Radio Science at Jupiter: Past Investigations, Current Results, and Future Prospects

NASA / JPL / Voyager ISS

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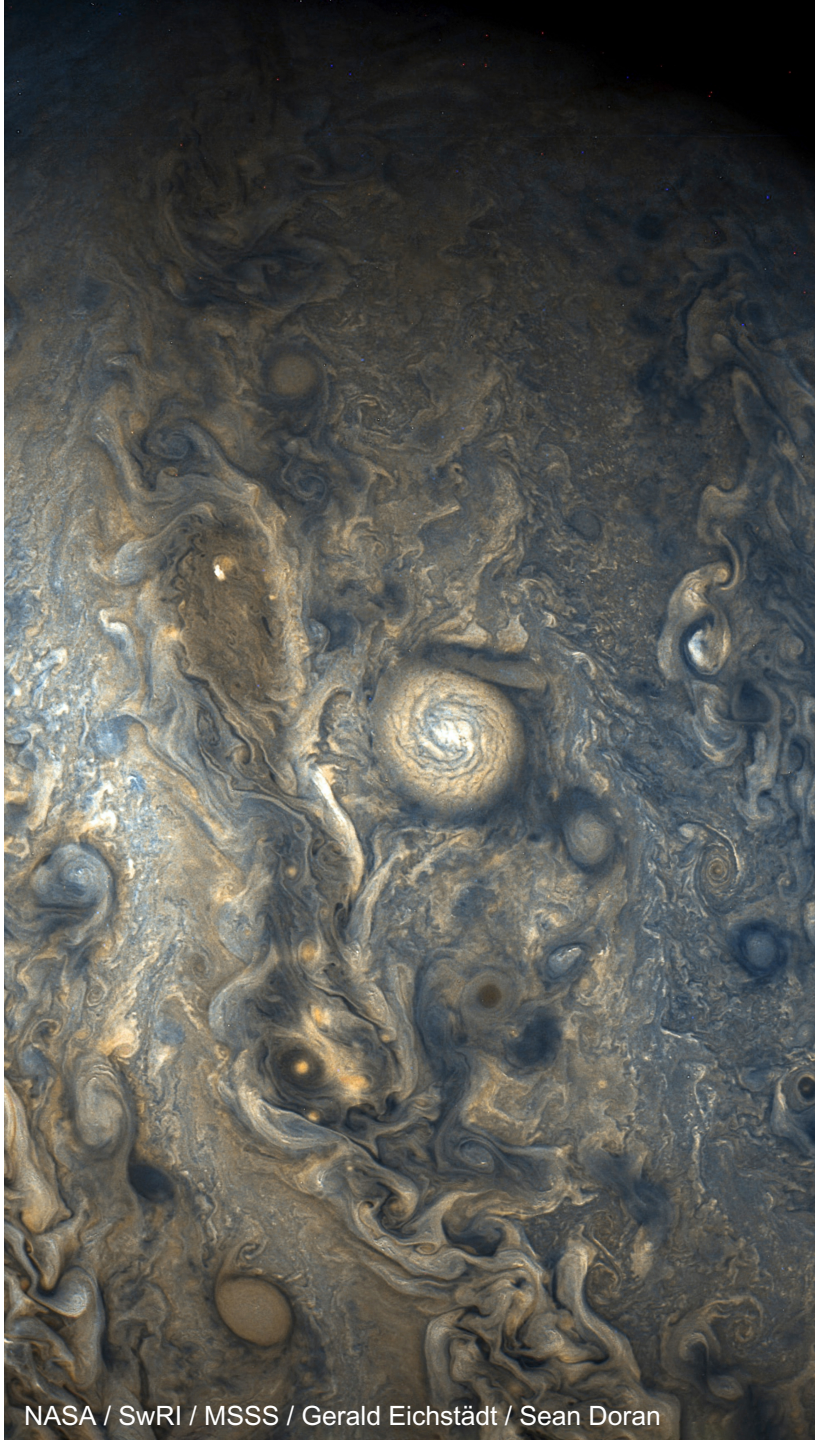
Overview

Agenda

1. Missions to Jupiter
2. Radio Science Instrumentation
3. Atmosphere and Ionosphere
4. Magnetosphere
5. Interior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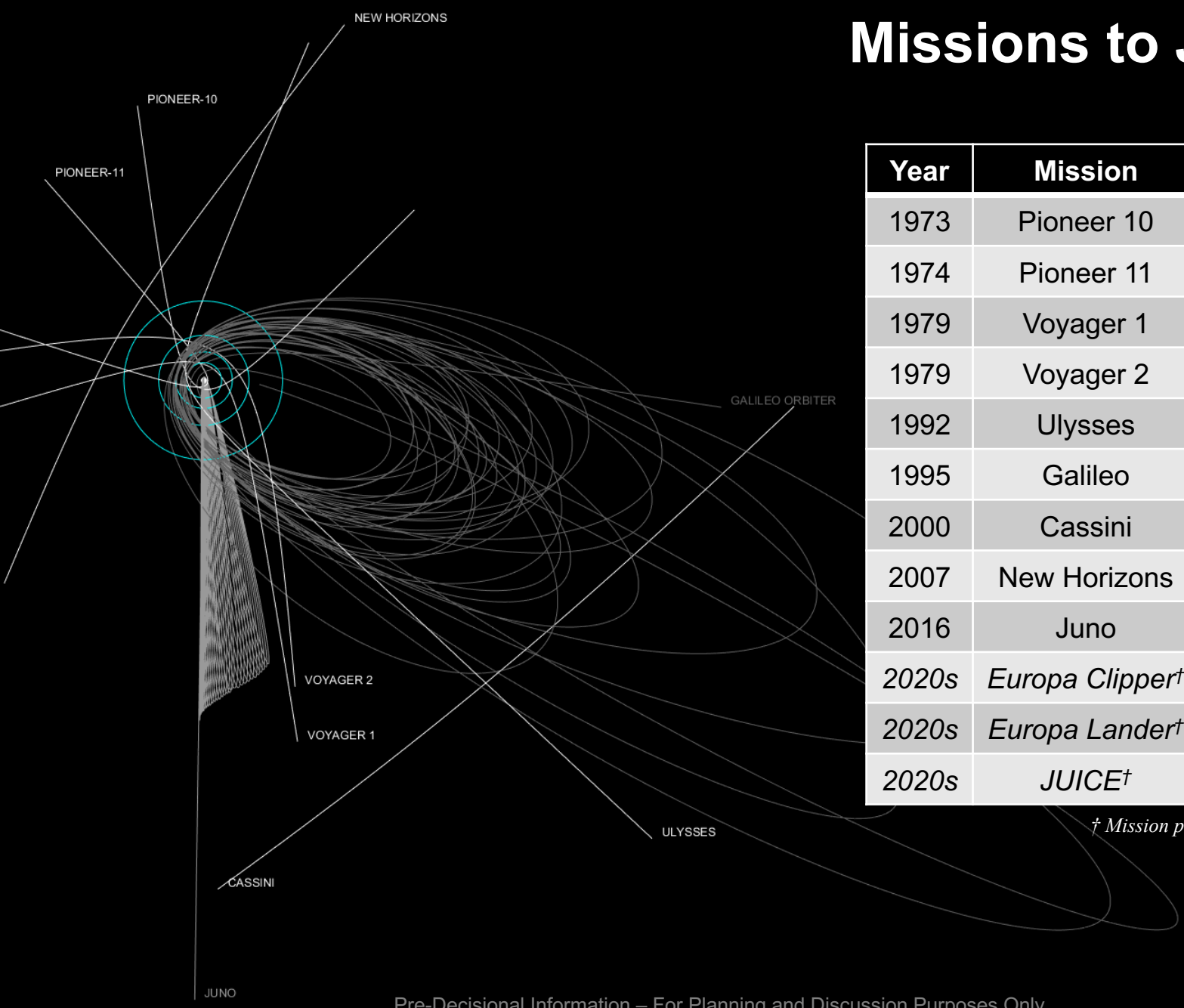
Missions to Jupiter

