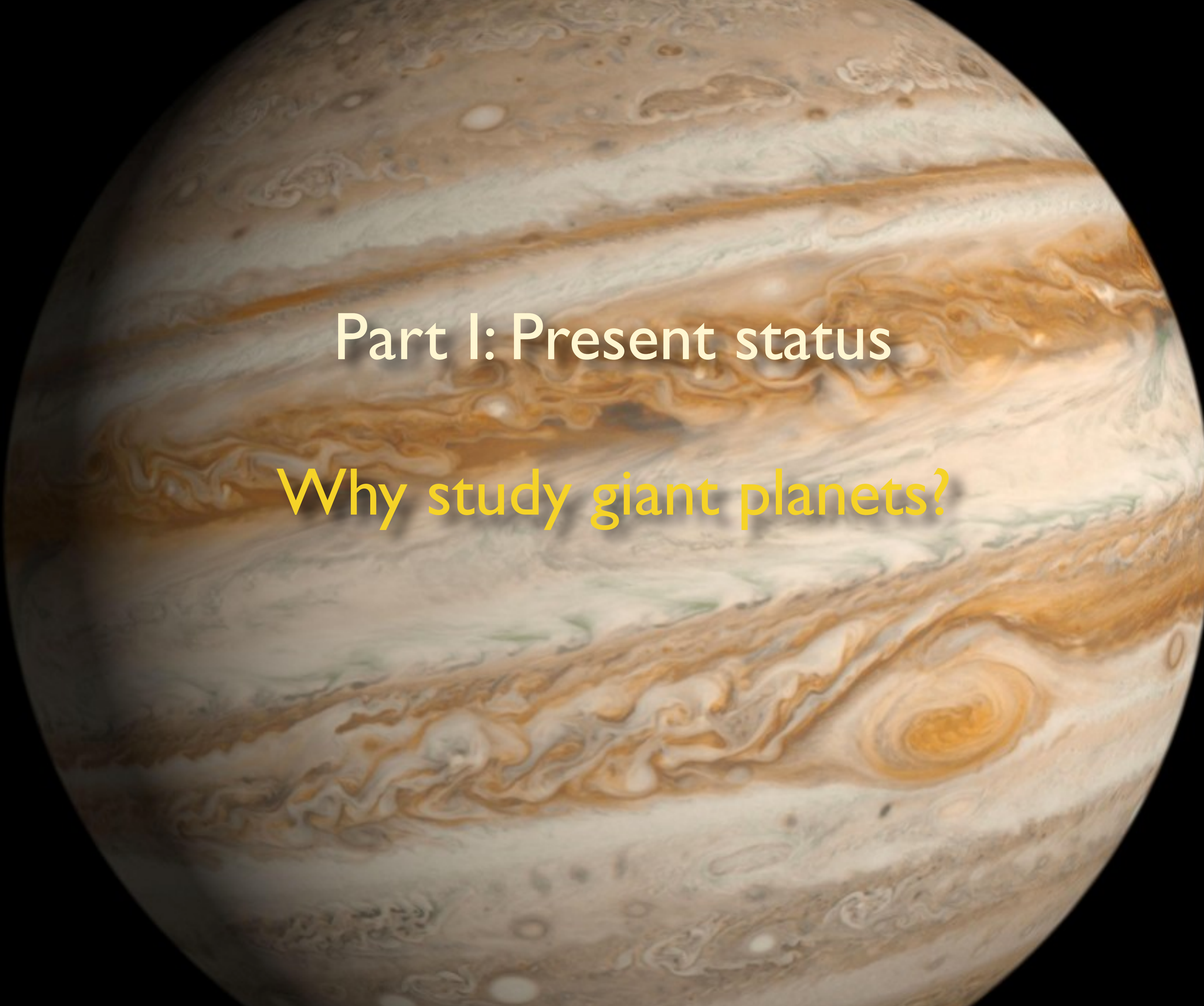
Part I: Present status

Part II: JUNO

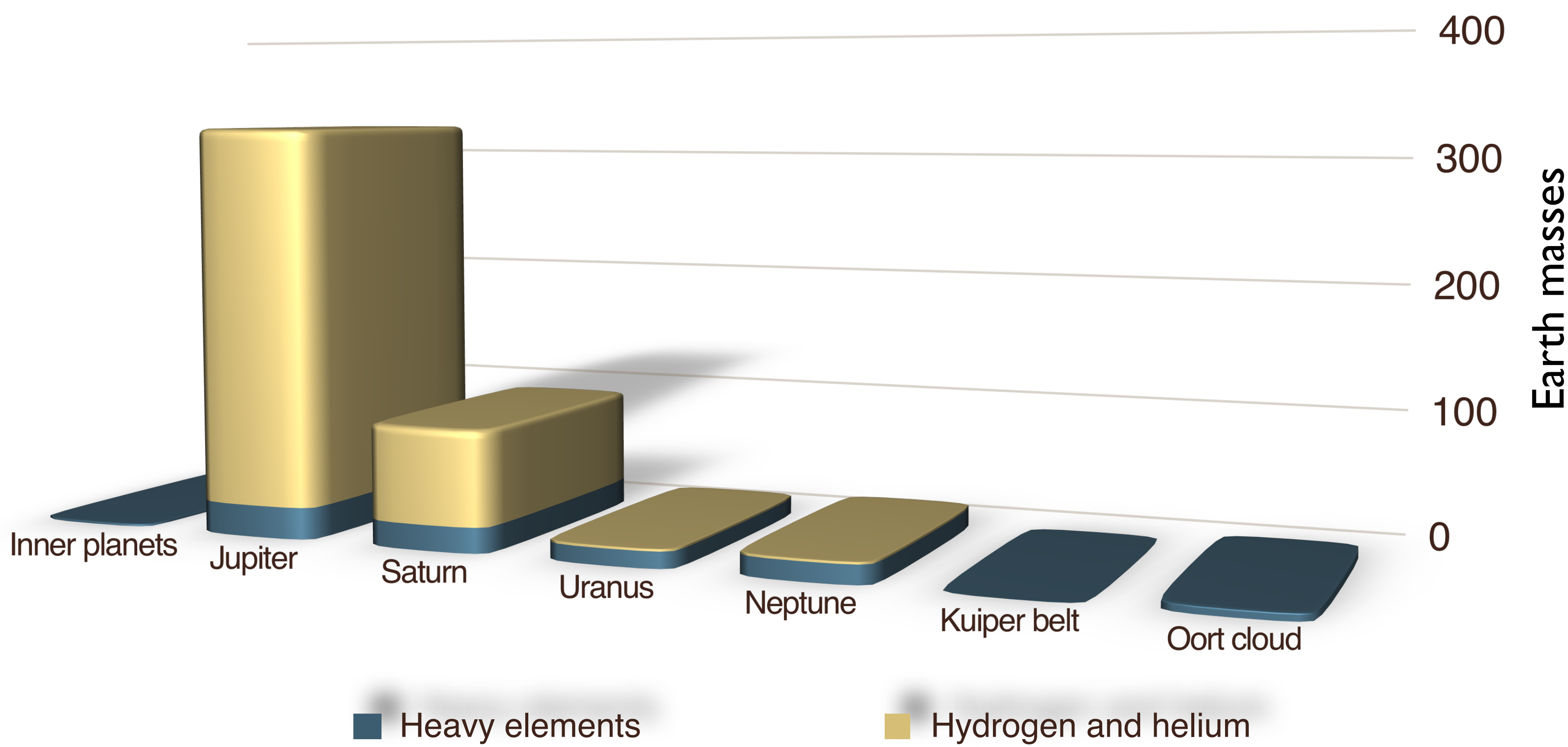
Part II: JOVIAL

Part I: Present status

Why study giant planets?

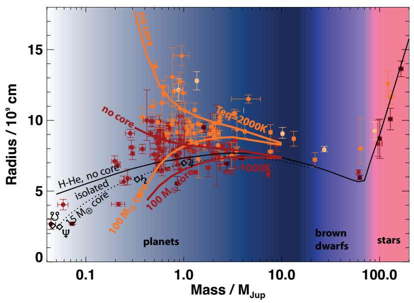


Completing the inventory



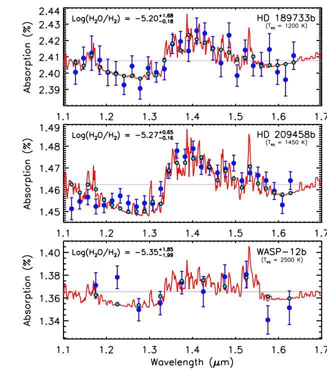
Giant planets possess 99.5% of all the mass in the Solar System except the Sun

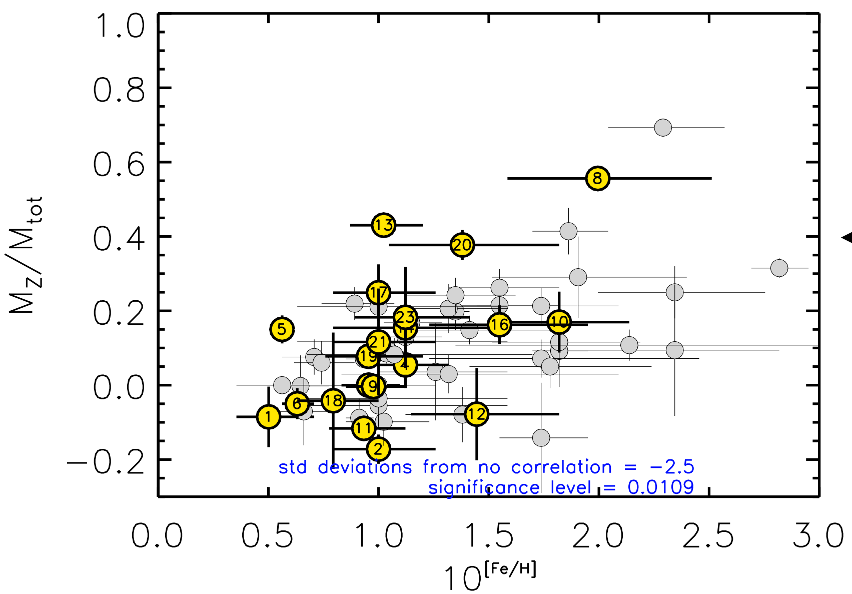
Exoplanetary compositions within reach

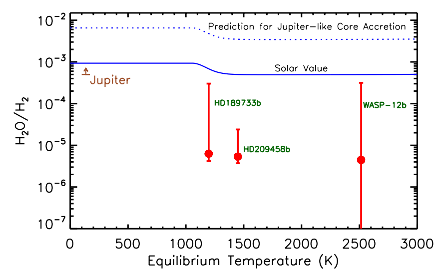


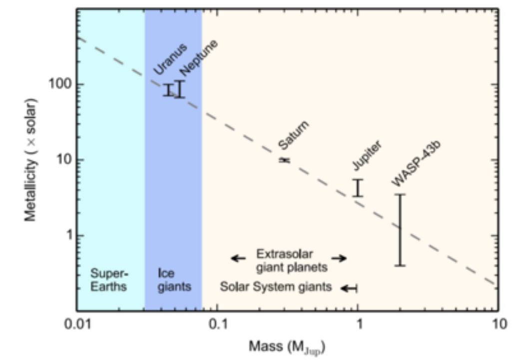
Interior

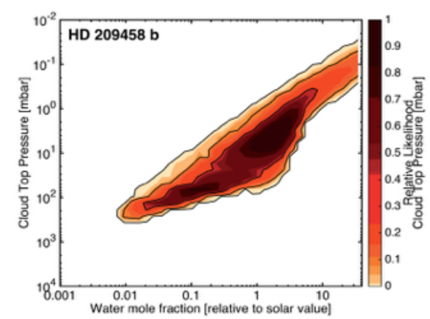
Atmosphere

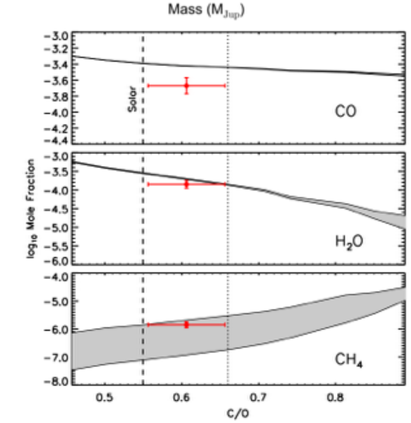






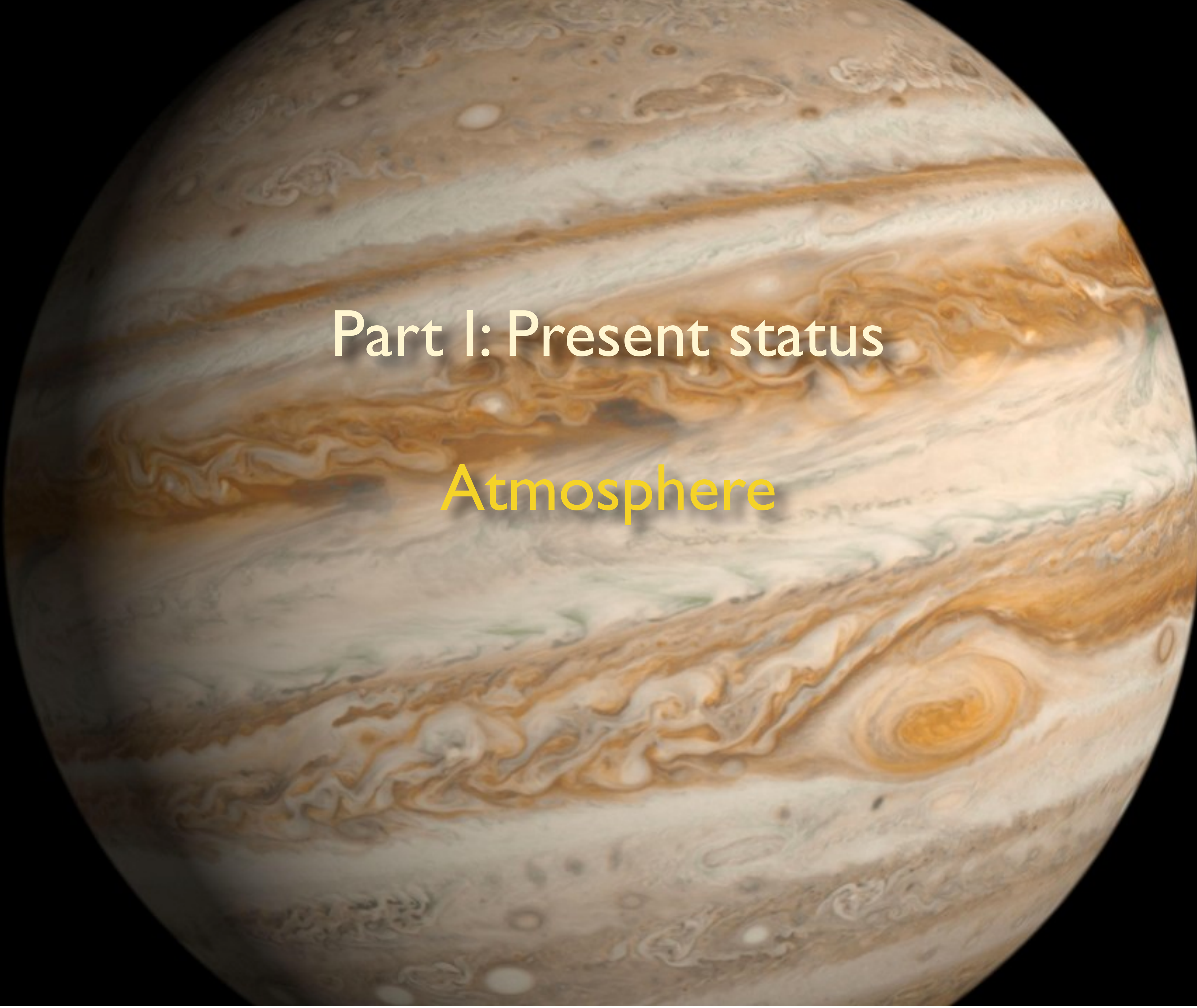




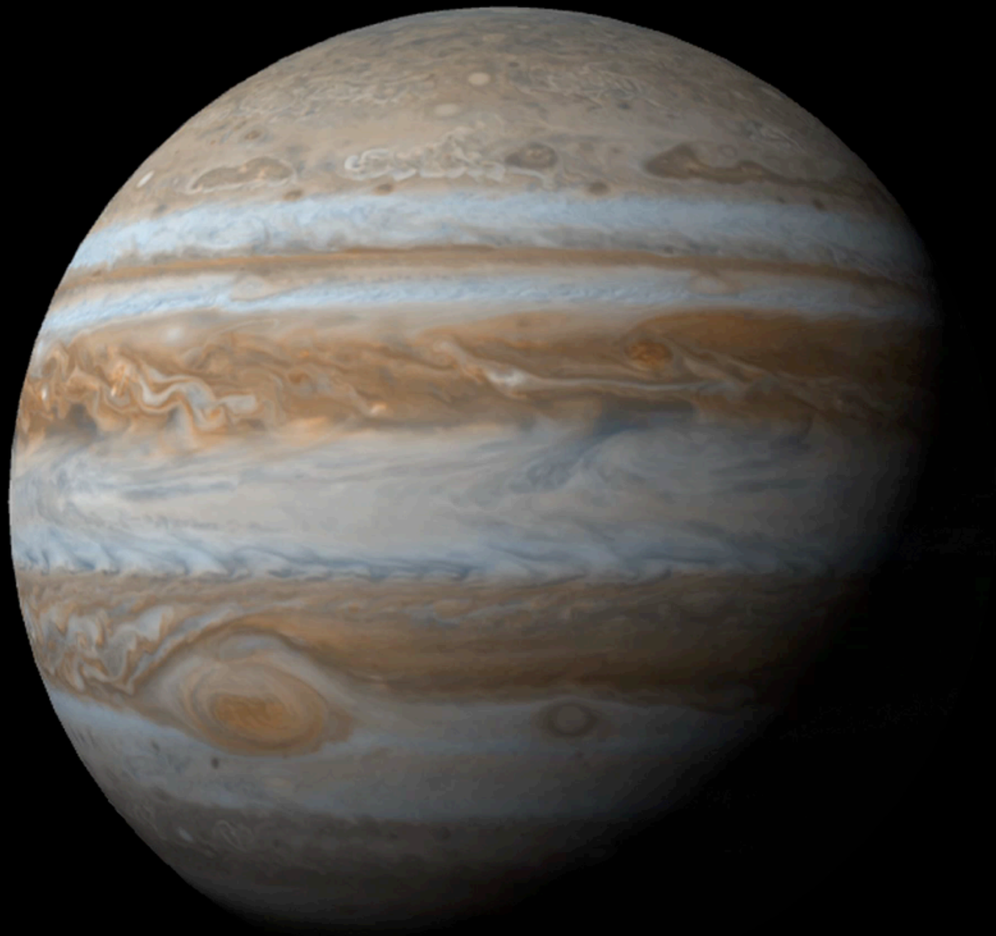


Guillot et al. (2006)
Burrows et al. (2007)
Miller & Fortney (2011)
Moutou et al. (2013)

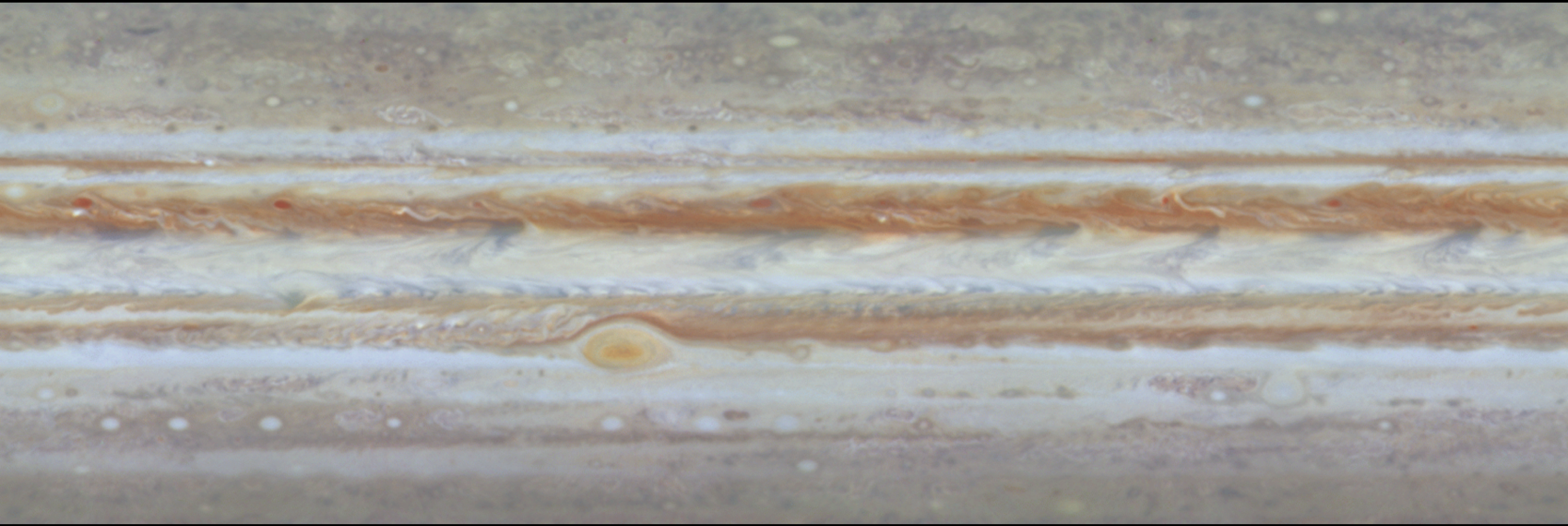
Madhusudhan et al. (2014)
Kreidberg et al. (2014)
Benneke (submitted, 2015)
Barman et al. (2015)


