

Geophysical Research Letters

RESEARCH LETTER

10.1029/2018GL078087

Special Section:

Cassini's Final Year: Science Highlights and Discoveries

Key Points:

- Cassini gravity measurements point to deep differential flows within Saturn
- Using a wide range of rigid body internal structure models, the required wind-induced gravity signal is defined
- With a conservatively modified cloud-level wind and an optimized vertical profile, extended to a depth of 8,800 km, all gravity measurements are explained

Supporting Information:

- Supporting Information S1

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Citation:

Galanti, E., Kaspi, Y., Miguel, Y., Guillot, T., Durante, D., Racioppa, P., & Less, L. (2019). Saturn's deep atmospheric flows revealed by the Cassini Grand Finale gravity measurements. *Geophysical Research Letters*, 46, 616–624. <https://doi.org/10.1029/2018GL078087>

Received 30 MAR 2018

Accepted 19 JUN 2018

Published online 30 JAN 2019

Saturn's Deep Atmospheric Flows Revealed by the Cassini Grand Finale Gravity Measurements

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Abstract How deep do Saturn's zonal winds penetrate below the cloud level has been a decades-long question, with important implications not only for the atmospheric dynamics but also for the interior density structure, composition, magnetic field, and core mass. The Cassini Grand Finale gravity experiment enables answering this question for the first time, with the premise that the planet's gravity harmonics are affected not only by the rigid body density structure but also by its flow field. Using a wide range of rigid body interior models and an adjoint based optimization for the flow field using thermal wind balance, we calculate the flow structure below the cloud level and its depth. We find that with a wind profile, largely consistent with the observed winds, when extended to a depth of around 8,800 km, all the gravity harmonics measured by Cassini are explained. This solution is in agreement with considerations of angular momentum conservation and is consistent with magnetohydrodynamics constraints.

Plain Language Summary Observations show strong east-west flows at the cloud level of Saturn. These winds are strongest at the equatorial regions, reaching up to 400 m/s, about 4 times stronger than tornado strength winds on Earth. Yet until now we had no knowledge on how deep these winds penetrate into the interior of the gas giant. The gravity experiment executed during the Grand Finale stage (May–August 2017) of the NASA Cassini mission helps answering this question. It is well established that any large-scale motion of the fluid would have a signature in the density distribution and therefore in the planet gravity field. If we can estimate the internal structure and shape of the planet, we might be able to decipher the depth of the winds from its signal in the gravity measurements. Moreover, the rigid-body and flow contribution to gravity field are entangled together, therefore it is necessary to use a wide range of rigid-body models in order to define the wind-induced gravity signal. In this work we propose a solution to the problem. We find that the gravity measurements can be explained with a flow pattern, similar to that observed at the cloud level, penetrating to depths of more than 8,000 km into the planet interior. This has important implications not only for the atmospheric dynamics but also for the interior density structure, composition, magnetic field, and core mass.

1. Introduction

Whether the fluid below Saturn's cloud levels is quiescent or exhibits strong zonal flows has been a long lasting open question. The zonal wind at the planet's cloud level is well established based on the Cassini measurements (Garcia-Melendo et al., 2011), with zonal flows that reach 400 m/s within a broad equatorial region, and a few narrower jets at higher latitudes (Figure 1a, white line). The flow is predominantly north-south hemispherically symmetric (Figure 1b, red line), with a much smaller asymmetric component that is more pronounced in the middle to high latitudes (Figure 1b, green line).

However, aside from some observed variations in the wind strength between the upper and middle troposphere, there has been very little knowledge on the nature of the flow below the cloud level. A possible answer was enabled by the gravity experiment conducted during the Grand Finale phase of NASA's Cassini spacecraft (Less et al., 2018). The measured gravity field (Figure 1c, red and green dots) was found to be considerably different from that predicted by typical internal rigid body (RB) models (gray dots), especially for gravity harmonics higher than J_6 . Initial estimates for the depth of the winds indicated very deep winds penetrating to a depth of more than 9,000 km (Less et al., 2018). This estimate, however, required a substantial modification of the