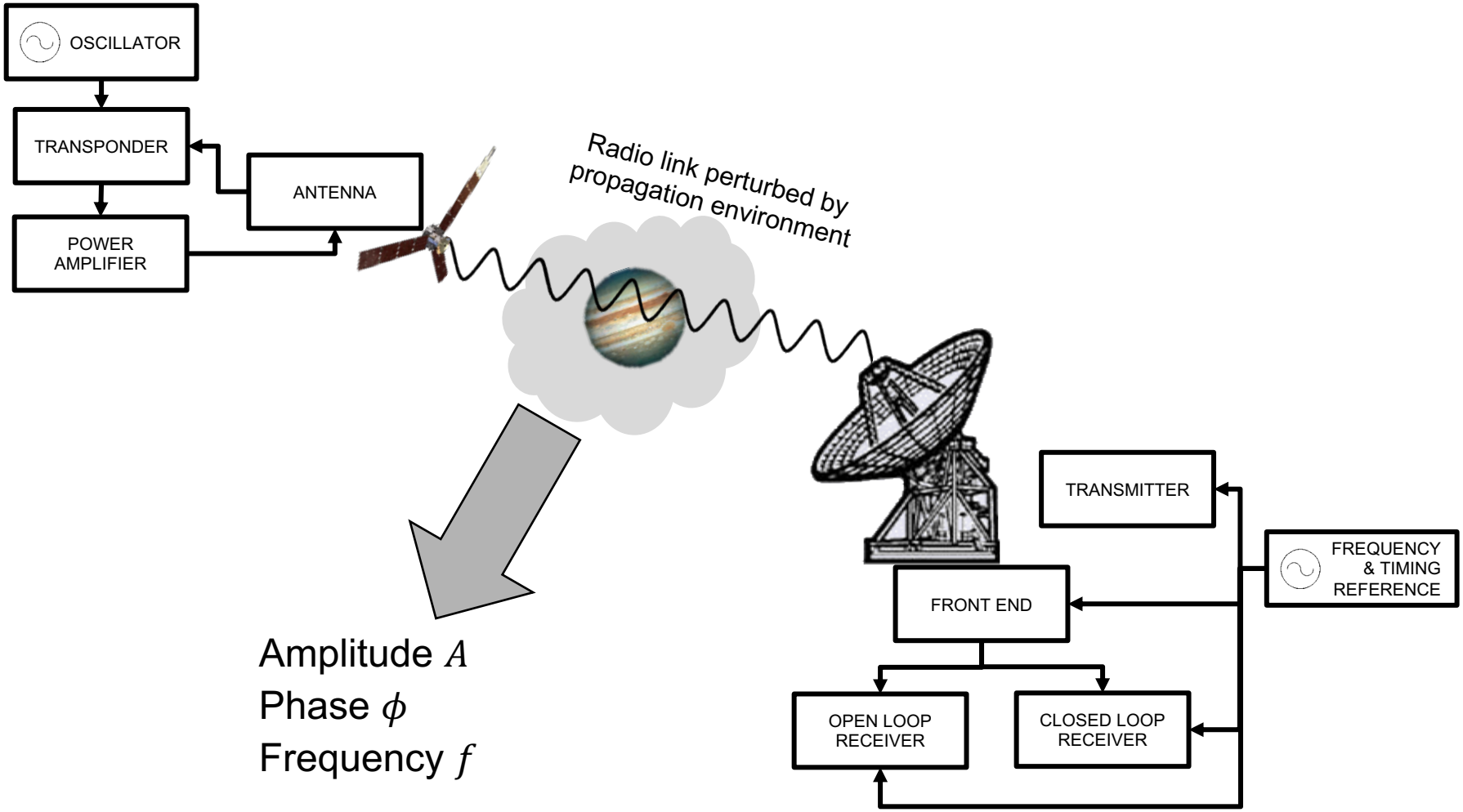


Year	Mission	Type
1973	Pioneer 10	Flyby
1974	Pioneer 11	Flyby
1979	Voyager 1	Flyby
1979	Voyager 2	Flyby
1992	Ulysses	Flyby
1995	Galileo	Orbiter/Probe
2000	Cassini	Flyby
2007	New Horizons	Flyby
2016	Juno	Orbiter
2020s	*Europa Clipper†*	*Orbiter*
2020s	*Europa Lander†*	*Lander*
2020s	*JUICE†*	*Orbiter*

