Probing Fifth Force Interactions by Planetary Science Data

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May 15, 2024

Beyond the Standard Model and Fifth Force

- In BSM physics, new light, weakly-coupled degrees of freedom are introduced in the form of hypothetical particles and interactions.
- New fundamental interactions introduced by these particles $\rightarrow$ "Fifth Force"
- These particles can arise from string theory.
- Can also be dark matter or dark energy candidates.

The Fifth Force and its Modeling

- Phenomenological model for fifth force is given by:

$$V(r) = -\frac{GMm_*}{(1+\alpha_1)\,r}\left(1+\alpha_2 \exp\left(-\frac{r}{\lambda}\right)\right)$$
$$\lambda \rightarrow \text{fifth force range}\left(\propto \frac{1}{\text{mediator mass}}\right) \tag{1}$$
$$m_* \rightarrow \text{mass of celestial body orbiting object of mass } M$$
$$\alpha_1, \alpha_2 \rightarrow \text{Yukawa parameters (model dependent)}$$

- First term: deviation from Newtonian gravity term

$$G \rightarrow \widetilde{G} \equiv \frac{G}{1+\alpha_1} \tag{2}$$

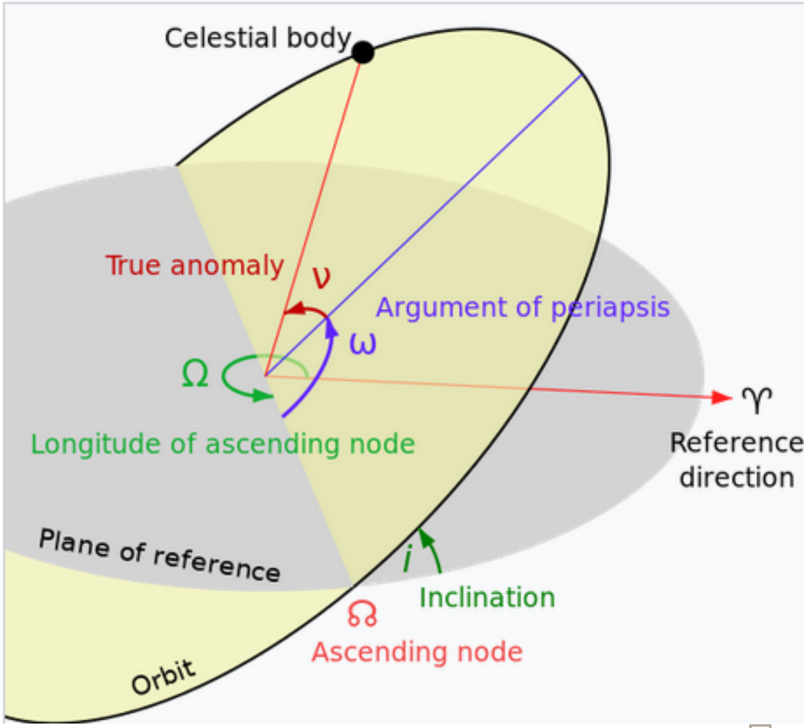
- Second term: Yukawa term due to the fifth force

$$V(r) \propto -\alpha_2 \frac{exp(-r/\lambda)}{r} \tag{3}$$

Probing the Fifth Force

- Can be probed by tracking the deviations of Keplerian orbits of celestial objects.
- Many such probes are similar to the tests for General Relativity (GR).
- Deviations can be quantified in terms of orbital parameters:

$$(a, e, i, \Omega, \omega, \nu)$$



Past Literature

In the literature, constraints on the fifth force due to deviations from Newtonian trajectory are given by:

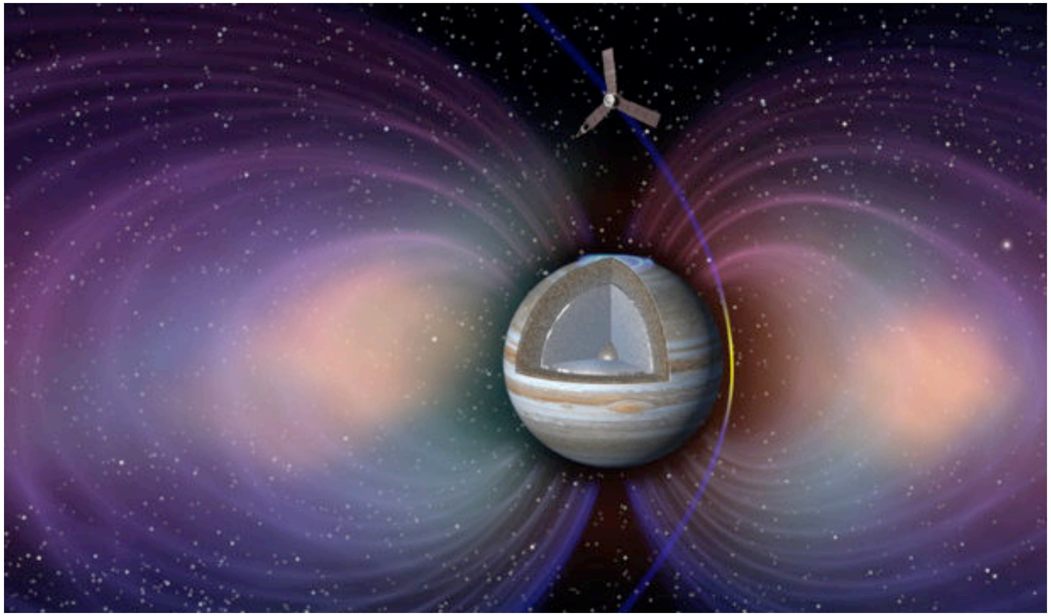
- Lunar Laser Ranging (Earth $\leftrightarrow$ Moon) (Bergé et al., 2018)
- Timing of pulsar around Sagittarius A^* (Dong et al., 2022)
- Orbital precession of:
  - Near-Earth Object (NEO) asteroids (Tsai et al., 2023)
  - Planets in the Solar system (Poddar et al., 2020)
  - S2 star around Sagittarius A^* (Borka et al., 2016)