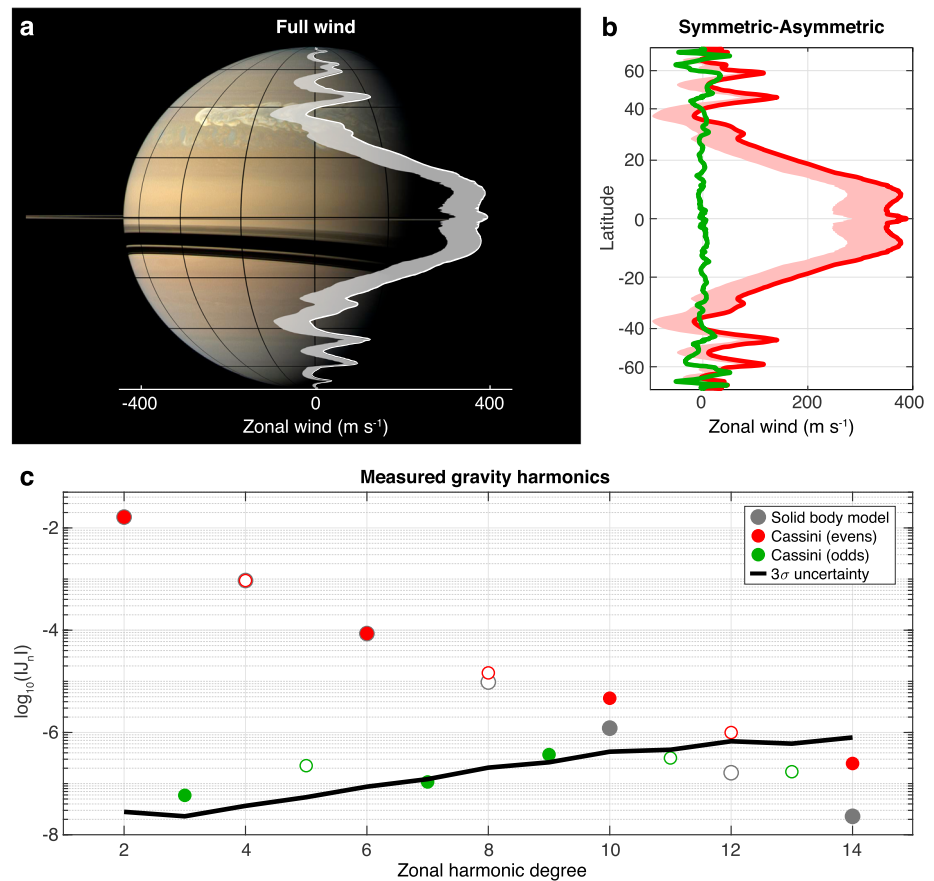


Figure 1. The Saturn's cloud-level winds (Garcia-Melendo et al., 2011, SB channels). (a) The full zonal wind as function of latitude, placed on top of a Cassini picture of Saturn (NASA/JPL-Caltech). Shown are the winds based on the Voyager rotation rate (white), and their change if the (Helled et al., 2015) rotation rate is used (gray area). (b) The hemispherically symmetric (red) and asymmetric (green) components of the wind. (c) The even and odd gravity harmonics measured by Cassini (red and green dots, respectively), and the gravity field predicted with a typical rigid body model (gray dots). Solid (empty) dots denote positive (negative) values. Also shown is the 3σ uncertainty associated with the measurements.

meridional profile of the cloud-level winds and was determined by matching only the even gravity harmonics J_8 , and J_{10} . In addition, the background density profile used in the calculation of the wind-induced (WI) gravity harmonics was based on a specific rigid-body model that might not represent all possible internal density structures.

It was recently found that for Jupiter, the part of the measured gravity field unaccounted for with RB models, and can be attributed to a downward extension of Jupiter's cloud-level winds to a depth of about $\sim 3,000$ km (Kaspi et al., 2018). This motivates consideration of whether a similar procedure works for Saturn. While the flow inside a gas giant is expected to be aligned parallel to the axis of rotation due to angular momentum constraints (see Kaspi et al., 2018, for a detailed discussion), it is not clear whether this flow is well represented in the observed cloud-level winds. The observations of Saturn's winds carry uncertainties that need to be taken into consideration (Garcia-Melendo et al., 2011). First, the sensitivity in the analyzed cloud-level winds reach ± 20 m/s at certain latitudes. Second, it was found that there exists a substantial wind shear between the wind at the upper (~ 250 mb) and middle (~ 500 mb) atmosphere, of up to ± 100 m/s at the equator and up to ± 20 m/s in the midlatitudes (Garcia-Melendo et al., 2011). A similar pattern was also found using thermal wind balance (Fletcher et al., 2008), suggesting that the variations represent changes with depth of the large-scale geostrophic flow. In addition, it was found that the flow exhibits variations in time of up to ± 50 m/s between the Voyager and Cassini observations. Therefore, it is possible that the flow structure in the depths relevant to the gravitational signal (thousands of kilometers deep) is somewhat different from that observed at the cloud level.

Another uncertainty in the determination of the cloud-level winds comes from the need to calculate it with respect to the planet's rotation rate, which is still not known with high certainty (Helled et al., 2015). The estimate of Garcia-Melendo et al. (2011; Figure 1a, white line) was done with respect to the Voyager rotation rate (Smith et al., 1982). More recent calculations (Anderson & Schubert, 2007; Helled et al., 2015; Read et al., 2009) show a faster rotation rate that shifts the winds to more negative values (Figure 1a, gray area). Note that only the symmetric part of the wind is affected by the value of the rotation rate (Figure 1b). This uncertainty was found to have an effect on the shape and density structure solutions of Saturn interior models (Helled & Guillot, 2013), and a substantial effect on the WI gravity harmonic ΔJ_2 , while having only minor effect on the higher WI even harmonics (Galanti & Kaspi, 2017).