† Mission proposed/in-development

Pre-Decisional Information – For Planning and Discussion Purposes Only

Radio Science Instrumentation



Radio Science Instrumentation at Jupiter

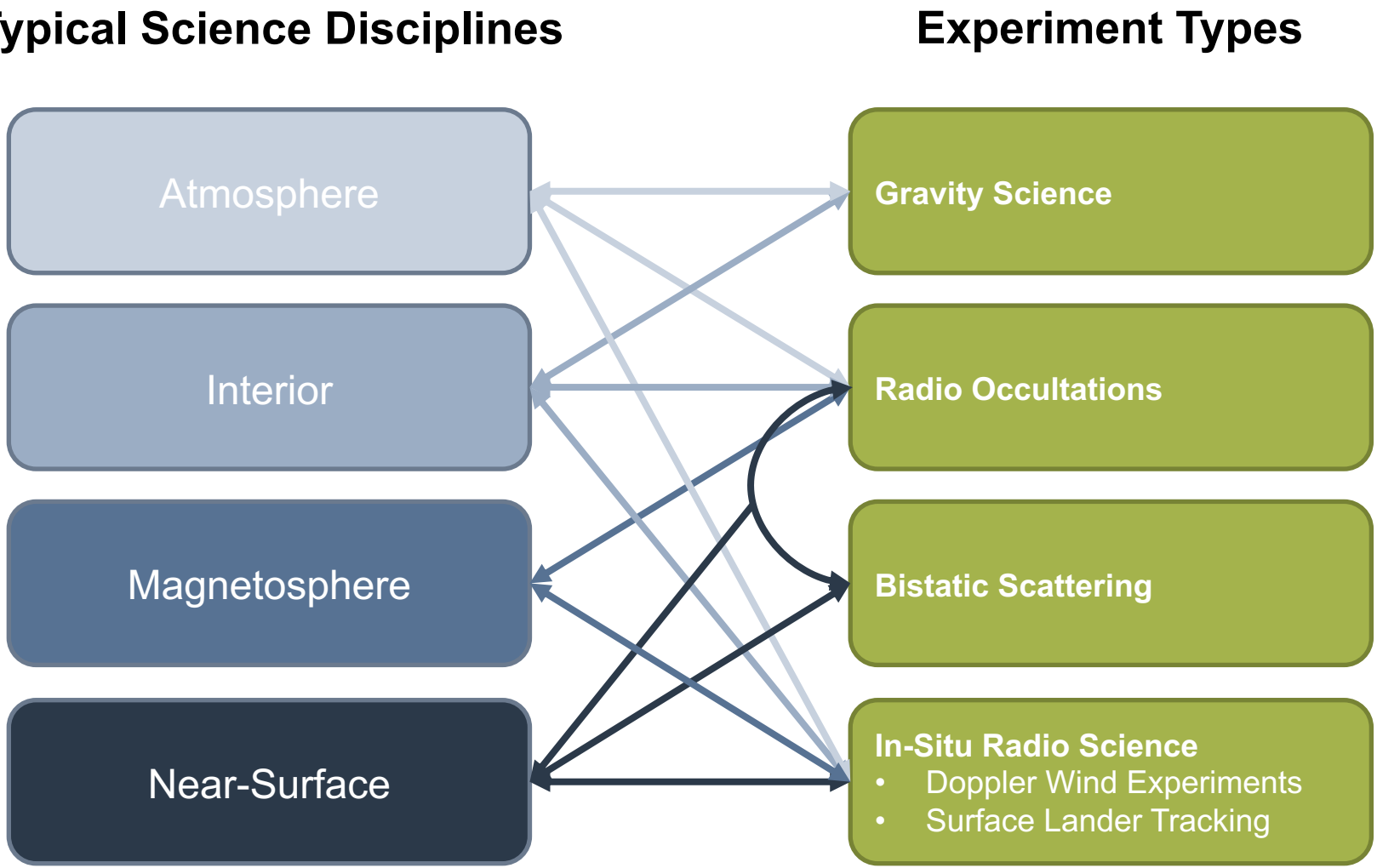
Year	Mission	Type	Radio Science Instrumentation	RS Investigation
1973	Pioneer 10	Flyby	S-band Transponder	● ● A
1974	Pioneer 11	Flyby	S-band Transponder	● ● A
1979	Voyager 1	Flyby	Dual S- & X-band with USO	● ● A
1979	Voyager 2	Flyby	Dual S- & X-band with USO	● ● A
1992	Ulysses	Flyby	Dual S- & X-band Radio System	M
1995	Galileo	Orbiter/Probe	S-band with Low Gain Antenna	● ● I ●
2000	Cassini	Flyby	*Triple S-, X-, & cross-link Ka-band with USO**	●
2007	New Horizons	Flyby	*X-band Transponder with USO and open-loop**	●
2016	Juno	Orbiter	Dual X- & Ka-band Links	● ● M
2020s	*Europa Clipper†*	*Orbiter*	*X-band and Ka-band Downlink Radio*	● ●
2020s	*Europa Lander†*	*Lander*	*X-band Radio*	● ● ●
2020s	*JUICE†*	*Orbiter*	*Dual/cross-link X- & Ka-band with USO*	● ● A

† Mission proposed/in-development, radio science investigations under study or proposed and may vary.

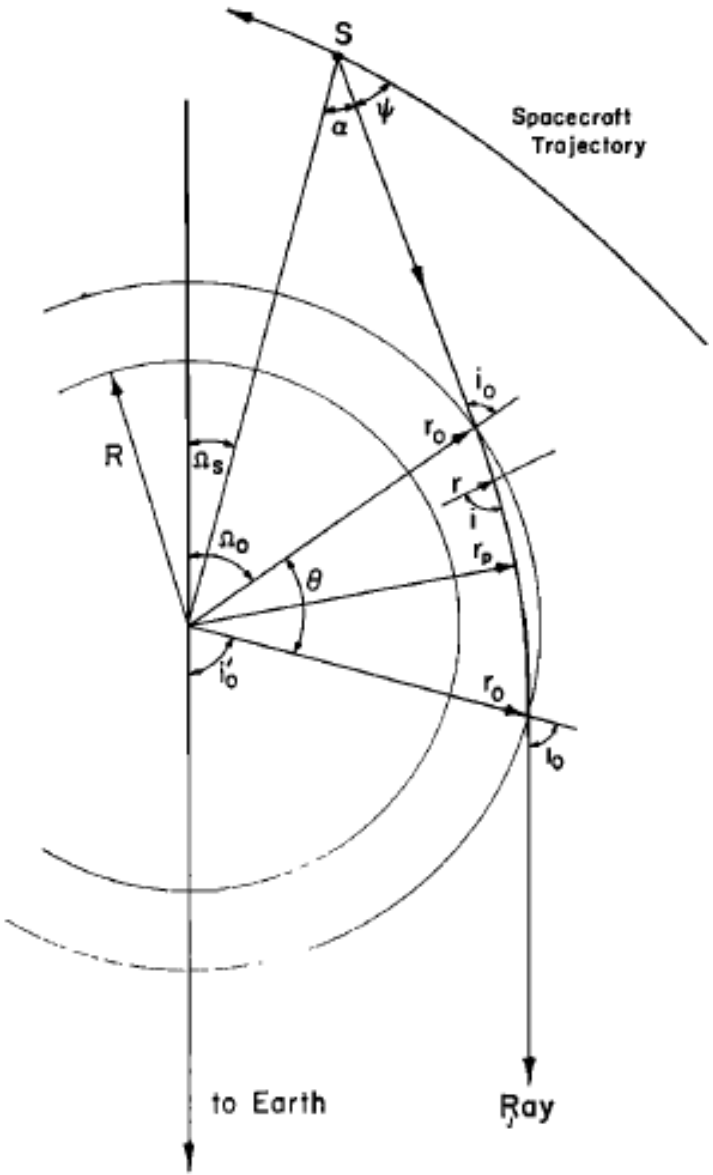
** Not used during flyby*

Gravity Science ●
Ephemeris/Celestial Mechanics ●
Atmosphere (A), Ionosphere (I), and /or Magnetosphere/Torus (M) Occultation ●
In-Situ Radio Science Observations ●

What does Radio Science do?