Part I: Present status
Atmosphere

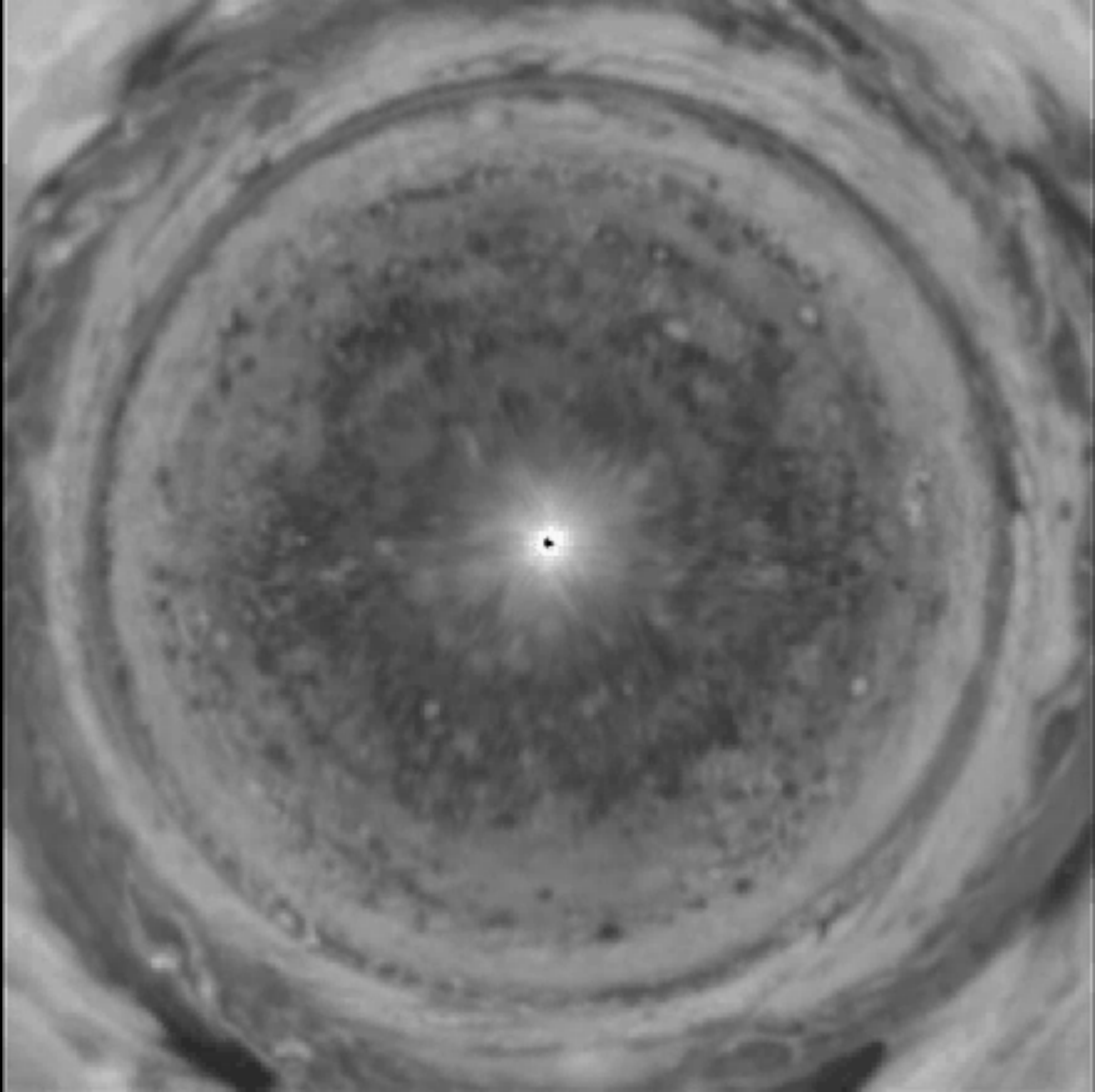
Jupiter



Cassini 2000



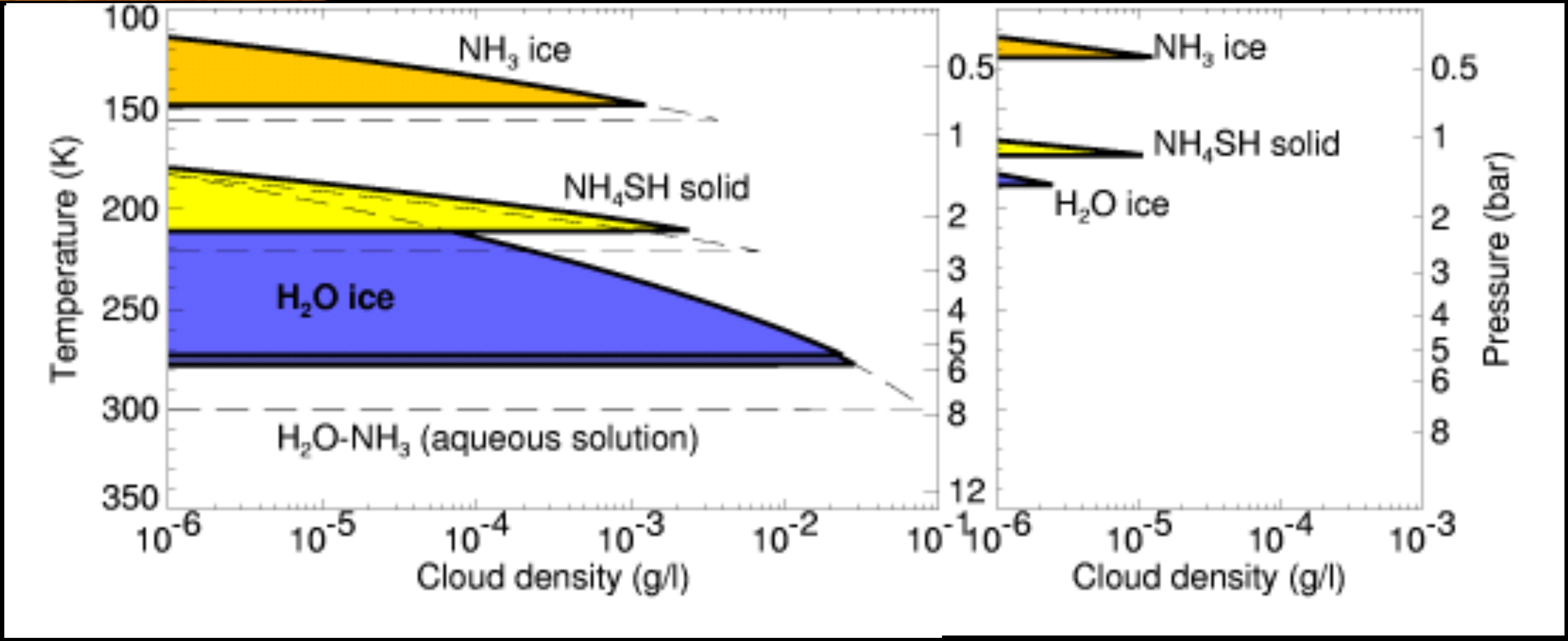
Cassini 2000

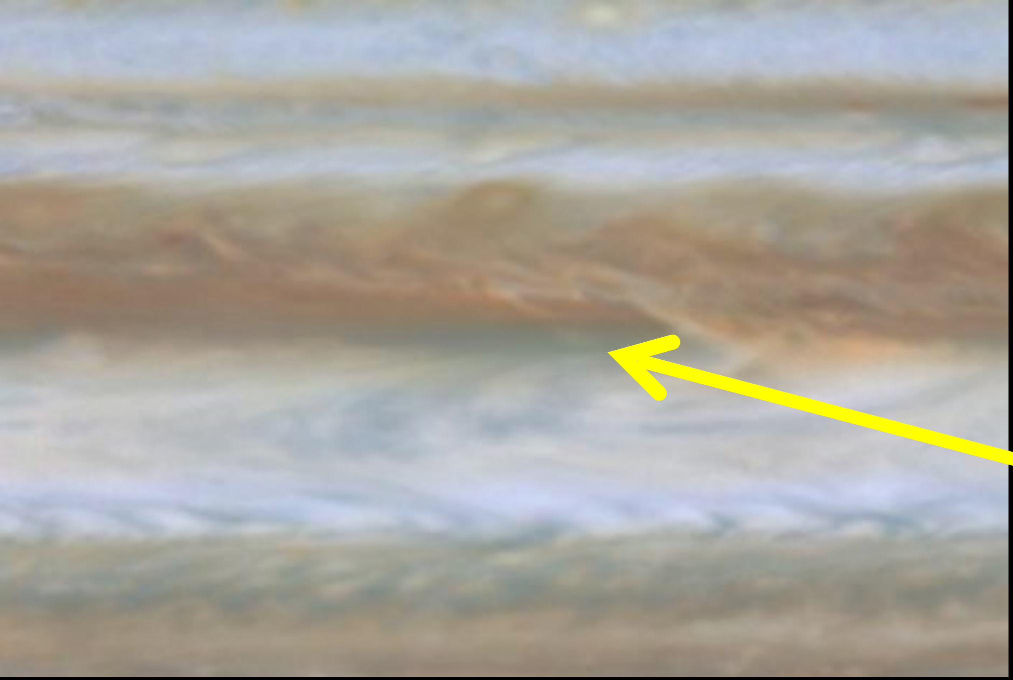


1995: Galileo Probe entered Jupiter clouds

Expected ammonia + water clouds

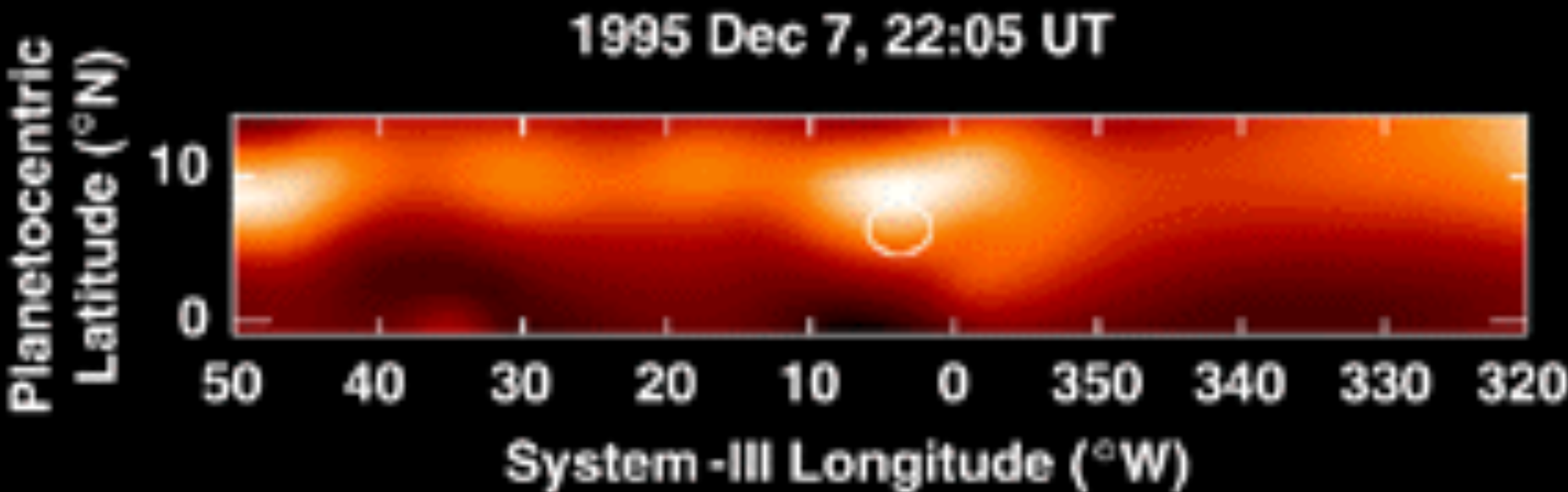
But found… very few clouds



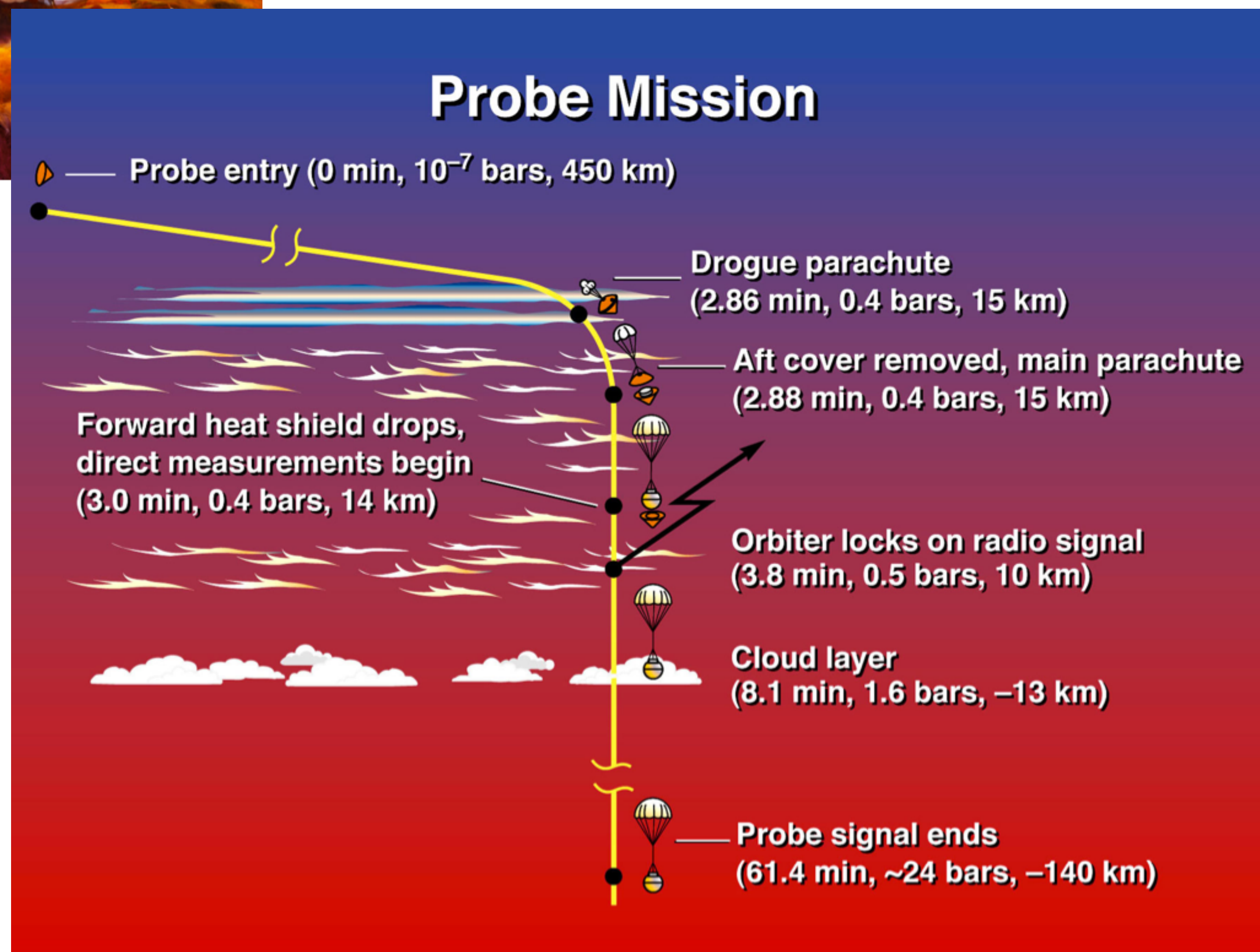


Probe entered here

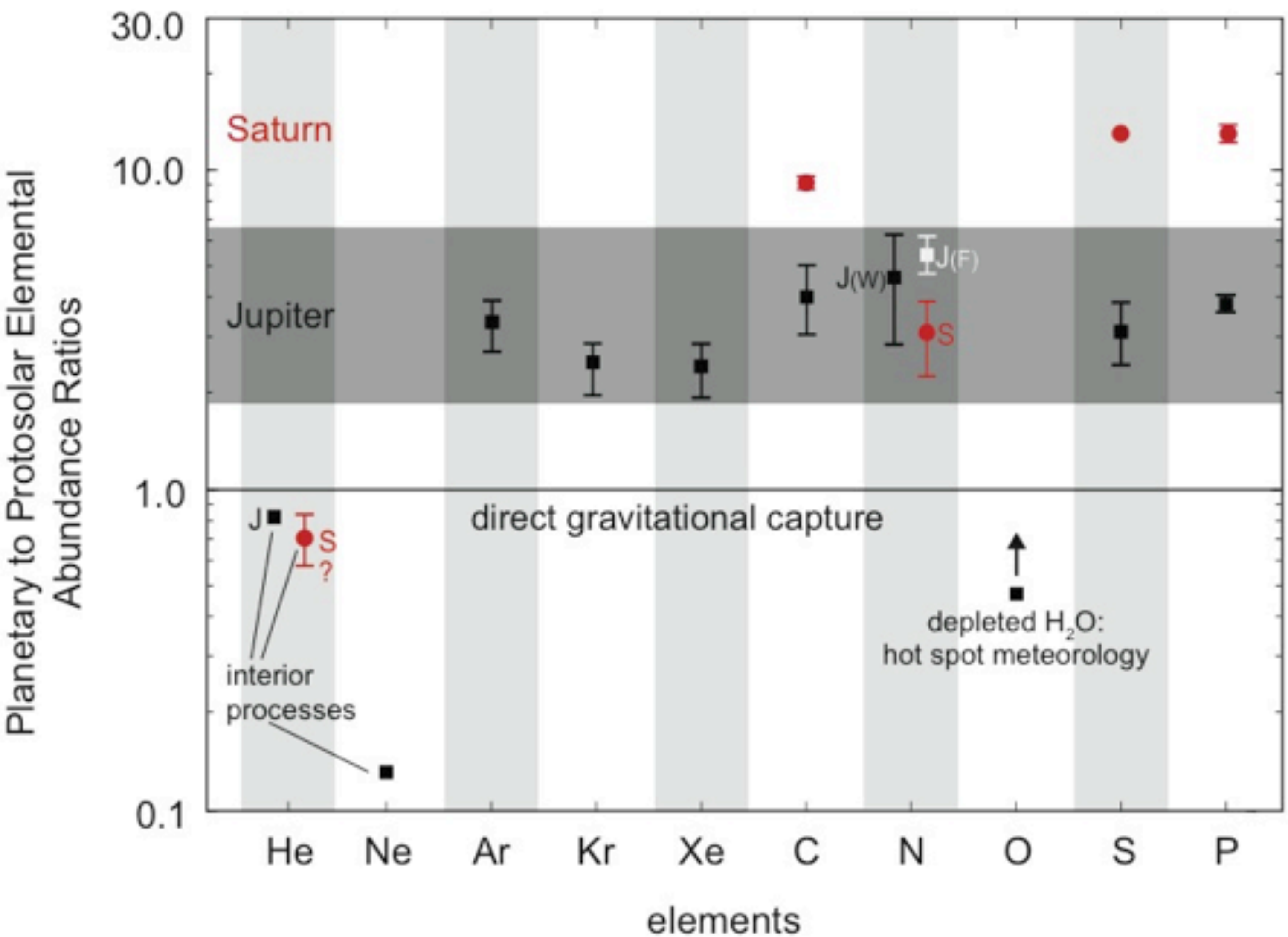
Infrared image from IRTF at time of probe

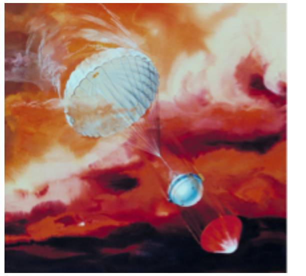


7 December 1995, 22:04-23:01 UTC

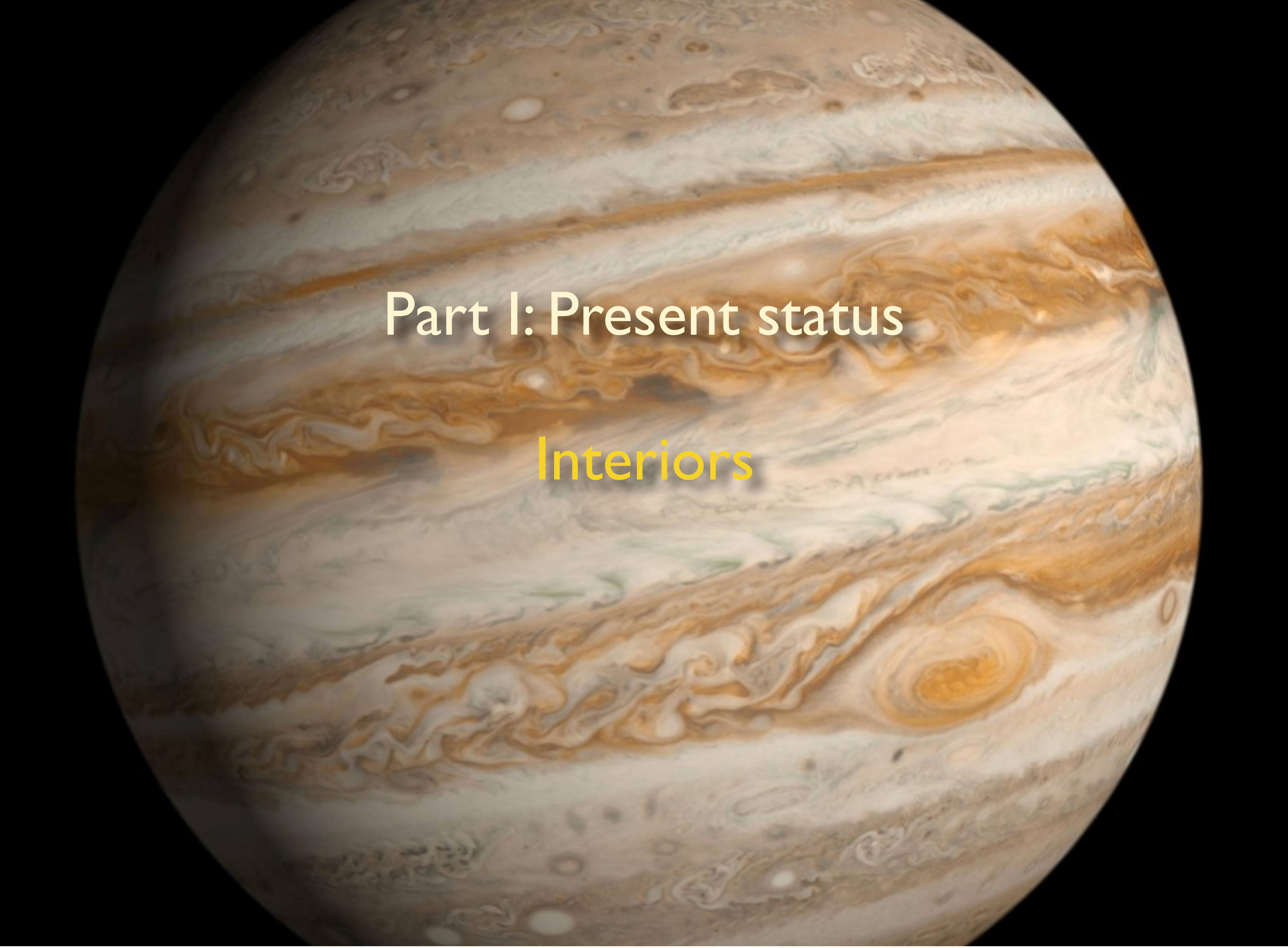


Constraints on atmospheric composition

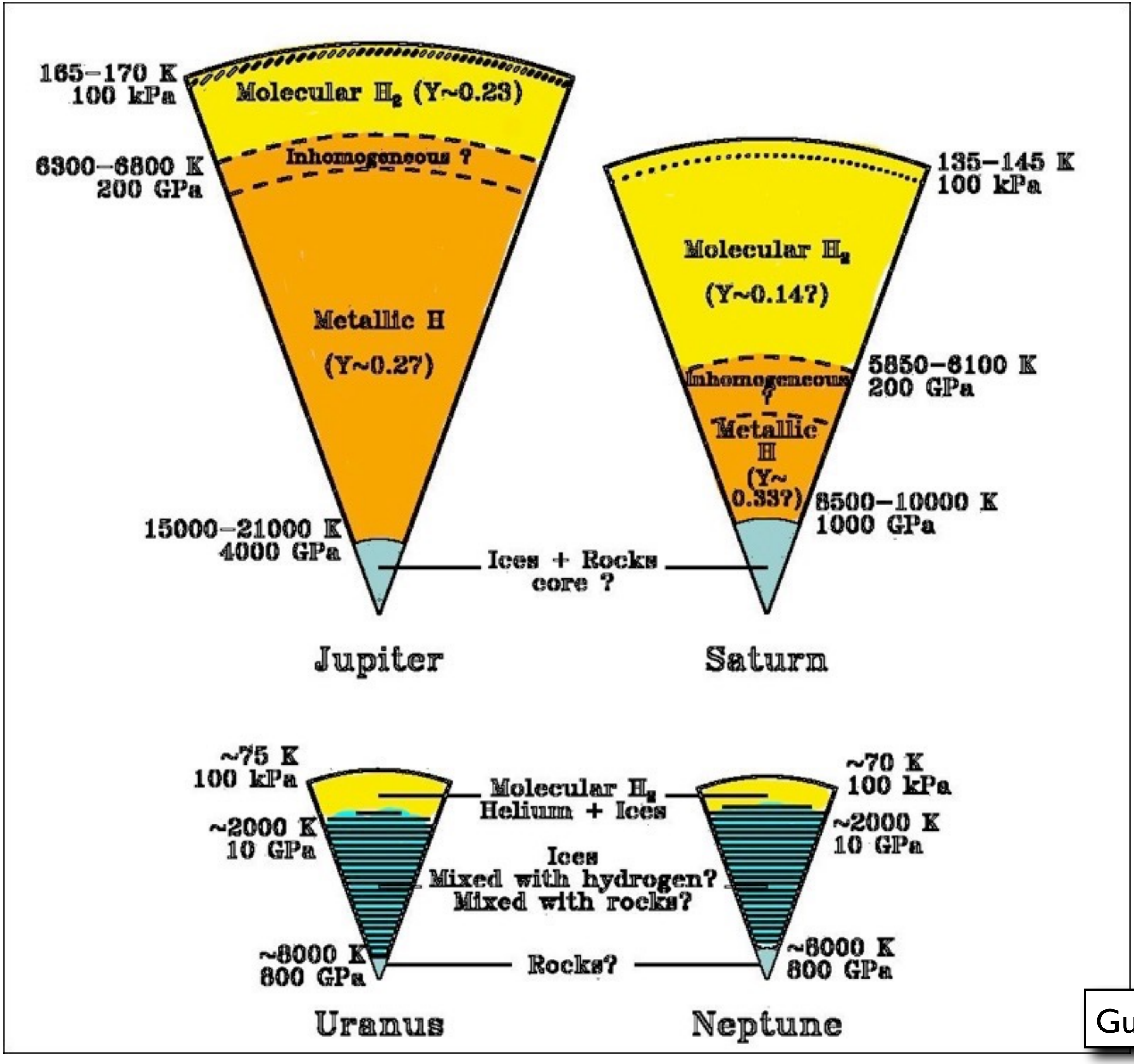




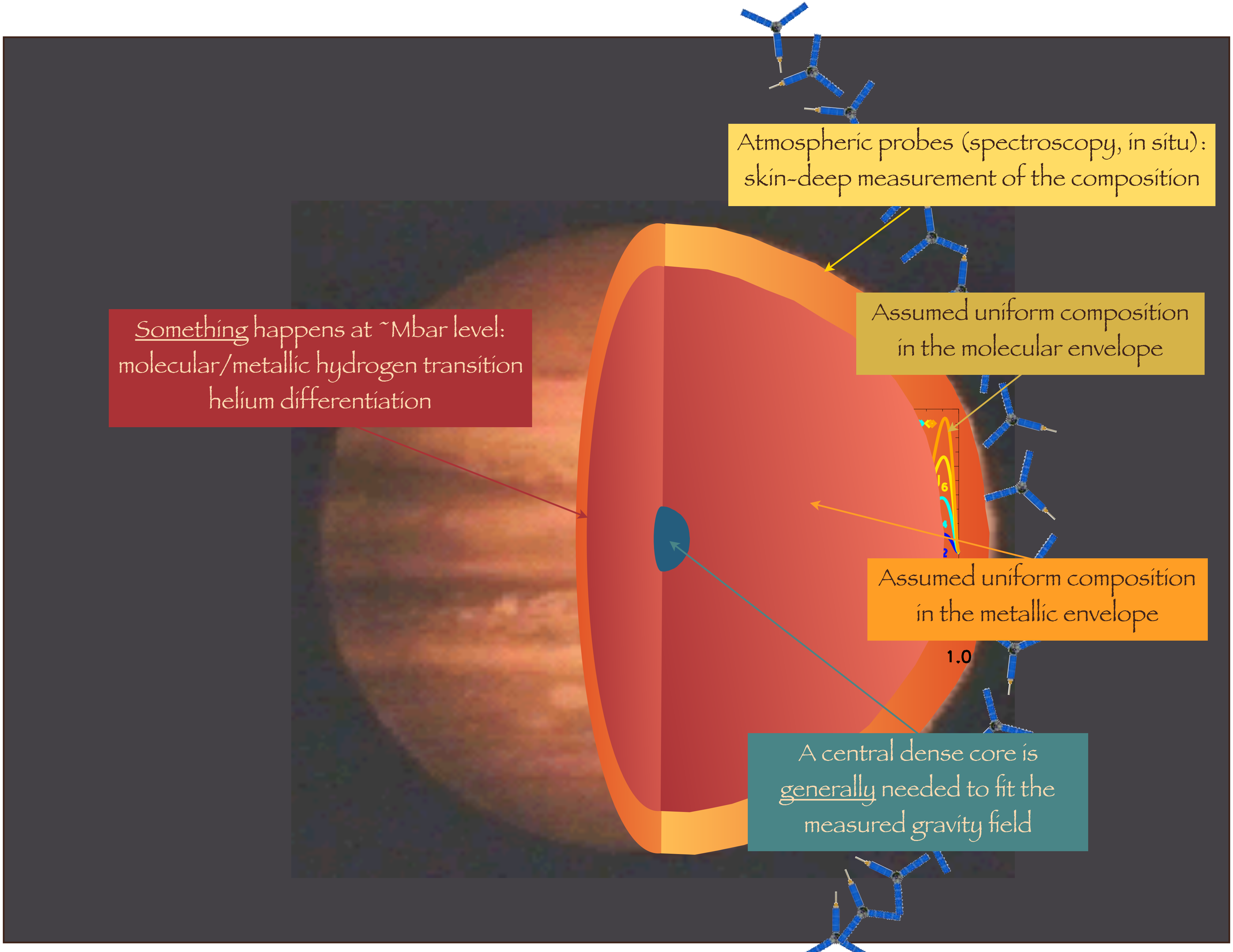
Atreya et al. (Saturn book chapter, in press)


Part I: Present status
Interiors

Three-layer models

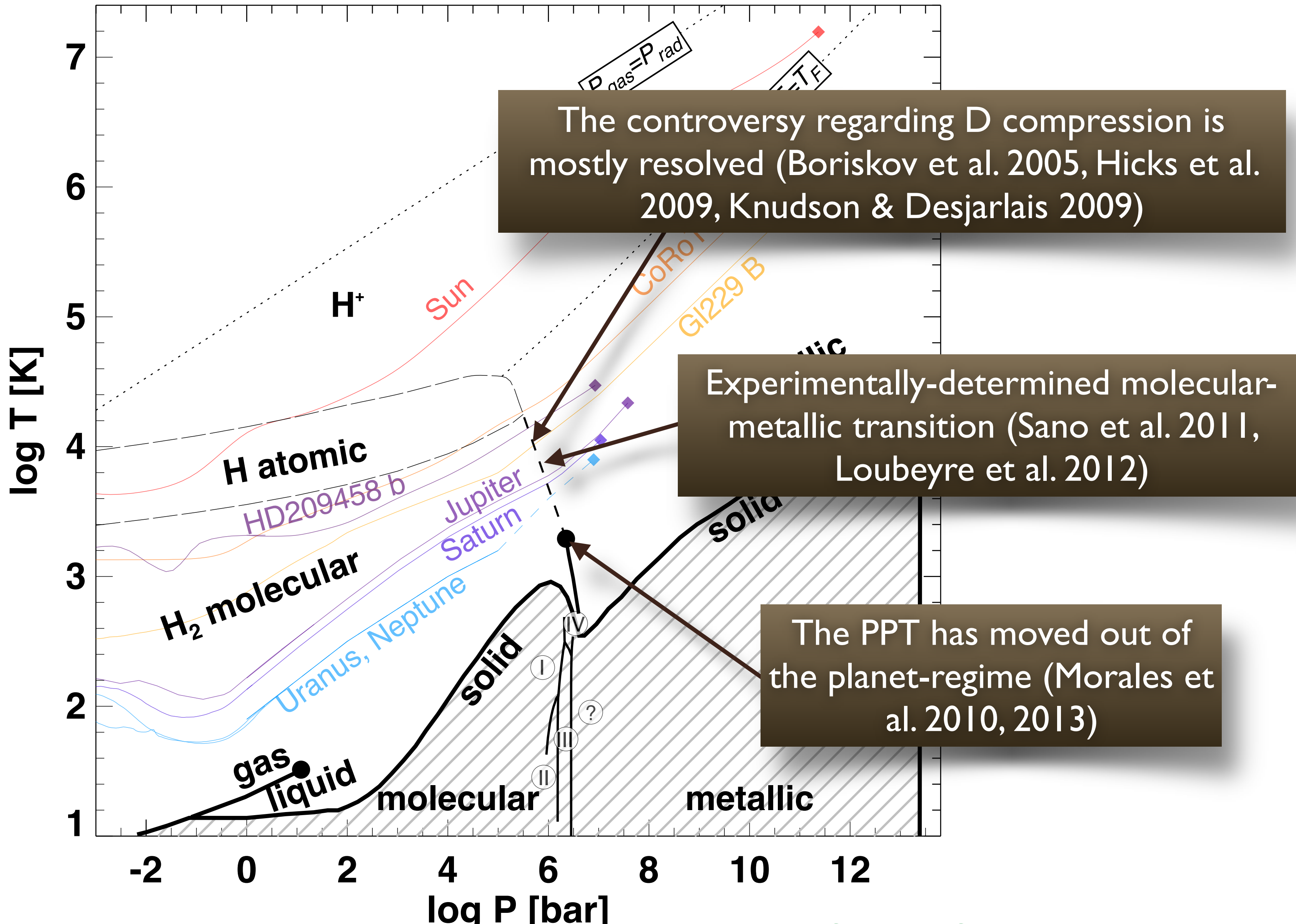


Guillot (1999)



Atmospheric probes (spectroscopy, in situ): skin-deep measurement of the composition
Something happens at ~Mbar level: molecular/metallic hydrogen transition helium differentiation
Assumed uniform composition in the molecular envelope
Assumed uniform composition in the metallic envelope
1.0
A central dense core is generally needed to fit the measured gravity field

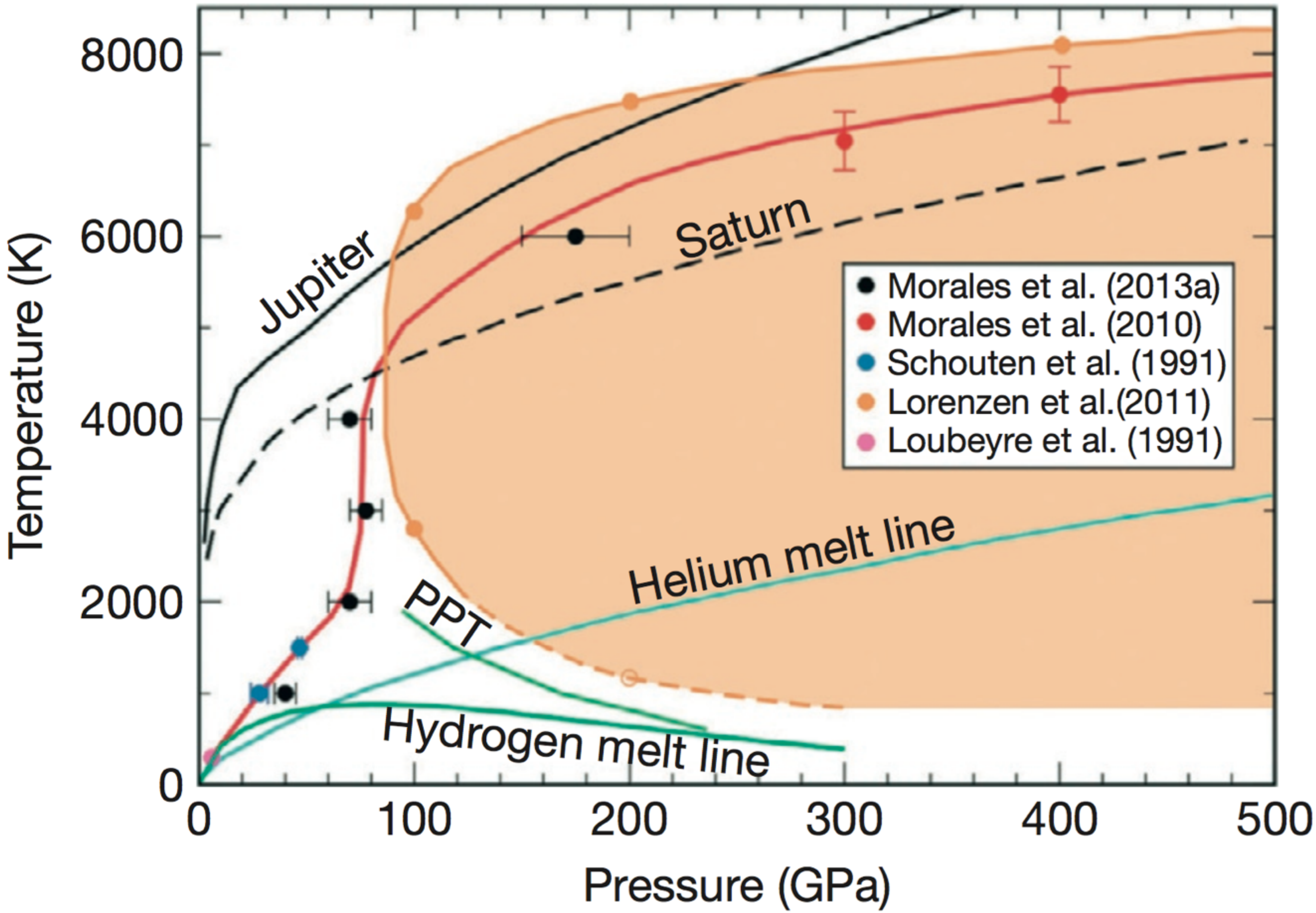
Hydrogen phase diagram



Guillot & Gautier (2015)

see also McMahon et al. (2012)

Hydrogen-helium phase separation



Construction of models

Equations of state

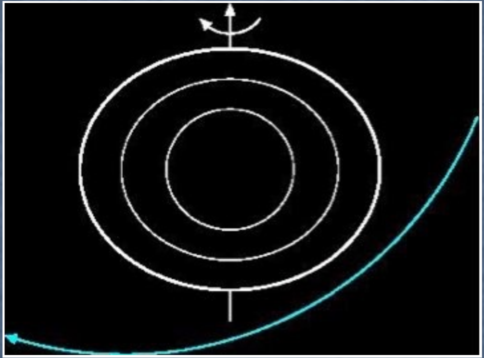
Opacities

Mass,
surface temperature…etc.