In this study we aim to decipher the flow structure that best explains all the gravity harmonics measured by Cassini in the gravity-dedicated Grand Finale orbits. Unlike Jupiter, where large odd harmonics were measured, in the case of Saturn we need to rely on the even harmonics, requiring the calculation of the contribution of Saturn's RB to the gravity field. We thus use a wide range of RB models to map both the residual even gravity harmonics to be explained by the flow, and to determine the preferable background density profiles to be used in the calculation of the WI gravity harmonics. Using thermal wind balance, we find the top level zonal wind structure and its radial profile that best explain the measured gravity field. This methodology provides a rigorous and complete analysis of the gravity measurements.

The manuscript is organized as follows: in section 2 we explore the RB solutions for the gravity field. These solutions are then used to define the residual even gravity harmonics to be explained by the flow, which is analyzed using the WI solutions (section 3). Next, we include in the WI gravity calculation a search for a top level wind that allows the explanation of all measured gravity harmonics (section 4). We discuss the results and conclude in section 5.

2. The Rigid-Body Gravity Field

In order to explore the range of gravity solutions consistent with the measurements we first construct interior models of Saturn that fit the observational constraints of Saturn's radius and gravity harmonic J_2 , under the assumption that the interior of the planet rotates as a RB following the methodology of Guillot et al. (2018), which was effectively used for the analysis of Juno-based Jupiter gravity field. Since J_2 is also affected by differential rotation (Galanti & Kaspi, 2017), we allow the RB solution to deviate from the measured value within the range $J_2^{\text{RB}} = J_2^{\text{obs}} \pm 50 \times 10^{-6}$, to cover a wide range of differential rotation scenarios corresponding to different rotation rates and depths of the zonal flows (Galanti & Kaspi, 2017).

We assume a nonhomogeneous structure for Saturn (e.g., Fortney & Hubbard, 2003; Guillot, 1999; Nettelmann et al., 2015; Vazan et al., 2016) with a possible diluted core scenario, as proposed recently for Jupiter (Wahl et al., 2017). The radial structure consists of four layers: (1) an H_2 and He -poor atmosphere, (2) a metallic H and He -rich envelope, (3) a dilute core which is a metallic H and He -rich region with an increase in the heavy elements abundance, and (4) a core composed by ices or rocks. The diluted core (layer 3) is omitted in some of the models to allow exploration of both possibilities in Saturn's interior. We assume an adiabatic interior, neglecting the effects of a nonadiabatic region on the gravitational harmonics, which are significantly smaller than the uncertainties discussed in this paper (Nettelmann et al., 2015). The outer boundary condition is set to $T = 135 \pm 5$ K at 1 bar based on Voyager measurements (Lindal, 1992). The abundance of He in Saturn's atmosphere is assumed to be 0.18 ± 0.07 (Helled & Guillot, 2013), and the value in the deeper layer is adjusted so that the overall He abundance corresponds to the assumed protosolar He abundance of 0.270 ± 0.005 (Bahcall et al., 1995). The He phase transition is set to occur at a pressure between 1 and 4 Mbar, in agreement with immiscibility calculations (Morales et al., 2013).

A crucial parameter in the modeling of the internal structures of giant planets is the equation of state (Hubbard & Militzer, 2016; Miguel et al., 2016). For H and He we use REOS3 (Becker et al., 2014) as well as MH13 (Militzer & Hubbard, 2013) that were derived using ab initio calculations, with some adjustments as detailed in Miguel et al. (2016). The heavy elements, composed by rocks and ices, are modeled using the equations of state for a mixture of silicates *dry sand* for rocks and *water* for ices (Lyon & Johnson, 1992).

In order to consider all possible interior structure configurations, some of the parameters that are poorly constrained were chosen randomly within a broad range (see supporting information). The simulations were performed with either a slow 10 hr 39 min 22 s rotation rate (Smith et al., 1982) or a fast 10 hr 32 min 45 s rotation rate (Helled et al., 2015). In total, a little over 1,700 possible interior models for Saturn were calculated.