Investigations of the Atmosphere & Ionosphere



Phinney and Anderson, 1968

Signal Frequency or Phase (ϕ)

$$(\nabla\phi)^2 = n^2 f^2/c^2$$

Refractivity (n)

$$T = \frac{n_b T_b}{n} + \frac{m}{nk}\int n(r)g(r)dr$$

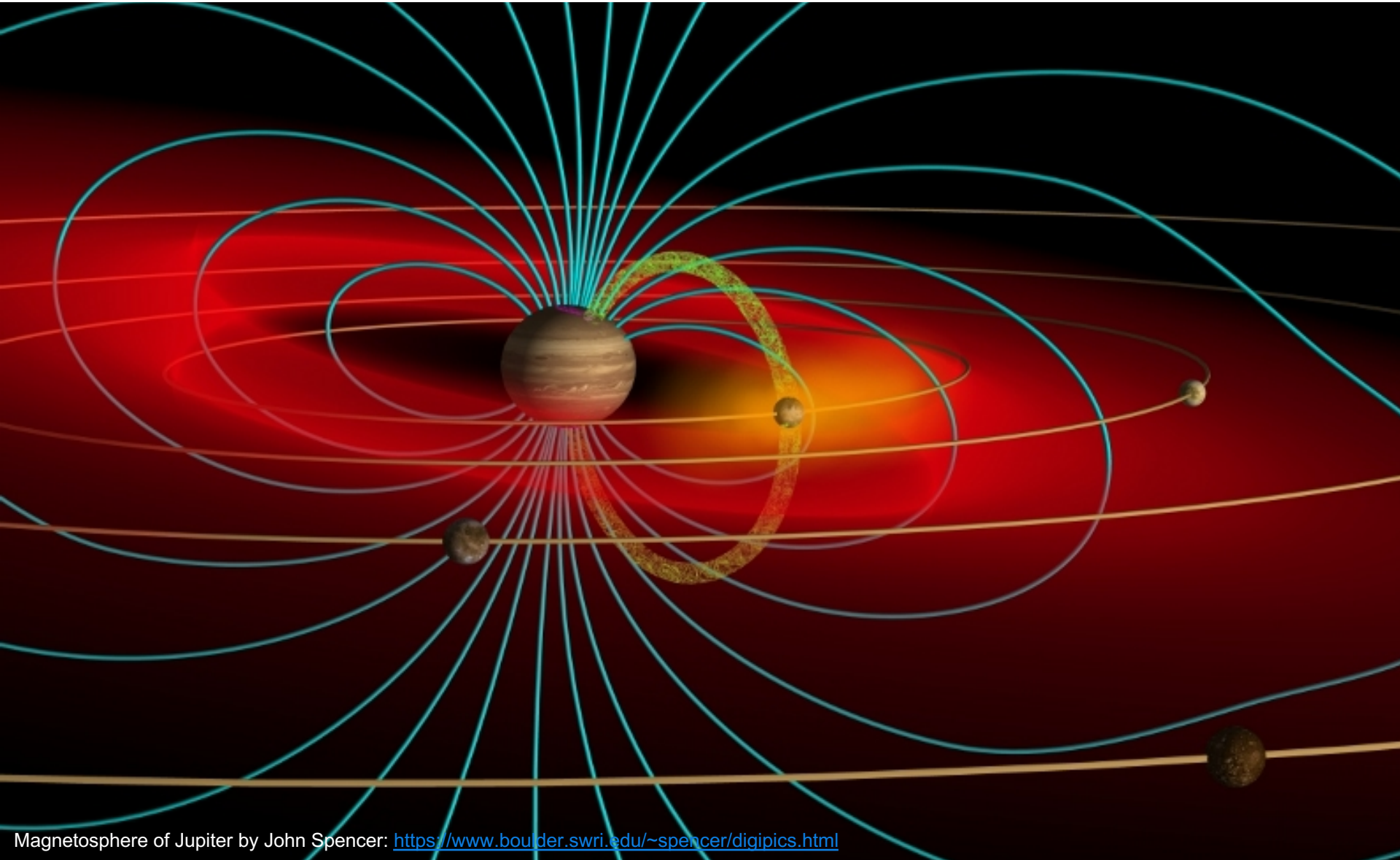
Temperature/Pressure (T/P) Profile

Occultation Results

- Early results by Pioneer 10/11 limited in scope by data analysis method used and poor instrumentation
- Galileo results limited by failure of HGA – stuck on LGA
- Voyager 1 and 2 occultations of atmosphere and ionosphere still the best available today

Date	Mission	Type	Lat	ID #
Dec 4, 1973	Pioneer 10	Ingress	28°N	P10N
Dec 4, 1973	Pioneer 10	Egress	58°N	P10X
Dec 3, 1974	Pioneer 11	Ingress	80°S	P11N
Dec 3, 1974	Pioneer 11	Egress	20°N	P11X
Mar 5, 1979	Voyager 1	Ingress	12°S	V1N
Mar 5, 1979	Voyager 1	Egress	~0°	V1X
Jul 10, 1979	Voyager 2	Ingress	66°S	V2N
Jul 10, 1979	Voyager 2	Egress	51°S	V2X
Dec 8, 1995	Galileo	Ingress	24°S	J00N
Dec 8, 1995	Galileo	Egress	43°S	J00X
Nov 8, 1996	Galileo	Ingress	28°S	J03N
Dec 21, 1996	Galileo	Ingress	23°S	J04N
Dec 21, 1996	Galileo	Egress	25°S	J04X

Investigations of the Magnetosphere

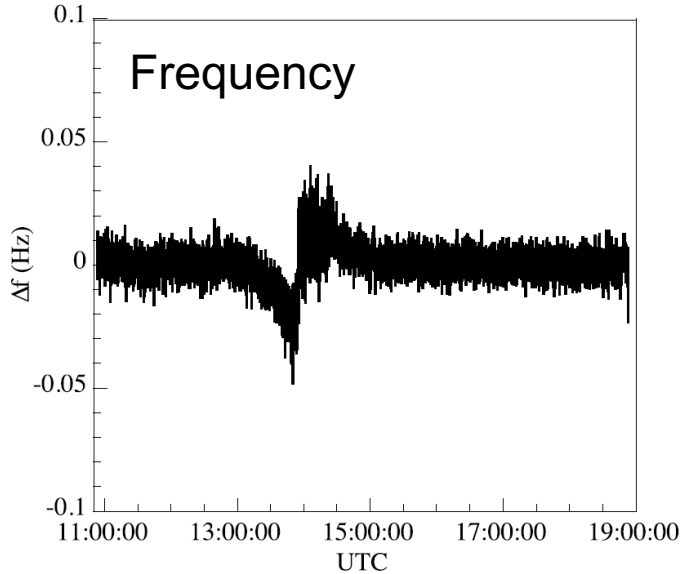


Magnetosphere of Jupiter by John Spencer: https://www.boulder.swri.edu/~spencer/digipics.html