Hydrostatic equations
(rotation to 4th order)

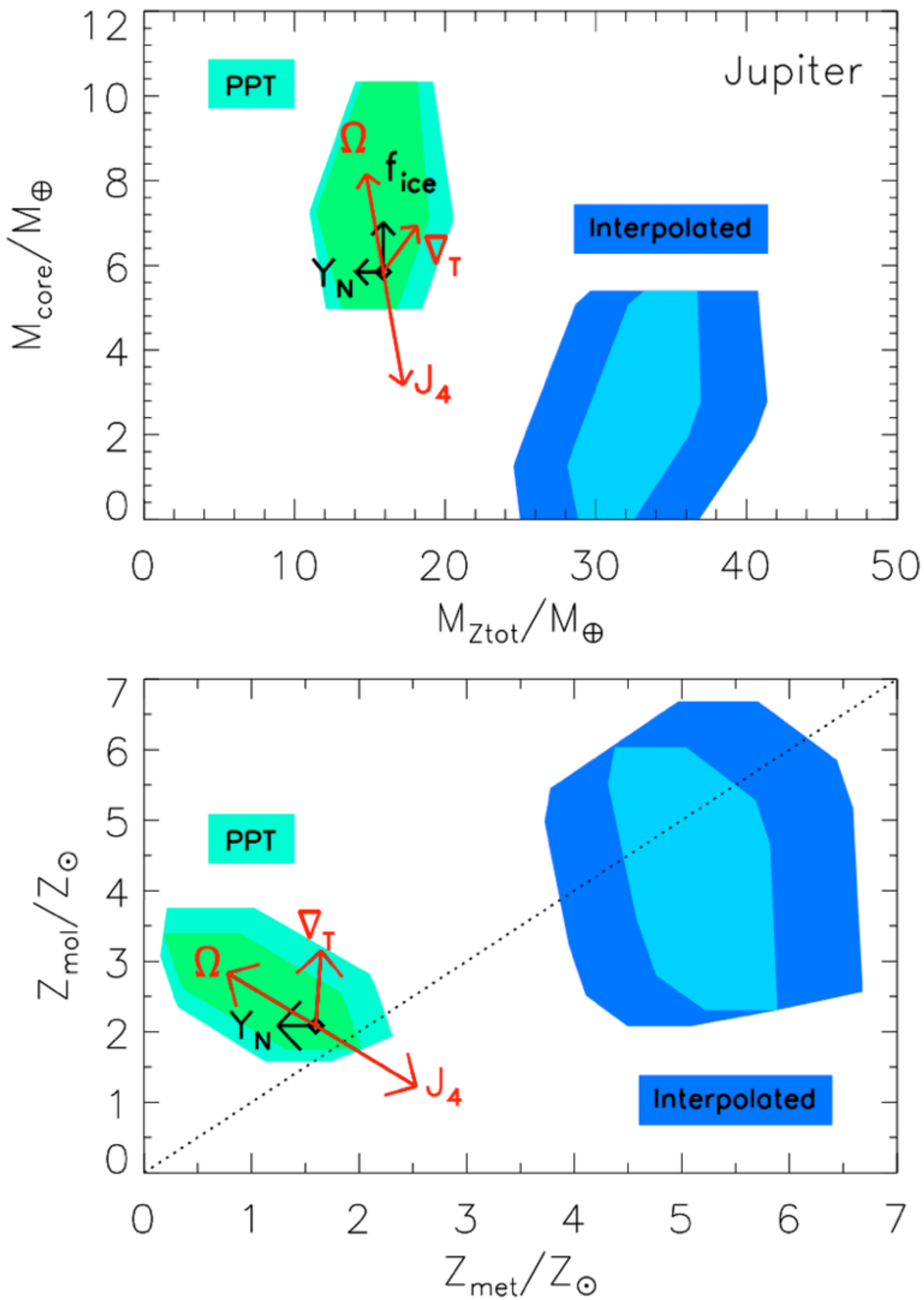
Theoretical gravitational
moments: J2, J4, J6,J8

Measured gravitational
moments: J2, J4, J6



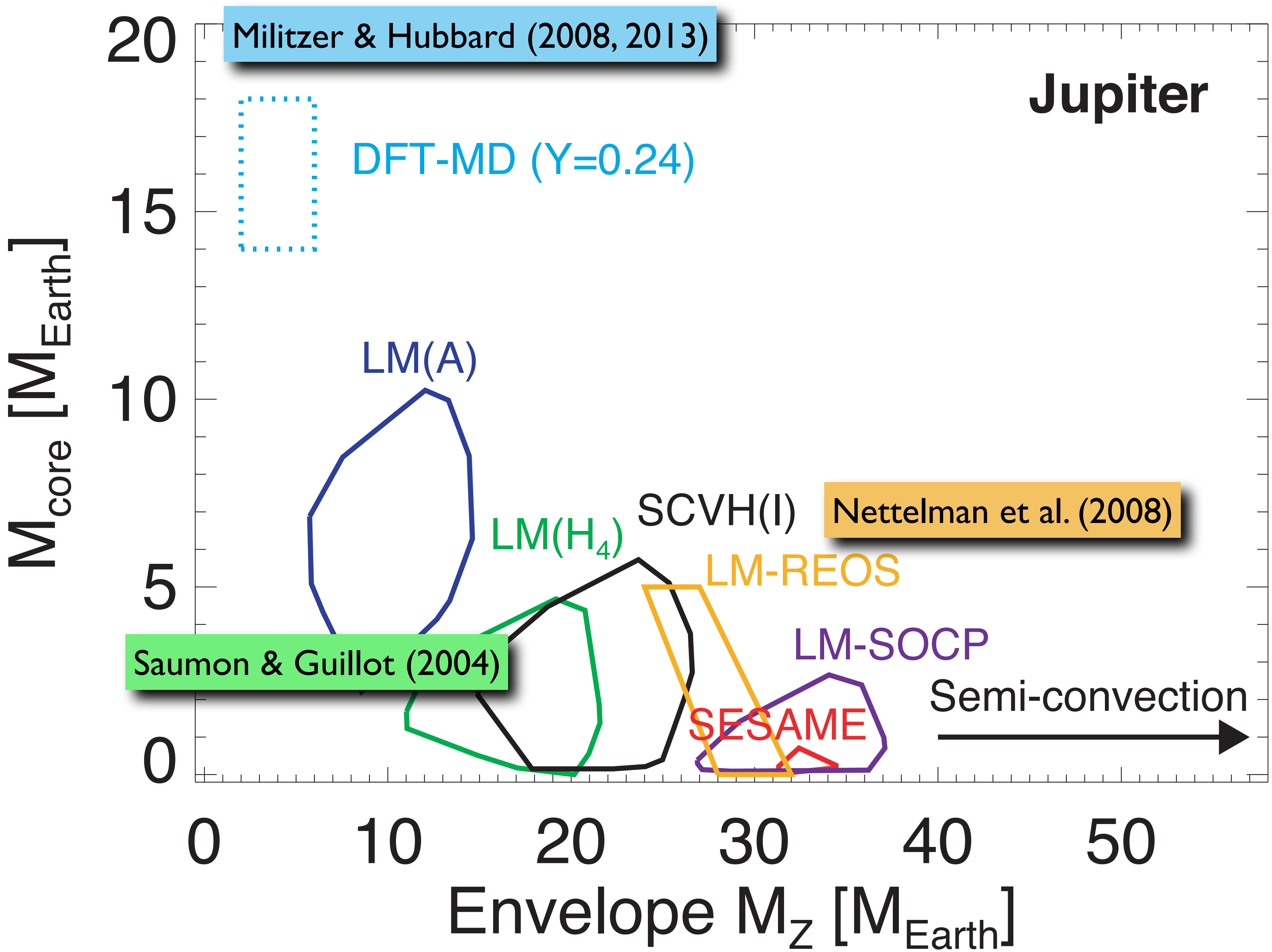
Mass of the rock/ice core
Y+Z in the metallic region
Y+Z in the molecular region

Results for Jupiter



Guillot 1999

Results for Jupiter




Part I: Present status
Origins

Where are the heavies?

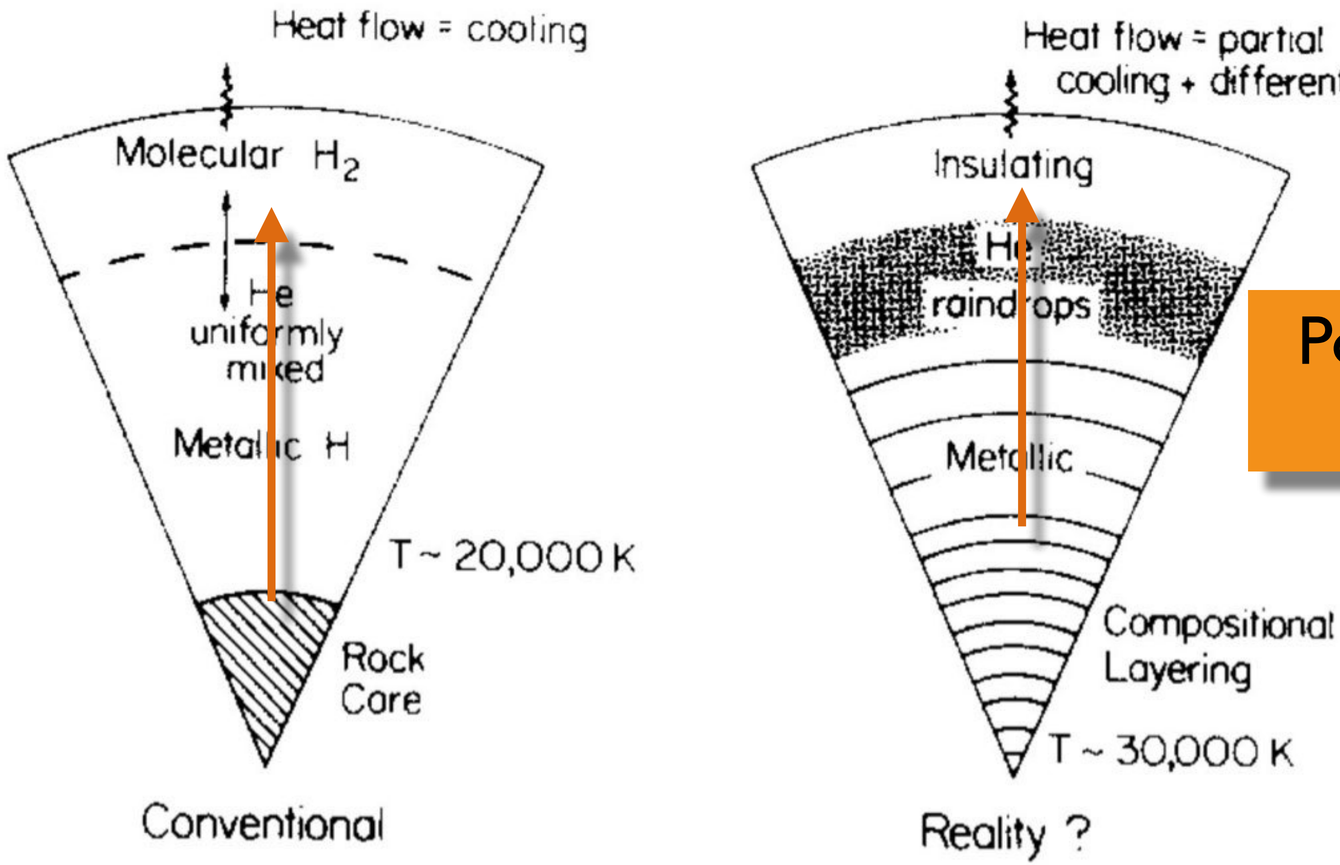


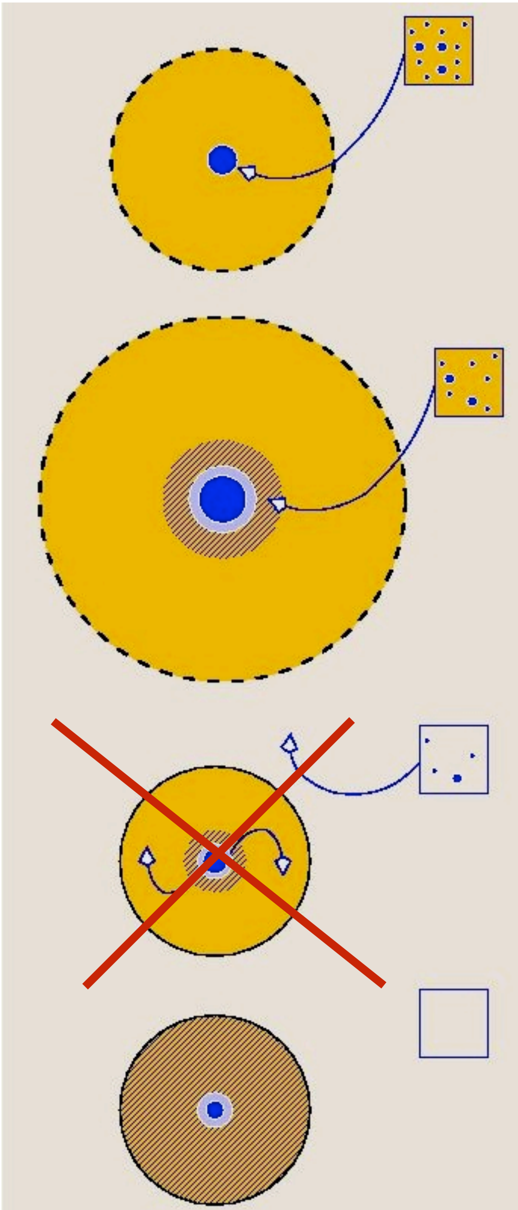
FIG. 3. Comparison of interior models for Jupiter according to the conventional view and in reality (similar to Table 1).

Possibility of erosion/ upward mixing

e.g. Stevenson 1981,
Guillot et al. 2004,
Wilson & Militzer 2011, 2012,
Leconte & Chabrier 2012,
Vazan et al. 2015

Stevenson (1985)

Was the primordial envelope metal-poor?

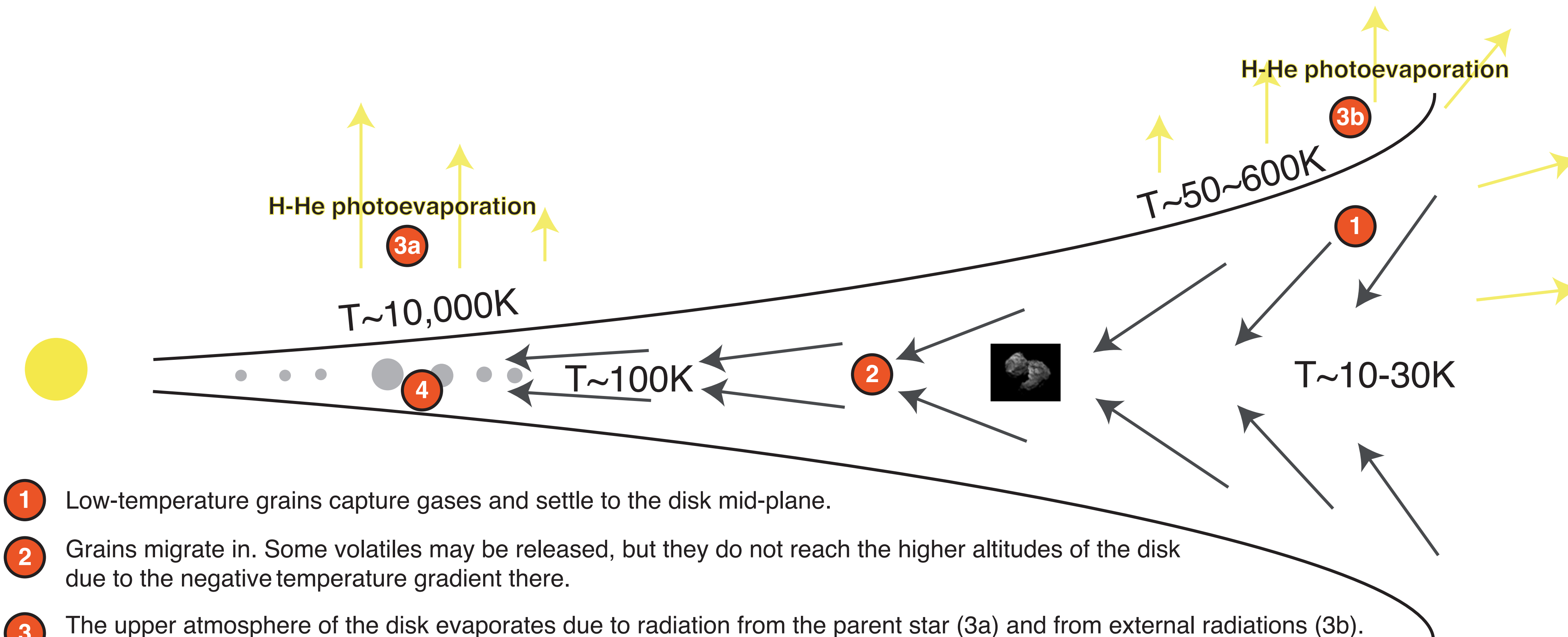


- Core accretion: planetesimals are delivered onto the central core.
- Core accretion: planetesimals cannot reach the core intact. (Podolak et al. 1988; Pollack et al. 1996)
- Envelope capture: accretion efficiency drops (Guillot & Gladman 2000): core erosion (see Guillot et al. 2004)?
- Present: enriched atmosphere.

or

- Heavies are accreted with the envelope because the feeding zone expands (e.g., Alibert et al. 2005; Lissauer et al. 2009)

How were noble gases delivered?

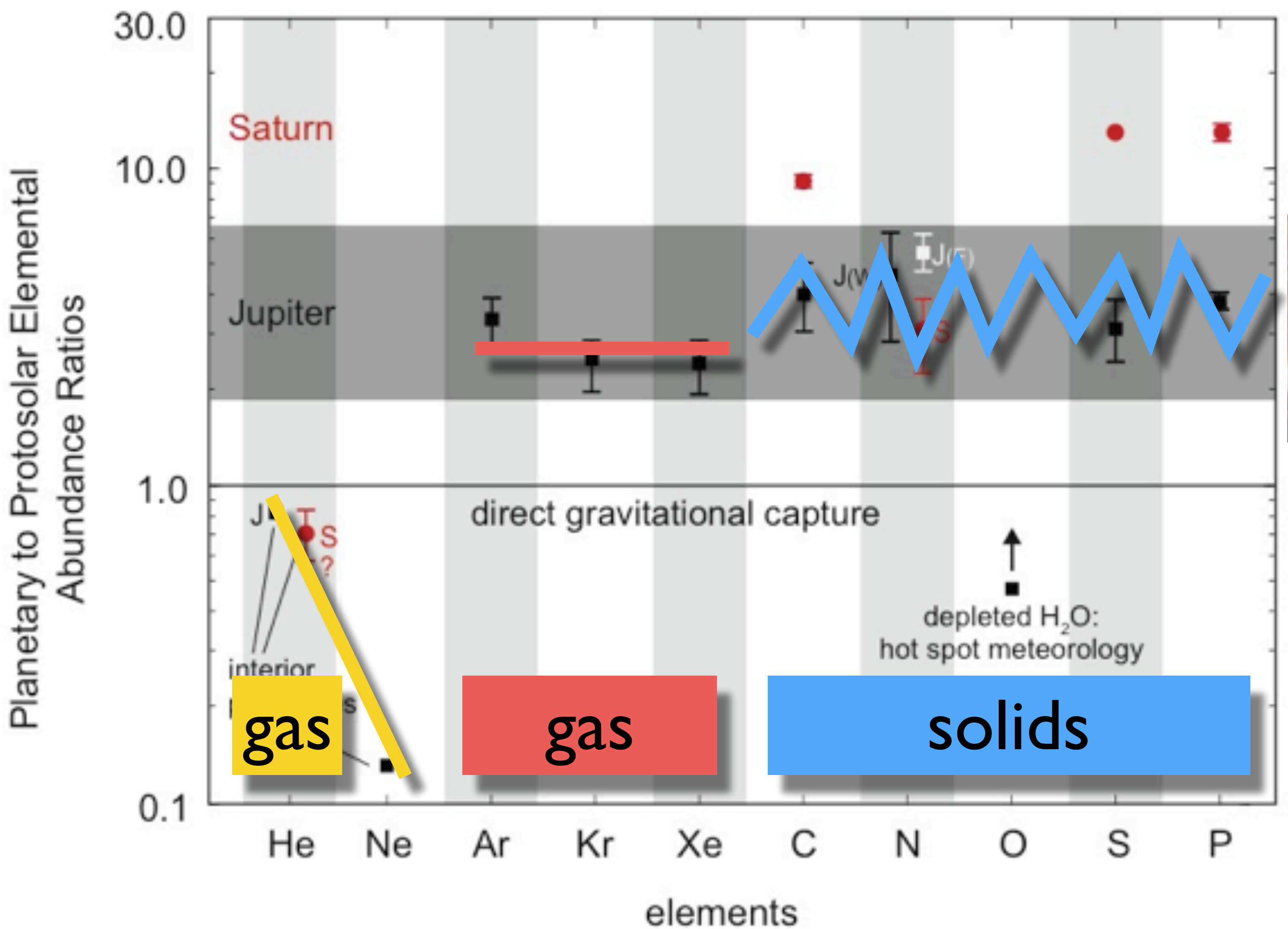


1. Low-temperature grains capture gases and settle to the disk mid-plane.
2. Grains migrate in. Some volatiles may be released, but they do not reach the higher altitudes of the disk due to the negative temperature gradient there.
3. The upper atmosphere of the disk evaporates due to radiation from the parent star (3a) and from external radiations (3b). This upper atmosphere contains moslty hydrogen and helium.
4. Giant protoplanets gradually capture a disk gas which is enriched in non-hydrogen-helium species.

Guillot & Hueso (2006)

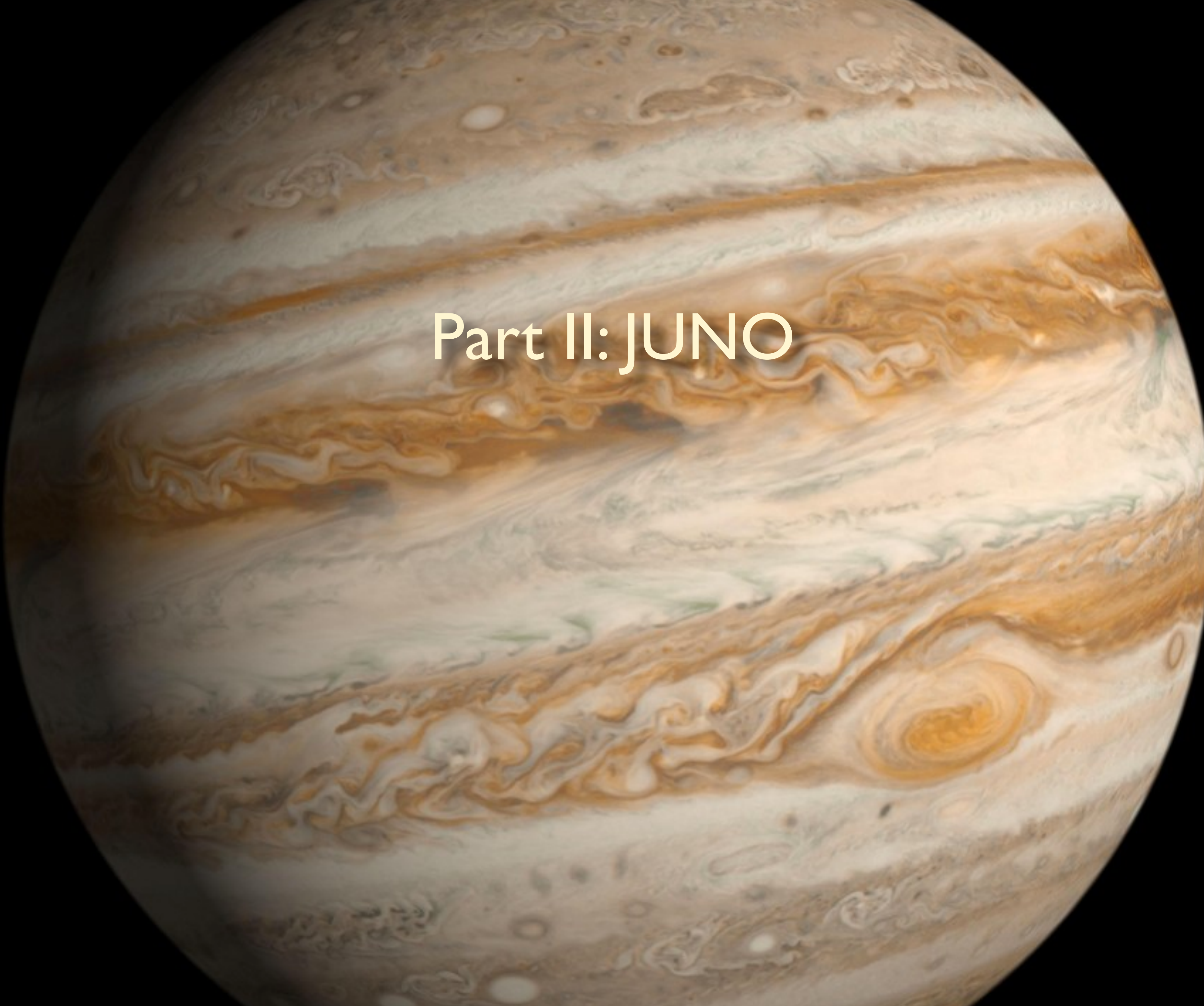
see also Throop & Bally (2010), Atreya et al. (in press), Monga & Desch (2015)

Explaining the atmospheric compositions…



Atreya et al. (Saturn book chapter, in press)

Part II: JUNO




National Aeronautics and Space Administration
NASA
Juno
Mission to Jupiter
Jupiter Orbit Insertion: 4 July 2016
www.nasa.gov

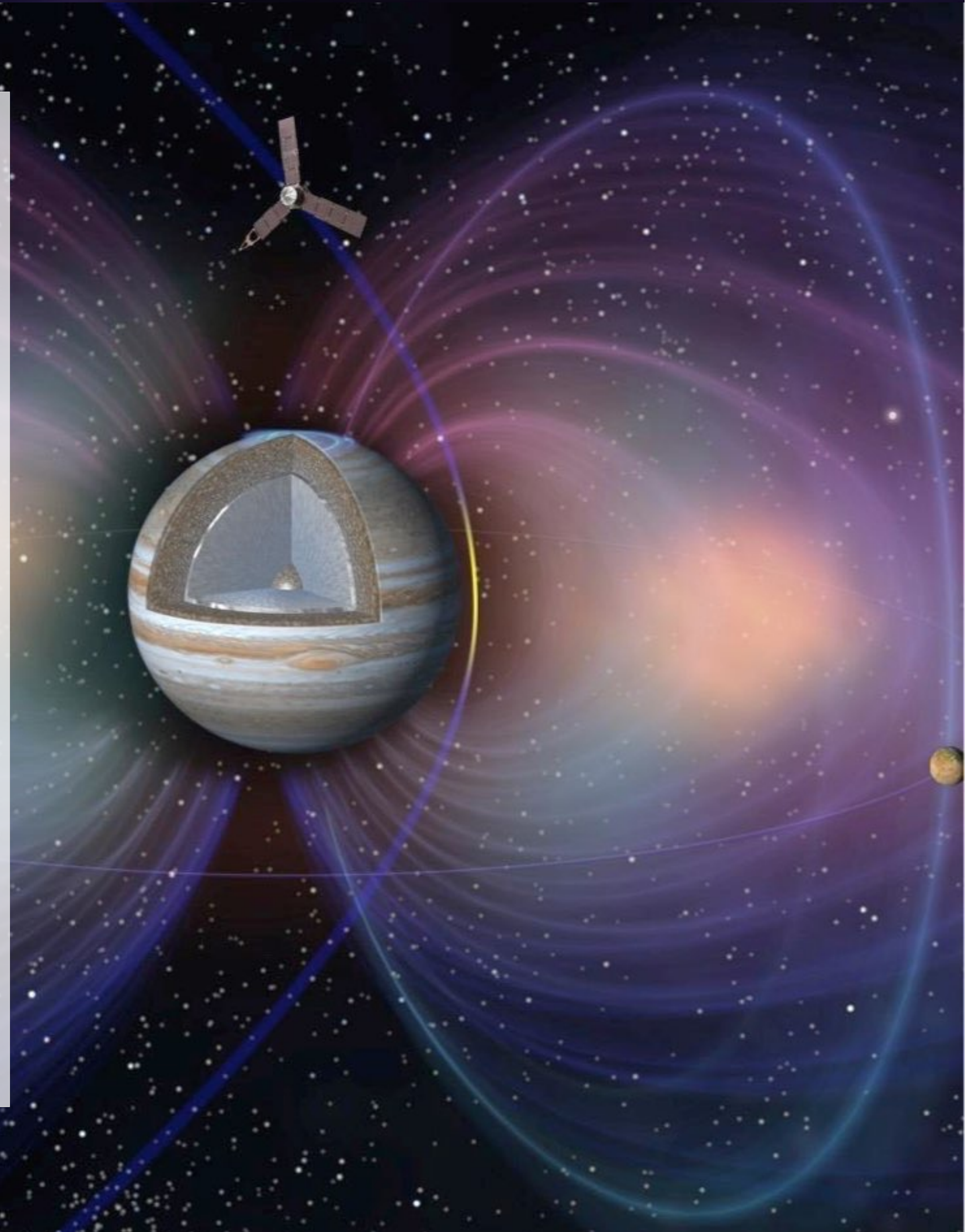
Juno project overview

Spacecraft:

- Spinning, polar orbiter spacecraft launches in August 2011
  - 5-year cruise to Jupiter, JOI on 4 July 2016
  - 1 year operations, EOM via de-orbit into Jupiter in 2017
- Elliptical 14-day orbit swings below radiation belts to minimize radiation exposure
- 2nd mission in NASA's New Frontiers Program First solar-powered mission to Jupiter
- Payload of eight science instruments to conduct gravity, magnetic and atmospheric investigations, plus a camera for E/PO

Science Objective: Improve our understanding of giant planet formation and evolution by studying Jupiter's origin, interior structure, atmospheric composition and dynamics, and magnetosphere

Principal Investigator: Dr. Scott Bolton
Southwest Research Institute



The Orbit: Key to the Whole Mission

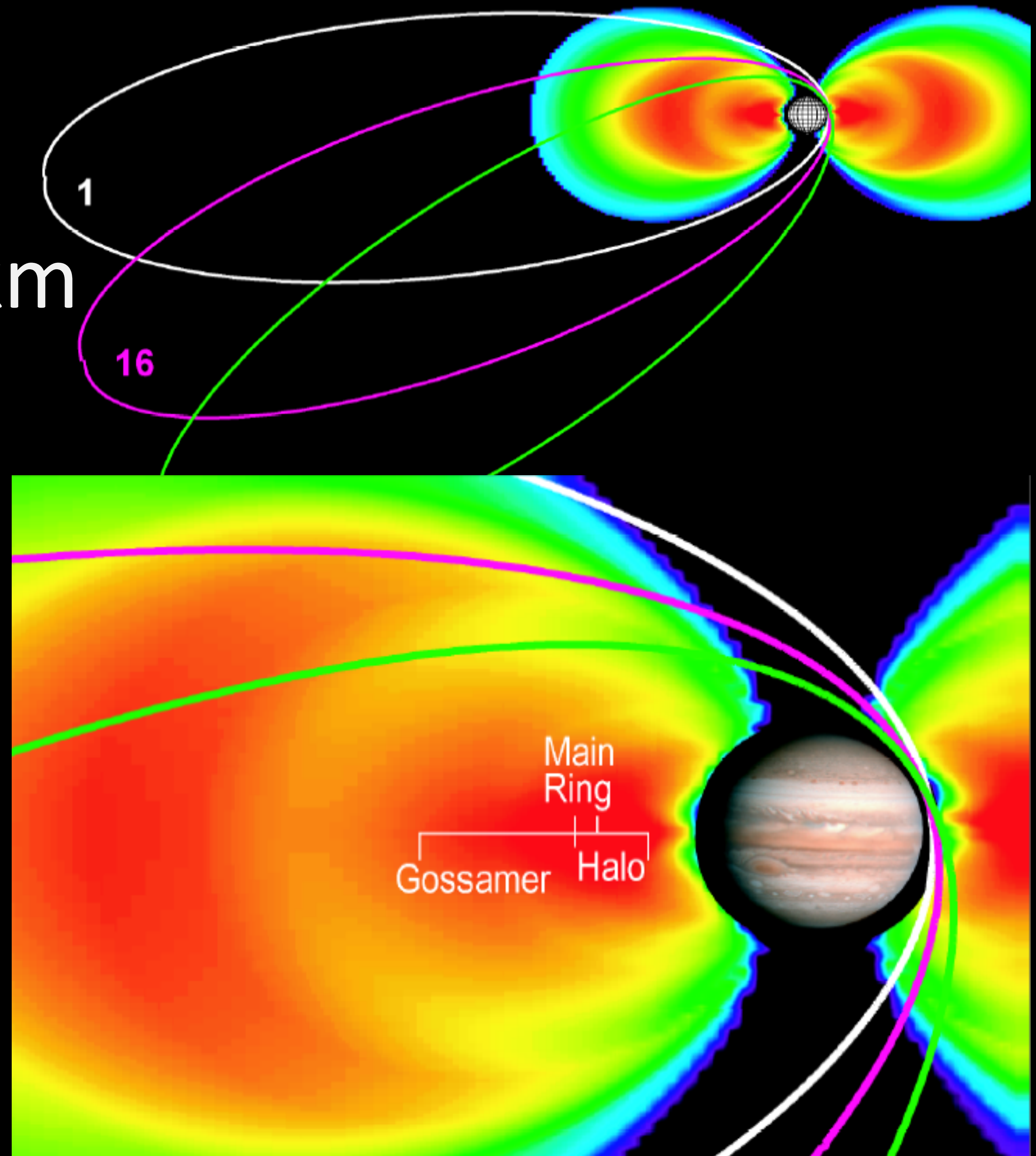
- 32 polar orbits

  Perijove ~5000 km

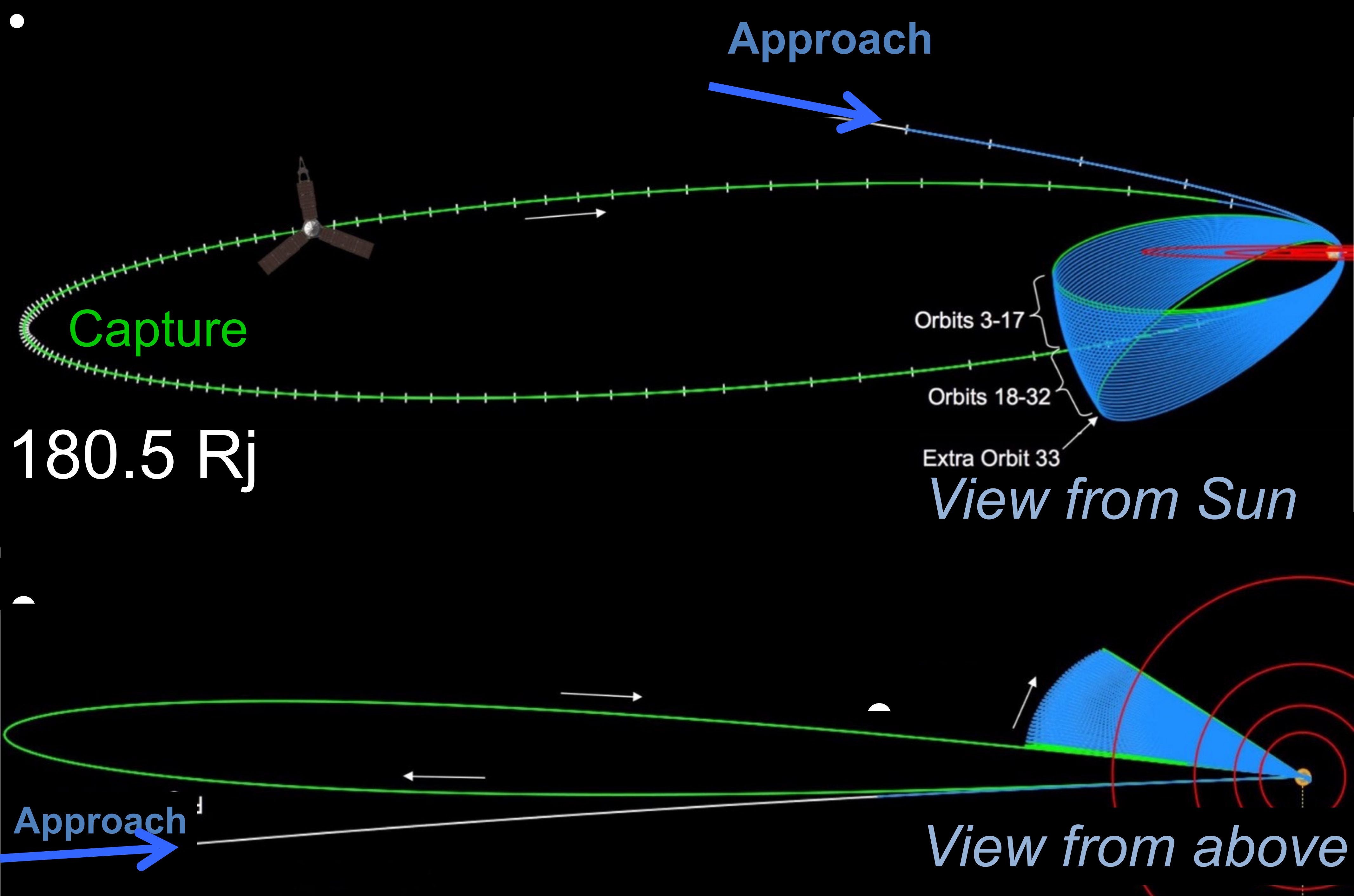
  14 day period

Duck under radiation belts…

Skim above clouds…

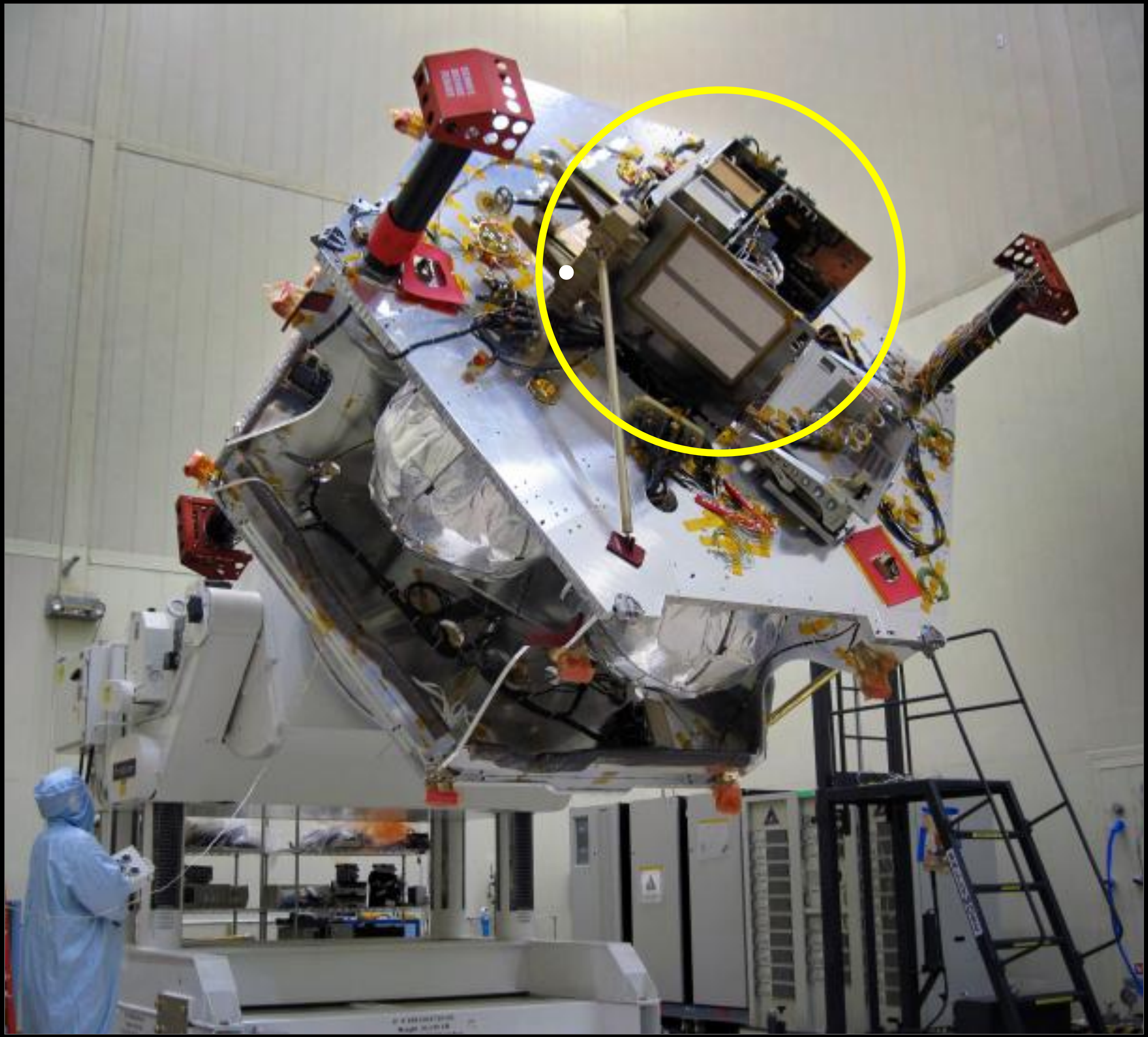


All orbits near the dawn terminator



The Juno Spacecraft

Juno's key components: **Radiation vault**



The Juno Spacecraft

Juno’s key components:

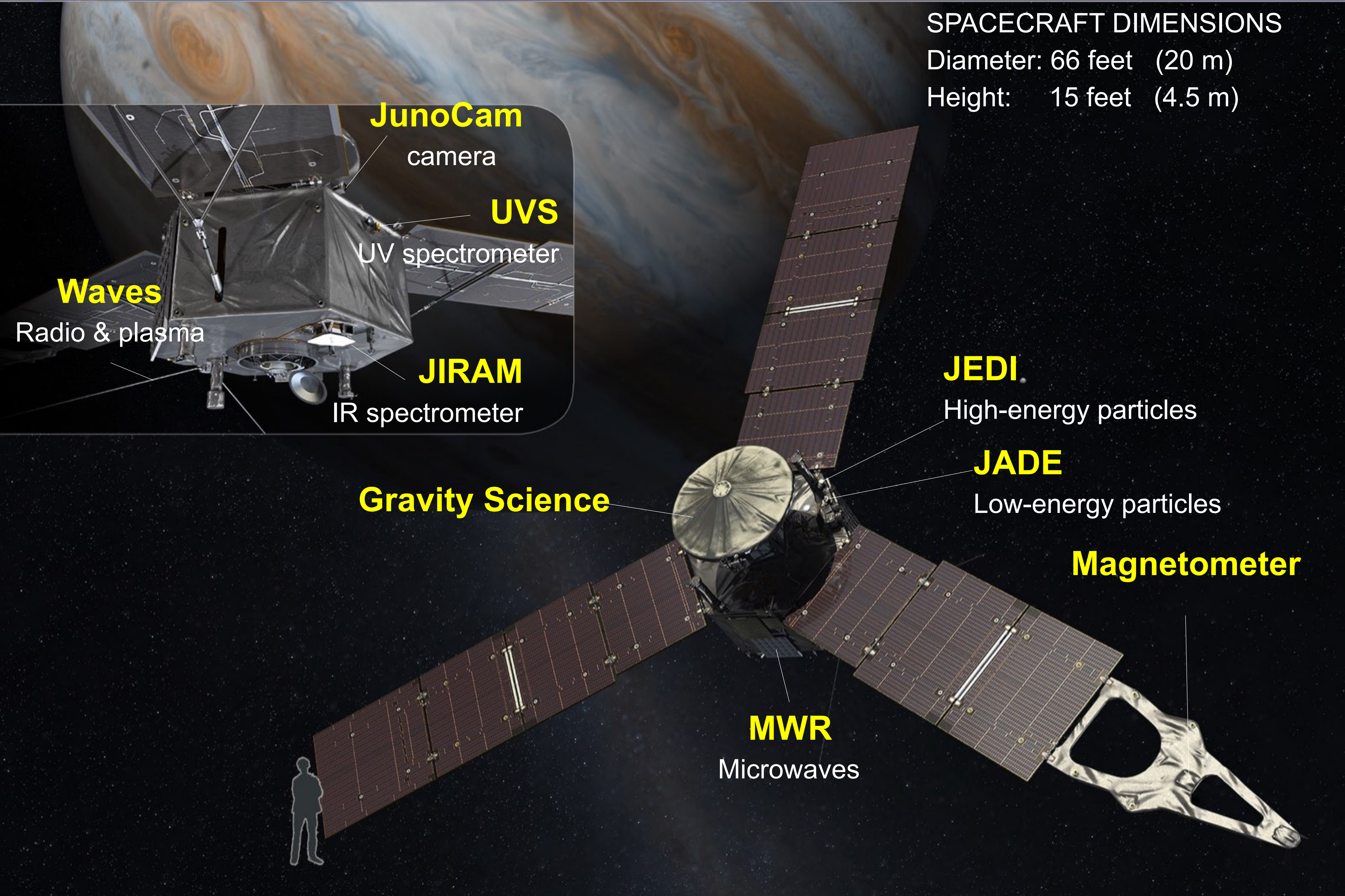
Solar arrays

2m x 7.5m arrays producing ~300 W

Sun-pointed, spinning 3 rpm

Spacecraft & Payload

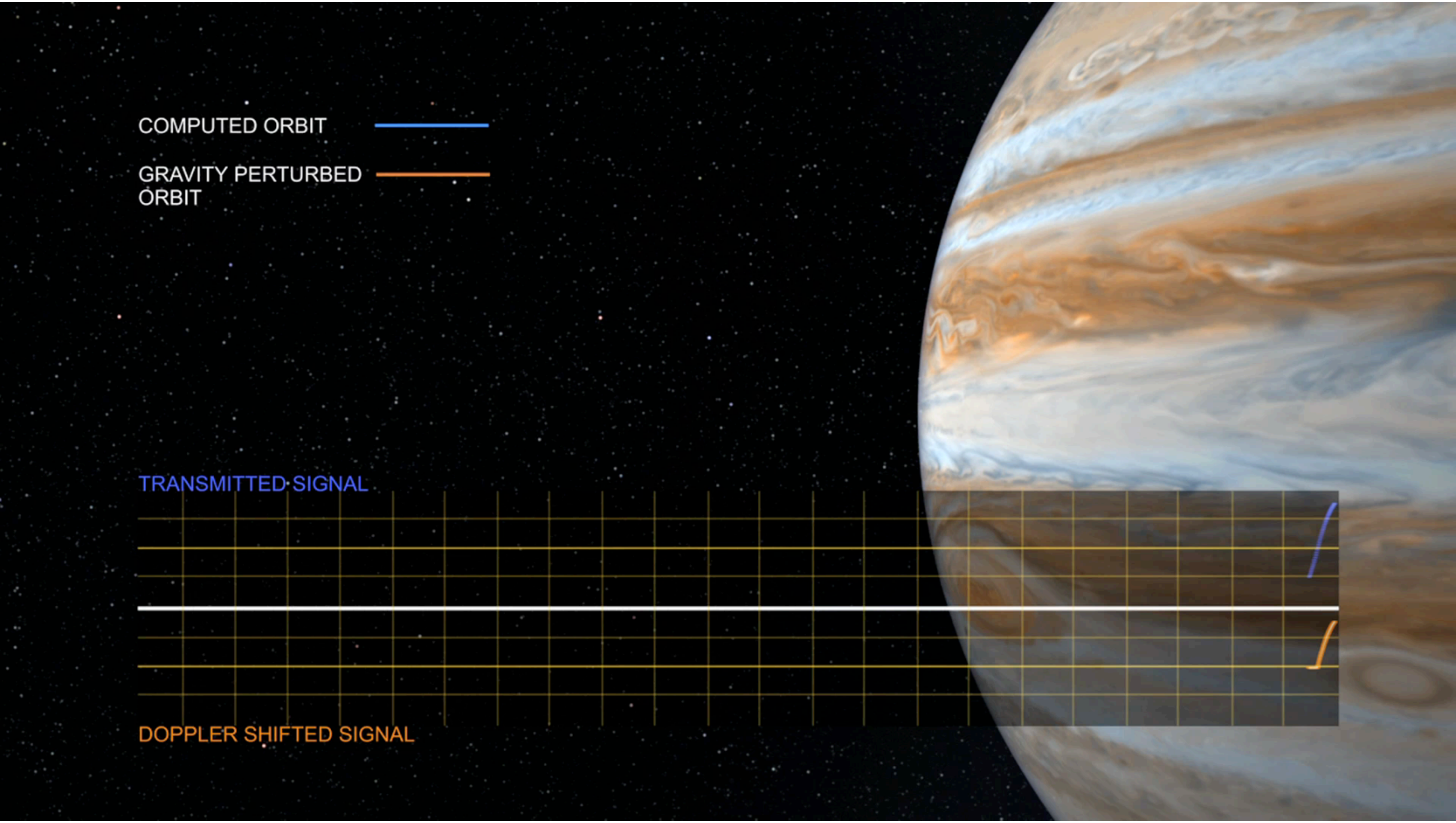
SPACECRAFT DIMENSIONS
Diameter: 66 feet (20 m)
Height: 15 feet (4.5 m)



Each Orbit Phased to Map Out Planet

Successive Orbits ~24° Apart

Juno's Motion Doppler Shifts Radio Signal



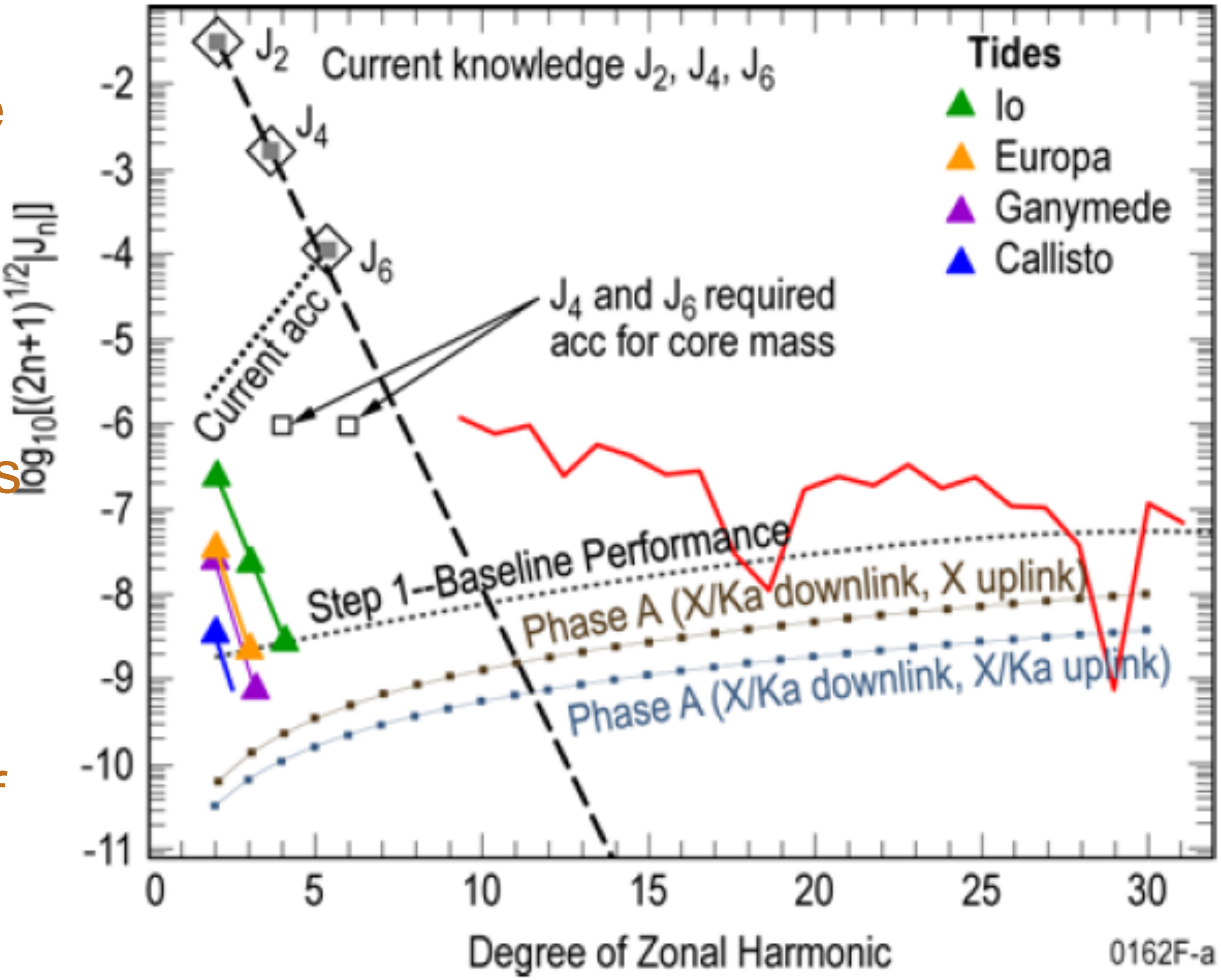
Juno's Motion Reveals Jupiter's Gravity

Internal Mass Distribution Determines Gravity

J_2, J_4, J_6 and tides give core mass once water abundance is known

J_8 - J_{30} give deep winds down to $r \sim 0.8\ R_J$

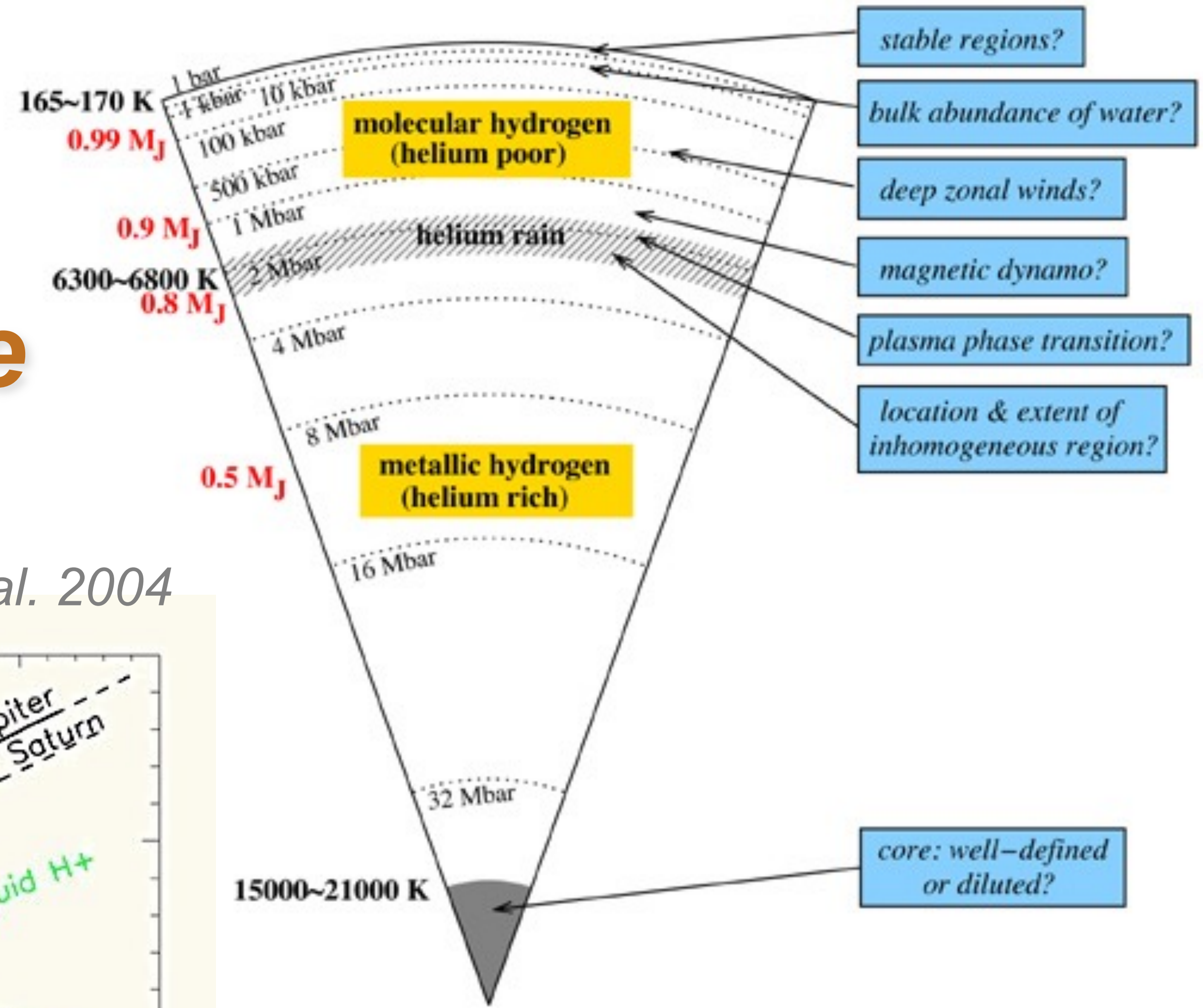
____ model signature of deep winds



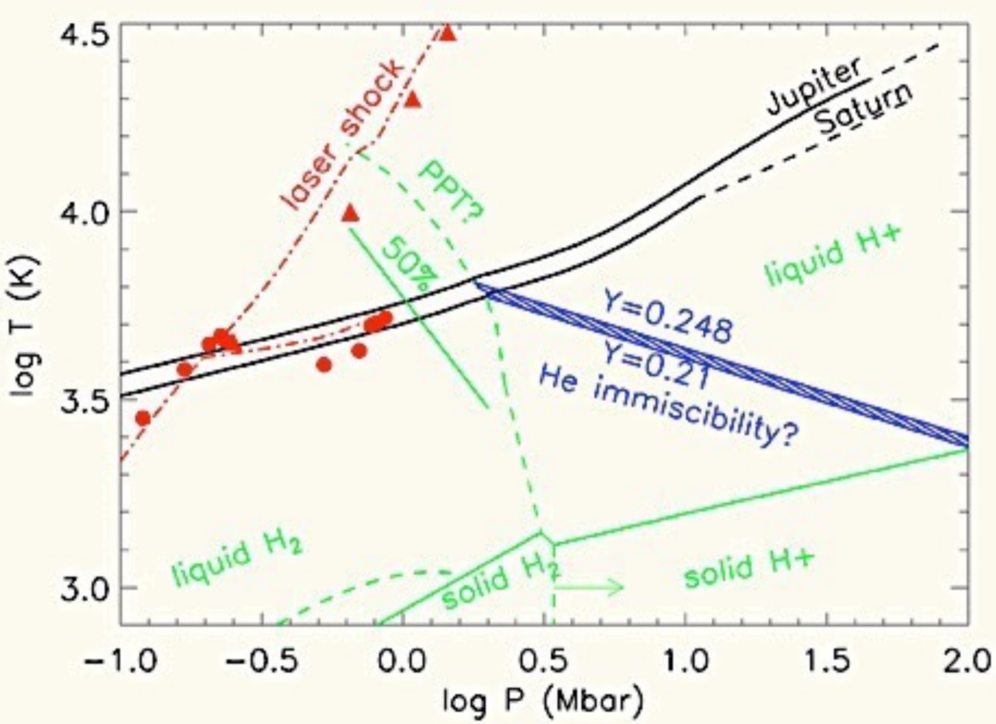
Reveals Core Mass & Deep Winds

Juno

Modeling Interior Structure Requires ***Equation of State*** + Gravity Data



Guillot et al. 2004



Juno Provides Gravity Data

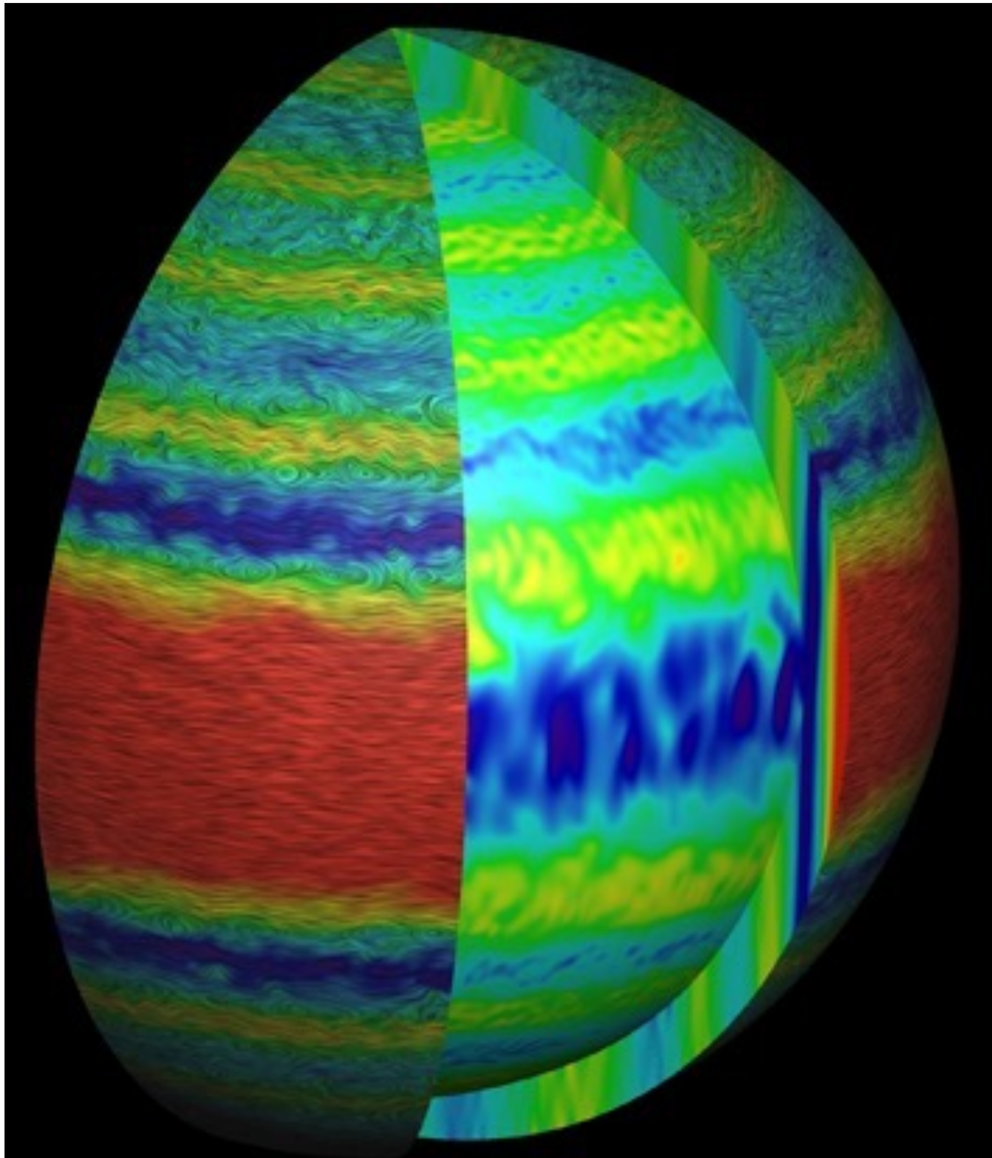
Juno Maps the Jupiter's Magnetic Field

Jupiter spins every 10 hours

Jupiter radiates 2.5x solar input

Internal heat & rotation drive flows

What internal flows drive Jupiter's magnetic dynamo?