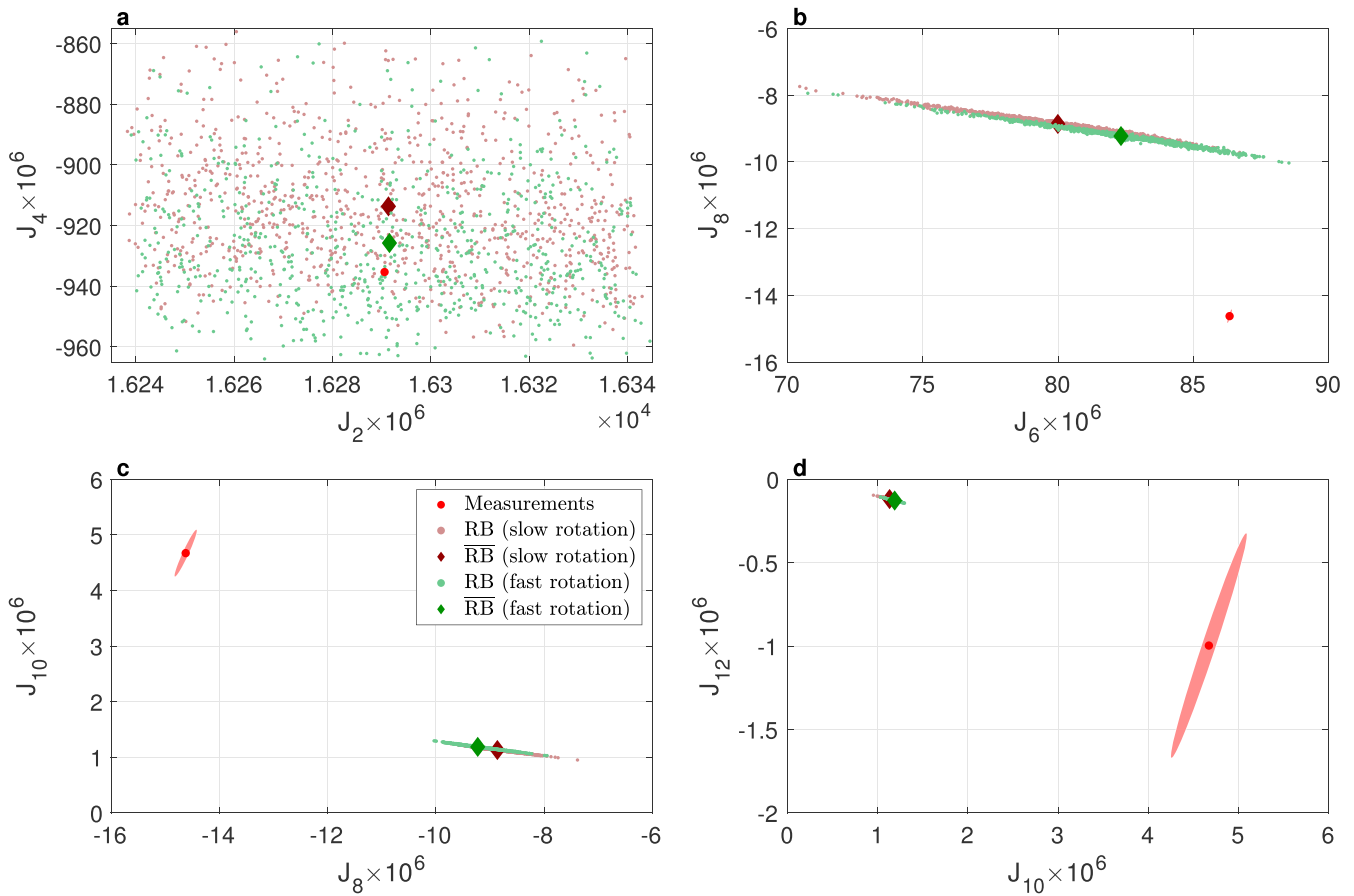


Figure 2. The even gravity harmonics calculated with the rigid body (RB) model based on the slow rotation rate, 10 hr 39 min 22 s, (blown dots) and the fast rotation rate, 10 hr 32 min 45 s, (green dots), and their mean (brown and green diamonds, respectively). Also shown are the Cassini measurements (red dots) and their 3σ uncertainties (red ovals).

The gravitational harmonics are calculated using the theory of figures fourth order (Nettelmann, 2017; Zharkov & Trubitsyn, 1978), combined with an integration of the recombined density structure in two dimensions using a Gauss-Legendre quadrature (Guillot et al., 2018). This numerically efficient method allows the execution of the large number of calculations required. It has a known systematic bias compared to more detailed calculations made with a Concentric Maclaurin Spheroids method (Hubbard, 2012, 2013); therefore, all gravity solutions presented here are corrected with $\delta J_2 = 33 \times 10^{-6}$, $\delta J_4 = -3.816 \times 10^{-6}$, $\delta J_6 = 0.069 \times 10^{-6}$, $\delta J_8 = 0.801 \times 10^{-6}$, $\delta J_{10} = -0.213 \times 10^{-6}$, and $\delta J_{12} = 0.0045 \times 10^{-6}$, calculated similarly to Guillot et al. (2018).

The range of RB solutions for the even gravity harmonics are shown in Figure 2 for the slower rotation rate (brown dots) and the faster rotation rate (green dots), together with the measurements (red dots and ovals). Out of the six parameters allowed to vary (see supporting information), the *He* transition pressure has the largest effect on the solutions—larger transition pressure results in larger absolute values of J_n for $n > 2$. Note that the parameters varied in the 1,700 RB models affect mostly the deep interior structure of Saturn, hence J_2 and J_4 , and have a weaker effect on the atmosphere of Saturn, reflected in the higher even harmonics. As a result, the solution dispersion is large for J_2 and J_4 , and gets smaller for higher harmonics. Note also that the fast rotation rate moves the solutions substantially toward the measurements, with larger absolute values in all harmonics. Most importantly, it is evident that while J_2 and J_4 can be explained entirely by the RB models (the measurements are well within the model uncertainties), the solutions for the higher harmonics, while closer to the measurements and having a much larger spread than the model used in less et al. (2018), cannot explain the measured values. The mean distance between the model solutions (brown and green diamonds) and the measured values (red dots) must to be the result of WI density anomalies.