Io Plasma Torus Occultations - Results

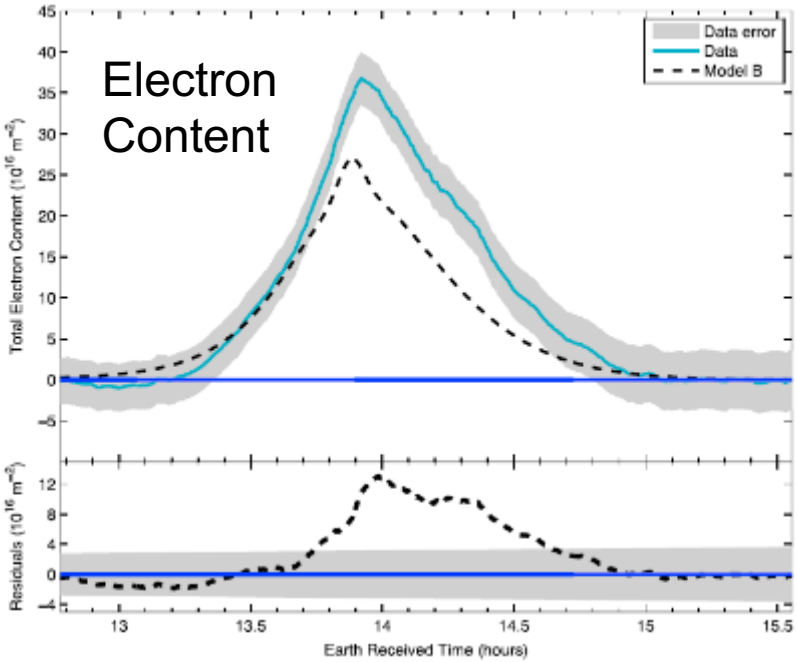
- Electrons in the IPT are dispersive:

$$\Delta f = f_X - f_{Ka}\left(\frac{f_{D,X}}{f_{D,Ka}}\right)$$



Folkner et al 2017

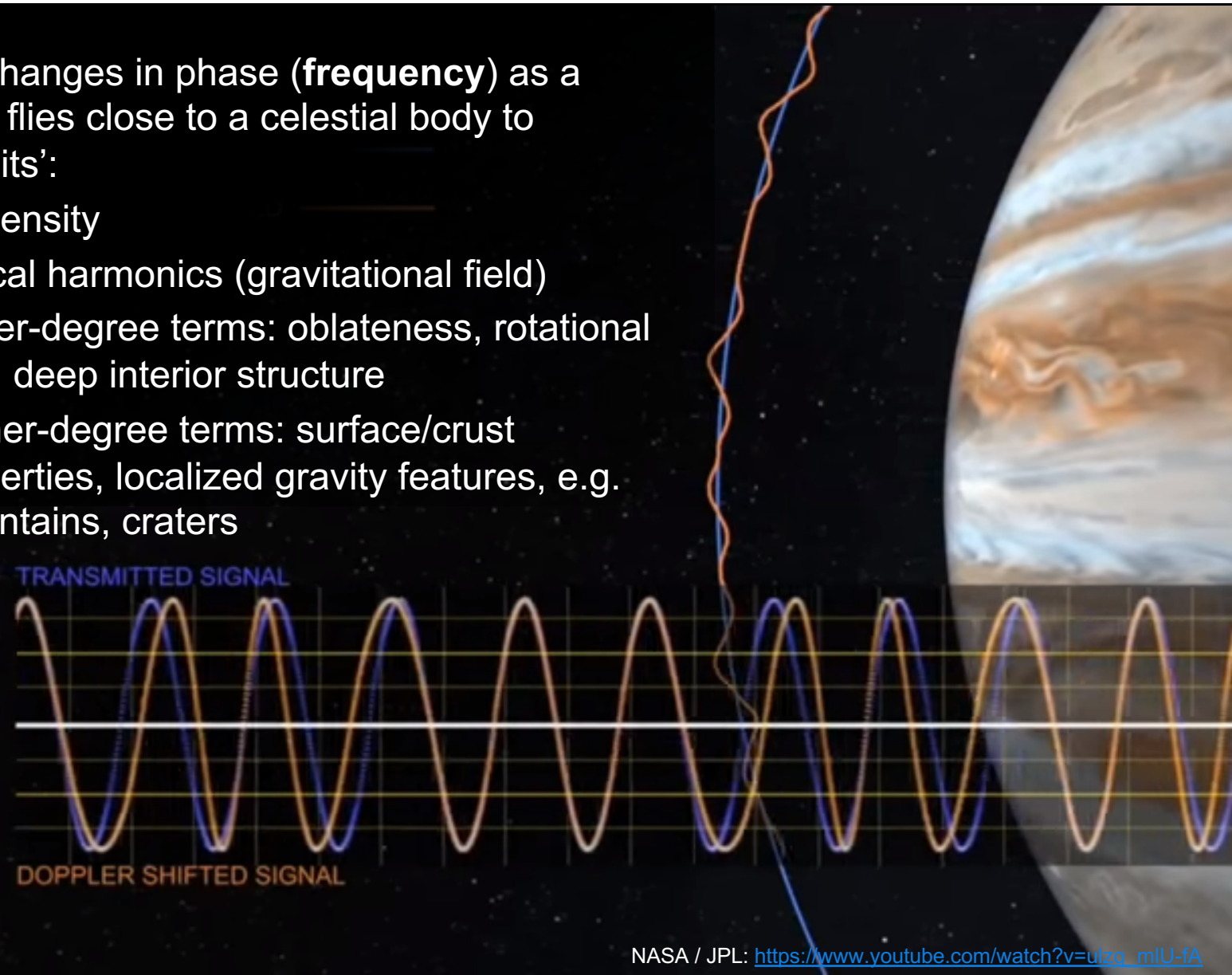
Models vs measurements allow refinement of Io Plasma torus model → improved magnetosphere models of Jupiter



Phipps et al 2018

Investigations of the Interior

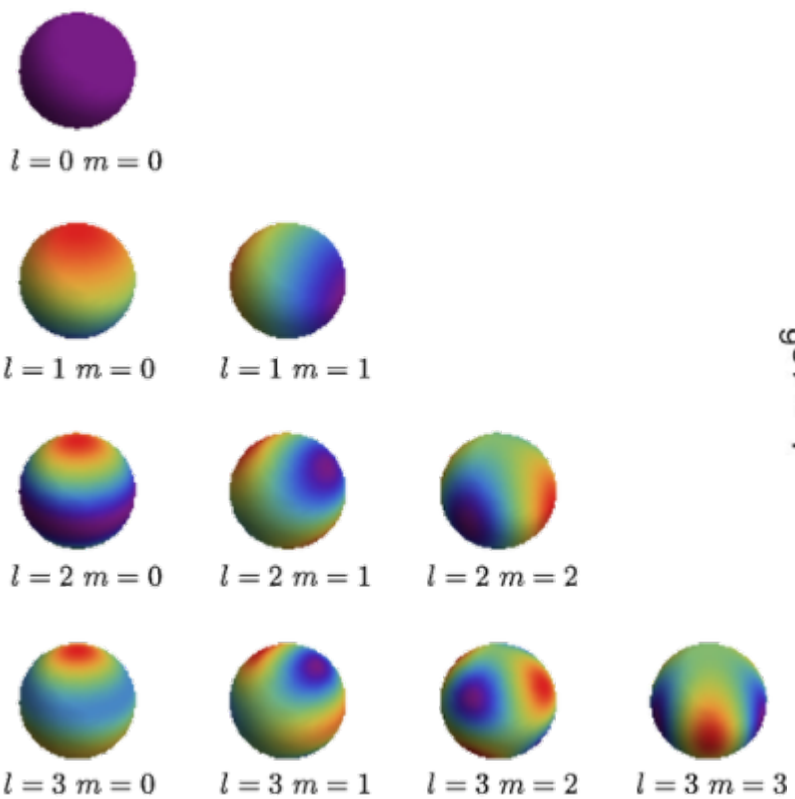
- Examine changes in phase (**frequency**) as a spacecraft flies close to a celestial body to determine its':
  - Mass/density
  - Spherical harmonics (gravitational field)
    - Lower-degree terms: oblateness, rotational axis, deep interior structure
    - Higher-degree terms: surface/crust properties, localized gravity features, e.g. mountains, craters