Heimpel & Aurnou

Reveals Jupiter's Dynamo Process

Juno

Juno Maps the Jupiter's Magnetic Field

Reveals Jupiter's Dynamo Process

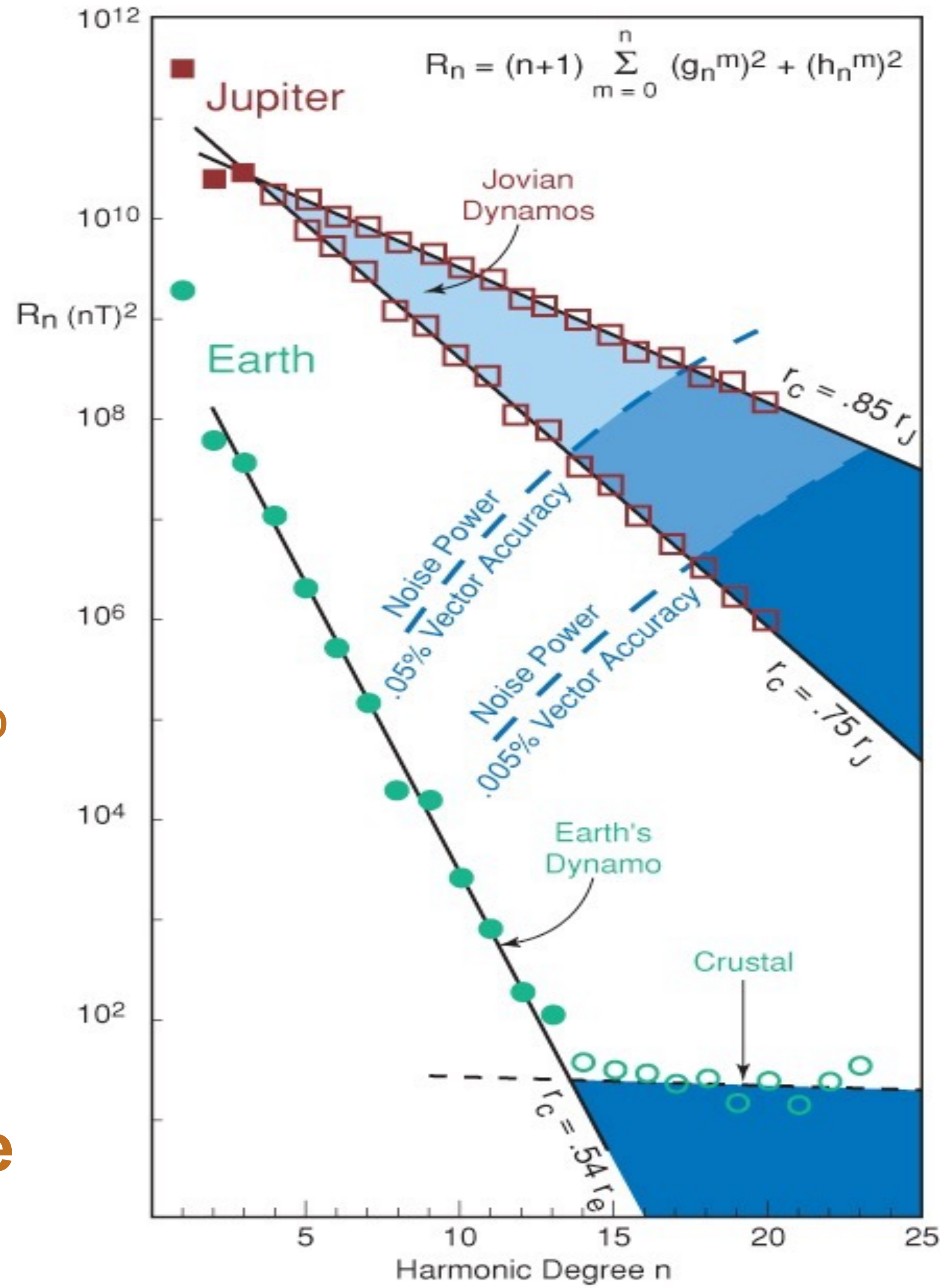
Magnetic Spectra of Earth and Jupiter

Current knowledge of Jupiter is limited to n < 4

Earth dynamo at n >14 is hidden by crustal field

Juno will measure out to n ~ 20

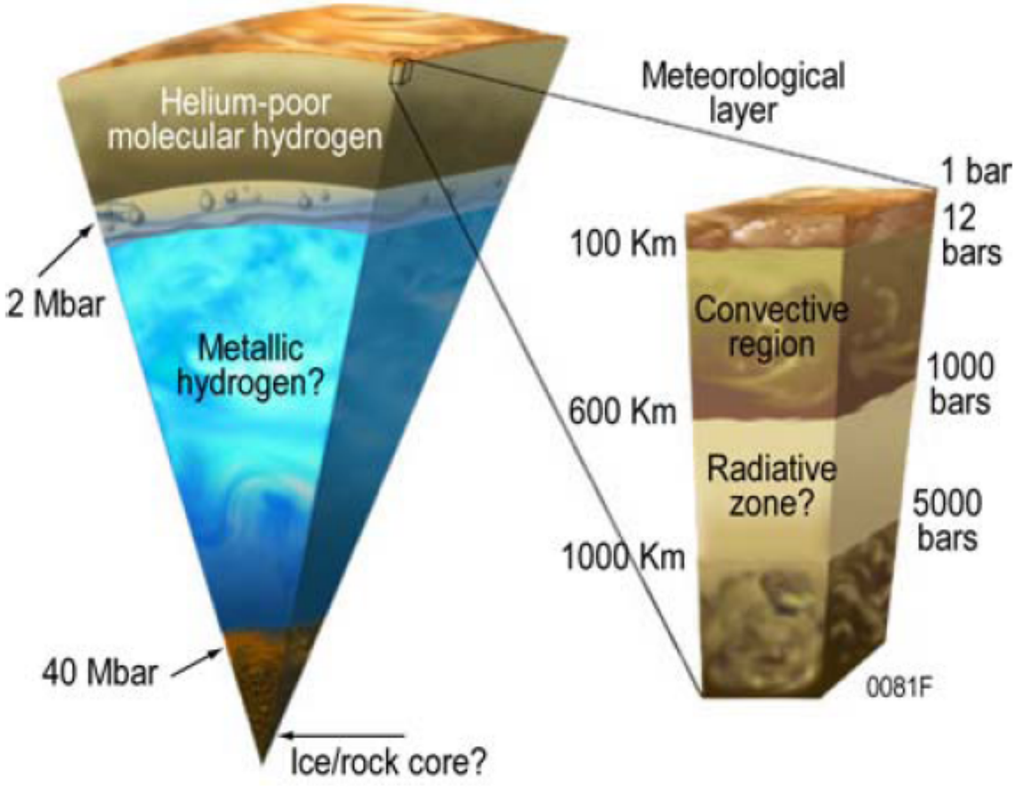
Determine spectral shape, dynamo radius, and secular variations

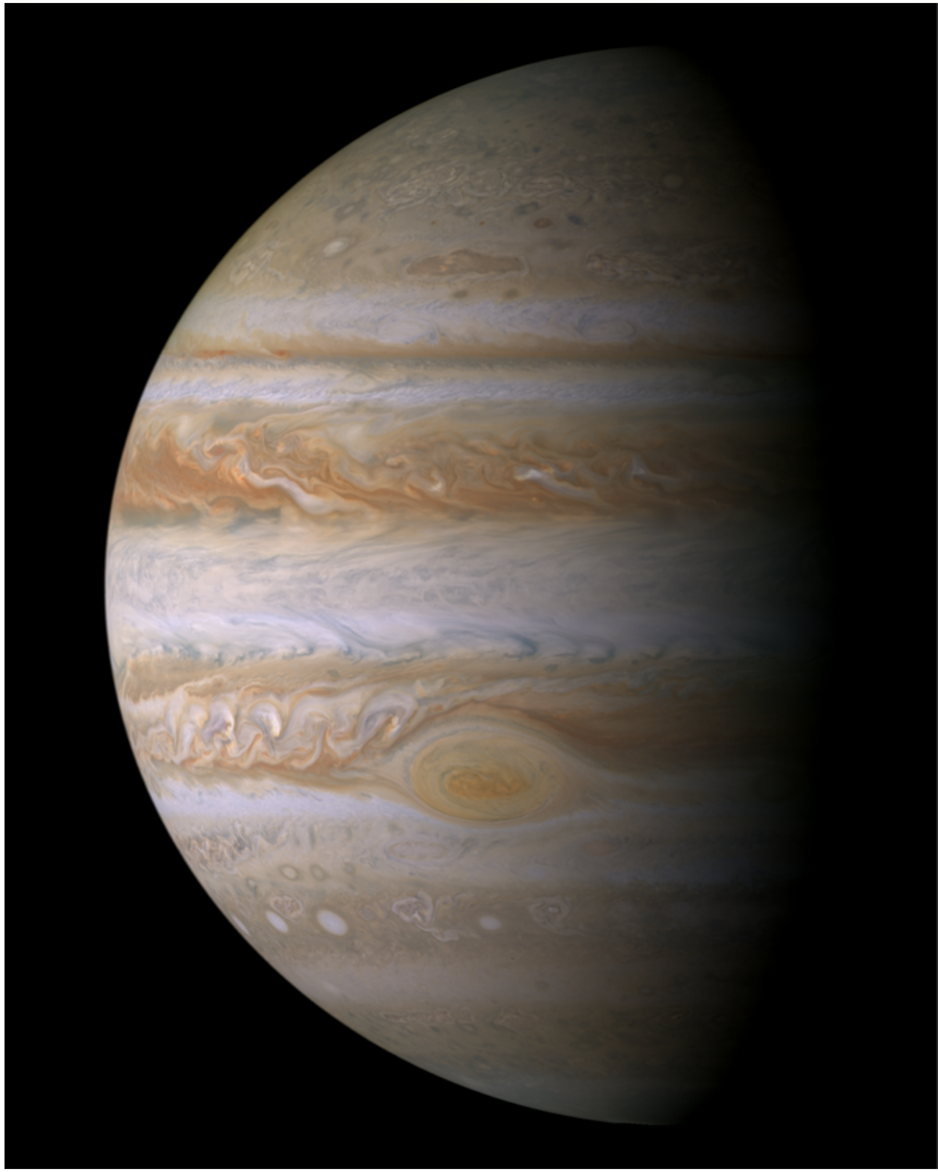


Reveals Dynamo Structure

Juno

Jupiter's Atmosphere





Where's the water?

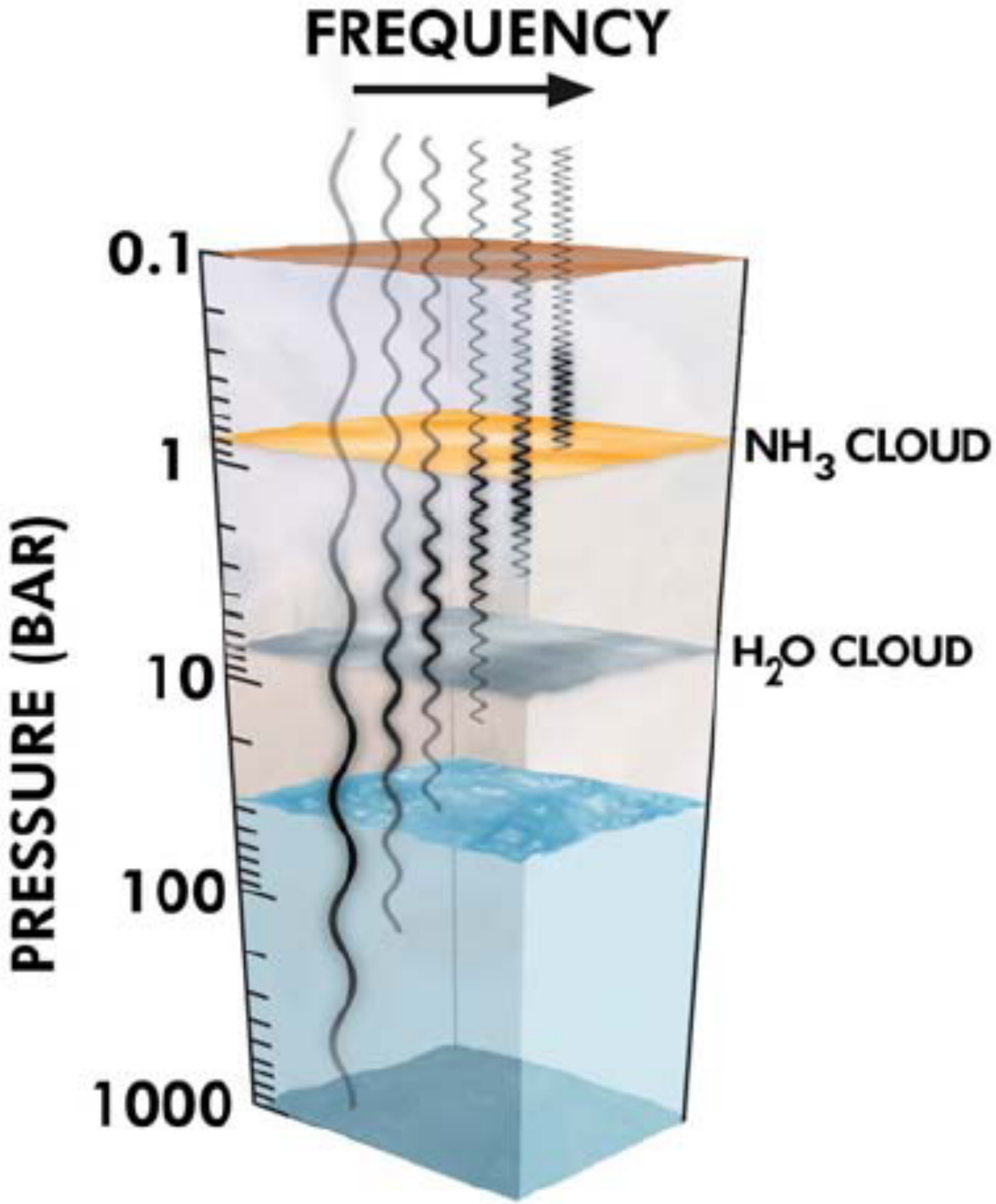
What drives the winds?

Microwave Radiometry

Radiometry sounds atmosphere to 1000 bar depth

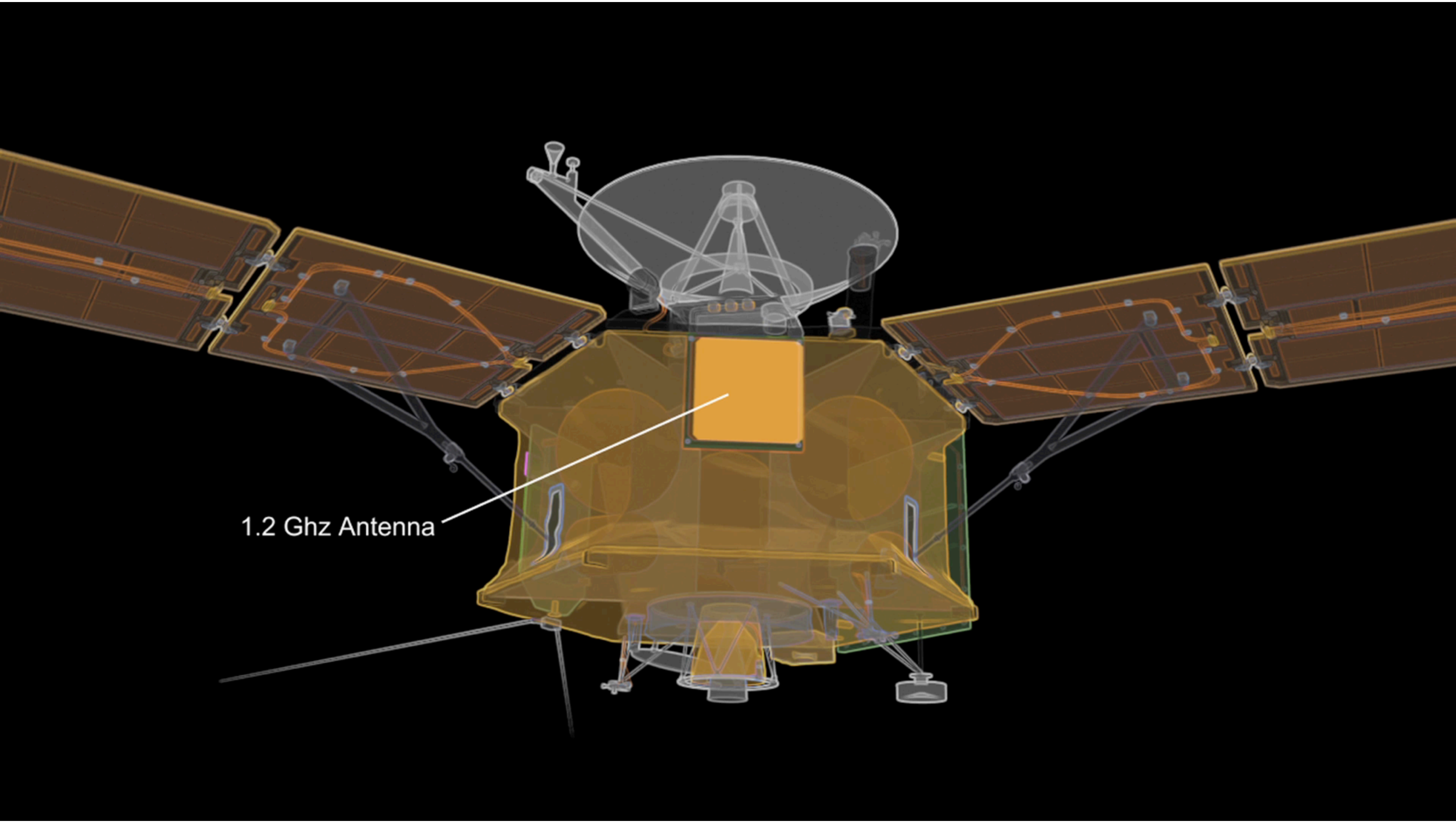
Determines water and ammonia global abundances

6 wavelengths between 1.3 and 50 cm



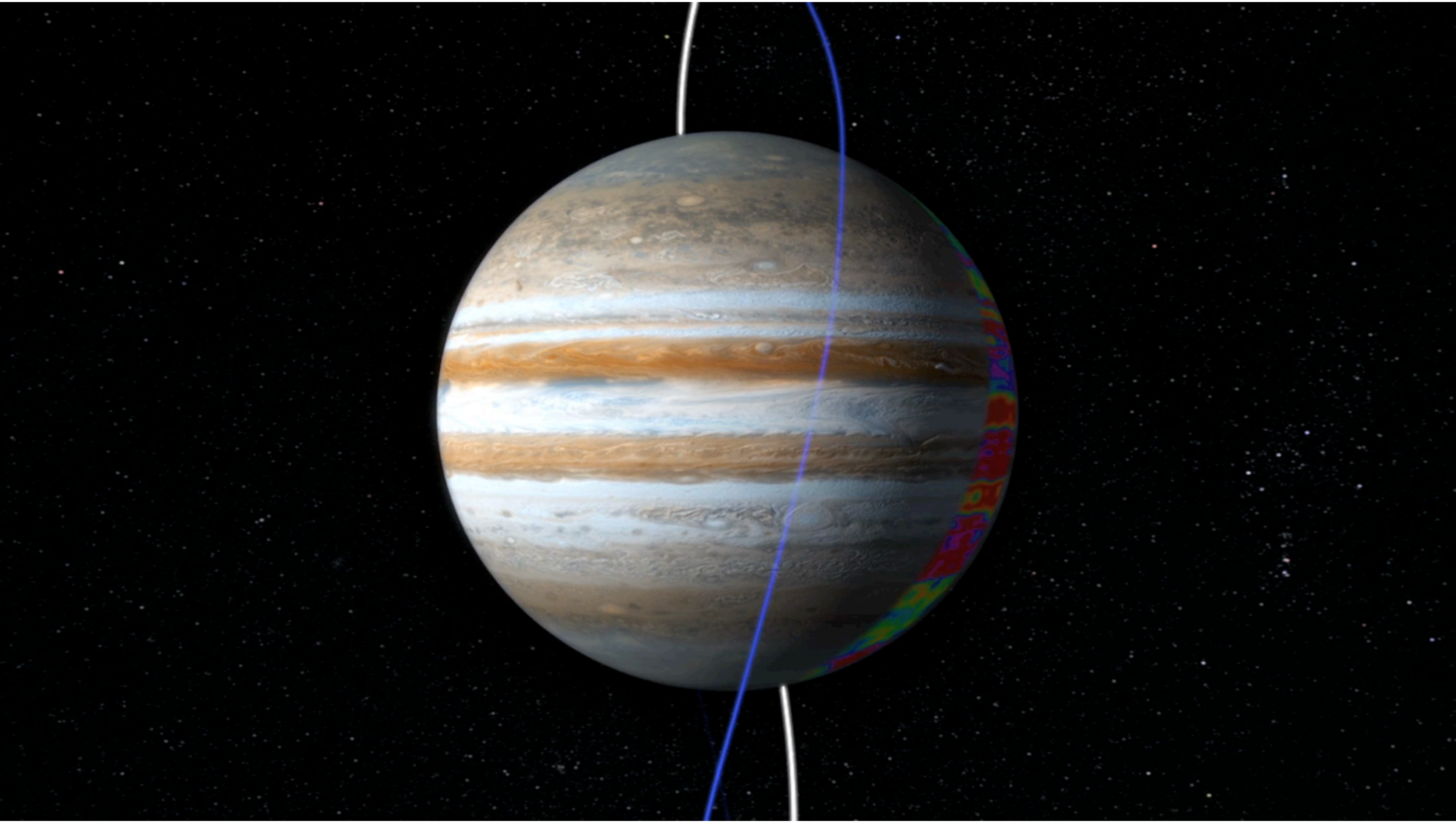
Using the Internal Heat to Map the Water

Microwave Radiometry



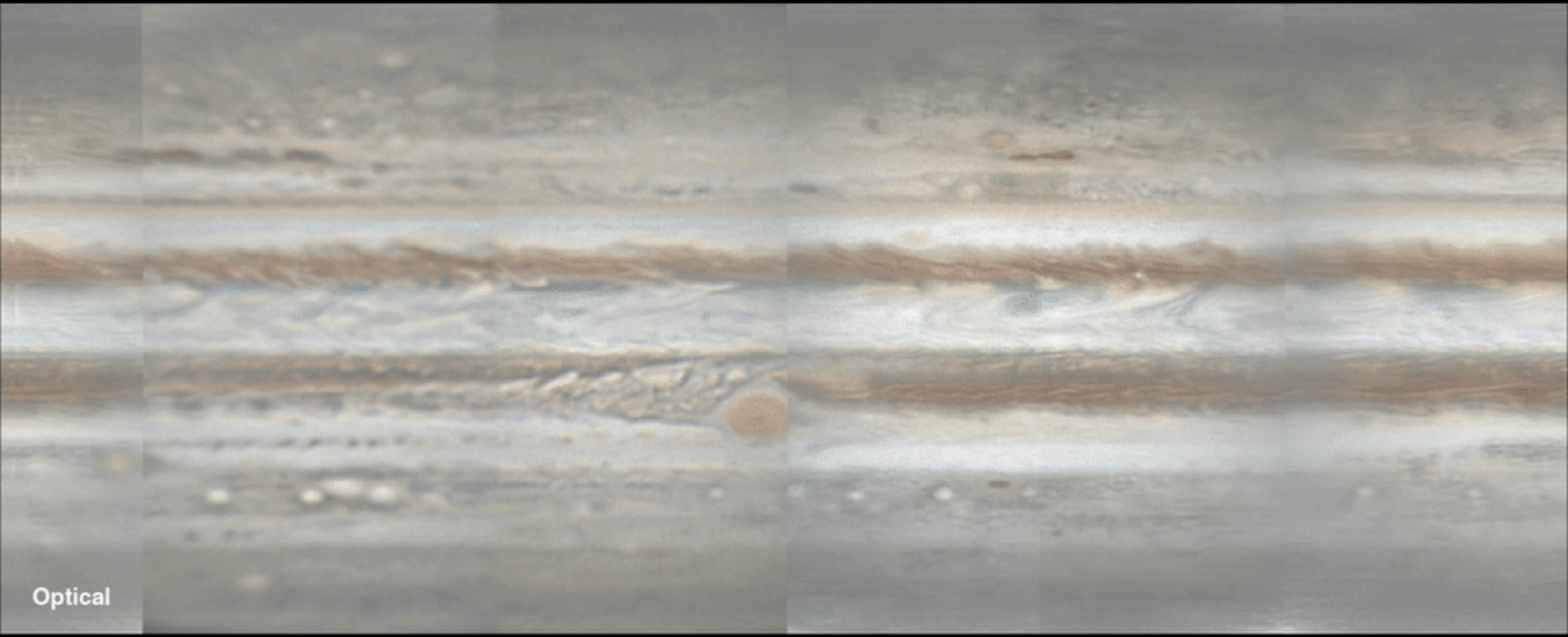
- *Using the Internal Heat to Map the Water*

