JUPITER’S GRAVITY FIELD UPDATES FROM JUNO

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INTRODUCTION

• Juno has been orbiting Jupiter since July, 2016. It completed 26 perijove passes (from PJ01 to PJ26), 15 dedicated to Jupiter’s gravity field determination.

• The data collected during PJ01+PJ02 have been explained through the presence of a diluted core expanded to 0.3–0.5 times Jupiter’s radius, with a mass of 7–25 Earth masses.

• The analysis of the first two gravity-dedicated perijove passes (PJ03+PJ06) allowed us to further constrain Jupiter’s internal structure and surface winds’ behavior:
  
  o The surface winds, by penetrating deep into the planet, perturb the density profile and affect the gravity field. The north-south asymmetry of Jupiter’s gravity field constrains the depth of the flow ($H_1\sim2\text{–}3000\text{ km}$), while the symmetric components revealed that Jupiter’s deep interior is rotating as a rigid body.

• The current Juno’s dataset can be explained to large extent by a purely zonal field (axial-symmetry). However, small scale structures started to appear in the data!
RADIO SCIENCE EXPERIMENT

• The Juno gravity investigation exploits the Doppler shift of a microwave signal to precisely determine the Earth-Juno radial velocity and to estimate Jupiter’s gravity field coefficients.

• Juno is the first mission to exploit a Ka-band radio link for the determination of a planetary field.

• The gravity determination is obtained by fitting the two-way radial velocity of the spacecraft down to accuracies as low as 0.01 mm/s (at 60 s).
ASYMMETRY OF JUPITER’S GRAVITY

- Gravity disturbances:
- Latitudinal wind gradient:

\[(2\Omega \cdot \nabla)[\bar{\rho} u] = \nabla \rho' \times g_0\]

H ~ 2–3000 km

JUNO’S DYNAMICAL MODEL

• Juno’s dynamical model accounts for:
  o Gravity (solar system bodies and Galilean satellites) in a relativistic context
  o Jupiter’s gravity field (spherical harmonics expansion)
  o Tides raised on Jupiter from Galilean satellites
  o Lense-Thirring effect (with fixed Moment of Inertia, NMoI=0.26)
  o Solar radiation pressure on Juno’s large solar panels
  o Jupiter’s albedo and IR emission

• Multi-arc least square estimation filter solves for:
  o Spacecraft state (position and velocity) at the beginning of each pass
  o Empirical accelerations (at the level of $2 \times 10^{-8} \text{ m/s}^2$)
  o Jupiter’s zonal harmonics ($J_2$ to $J_{30}$) and degree 2 tesseral coefficients
  o Jupiter’s Love numbers up to degree 4
  o Spin axis inertial orientation (RA and Dec) and rate
GRAVITY ANOMALIES

- Juno’s sampling is very broad in longitude. Still, the recovered gravity anomalies is largely axially-symmetric, and correlates with Jupiter’s well-known banded structure.
- Uncertainties vary from 0.1 mGal (equatorial regions) to ~1 Gal (at the poles).

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JUPITER’S TIDAL MODEL

• We explored two different tidal models, and compared with static model predictions:
  o Standard tidal model (assumes the same $k_{nm}$ for all the satellites)
  o Satellite-dependent tidal model (each satellite, i.e., forcing frequency, has a different $k_{mn}$)
• Any deviation would be important to characterize the dynamical contribution to the tidal response.
• With the current data set, we still cannot separate the Love numbers (only $k_{nm}^{Io}$ are determined).

<table>
<thead>
<tr>
<th></th>
<th>Model value for Io</th>
<th>Observed value ± 3-σ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Standard</td>
</tr>
<tr>
<td>$k_{22}$</td>
<td>0.589</td>
<td>0.565 ± 0.018</td>
</tr>
<tr>
<td>$k_{31}$</td>
<td>0.19</td>
<td>0.25 ± 0.05</td>
</tr>
<tr>
<td>$k_{33}$</td>
<td>0.24</td>
<td>0.34 ± 0.12</td>
</tr>
<tr>
<td>$k_{42}$</td>
<td>1.74</td>
<td>1.29 ± 0.19</td>
</tr>
<tr>
<td>$k_{44}$</td>
<td>0.14</td>
<td>0.54 ± 0.41</td>
</tr>
</tbody>
</table>

• Currently, the deviations from the static model values are below the satellite-dependent model uncertainties.
JUPITER’S SPIN POLE

- The motion of Jupiter’s spin axis is reconstructed (green line with 3-σ uncertainties) and compared with IAU latest’s model, based on integration of satellites and Sun’s torques.
- The model (red line) is based on Galileo’s data back in the 2000’s.

D. Durante, et al. (2020). Jupiter’s gravity field halfway through the Juno mission, GRL 47, 4
The zonal coefficients are stable with the inclusion of new data.

- This work
- Less 2018

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When empirical accelerations are not included, the residuals show signatures up to 0.1 mm/s at a time scale of ~15 minutes.

The required empirical accelerations are of the order of $5 \times 10^{-8}$ m/s$^2$, with larger magnitude close to the perijove: indication of unmodelled gravity?

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STATUS OF GRAVITY ANALYSIS

• The root cause of these additional accelerations is actually unknown.
• All the instrumental effects we are aware of (Juno’s spin, station delays, solar panels bending, etc.) cannot solve the issue.
• It is likely that those signals are due to Jupiter’s gravity.
• Similar unexplained accelerations have been observed in Cassini’s Doppler data during the Grand Finale orbits (but with ~20 times larger amplitudes!).
• Possible explanations:
  o Normal modes (acoustic or gravity)
  o Large-scale atmospheric vortices
  o Deep-rooted gravity anomalies, possibly related to the magnetic field
A POSSIBLE EXPLANATION: JUPITER’S NORMAL MODES

- Normal modes are a possible explanation of Juno’s data.
- Ground-based SYMPA’s measurements of Jupiter are compatible with amplitudes $10^{-10} - 10^{-9}$.

- Discriminating dominating modes with Juno is difficult because several subsets of those can fit the data (large parameter space and limited observations in space and time).
- Data can be explained by normal modes having amplitudes larger than $2 \times 10^{-10}$.
- Slight preference for low-freq. modes: g- and f-modes have larger amplitudes when p-modes are not included.
- The p-modes’ solution (large number of modes) does not prefer any frequency.
A POSSIBLE EXPLANATION: LARGE SCALE ATMOSPHERIC DYNAMICS

- **Localized features** of Jupiter’s surface winds (i.e., vortices) can provide non-zonal gravity anomalies (signal different in each arc).

- Predictions can be made through thermal-wind balance and an exponential decay ($H_2$).

- The data can be fitted with a 6x6 static field, compatible with non-zonal winds of $H_2 \lesssim 500$ km.

![Wind speed](image1.png)

![Signal from Great Red Spot](image2.png)

*Model prediction for $H_2 = 500$ km*
CONCLUSION

• We provided a mid-term update on Jupiter’s gravity field. Our results are in good agreement with previous estimates and provide new clues about the gravity field of the gas giant planet.

• The gravity anomalies are largely symmetric about the rotation axis, and strongly north-south asymmetric after removing the effect of the uniform rotation.

• Smaller contributions from several, yet indiscernible, physical phenomena are possible. These include Jupiter’s normal modes, localized atmospheric dynamics, or deeply-rooted density anomalies, possibly related to Jupiter’s magnetic field.

• The empirical accelerations are $\sim 2 \times 10^{-8}$ m/s$^2$, or 0.1 mGal on the surface.

• Our improved determination of Jupiter’s tidal response (Love numbers up to degree 4) is compatible with static tidal model predictions.