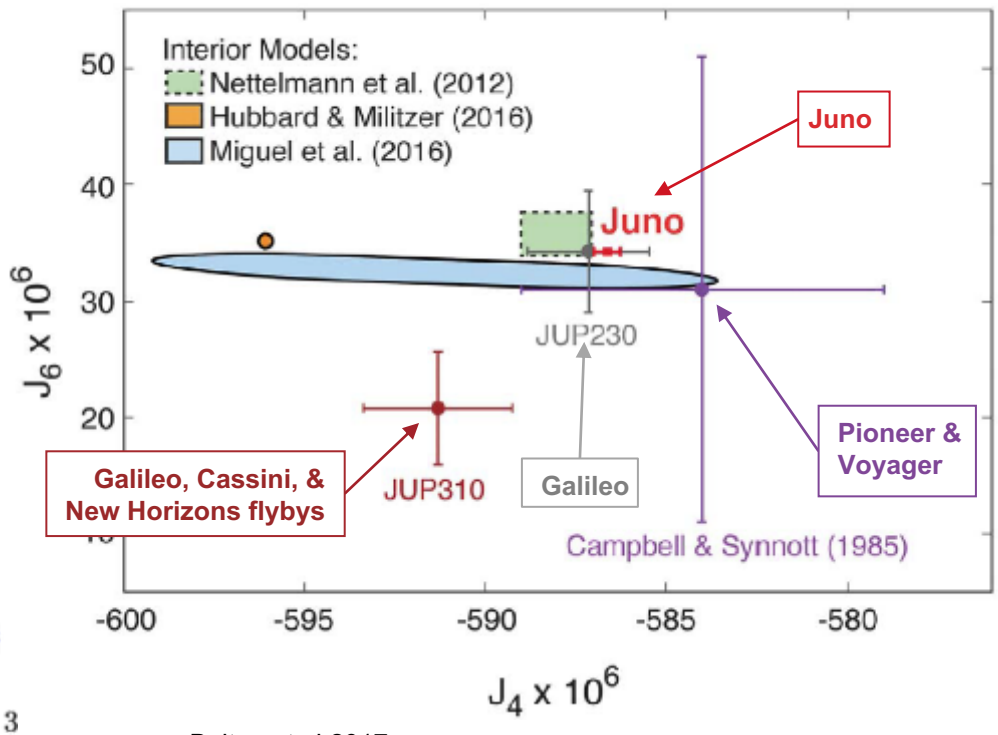


NASA / JPL: https://www.youtube.com/watch?v=ulzg_mlU-fA

Juno and the New Age of Gravity Science

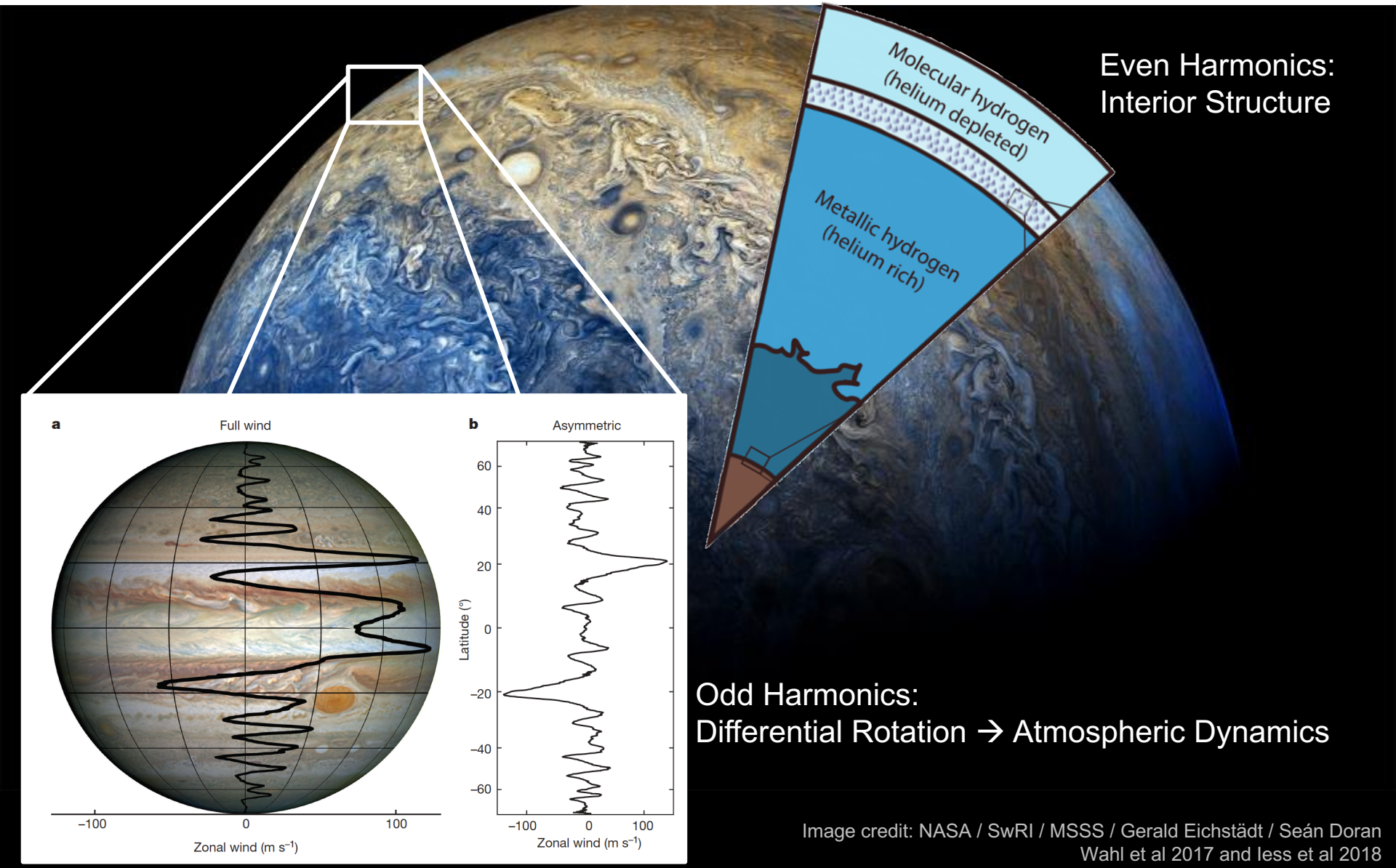
$$U = \frac{\mu}{r} - \frac{\mu^*}{r}\sum_{l=1}^{\infty}\left(\frac{a_e}{r}\right)^l P_l(\sin\phi)J_l + \frac{\mu^*}{r}\sum_{l=1}^{\infty}\sum_{m=1}^{l}\left(\frac{a_e}{r}\right)^l P_{lm}(\sin\phi)[C_{lm}\cos m\lambda + S_{lm}\sin m\lambda]$$