Microwave Radiometry



Using the Internal Heat to Map the Water

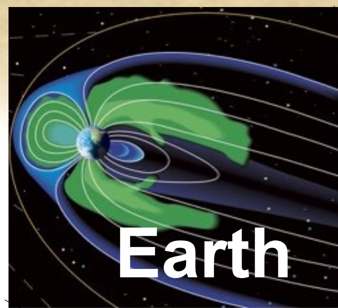
VLA observations of Jupiter



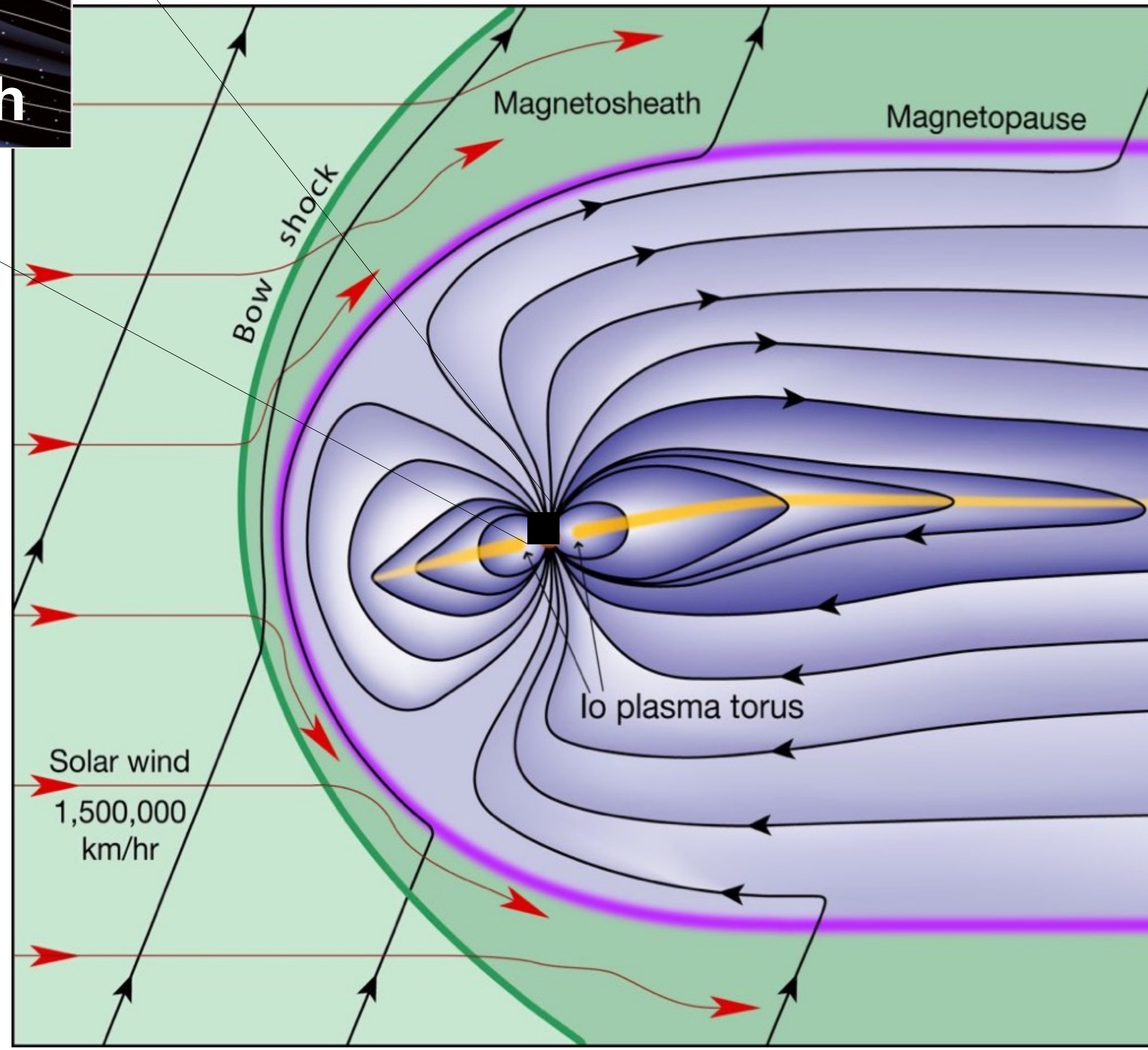
De Pater et al., (2016)

Juno

Jupiter's Magnetosphere

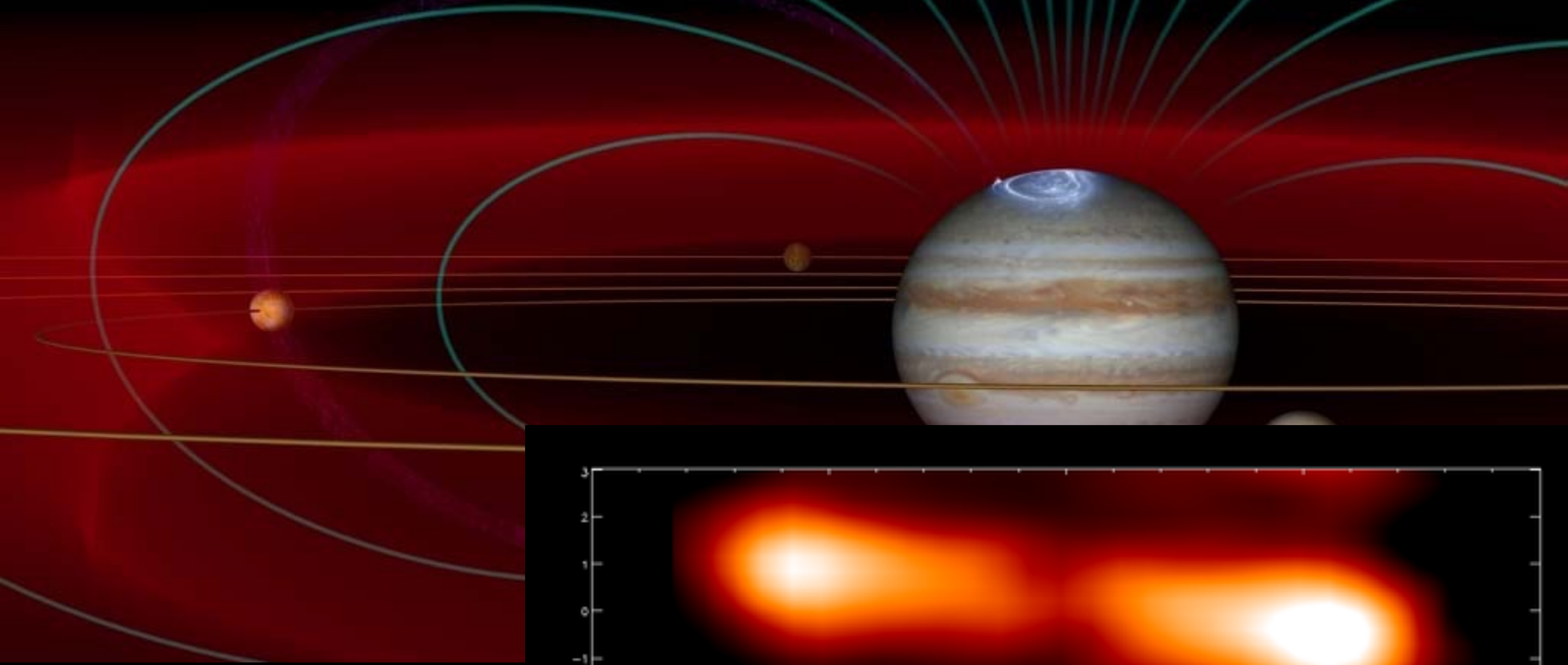


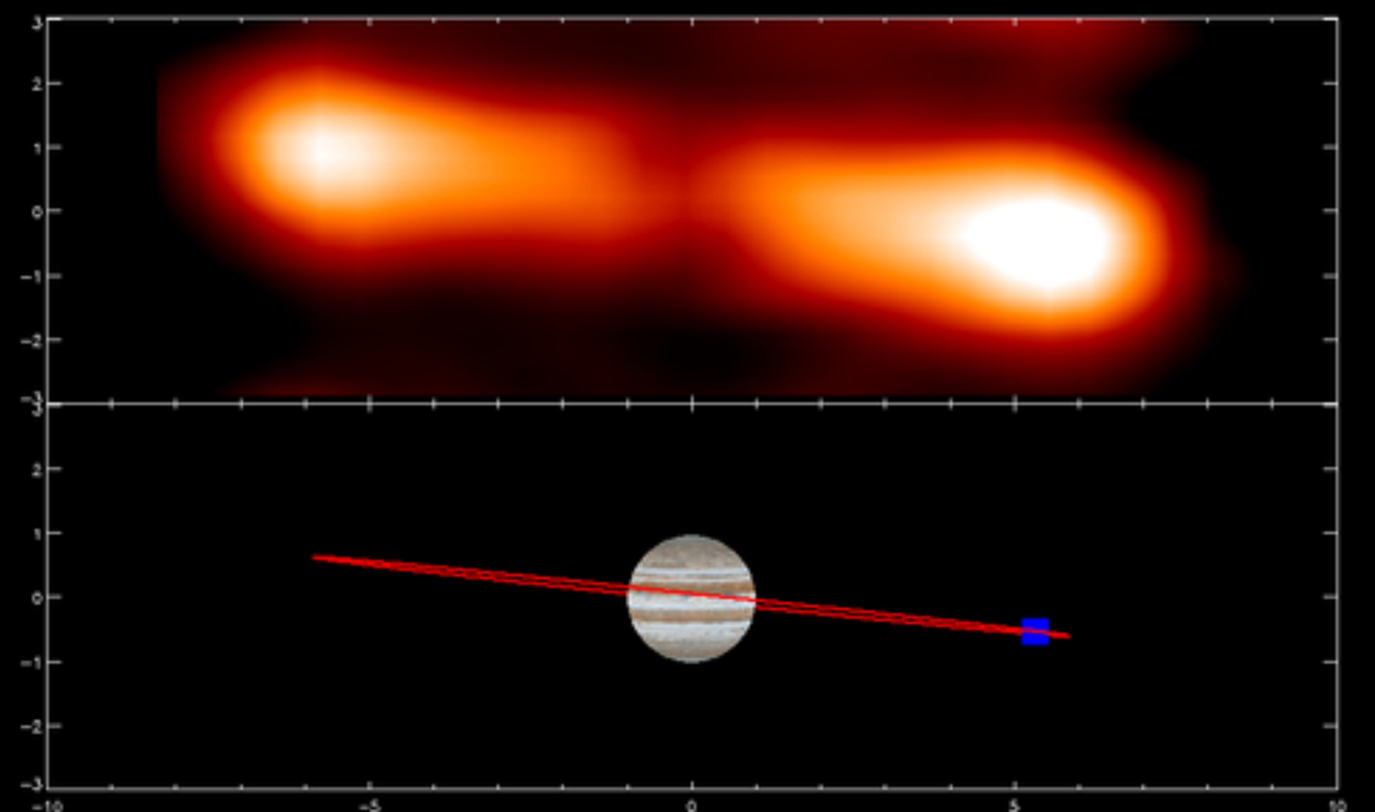
- **Strong Magnetic Field**
- **Large**
  100 x Earth's magnetosphere
- **Rotation-dominated**
  10 hour period
- **Io plasma source**
  ~1 ton/sec S,O ions
- **Equatorial region is well studied**



Jupiter's Polar Magnetosphere is completely unexplored

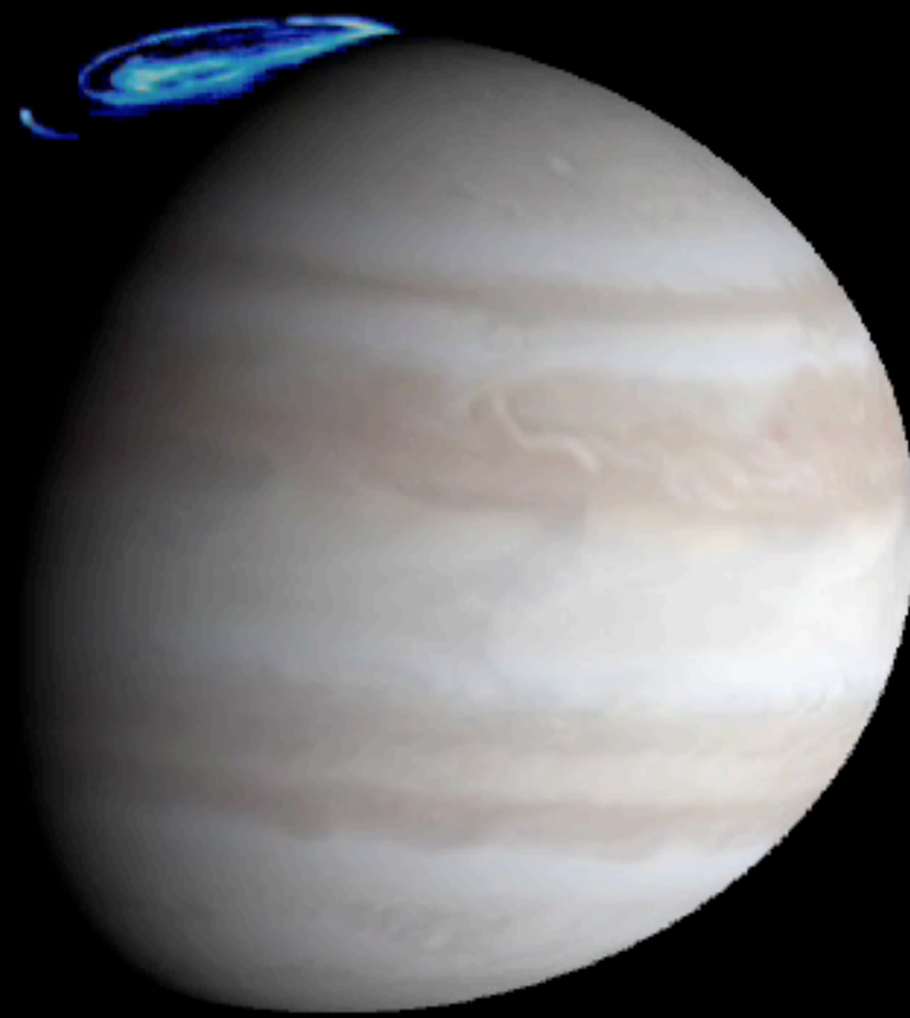
Io Plasma Torus





2 TW UV emission
Total mass 2 Mton
Source 1 ton/s
Replaced in
20-50 days

HST - John Clarke, Boston U.



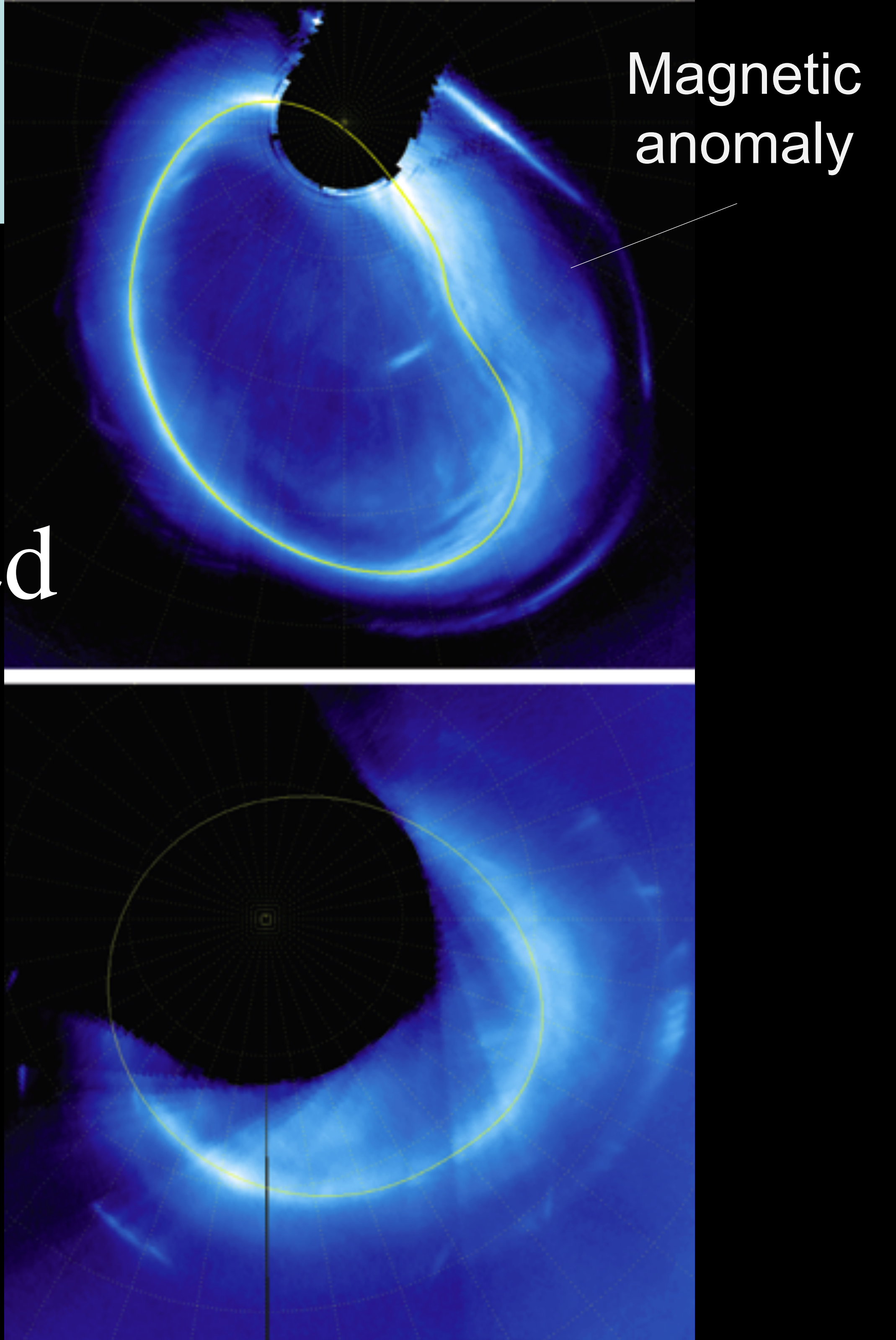
Main Aurora

~1° Narrow

Shape constant, fixed in magnetic co-ordinates

Steady intensity

Clarke et al., Grodent et al. HST



Juno

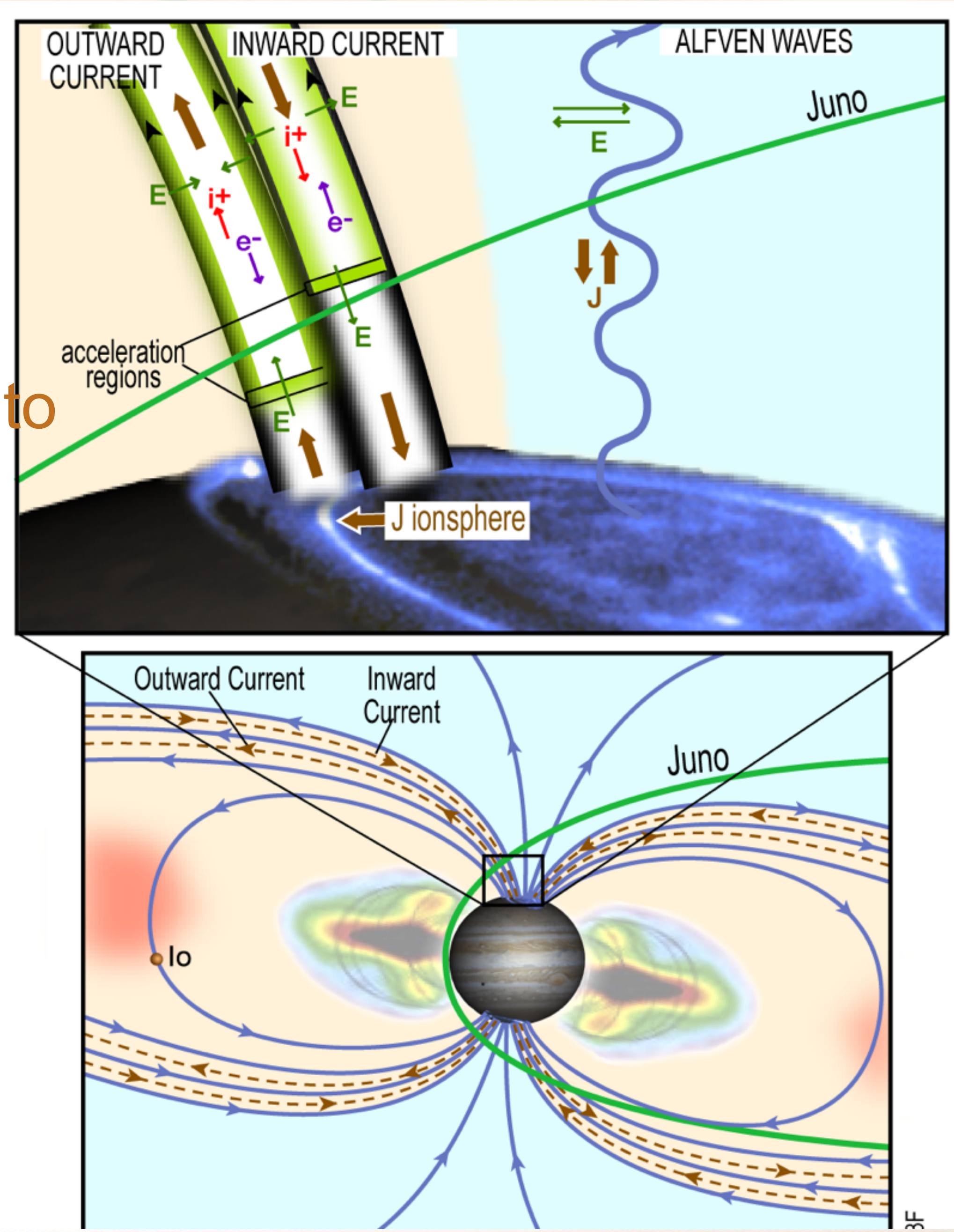
Polar Magnetosphere Exploration

Juno passes directly through auroral field lines

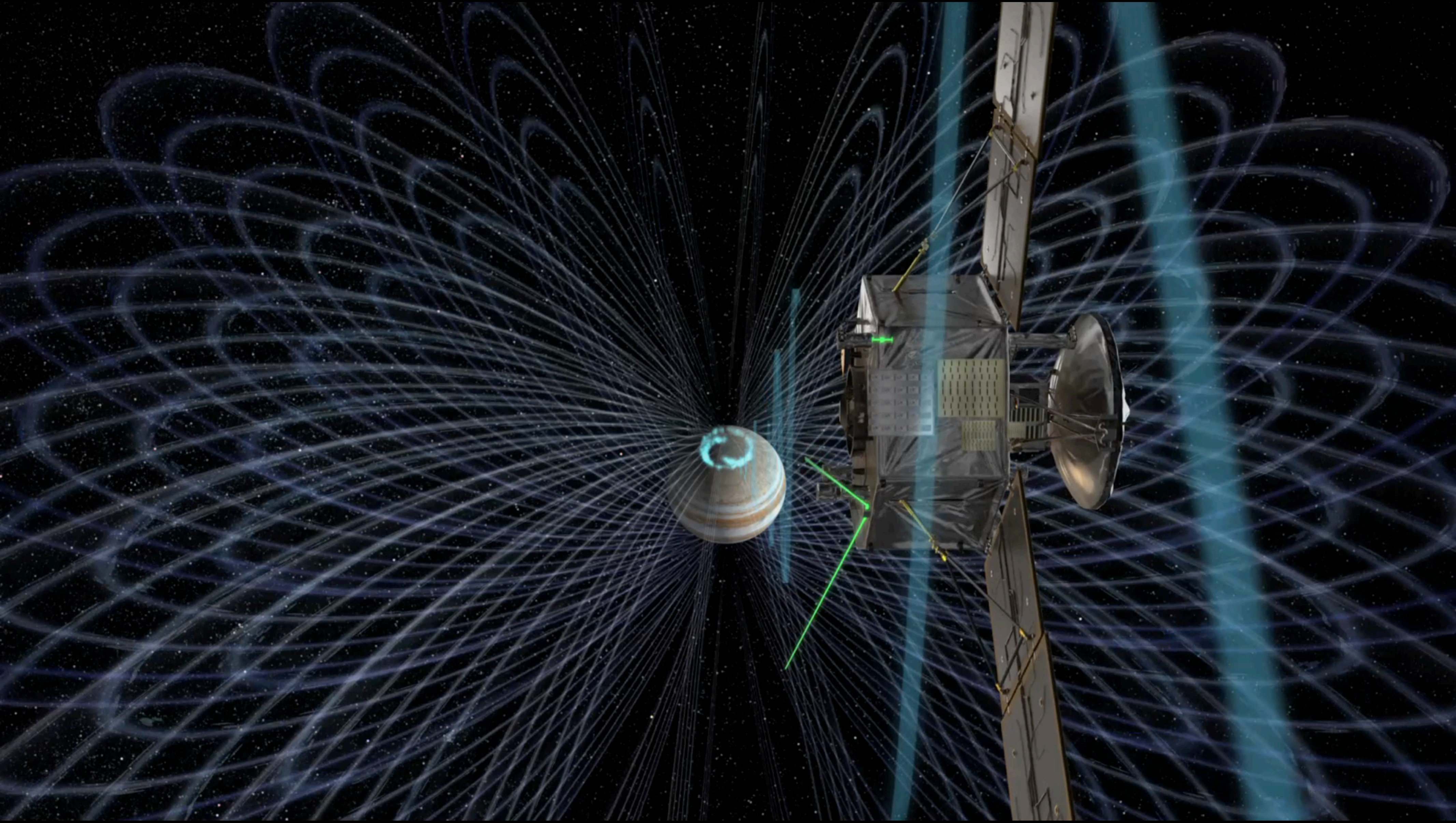
Measures particles precipitating into atmosphere creating aurora

Plasma/radio waves reveal processes responsible for particle acceleration

UV & IR images provides context for *in-situ* observations



Juno's orbit: perfect for exploring polar magnetosphere



Time-lapse movie of assembly

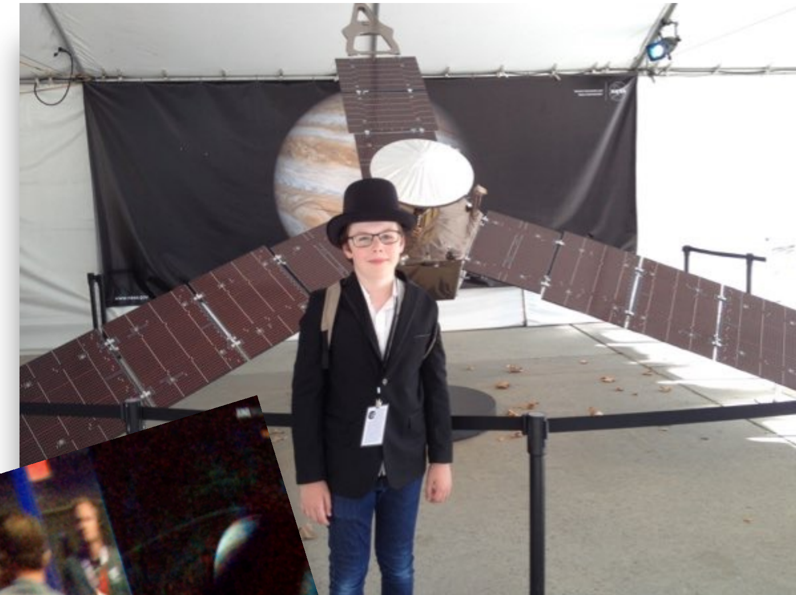
At Lockheed-Martin, Denver CO


NASA
KAMAG
KAMAG


Juno Launch
Aug 5, 2011

[http://www.youtube.com/user/NASAJuno?blend=5&ob=5 - p/f/5/ki_vL-v9WG0](http://www.youtube.com/user/NASAJuno?blend=5&ob=5#p/f/5/ki_vL-v9WG0)

Juno’s Jupiter Orbit Insertion
4 July 2016



What Juno will do

- Improvement of a factor >100 of the accuracy of the gravity field measurement
  - Crucial constraint for interior models
  - Ability to learn about differential rotation in the interior
  - Determination of Jupiter's moment of inertia, tidal k2
  - Possibility to see oscillations (work by Durante, less & Guillot)
- First deep measurement of Jupiter's magnetic field
  - Understand dynamo mechanism
  - Enable linking dynamo generation and interior structure
- Probing Jupiter's deep atmosphere with MWR
  - Constraint on the abundance of water
  - Probe atmospheric dynamics including in deep regions.
- + Many other things (first look at the poles, magnetospheric science, auroras, etc.)