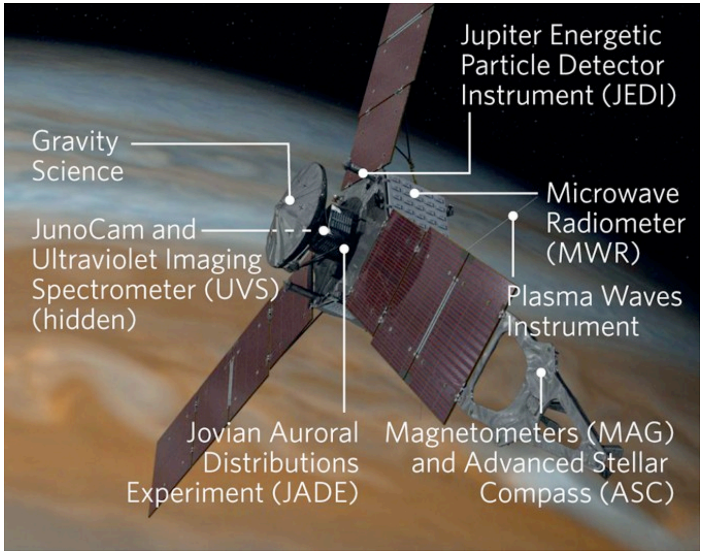
Jupiter Near-Polar Orbiter (JUNO) Mission

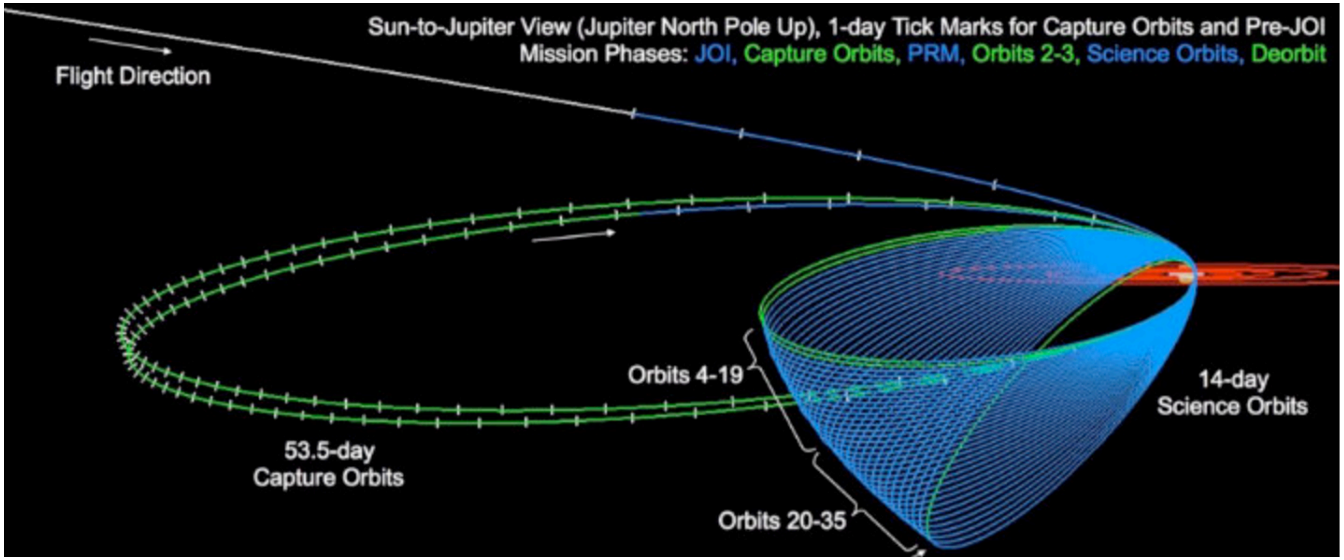
The JUNO mission aims to perform a comprehensive study on the planet Jupiter by:

- Mapping its gravitational and magnetic fields.
- Exploring its structure of polar magnetosphere and auroras.
- Mapping variations in atmospheric composition, temperature and cloud opacity.
- Determining the abundance of water and place an upper limit on the mass of Jupiter's possible solid core.