Bolton et al 2017

More than Just the Interior…

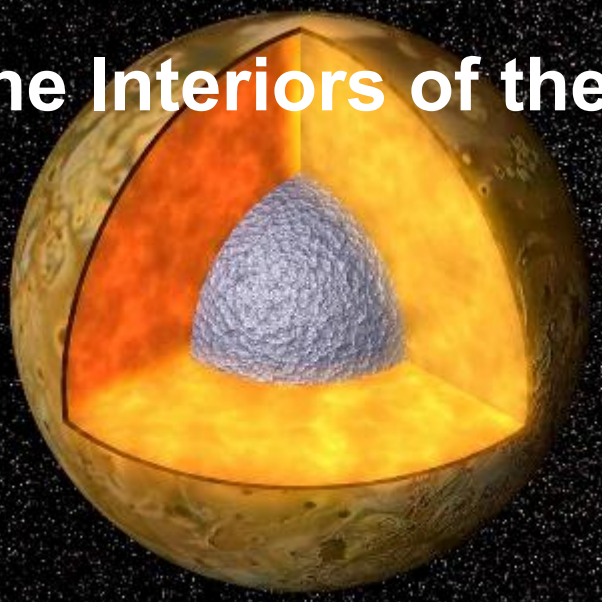


Even Harmonics:
Interior Structure

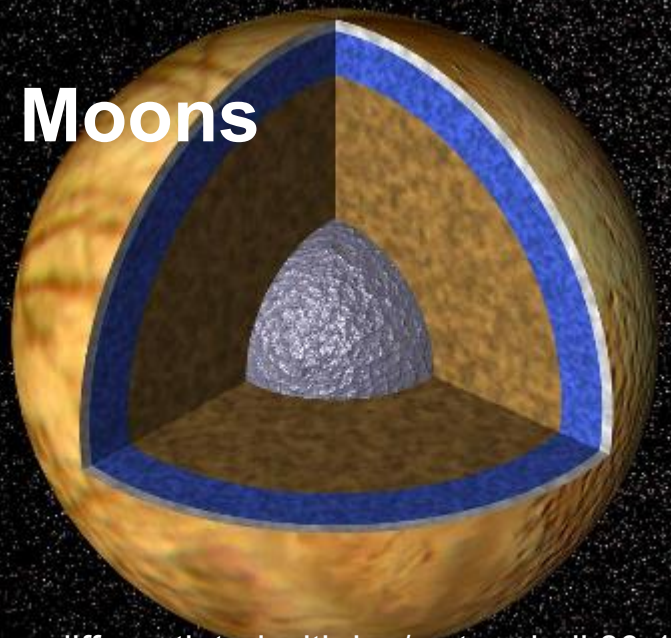
Odd Harmonics:
Differential Rotation → Atmospheric Dynamics

Image credit: NASA / SwRI / MSSS / Gerald Eichstädt / Seán Doran
Wahl et al 2017 and Iess et al 2018

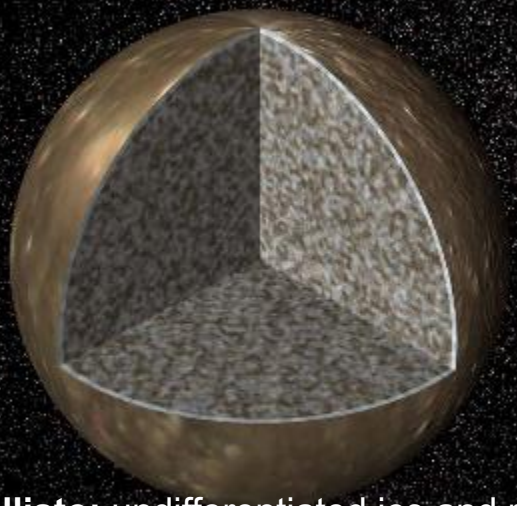
The Interiors of the Galilean Moons



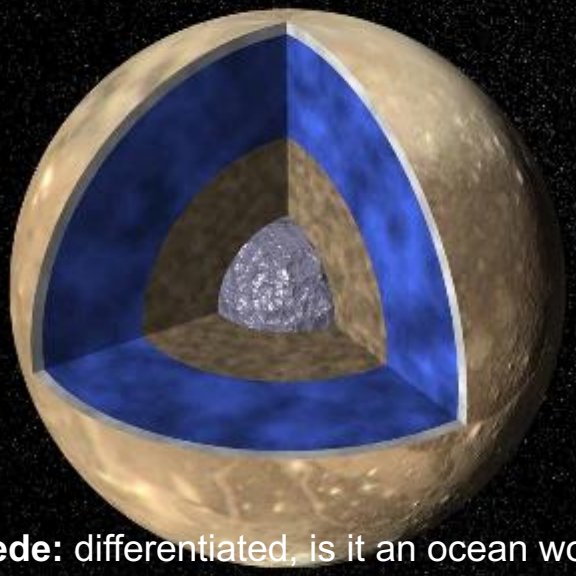
Io: a more traditional terrestrial world



Europa: differentiated with ice/water shell 80-170 km



Callisto: undifferentiated ice and rock



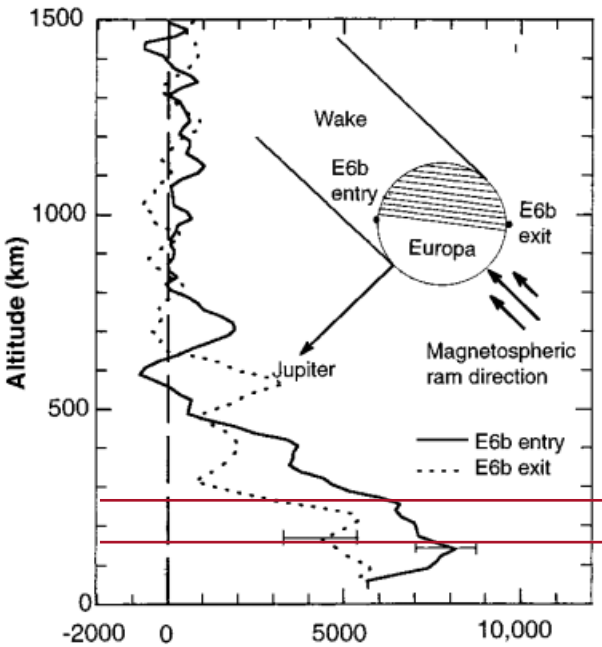
Ganymede: differentiated, is it an ocean world too?