What Juno will not do

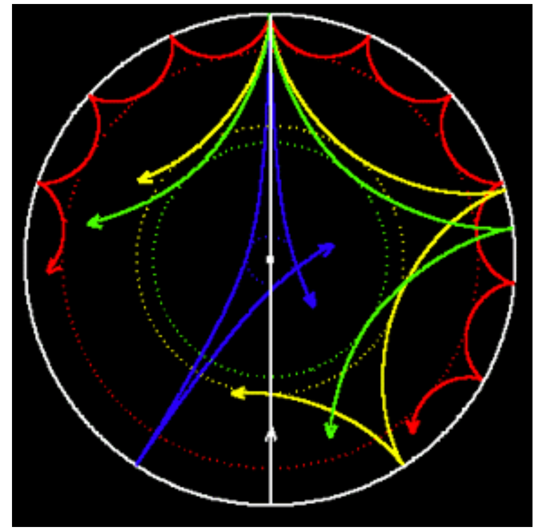
- Determine interior structure independently of models
  - Core mass
  - Total mass of heavy elements
  - Measure discontinuities in the interior
- Measure interior rotation rate as a function of depth & latitude
- Observe the evolution of dynamical structures, winds…

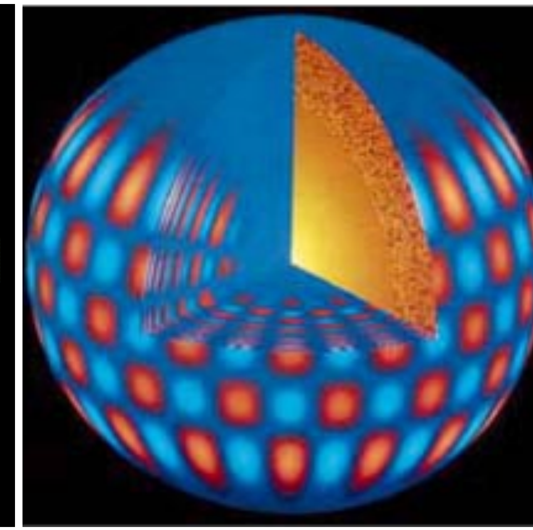
Part III: JOVIAL

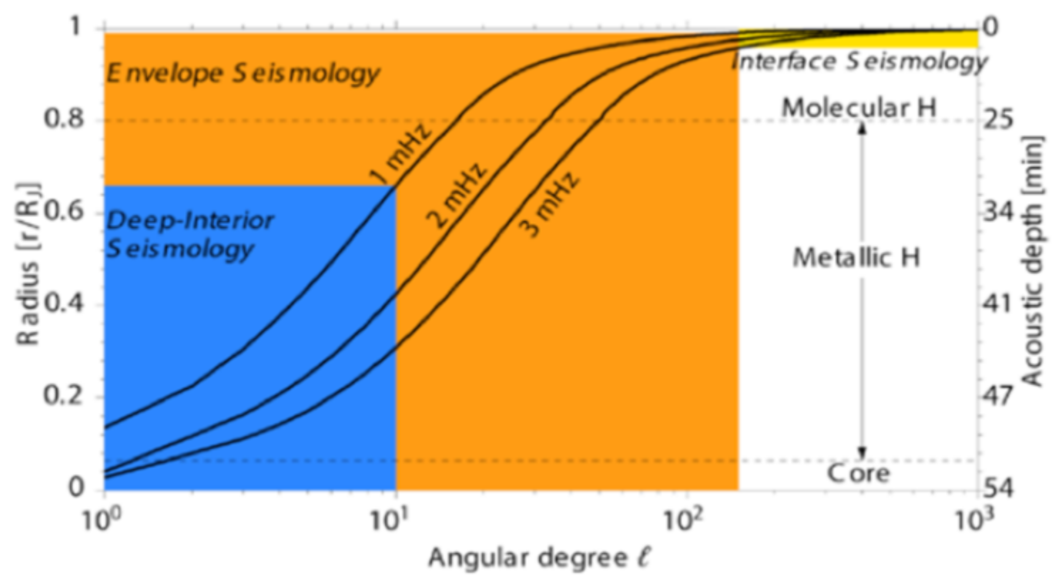
The power of seismology

Giant planet seismology: principle

- As terrestrial seismology, asteroseismology allows the study of internal structure
- Modes frequencies depends on density (and rotation)
- Modes of different degrees penetrate to different depths







ν_{obs} - $\nu_{theoretical}$

↓

Inversion method

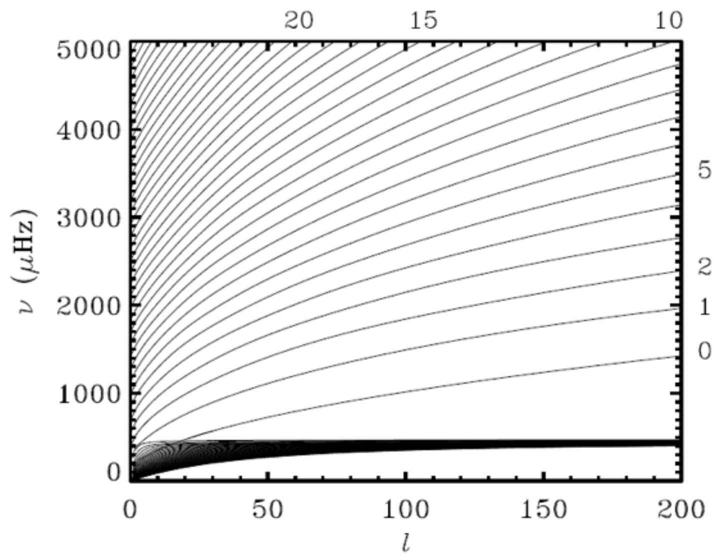
↓

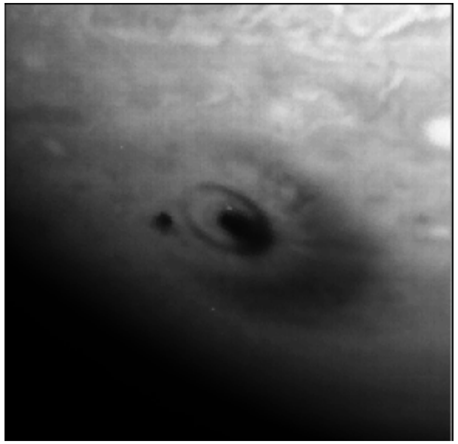
ρ_{obs} - $\rho_{theoretical}$

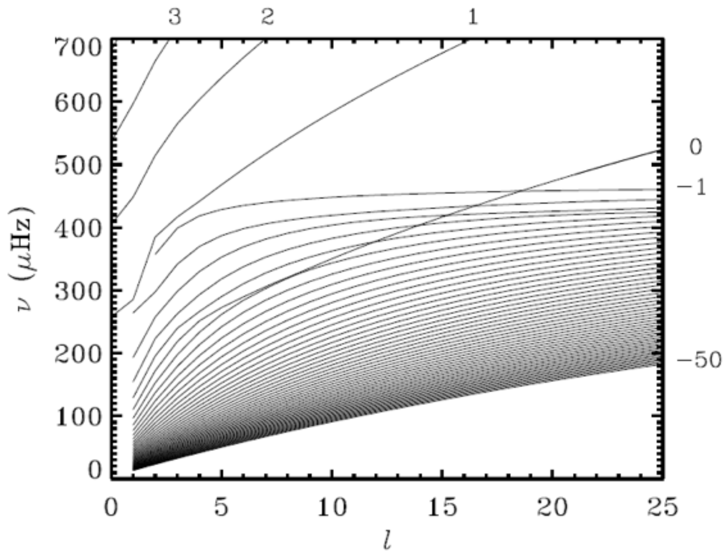
Jackiewicz et al. (2012)

Mode types

- Following the main restoring force, modes could be of different types
- Acoustic modes or p modes
- Gravity modes or g modes
- Surface modes or f modes







seismology of giant planets: 2 results

- Jupiter
  - SYMPA project: 2000 – 2010

  - Gaulme et al 2011

- Saturn
  - Cassini

  - Hedman & Nicholson 2013

Opens a new window on the interior of giant planets

Jovian seismology

•Ground based observations with SYMPA

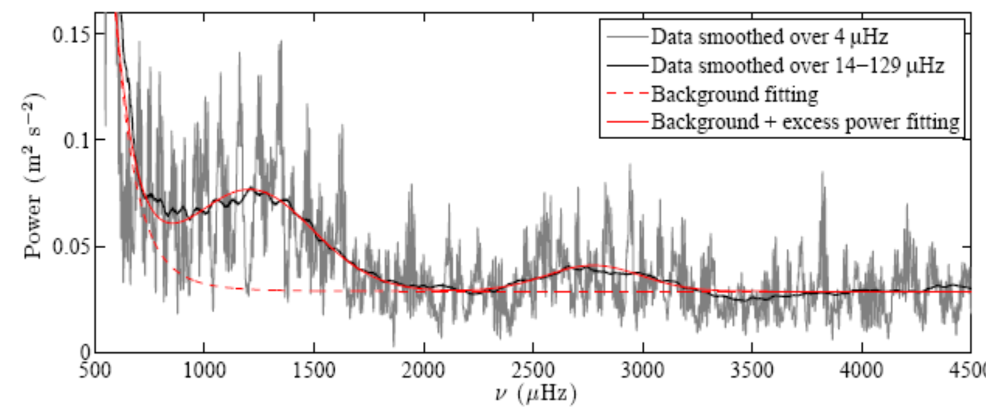
•Power excess in the range [800 – 3000] μHz

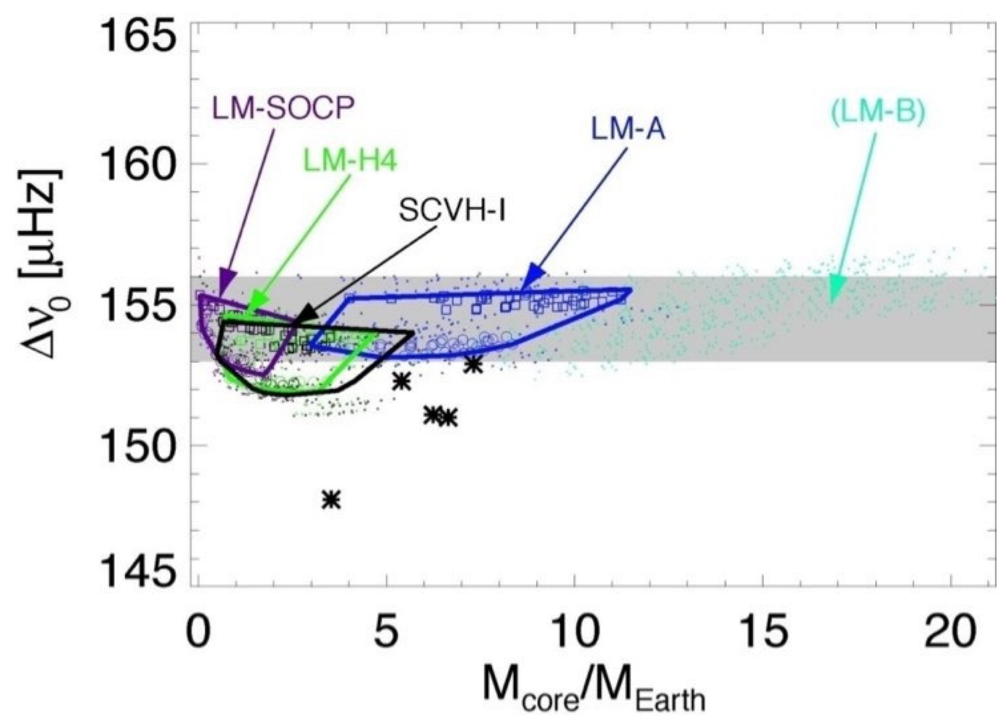
•~ 20 individual peaks with mean amplitude 30 cm/s ± 10 cm/s

•Regularly spaced peaks: $\Delta\nu_0$= 154.5 μHz ± 1.5 μHz

• Fundamental frequency good agreement with most models (mean density)

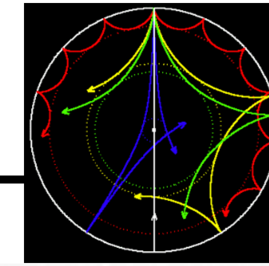
Individual modes identification requires <u>long continuous observation with good spatial resolution</u>





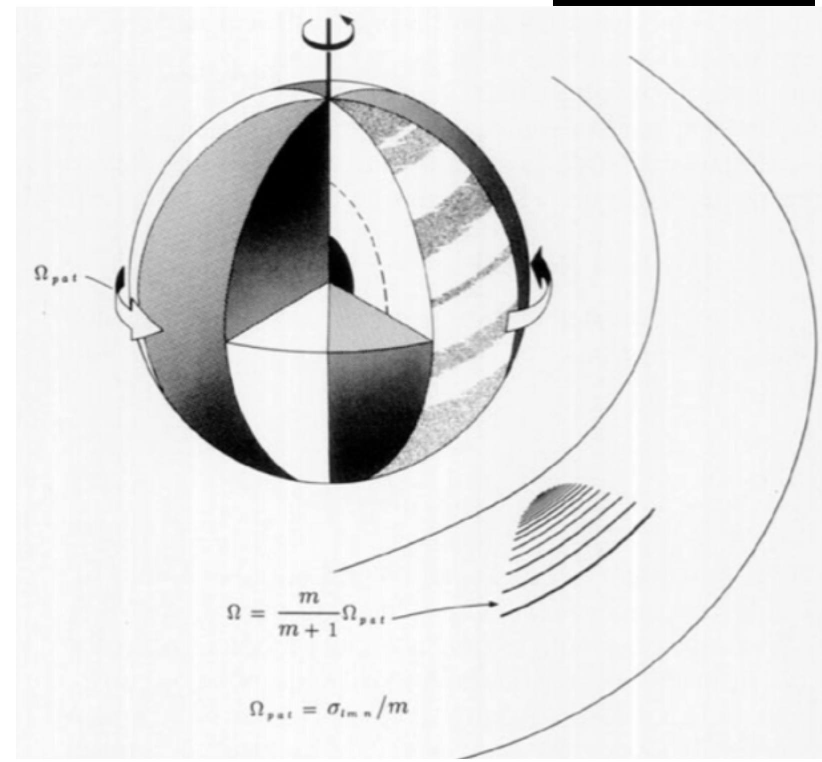
Gaulme et al, 2011

Saturn’s seismology

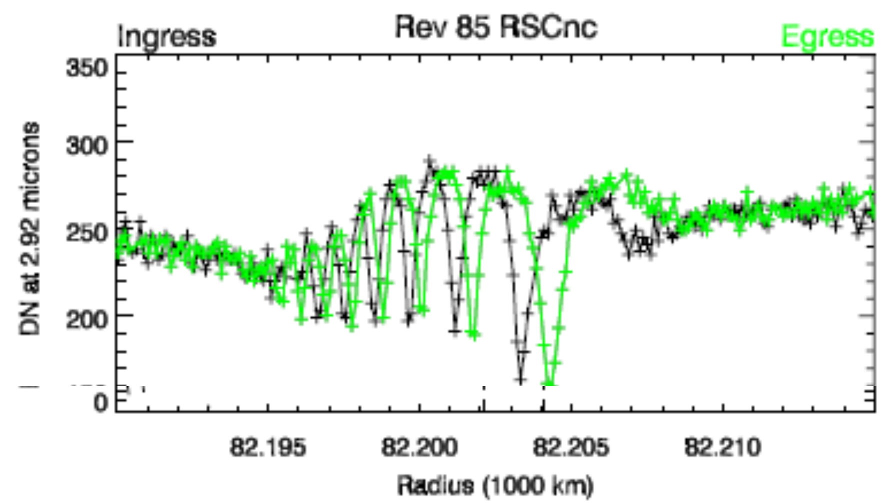


- Density waves in Saturn rings

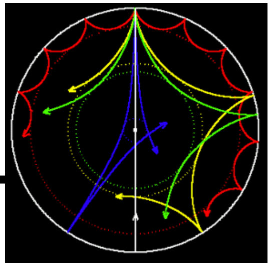
  (Hedman & Nicholson, 2013)
- Predicted by Porco & Marley 1991
- Cassini observations of stellar occultations
- Identification of azimutal number
- Saturn f-modes have long life-time

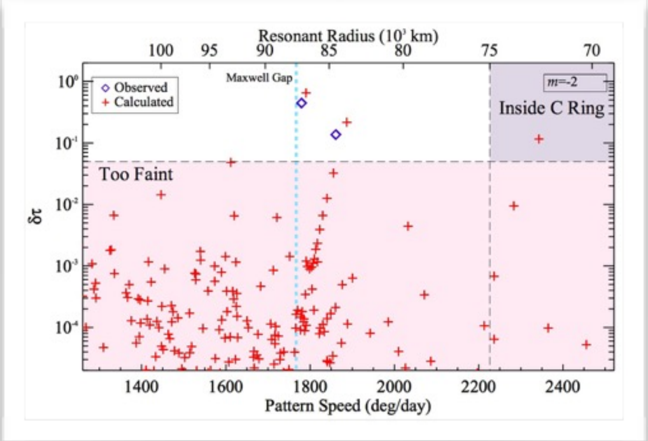


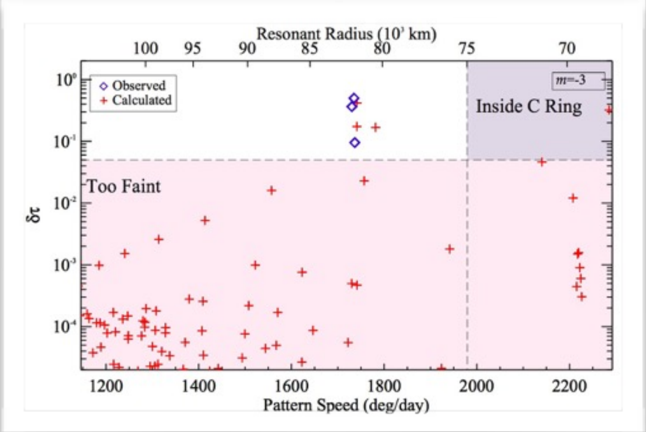
f-modes identified
low-degree (l=2-4)
frequencies: 0.7-1.3 mHz
amplitudes: ~1m

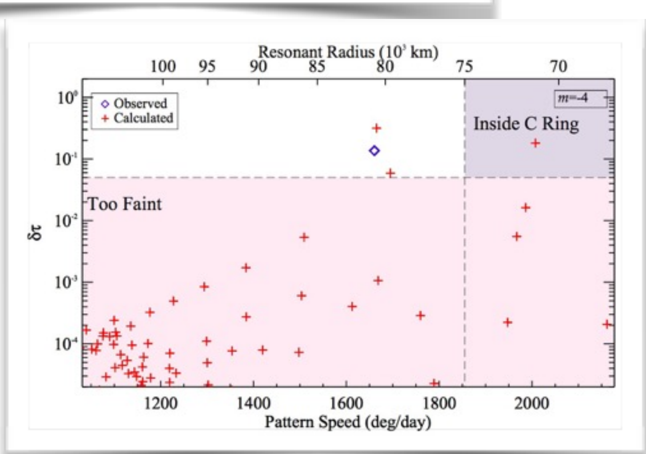


Saturn's seismology

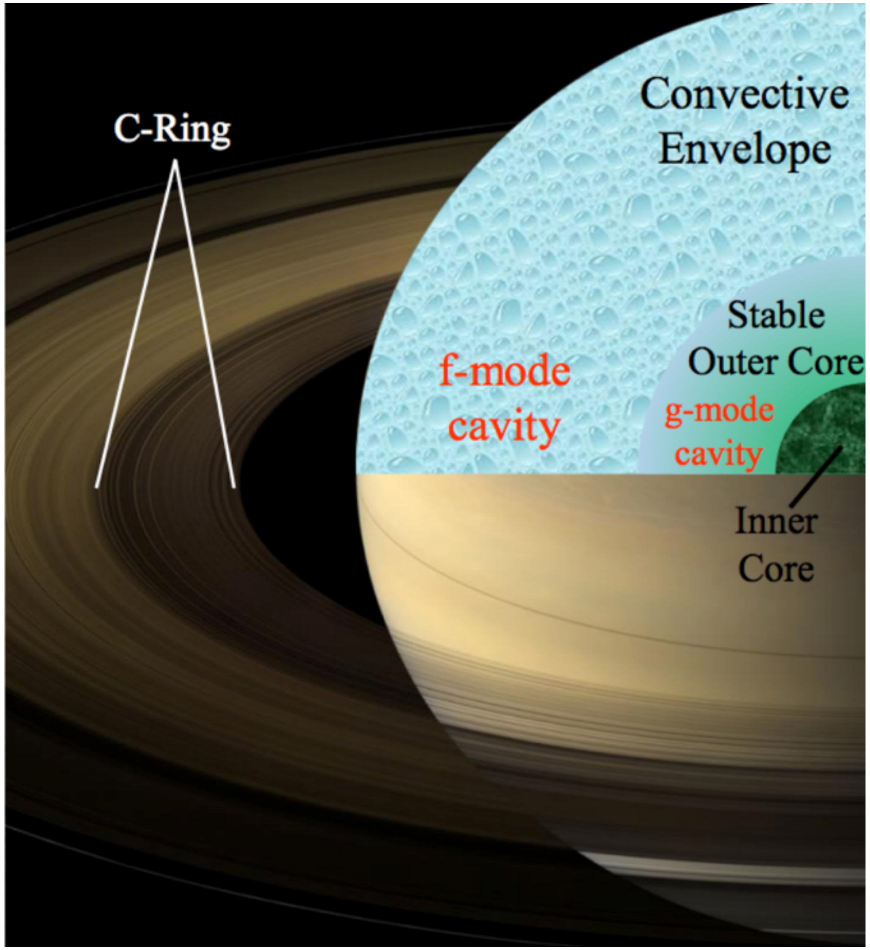








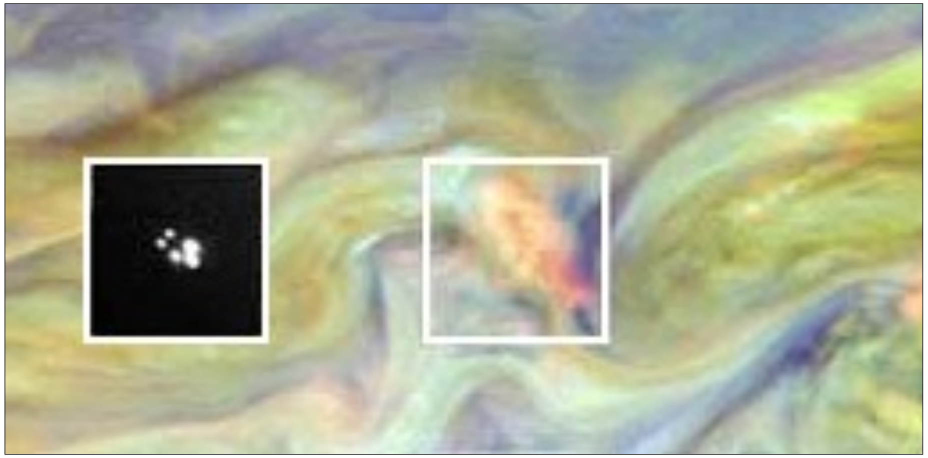
Fuller (2014)

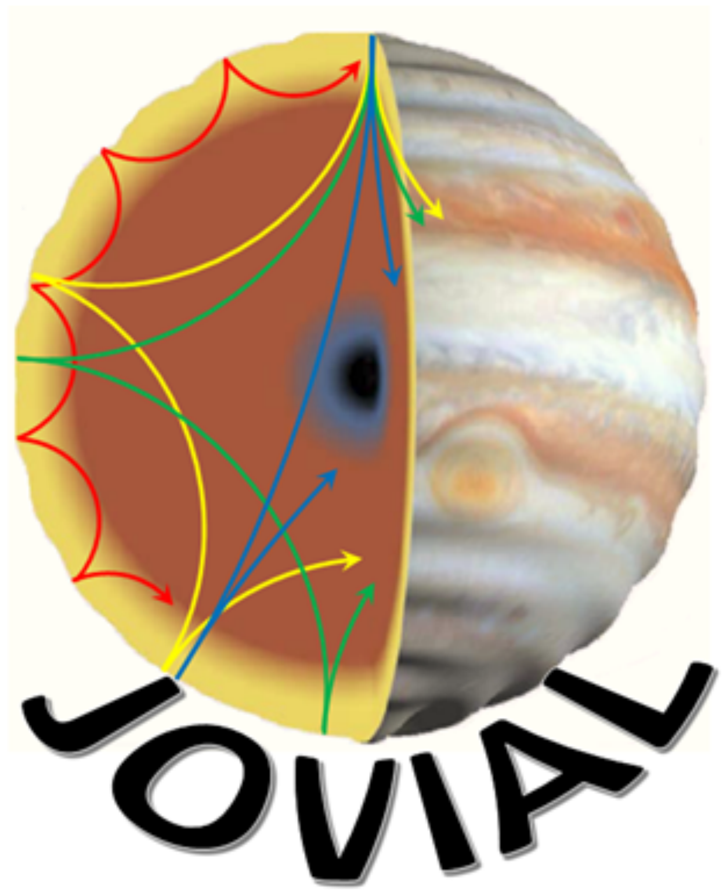


How are the oscillations excited?

- Few theoretical works
- Estimation by Bercovici & Schubert (1987) for Jupiter: 0.5 m/s
- Energy in convection is sufficient
- Solar mechanism would be inefficient

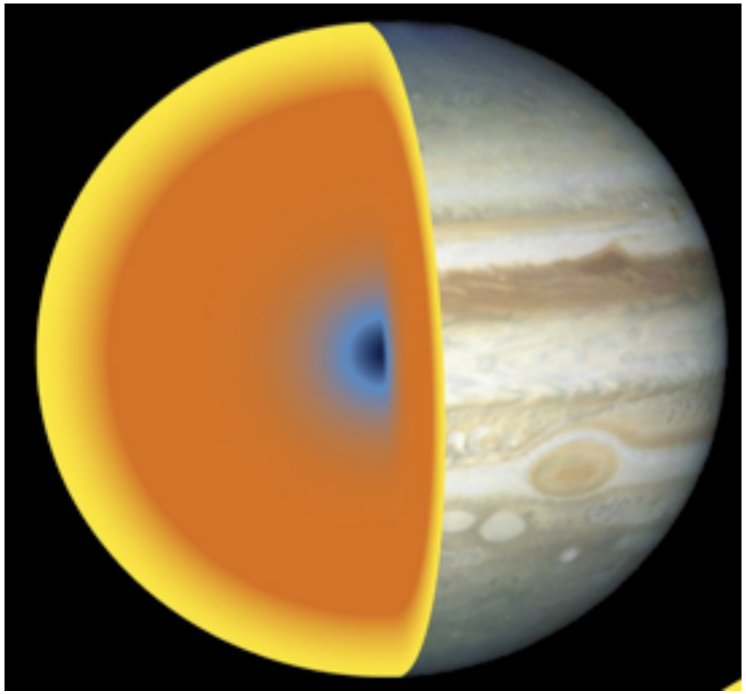
- Other coupling mechanism ?
- Kappa mechanism ?
- Moist convection ?



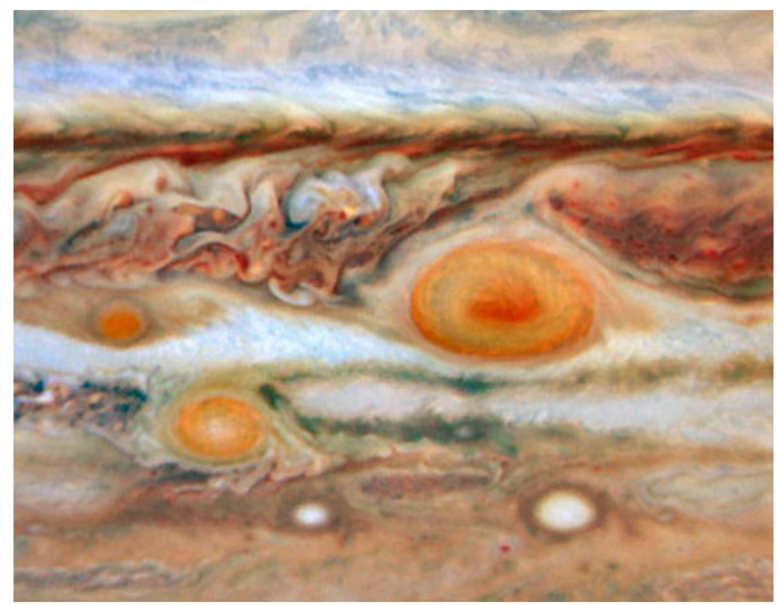


Jovian Oscillations through radial Velocimetry ImAging
observations at several Longitudes

JOVIAL



- Scientific goals
  - Internal structure of giant planets by seismology
  - Study of planetary atmosphere dynamics



- Observation strategy
  - Fourier imaging tachometer
  - Observation network

Project history

SYMPA project (2000-2010)
Echoes proposal for JUICE mission
Doppler Sismo Imager (R&T CNES 2009 -2013)

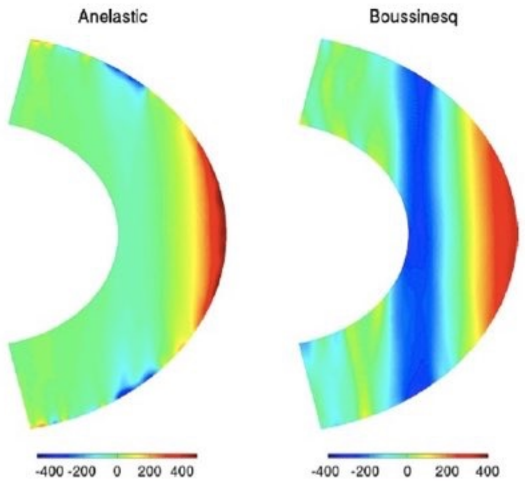
2014: JIVE in NM (NASA-EPSCOR)

2015: JOVIAL selection

- ANR (Agence Nationale pour la recherche) white program
- 4 years project (2016 -2019)
- 420 k€

Probing internal structure

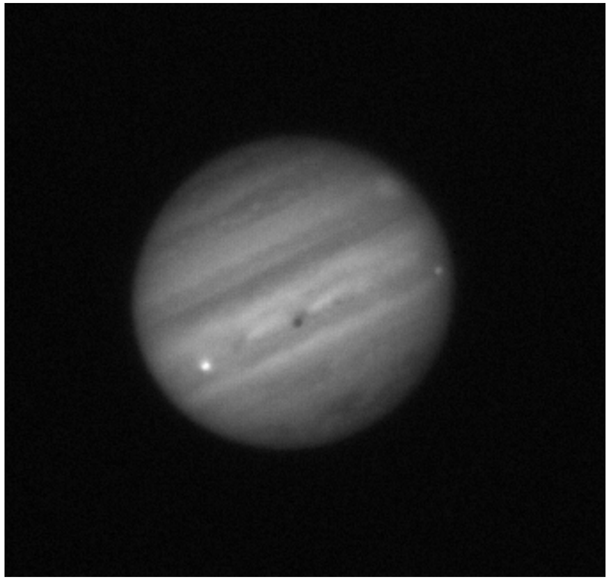
- Complete gravitational moments (JUNO)
- Measure the size of the core
- Investigate H-H2 transition
- Give internal rotation profile

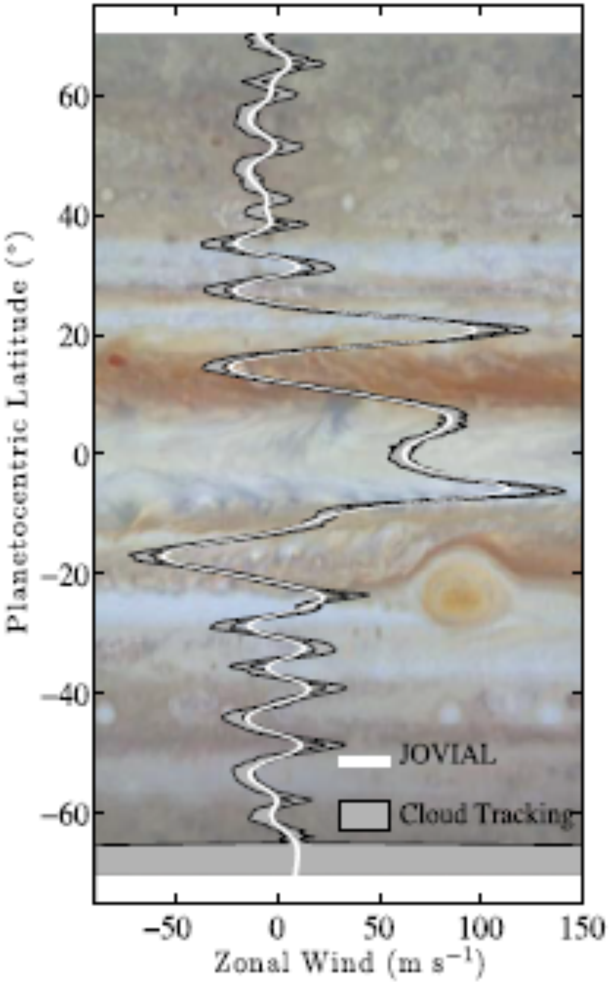


	$\delta\nu(n,l)/\nu(n,l)$	Degree
Core	4 %	$l = 0\text{-}2$
H2-H transition	3-7 %	$l = 15\text{-}25$
Enveloppe dynamics	0.1-0.5 %	$l = 50\text{-}100$