Jupiter Near-Polar Orbiter (JUNO) Mission







Probing the Fifth Force with JUNO

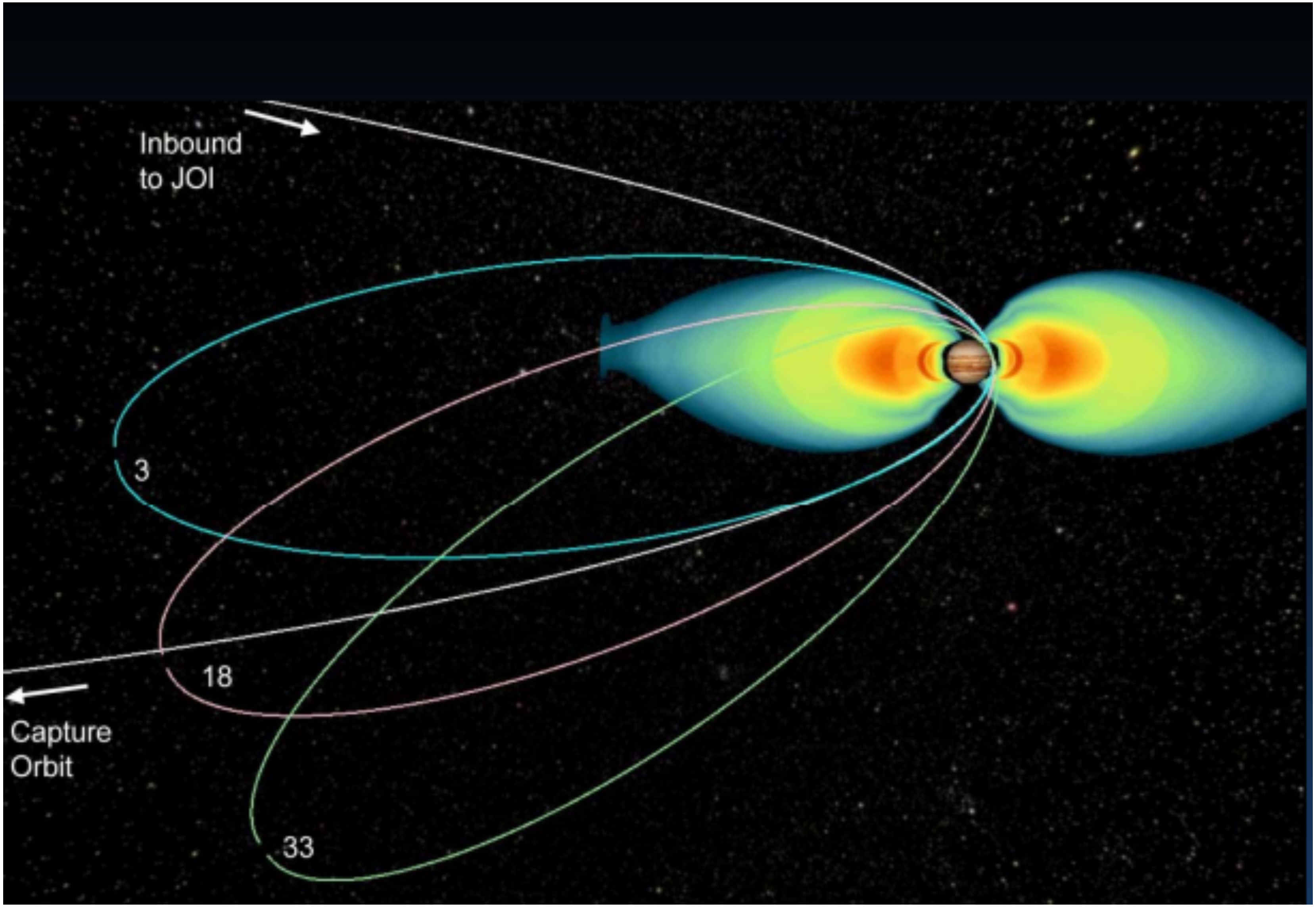
- Jupiter's Gravity field data reconstructed in the form of:
  1. Central mass value $\rightarrow G \times M$
  2. Gravity anomaly coefficients $\rightarrow J_i$ etc.
  3. Tidal Love numbers $\rightarrow h$
- Fifth force perturbation $\Longrightarrow$ perturbation in orbital parameters $(\delta a, \delta e, \delta\Omega, \delta\omega, \delta i)$
- We constrain fifth force via the precession angle of JUNO's orbit (ω):

$$\Delta\omega^2_{\text{fifth-force}} < \sum_{i=2}^{12} \left|\frac{\partial\omega}{\partial J_i}\right|^2 \sigma^2_{J_i} \tag{4}$$

$\sigma_{J_i} \rightarrow$ Uncertainty in J_i

- Unique from geocentric/ heliocentric celestial body probes.

Precession of Orbits



Fifth Force as Perturbation Force

- Perturbed force in Satellite-Normal co-ordinate system (RTN) is of the form:

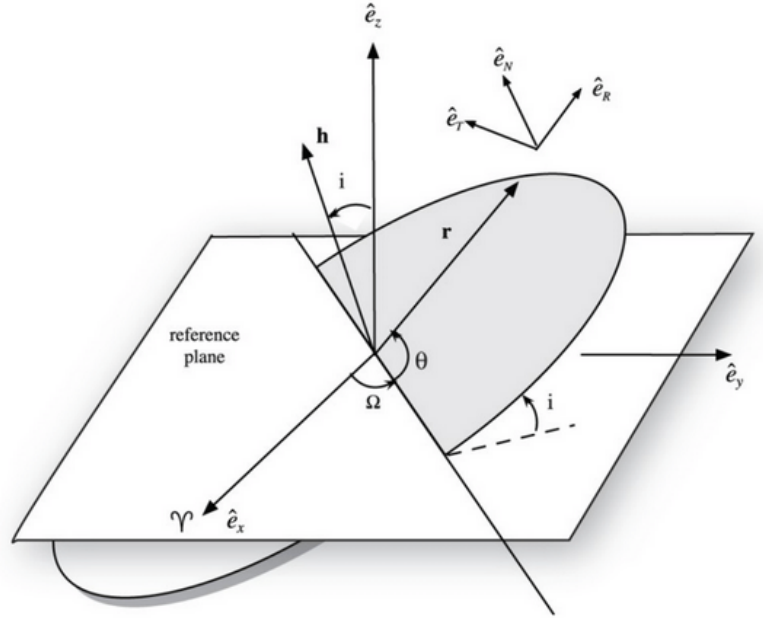
$$\vec{F} = R\hat{e}_R + N\hat{e}_N + T\hat{e}_T$$

- For Yukawa force term we have:

$$R = -\alpha_2 \frac{GM}{(1+\alpha_1)r^2}\left(1+\frac{r}{\lambda}\right) exp(-r/\lambda) \qquad (5)$$
$$N = T = 0$$

- For Satellite-Normal CS (R-T-N):
  - $\hat{e}_R$ points along the Jupiter $\rightarrow$ JUNO.
  - $\hat{e}_N$ along $\vec{h}$ (angular momentum)
  - $\hat{e}_T$ is defined by the right hand rule:

$$\hat{e}_T \cdot v > 0$$

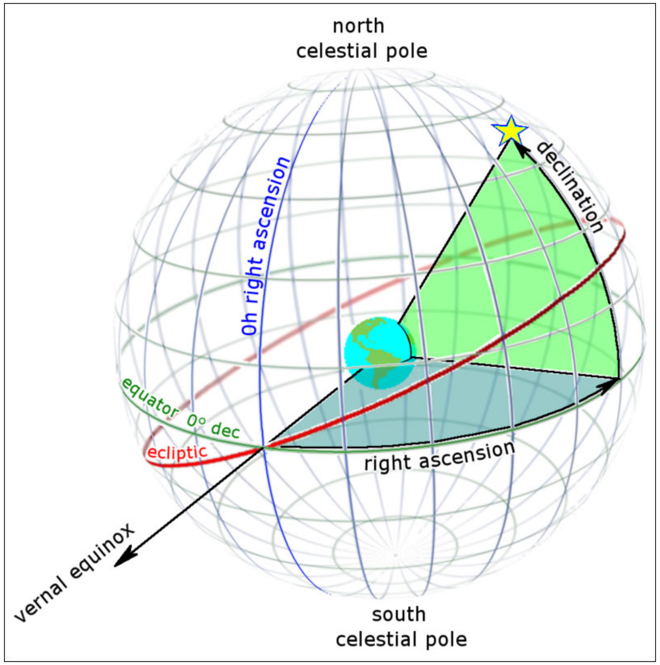


The Zonal Harmonics

- The non-spherical feature of the planet, can be accounted by expanding Newtonian potential in spherical harmonics basis.
- For our work, we only focus on zonal harmonics:

$$U_{\text{zonal}}\;(r,\phi) = \frac{GM}{r}\sum_{n=2}^{\infty} J_n \left(\frac{R_J}{r}\right)^n P_n\left(\sin\phi\right) \tag{6}$$

- Coordinates given by:
  - $\phi \rightarrow$ declination from equatorial plane.
  - $r \rightarrow$ radius
  - $\lambda \rightarrow$ right ascension (from a meridian)



Precession Angle

- Plugging Perturbation force in:

$$\dot{\Omega} = \sqrt{\frac{a\left(1-e^2\right)}{\mu}} \frac{N \sin(\omega+\nu)}{\sin i(1+e\cos\nu)}$$

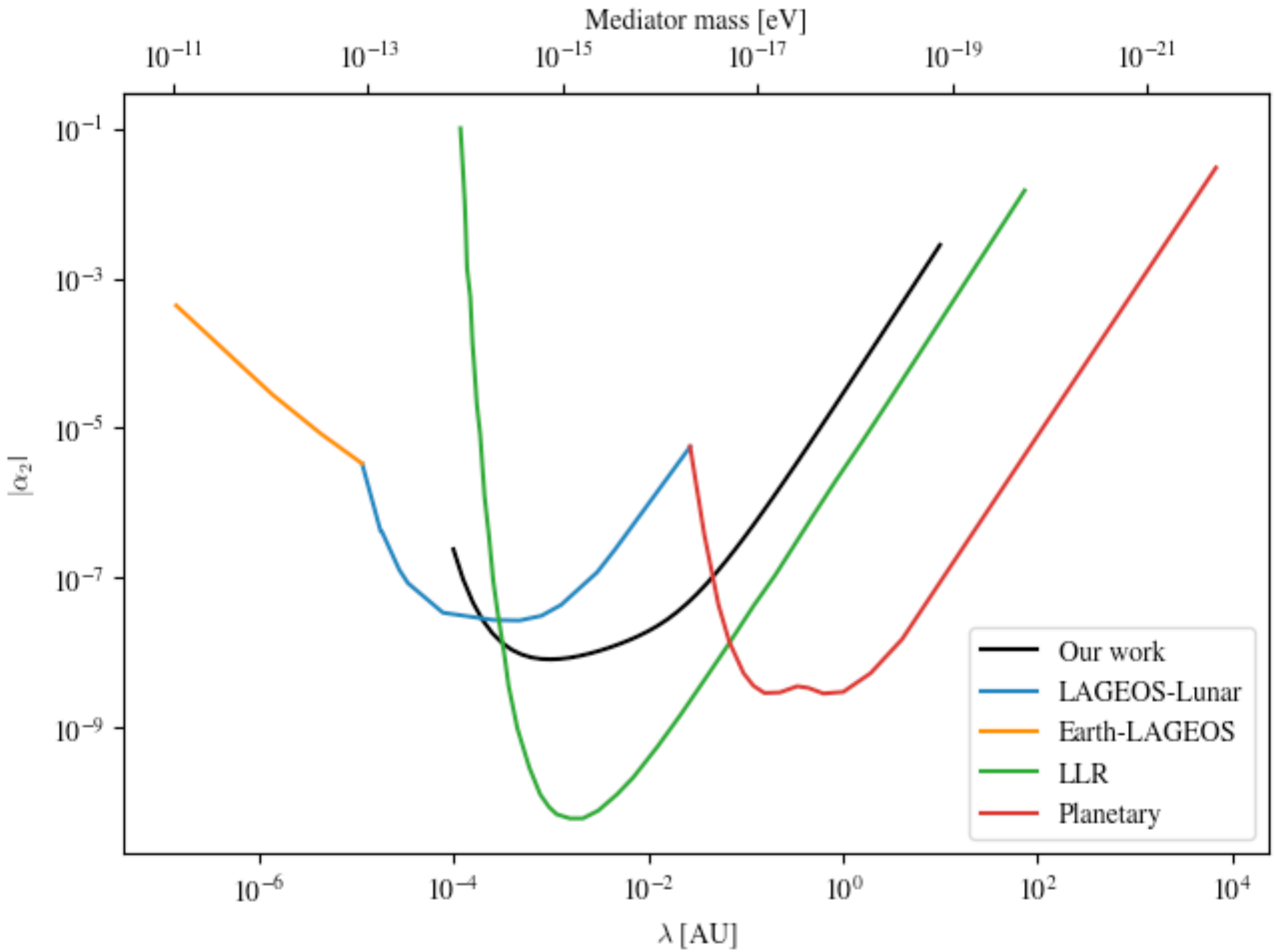
$$\dot{\omega} = -\dot{\Omega}\cos i + \sqrt{\frac{a\left(1-e^2\right)}{e^2\mu}}\left(-R\cos\nu + T\frac{(2+e\cos\nu)\sin\nu}{1+e\cos\nu}\right)$$