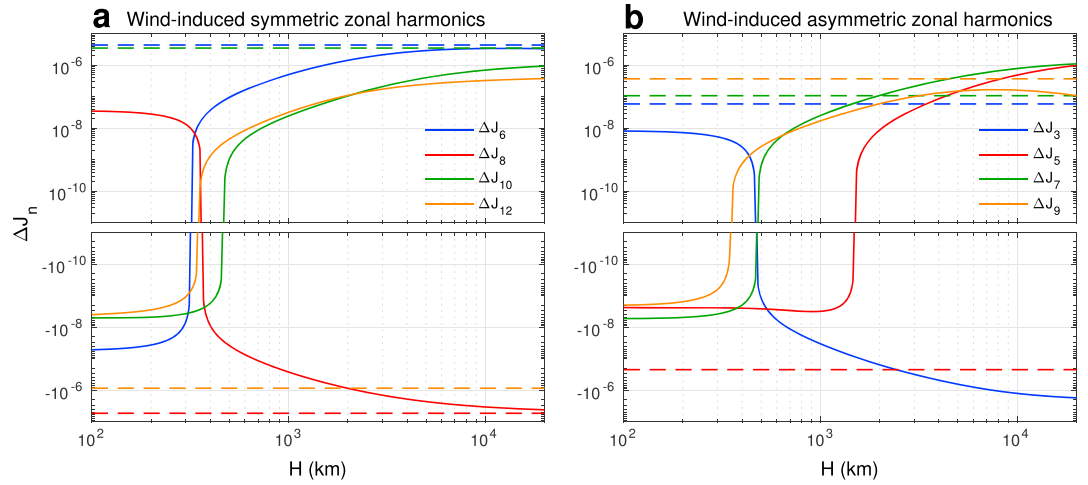


Figure 3. The wind-induced gravity harmonics as predicted by the thermal wind solution with an exponential decay vertical profile, as function of the e-folding depth H . (a) The even harmonics J_6, J_8, J_{10} , and J_{12} . (b) The odd harmonics J_3, J_5, J_7 , and J_9 . Also shown are the measured harmonics (dashed lines) of the even harmonics calculated from Figure 2, and the odds harmonics taken directly from the measurements.

3. The Wind-Induced Gravity Field

Given that Saturn is a large planet and a fast rotator, any large-scale flow is governed by thermal wind balance, relating the flow to the density field (Kaspi et al., 2009; Pedlosky, 1987). Assuming the flow is zonally symmetric and assuming sphericity (Galanti, Kaspi, & Tziperman, 2017), the dynamical balance is between the flow gradient in the direction parallel to the axis of rotation and the meridional gradient of density perturbations

$$2\Omega r \frac{\partial}{\partial z} (\rho_0 u) = g_0 \frac{\partial \rho'}{\partial \theta}, \quad (1)$$

where Ω is the planet's rotation rate, $\rho_0(r)$ and $g_0(r)$ are the RB density and gravity fields, $u(r, \theta)$ is the flow field, $\rho'(r, \theta)$ is the anomalous density field, and r, θ , and z are the radial, latitudinal, and axis of rotation directions (see supporting information for a detailed derivation). This balance was used extensively to study the wind structure on Jupiter (e.g., Galanti, Kaspi, & Tziperman, 2017; Kaspi, 2013; Kaspi et al., 2010, 2016; Liu et al., 2013; Zhang et al., 2015), as well as for the prediction of the WI gravity field to be expected on Saturn (Galanti & Kaspi, 2017; Kaspi, 2013). The WI gravity harmonics are calculated as the volume integral of ρ' projected onto Legendre polynomials

$$\Delta J_n = -\frac{2\pi}{MR_e^n} \int_0^{R_e} r^{n+2} dr \int_{\theta=-\pi/2}^{\pi/2} P_n(\sin \theta) \rho'(r, \theta) \cos \theta d\theta, \quad (2)$$

where M is the planetary mass, R_e is the planet equatorial radius, and P_n is the Legendre polynomials. For a detailed discussion of the method refer to Kaspi et al. (2018).