Image credit: NASA / JPL

Science References: Moore et al 2007, Anderson et al 1998, Anderson et al 1996, Anderson et al 2001

Europa's Ionosphere Observed via Occultation

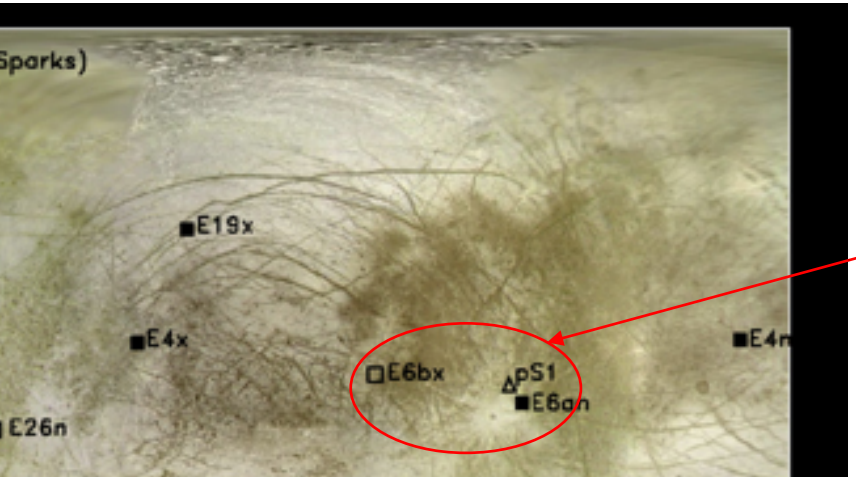
Galileo E6b Flyby – Feb 25, 1997



- Radio signal phase-advanced by electrons in planetary ionospheres
- Six occultations of Europa by Galileo found evidence of an active ionosphere on Europa
- Placed constraints on the size of Europa's atmosphere

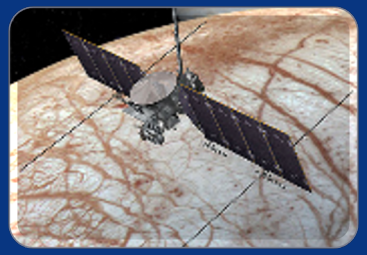
240 km Ionosphere scale height **implies a**
120 km Atmosphere (neutral gas) scale height

- Further research discovered plumes coincident in location with occultation E6b where abnormally high electron density was observed
  - Part of 4 independent detections of a long-lived pS1 plume activity on Europa



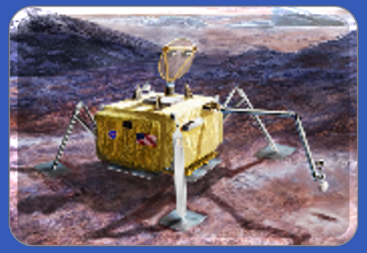
Kliore et al 1997
McGrath and Sparks 2017

Future and Upcoming Investigations



NASA's Europa Clipper

- …may measure tidal perturbations to the **gravity field** of Europa during flybys to detect a subsurface ocean (Park et al 2011)



NASA's *(potential)* Europa Lander

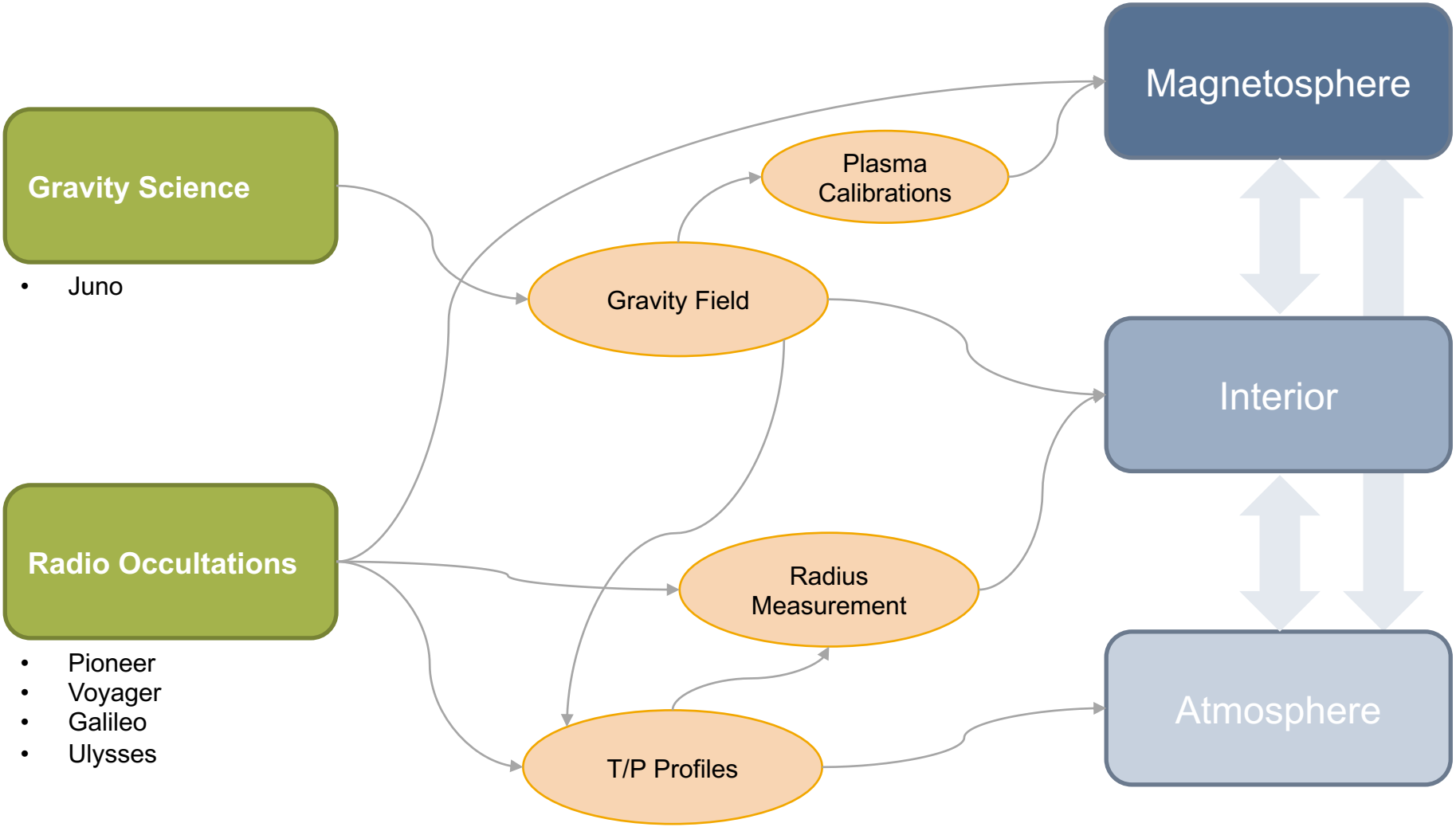
- …may measure the **local dynamic variability** of the lander through **tracking the Doppler shift** between the lander and Earth or a relay spacecraft (Hand et al 2017)

ESA's Jupiter Ice Moons Explorer (JUICE)

- …may probe the **gravity fields** of Ganymede, Callisto and Europa along with **radio occutlations** of Jupiter with the 3GM instrument (less 2013)

The Importance of the Investigations

Cross-discipline collaboration – An Example from Juno



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