- Average change over an orbit:

$$\frac{d\omega}{d\nu} = \frac{\dot{\omega}}{h/r^2}$$

$$\Rightarrow \left.\frac{d\omega}{d\nu}\right|_{AV} = \frac{1}{2\pi}\int_0^{2\pi}\frac{d\omega}{d\nu}d\nu \qquad (7)$$

Constraints on Yukawa Parameters



Summary

- Fifth force arises due to new light, weakly-coupled degrees of freedom in BSM physics.
- They can be modeled in the form of Yukawa potential.
- Fifth force can be constrained via deviations from Newtonian orbits of various celestial objects.
- We constrain fifth-force via precession angle (ω) of JUNO's orbit around the Jupiter.
- Constraints obtained are shown to be most relevant in the force range region $\lambda \approx 10^{-4} - 10^{-2}$ AU

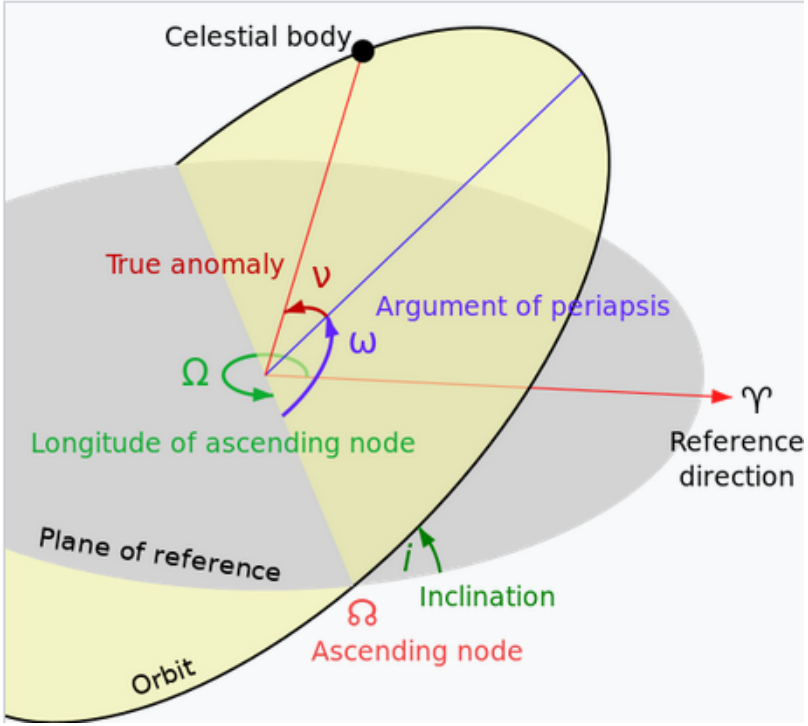
Curious to know more?

Stay tuned!

Supplementary Slides

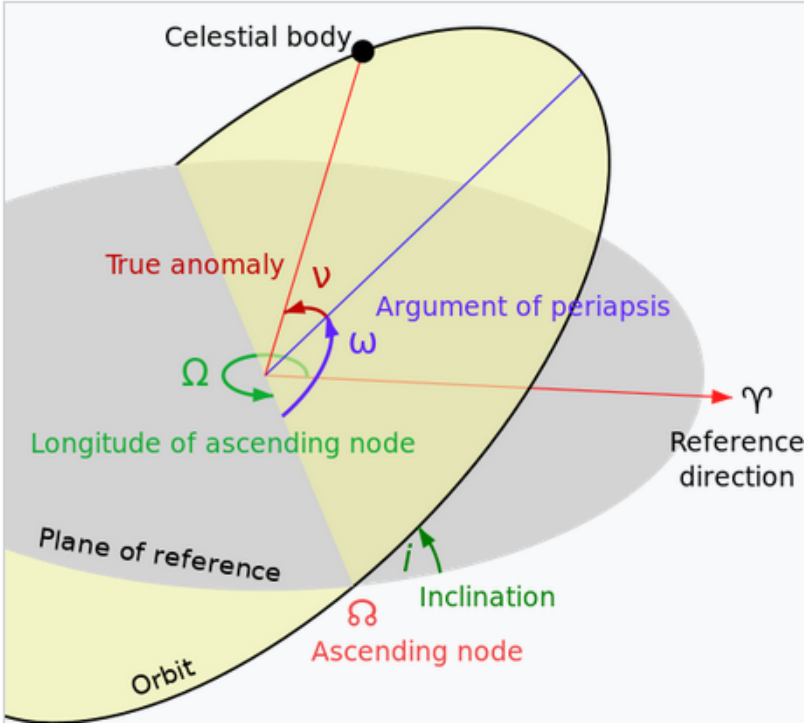
Orbital Parameters

- $a \rightarrow$ semi-major axis (half the distance between the apojove and perijove)
- $e \rightarrow$ eccentricity of the ellipse
- $\nu \rightarrow$ defines the position of the orbiting body along the ellipse at a specific time



Orbital Parameters

- $i \rightarrow$ vertical tilt (inclination) of the ellipse with respect to the reference plane, measured at the ascending node
- $\omega \rightarrow$ angle measured from the ascending node to the perijove of the orbit
- $\Omega \rightarrow$ Longitude of the ascending node



Orbital Parameter Perturbations

- Taking Newtonian orbit to be ellipse (unperturbed): $r = \frac{a(1-e^2)}{1+e\cos\nu}$
- Perturbation in orbital parameters:

$$\dot{a} = 2\sqrt{\frac{a^3}{\mu\,(1-e^2)}}[eR\sin\nu + T(1+e\cos\nu)]$$

$$\dot{e} = \sqrt{\frac{a\,(1-e^2)}{\mu}}\left[R\sin\nu + T\left(\cos\nu + \cos\left(\sqrt{\frac{1-e}{1+e}}\tan\frac{\nu}{2}\right)\right)\right]$$

$$\frac{d}{dt}i = \sqrt{\frac{a\,(1-e^2)}{\mu}}\frac{N\cos(\omega+\nu)}{1+e\cos\nu}$$

$$\dot{\Omega} = \sqrt{\frac{a\,(1-e^2)}{\mu}}\frac{N\sin(\omega+\nu)}{\sin i(1+e\cos\nu)}$$

$$\dot{\omega} = -\dot{\Omega}\cos i + \sqrt{\frac{a\,(1-e^2)}{e^2\mu}}\left(-R\cos\nu + T\frac{(2+e\cos\nu)\sin\nu}{1+e\cos\nu}\right)$$