Following the same methodology used in Kaspi et al. (2018), we first assume that the wind decays exponentially with a decay depth H (see supporting information) and calculate the resulting gravity harmonics ΔJ_n as function of H (Figure 3, solid lines). Given the mean values of the even harmonics of the RB model (Figure 2, green diamonds), we can now plot the measured ΔJ_n (Figure 3a, dashed lines) in addition to the measured odd harmonics Figure 3b, dashed lines), which are not affected by the RB solutions. Based on the observed cloud-level winds, this model is able to partially explain the even harmonics J_6, J_8 , and J_{10} , for which it asymptotically reaches the measured values of J_6 and J_8 , and about one third the value of J_{10} , but cannot explain the odd harmonics. The WI solutions are found to be affected by the background density ρ_0 taken from the RB solutions—profiles with the highest densities in the outer layers ($r > 0.7R_s$) increase the value of the gravity harmonics by up to 50%, compared to RB profiles with the lowest values.

We can then expend our search with a more complex decay function (see supporting information), looking for the optimal radial structure of the wind that gives the best fit to the measured gravity harmonics. The optimal solution is found with $H_0 = 11,547 \pm 875$ km, $\Delta H = 1100 \pm 308$ km, and $\alpha = 0.89 \pm 0.11$, where H_0 is

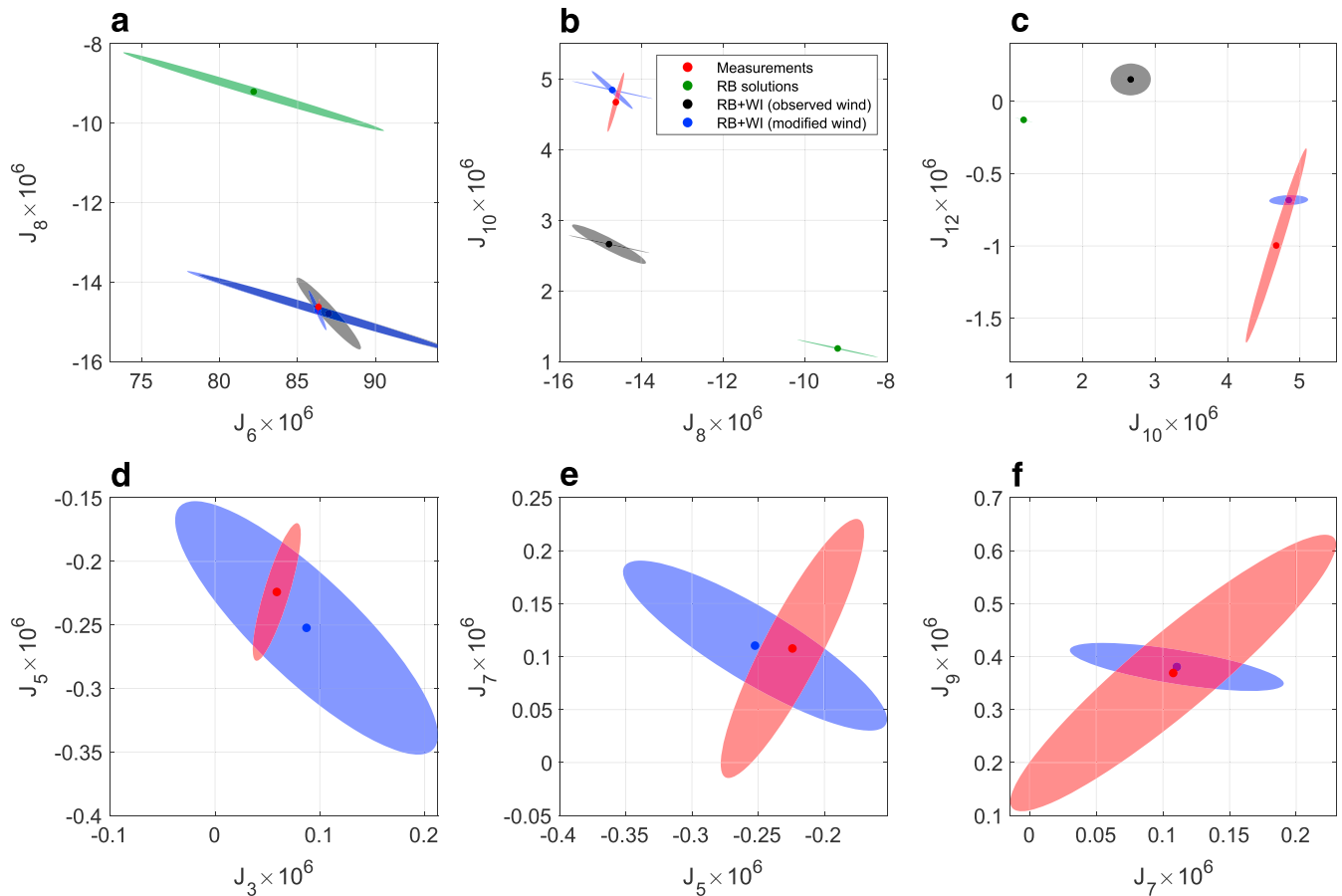


Figure 4. The gravity harmonics calculated using the rigid body (RB) model only (green), RB combined with the wind-induced (WI) based on observed winds (gray), and RB combined with WI based on optimal winds (blue). Also shown are the measured values (red). (a–c) The even harmonics J_6 , J_8 , J_{10} , and J_{12} . (d–f) The odd harmonics J_3 , J_5 , J_7 , and J_9 , which have no RB solutions. The uncertainties of the RB solutions are calculated from the range presented in Figure 2. For the WI solutions we show both the uncertainties resulting from the RB solutions and those associated with the WI solutions.