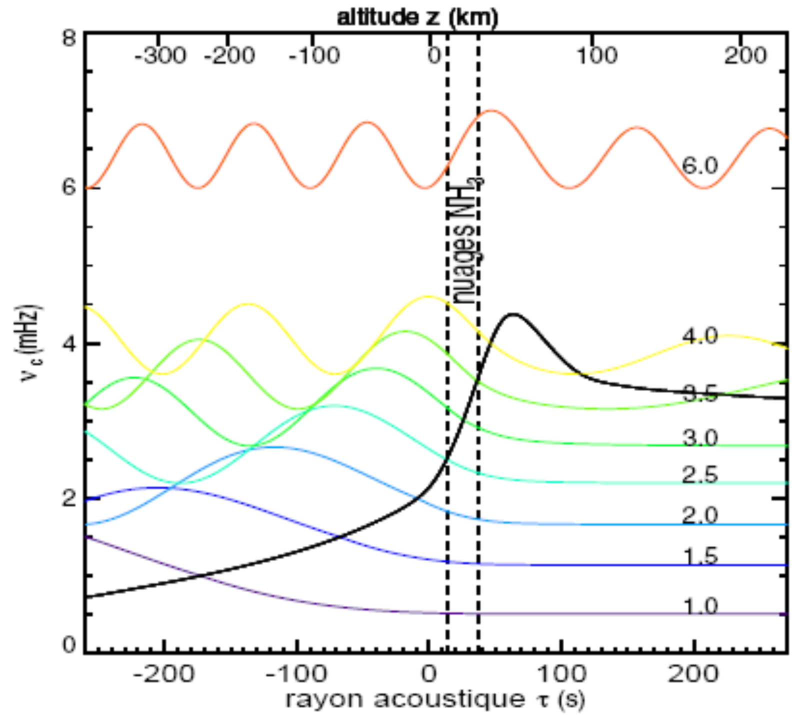
Wind speed measurement

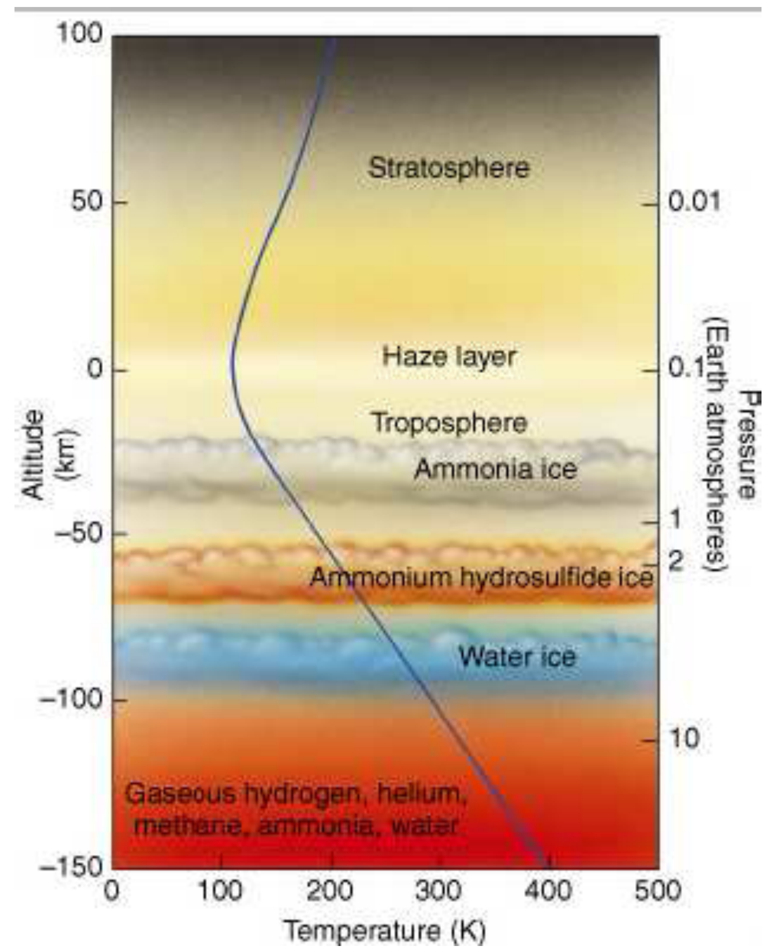
- Cloud-tracking is affected by cloud deformation and waves
- Doppler measurements give true aerosol displacement
- Complete High Angular Resolution follow-up





Detection of acoustic modes





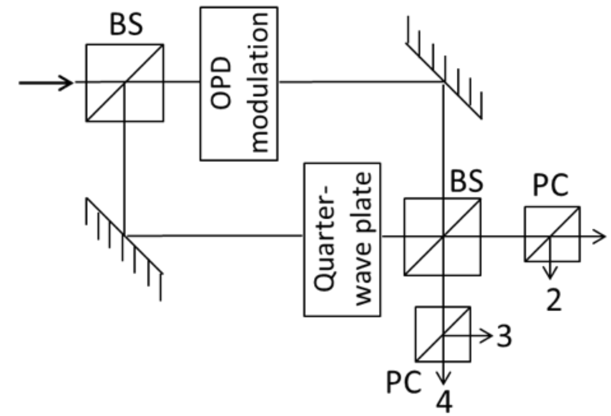
Best detection level: 1 bar

Top of the cloud (visible)

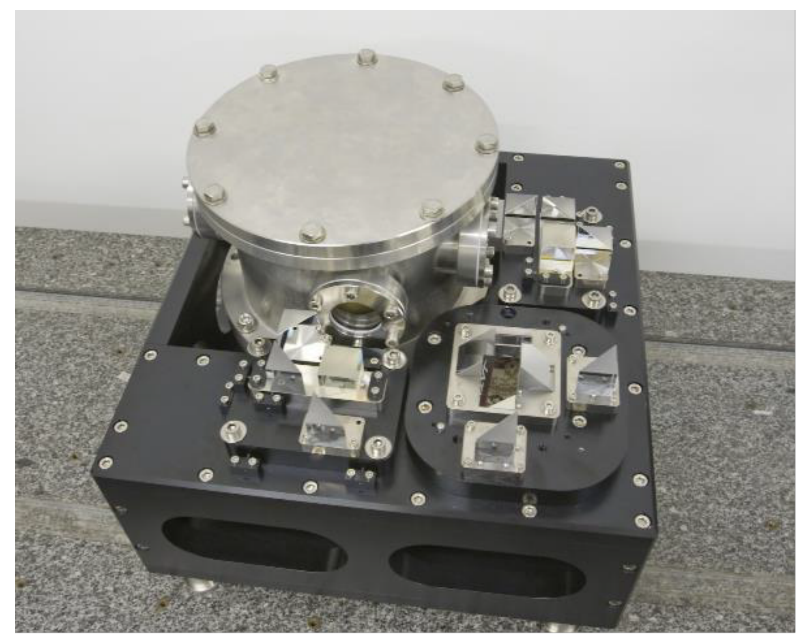
Resolved images and velocity maps

Instrumental Concept

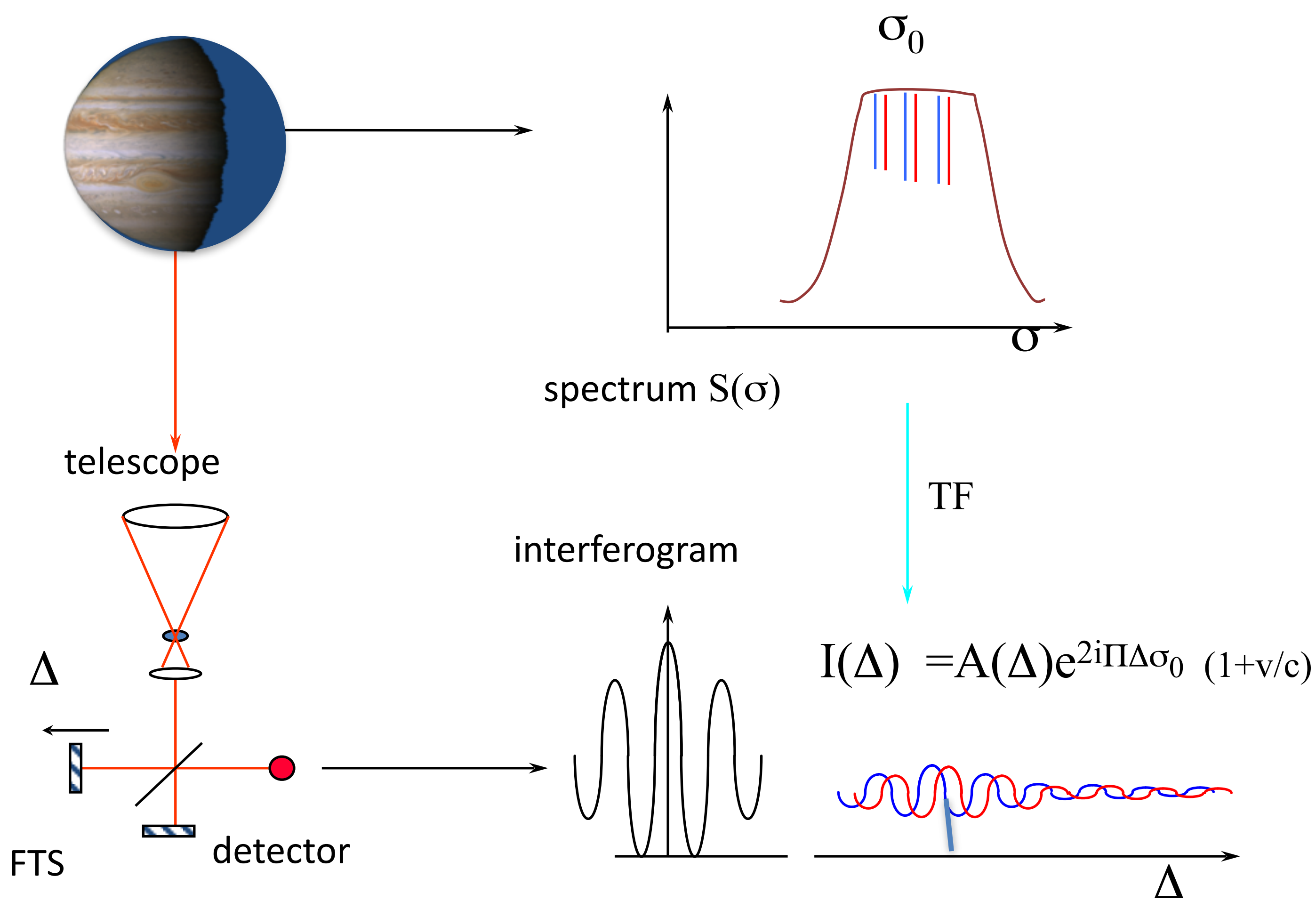
- JOVIAL is a Doppler Spectro-Imager
  - Mach-Zehnder Interferometer:
  - spectral FT at each point of the image
  - Measures the Doppler shift of reflected solar lines



- Optimisation of mesurement stability, precision, resolution
  - Large Field Optique Adaptative
  - Simultaneous multi-sites observations
  - Noise level < 4 cm/s in 2 weeks



Fourier tachometer



The JOVIAL network

Goal: Simultaneous observations from 3 sites

Target: Duty-cycle > 50 % over two weeks

Observatoire de Calern (France)

- C2PU: 1 m telescope with DSI prototype

New Mexico (USA)

- Dunn Solar telescope (Sacramento Peak)

Okayama Observatory (Japan)

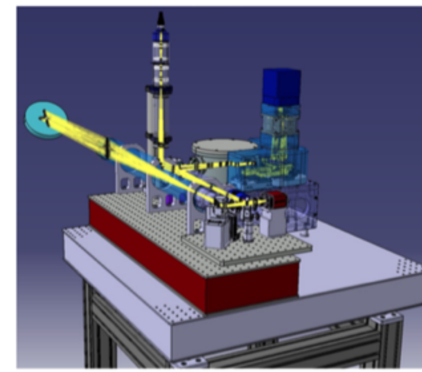
- Telescope de 1.88 m
- Backup: Ishigaki observatory

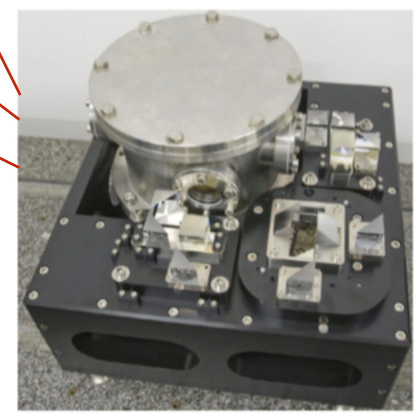
JOVIAL

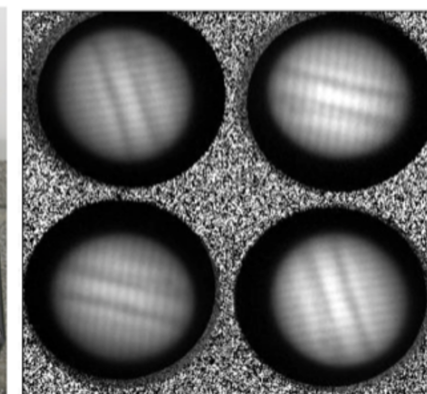
A network of Doppler Imagers to study Jupiter's and Saturn's global oscillations

A solid base: a prototype developed and built in Nice, France

JIVE will measure the velocity of the cloudy "surface" of Jupiter, to look for tiny fluctuations due to the seismic oscillations. The instrument principle is based on high-resolution spectro-imaging in the visible domain. The optical design as well as a prototype weres developed in Nice in the frame of a study for a instrument to be placed on an ESA space-mission. It was successfully tested from the ground early 2014.







Prototype instrument and preliminary observations. The top panel shows the whole design of the instrument. The bottom left shows the components of the prototype corresponding to the interferometer. On the bottom right are the four output images of Jupiter used to compute velocity maps from the interferometric fringes (barely seen in this image rendering). The two main bands in each image at about 45 are zonal features of Jupiter's clouds.

The JOVIAL network

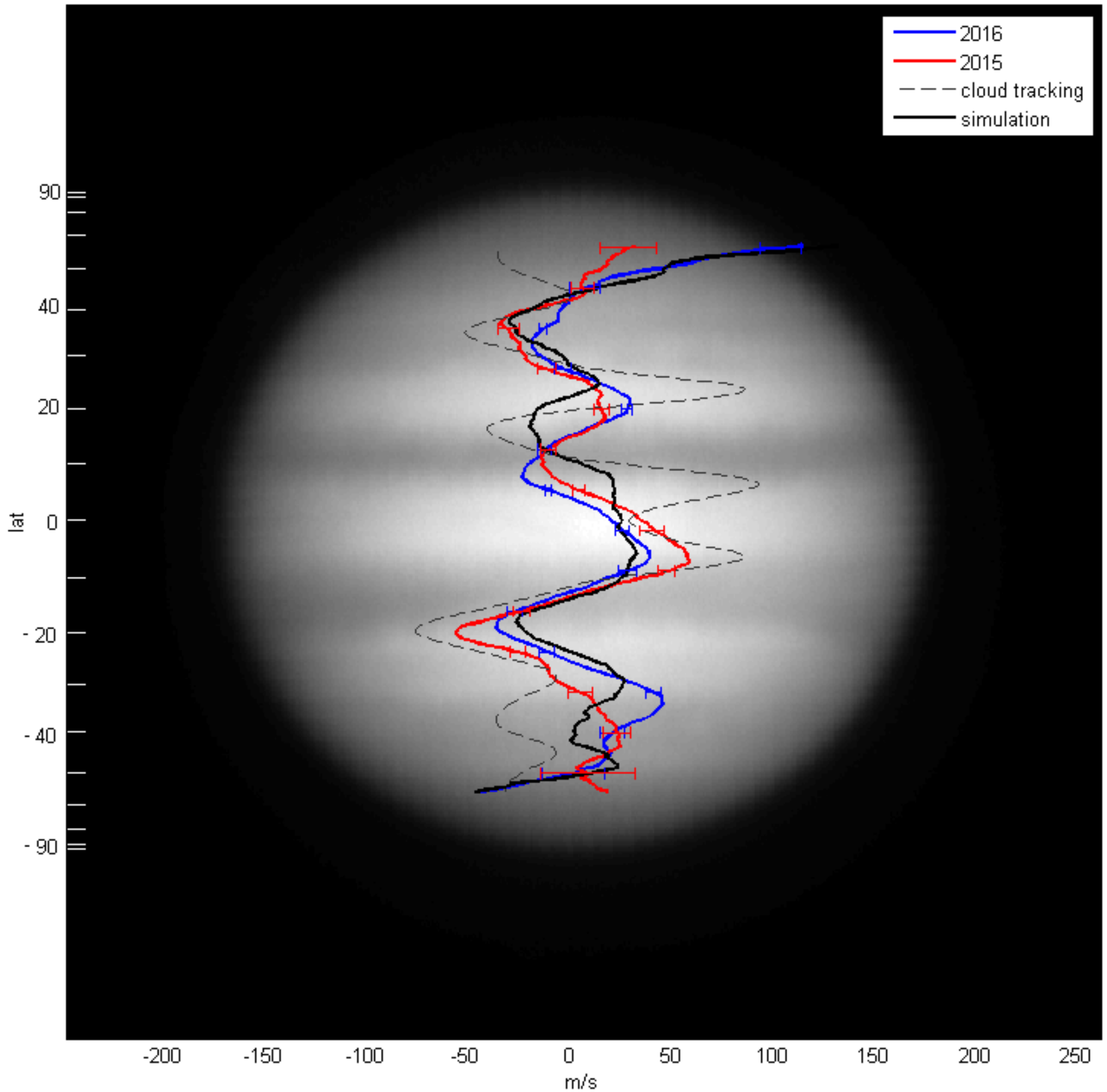
Possible evolutions

- Larger telescopes
- Additional instrument
  - AO for JIVE

- Space mission
  - Saturn
  - Uranus

Zonal winds: preliminary results

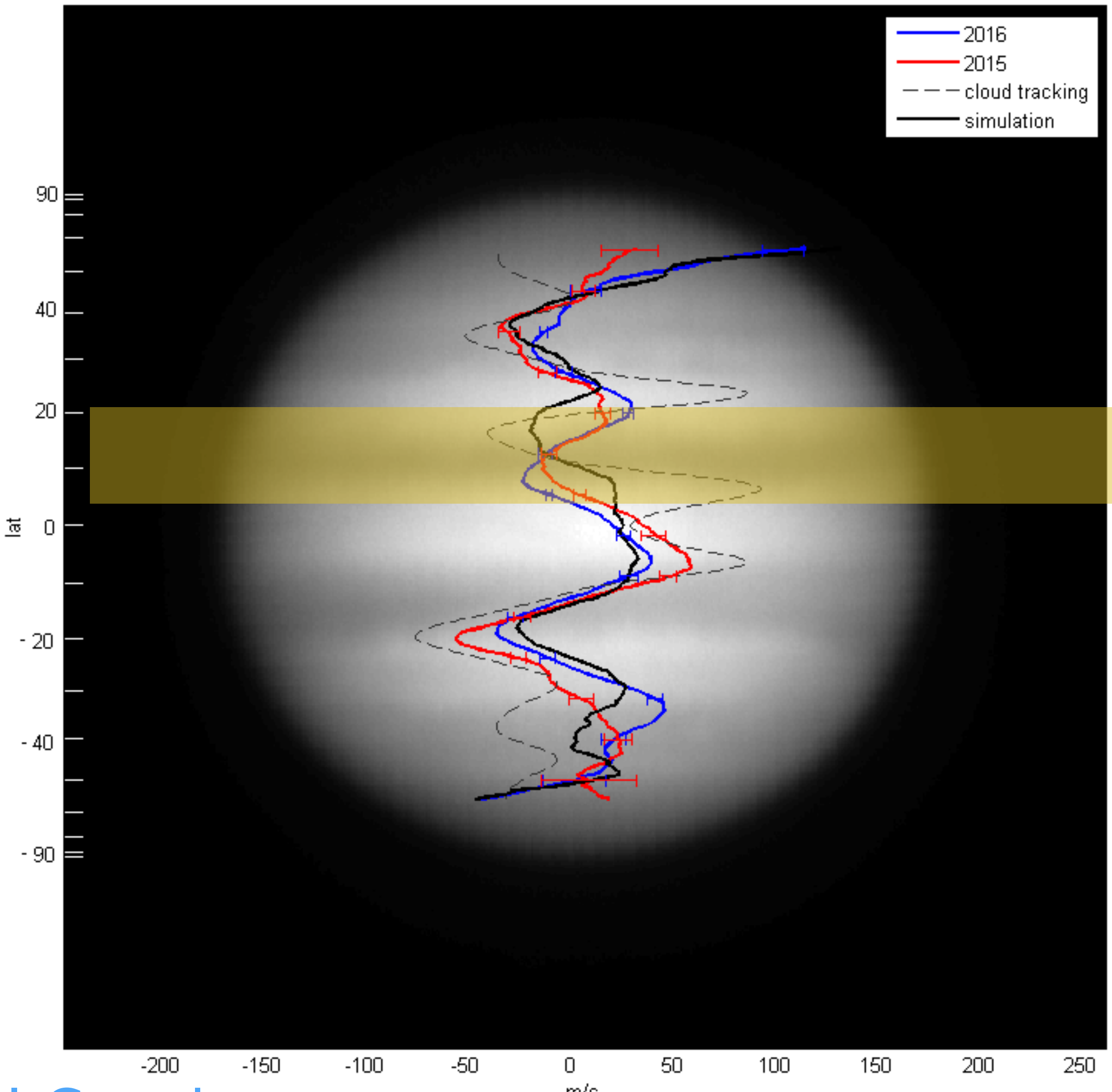
Based on observations with one instrument (in Calern, France)

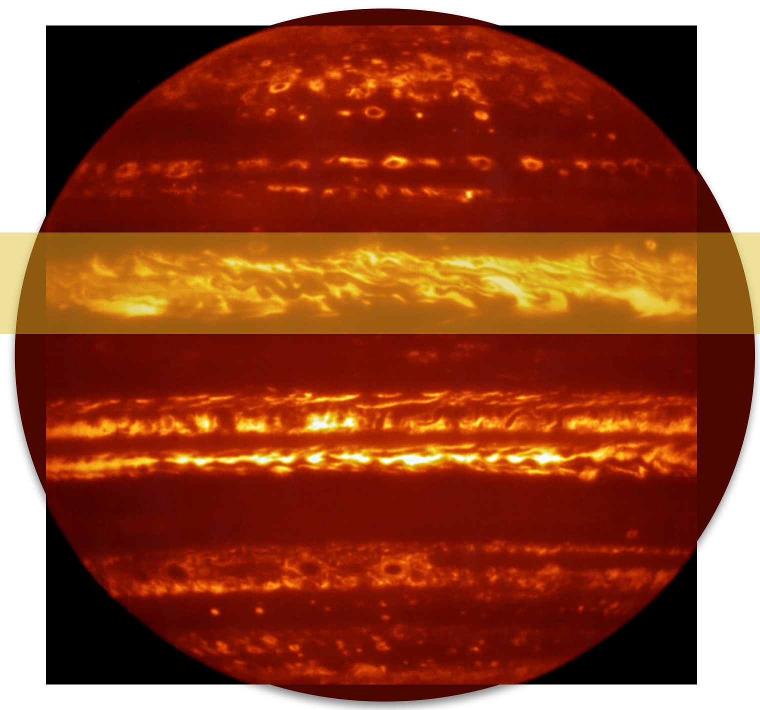


I. Gonçalves

Zonal winds: preliminary results

Based on observations with one instrument (in Calern, France)



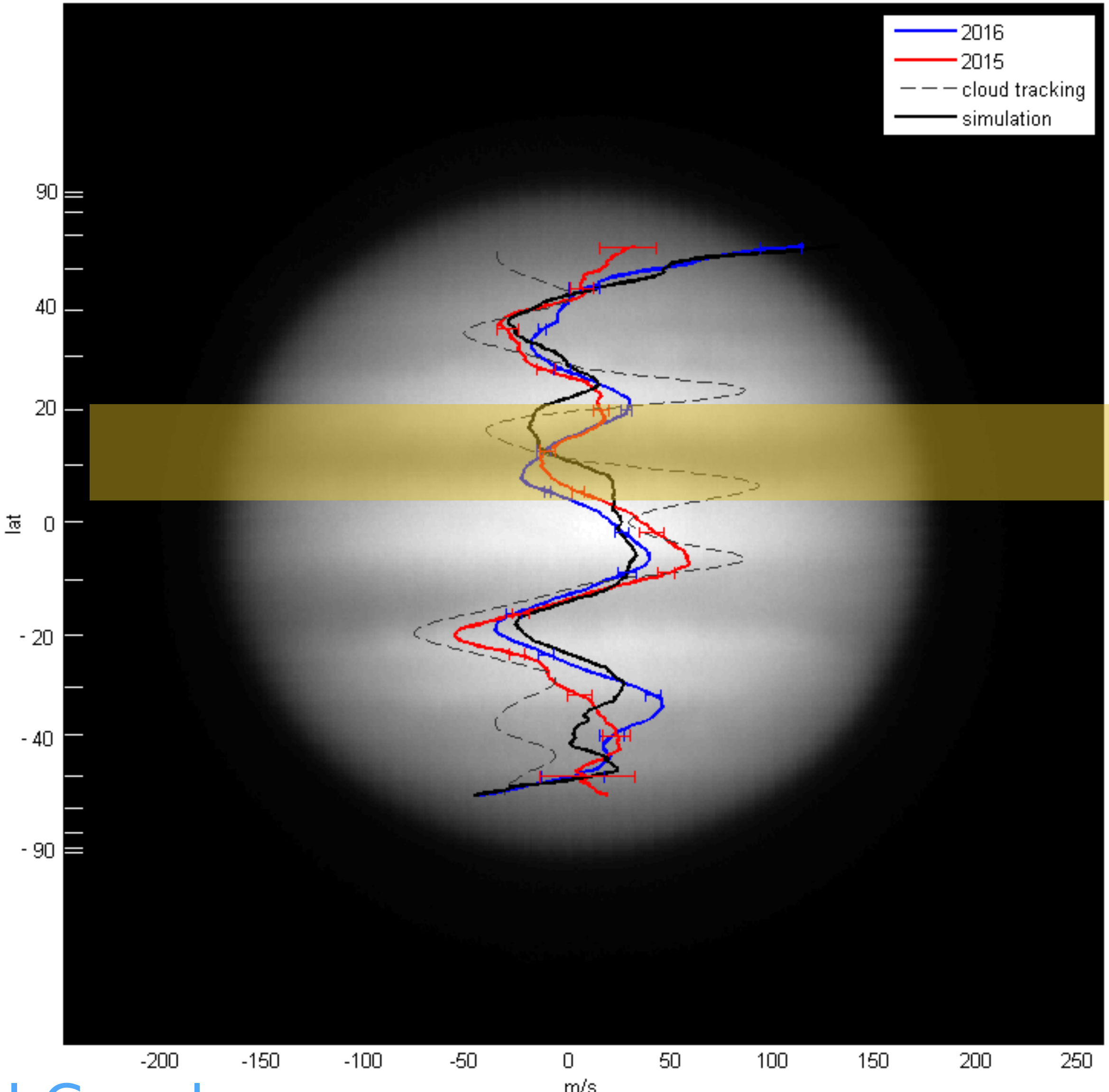


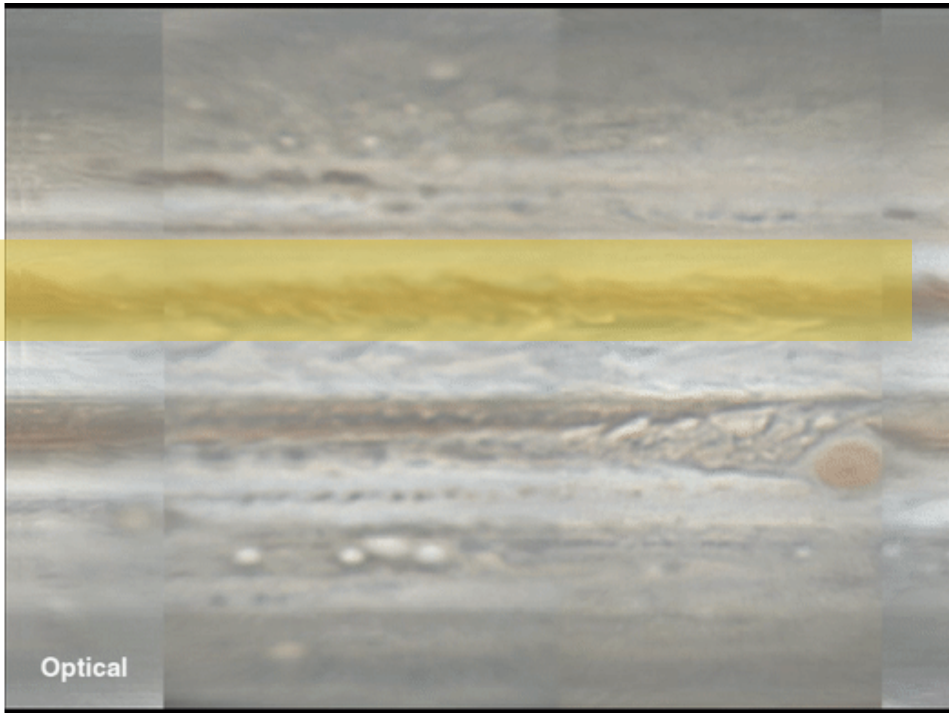
Fletcher et al. (2016)

I. Gonçalves

Zonal winds: preliminary results

Based on observations with one instrument (in Calern, France)





De Pater et al. (2016)

I. Gonçalves

Conclusions

The compositions and structures of giant planets are still uncertain

Juno will provide new constraints from gravimetry, magnetic field measurements, microwave emission

With seismology and dedicated observations from a network of telescope, we can complete the picture!