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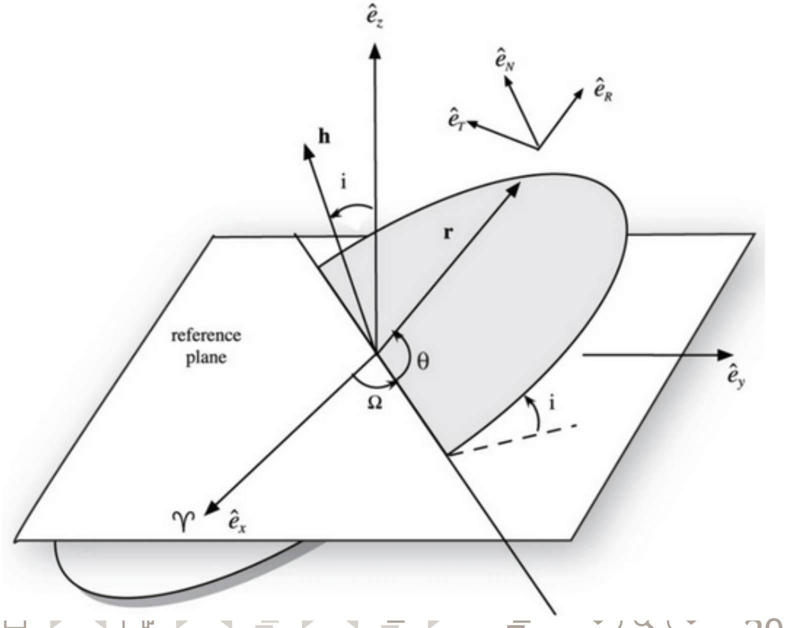

The Zonal Harmonics

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- For our work, we only focus on zonal harmonics:

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- Coordinates given by:
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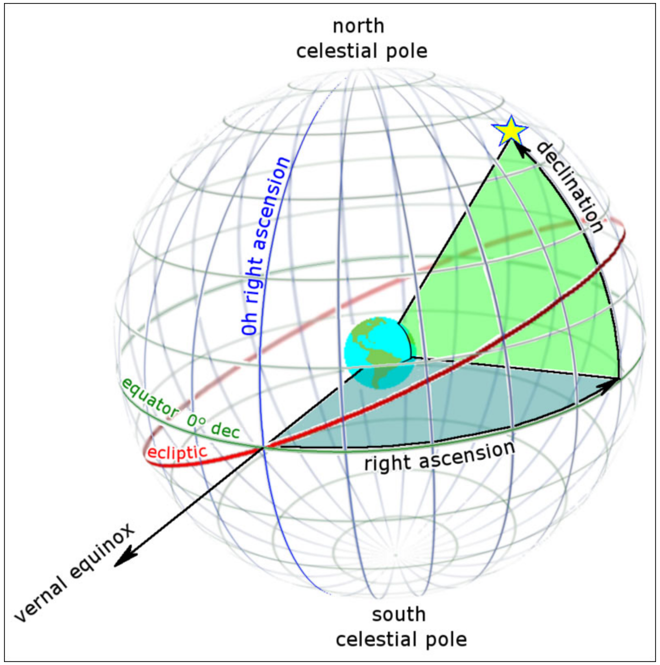


Precession due to J_n Perturbation

$$U_{J_n}(r,\phi) = \frac{GM}{r} J_n \left(\frac{R_J}{r}\right)^n P_n(\sin\phi) \tag{10}$$

- In Jupiter-centered inertial (JCI) frame: $\phi = \frac{z}{r}$
- Perturbation force due to J_n term:

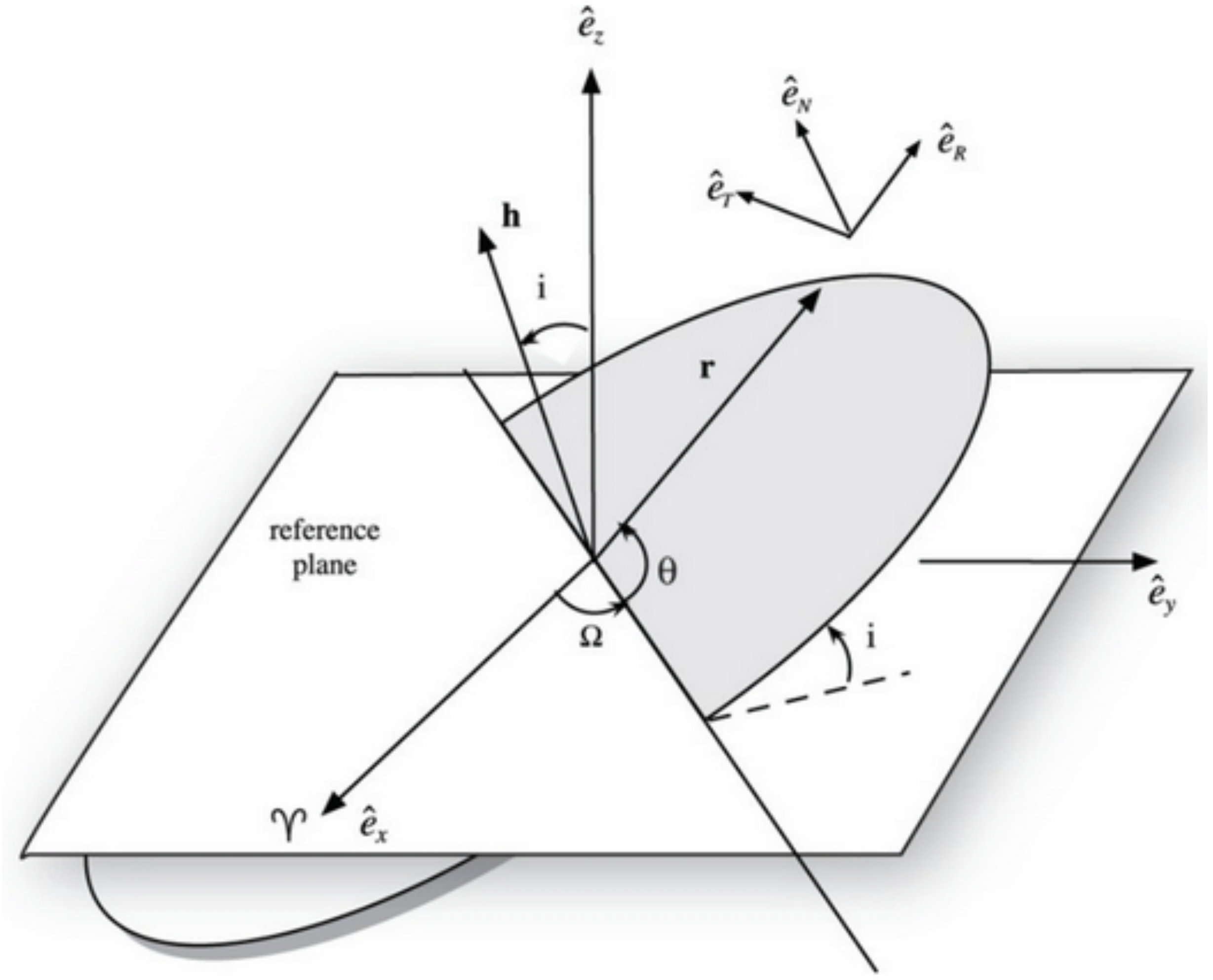
$$\vec{F} = -\frac{\partial U_{J_n}}{\partial r}\hat{e}_R + \frac{\partial U_{J_n}}{\partial z}\hat{e}_z \tag{11}$$