the depth of a hyperbolic tangent and exponential radial profiles, ΔH is its width, and α is the ratio between the two functions (see supporting information equation 8 for details of this vertical decay profile). The resulting gravity harmonics for J_6 , J_8 and J_{10} are shown in Figures 4a–4c as (black dots) along with the uncertainties associated with them (gray ovals). Also shown are the uncertainties associated with the RB solutions (additional gray ovals). As predicted with the simple model (Figure 3), the optimal J_6 , J_8 , and J_{10} are able to move the RB solution (green dots and ovals) in the direction of the measurements (red dots and ovals), with J_6 and J_8 explained within the uncertainties associated with the model, and J_{10} being pushed half the way to the measurements. The odd harmonics remain inconsistent with the measurements and are outside the range presented in the figure. This implies that the observed cloud-level wind profile might not represent accurately the flow affecting the gravity field.

4. The Wind Below the Cloud Level

The limited ability to explain all the measured ΔJ_n when using the observed cloud-level wind suggests that the WI gravity signal might be a result of a flow field that is somewhat different from that observed at the cloud level. As discussed in section 1 this possibility has support in the observations, in which uncertainties in the analysis as well as variations in both time and depth are observed (Garcia-Melendo et al., 2011, Figures 3 and 9). This implies that the search for a flow field that explains the measured gravity field requires an augmented

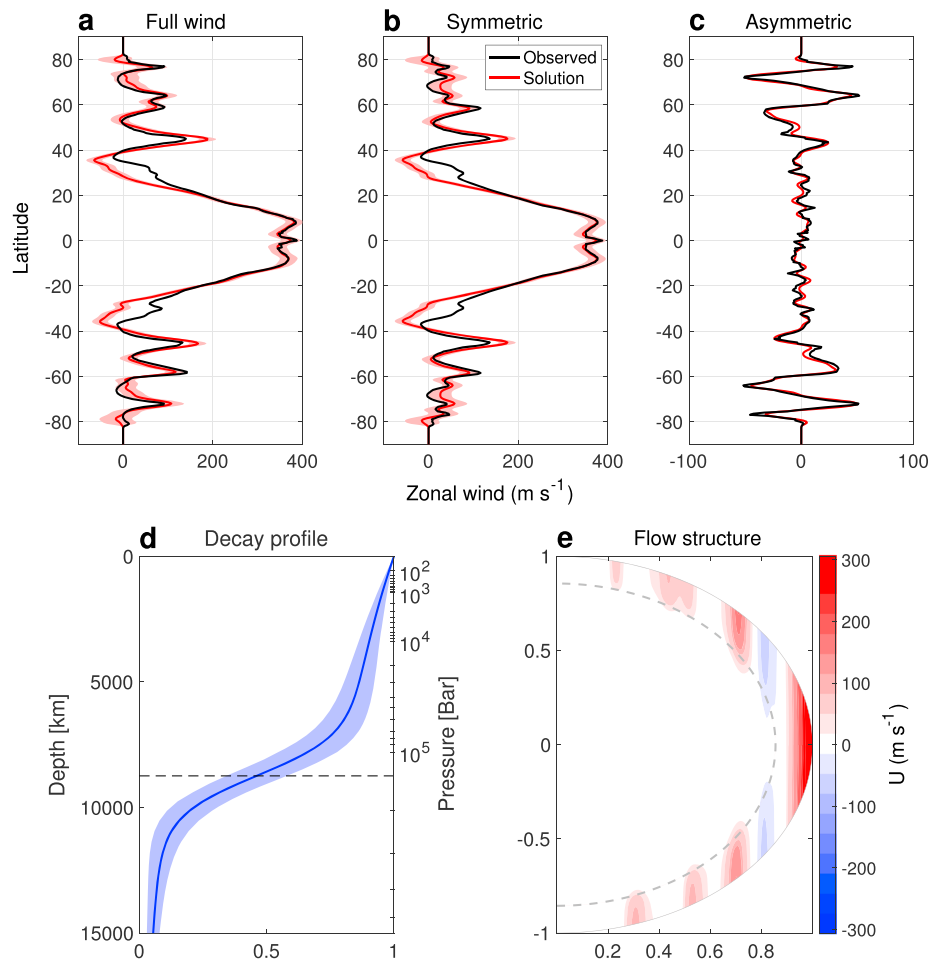


Figure 5. The model solution with modified cloud-level wind. (a) The observed cloud-level winds (black) and the optimized wind profile (red lines), together with the uncertainty (red shading) associated with the model solution (blue shadings in Figure 4). (b) The symmetric part of the winds, and (c) the asymmetric part of the winds. (d) The optimized radial decay of the winds as function of depth and pressure, with its uncertainty in blue shading. (e) The flow structure resulting from the model solution for the cloud-level wind (red line in panel a), projected inward in the direction of the spin axis and decaying radially according to the profile in panel d. The dashed line in both (d) and (e) denotes the depth of 8,743 km.