- For JCI $\longrightarrow$ RTN frame:

$$\begin{aligned} \hat{e}_z &= \sin i \sin(\omega+\nu)\hat{e}_R + \sin i \cos(\omega+\nu)\hat{e}_T + \cos i\,\hat{e}_N \\ z &= r\sin\phi = r\sin i \sin(\omega+\nu) \end{aligned} \tag{12}$$

- For brevity: $\theta = \omega + \nu$

JCI $\longrightarrow$ RTN Coordinates



Precession Angle

- Plugging Perturbation force in:

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- Average change over an orbit:

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$$\Rightarrow \left.\frac{d\omega}{d\nu}\right|_{AV} = \frac{1}{2\pi}\int_0^{2\pi}\frac{d\omega}{d\nu}d\nu \tag{13}$$

The Harmonics

- Spherical harmonic expansion of potential is given by:

$$U(\phi,\lambda,r) = \frac{GM}{r} + U_{\text{zonal}}(r,\phi) + U_{\text{sectorial}}(r,\phi,\lambda) + U_{\text{tesseral}}(r,\phi,\lambda) \tag{14}$$

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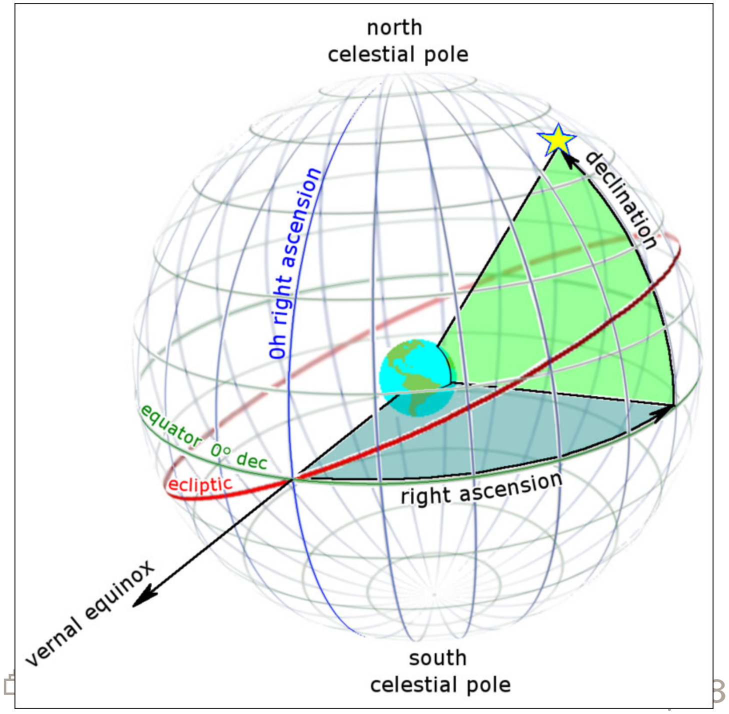
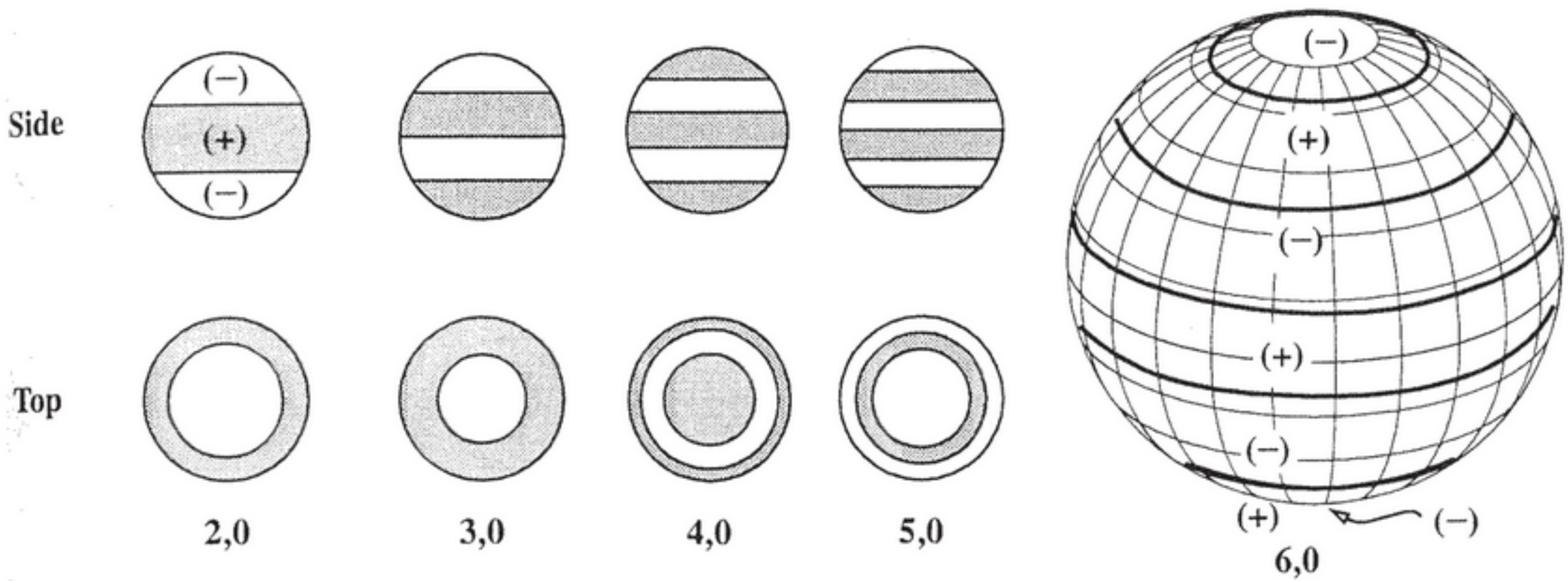


Zonal Harmonics

$$U_{\text{zonal}}\ (r,\phi) = \frac{GM}{r}\sum_{n=2}^{\infty} J_n \left(\frac{R_J}{r}\right)^n P_n(\sin\phi) \quad (15)$$

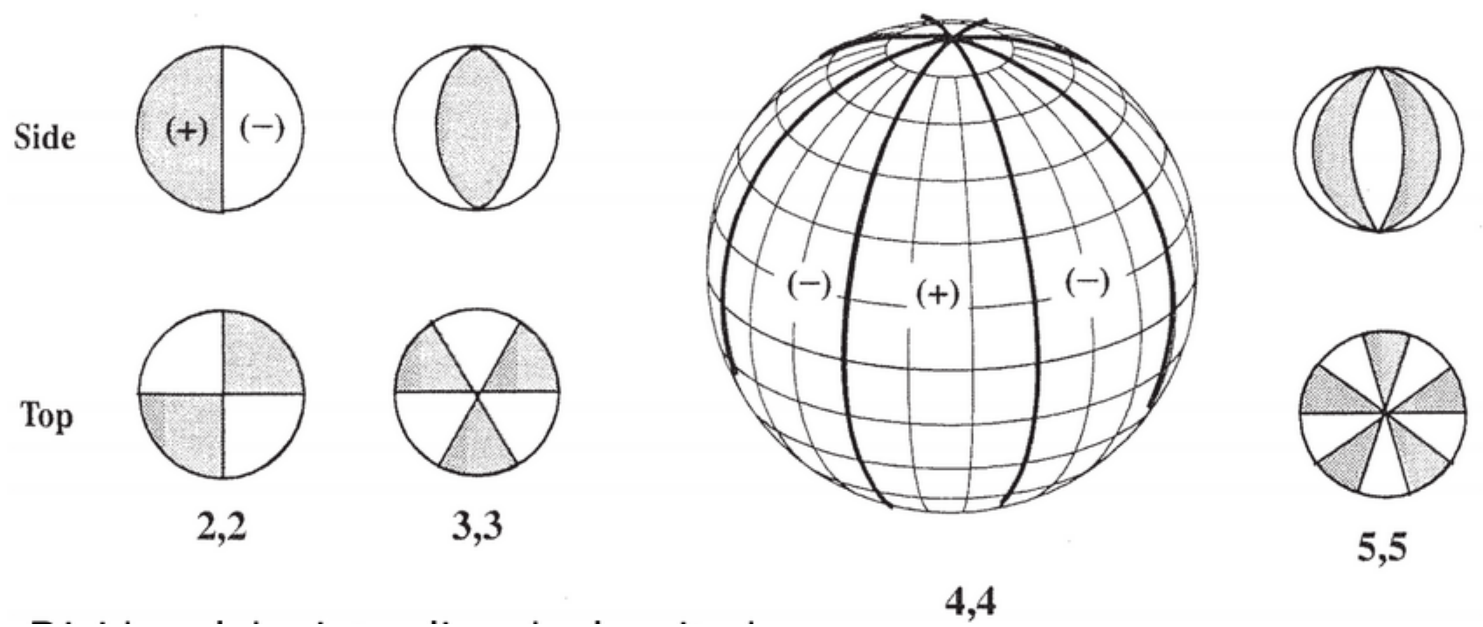
- $P_n \rightarrow$ Legendre Polynomial
- Zonal harmonics vary only with latitude.



The Sectorial Harmonics

$$U_{\text{sect}}\ (r,\phi,\lambda) = \frac{GM}{r}\sum_{n=2}^{\infty}\left(C_{n,\ \text{sect}}\ \cos(n\lambda) + S_{n,sect}\sin(n\lambda)\right)\left(\frac{R_J}{r}\right)^n P_n\left(\sin\phi\right) \tag{16}$$

- Divides globe into slices by longitude.
- Varies only with longitude.



The Tesseral Harmonics

$$U_{\text{tesseral}}\ (r,\phi,\lambda) = \frac{\mu}{r}\sum_{i,j=2}^{\infty}\left(C_{i,j}\cos(i\lambda) + S_{i,j}\sin(i\lambda)\right)\left(\frac{R_J}{r}\right)^i P_{i,j}\left(\sin\phi\right) \tag{17}$$

- Divides globe into slices by longitude and latitude.