optimization, one that would also allow the cloud-level wind itself to vary in addition to its radial decay profile. This can be achieved by decomposing the meridional wind profile into the first N Legendre polynomials

$$U^{\text{sol}}(\theta) = \sum_{i=0}^N A_i^{\text{sol}} P_i(\sin \theta), \quad (3)$$

where A_i^{sol} is the coefficients defining the meridional wind profile solution. The optimization procedure for calculating A_i^{sol} is constructed to ensure that the deviation of the meridional wind profile solution from the observed cloud-level wind is not larger than what is necessary to bring the gravity field solution within the uncertainty range of the measured field (see supporting information).

The optimal solution for the radial structure of the flow is found with $H_0 = 8,743 \pm 102$ km, $\Delta H = 1577 \pm 1435$ km, and $\alpha = 070 \pm 0.129$. The wind solution is shown in Figures 5a–5c (red lines), together with its uncertainty (red shading). Also shown is the observed cloud-level wind (black lines). In most latitudes the wind solution is very similar to the observed cloud-level wind and is well within the expected uncertainties discussed in section 1). The largest deviations are around latitudes 25–35° north and south, similar in location to the findings of less et al. (2018), but about half the size. The wind decay profile and the resulting flow structure (Figures 5d and 5e) reveal that the wind behaves nearly barotropically in the equatorial region (extending

all the way to the equatorial plain in the direction of the spin axis) but baroclinically outside latitudes 20°N and 20°S, that is, decaying before reaching the equatorial plain.

With the modified wind the WI model is able to fit all gravity harmonics taken into consideration (Figure 4, blue dots and ovals), for both the even and the odd harmonics. Importantly, the goal here is to have an overlap between the uncertainty of all the model gravity harmonics solutions (blue ovals) and the measurement uncertainties (red ovals). It would have been easy to get the model solutions (blue dots) to fit exactly the measurements (red dots), simply by relaxing the regularization of the winds ϵ_U (see supporting information) but with the cost of the wind solution getting farther away from the observations. By aiming for an overlap of the uncertainty ovals only, a balance is reached between the need for a viable solution and the need to keep the optimized winds as close as possible to the cloud-level observations.

5. Discussion and Conclusion

The Cassini gravity measurements provide a unique opportunity to decipher the nature of the flow on Saturn. The initial analysis of less et al. (2018) pointed to the existence of deep flows in the equatorial region, yet these results were limited to a specific RB model, and as a result, required the surface wind to be substantially different from the observed cloud-level winds.

In this study we investigate the gravity field of Saturn, using a wide range of RB gravity models and a WI gravity model in which the top-level wind is allowed to differ from the observed cloud-level wind. The RB solutions, while having a much broader range of solutions than those used in less et al. (2018), are still distinctively different from the measurement for all even harmonics higher than J_4 , therefore implying the existence of strong differential flows underneath the cloud level. They also exhibit a considerable variance in the radial density structure, with higher densities in the outer layers associated with up to 50% higher values of J_6 , J_8 , and J_{10} , compared with the values obtained with the lower background density. These cases, explaining better the measurements, are mostly associated with a deeper He transition depth ($P \approx 4$ Mbar). Interestingly, these cases also allow the WI gravity signal to match the measurements with less modification of the cloud-level wind, since both the RB and the WI solutions have higher values of J_6 , J_8 , J_{10} , and J_{12} , thus pushing their sum farther toward the measurements.

With a conservatively modified cloud-level wind, extended to a depth of around 8,800 km, all the relevant gravity harmonics can be explained, taking into account the associated uncertainties in both the measurements and the model solutions. In most latitudes the optimal top level wind is similar to the observed wind, with the largest deviations found around latitudes 25–35° north and south, similar to the deviation found by less et al. (2018) but twice as small. This is a result of the different SB background density and gravity harmonics solutions used here, as discussed above. In order to explain the measured odd harmonics, the modifications needed in the asymmetric flow are minor and are well within the uncertainty in the cloud-level wind observations.

The optimal flow depth of 8,800 km is consistent with estimates of the depth in which the conductivity of the fluid prohibit strong flows (Cao & Stevenson, 2017; Liu et al., 2008). Interestingly, this depth, taken at the equator, is approximately the location where the cylindrical flow outcropping at 25–35° is, and where the flow is found to be most different from that observed at the cloud level. Investigating this circumstantial result might require the analysis of a dynamical model in which magnetohydrodynamical considerations are included (Galanti, Cao, & Kaspi, 2017).

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Acknowledgments

E. G. and Y. K. acknowledge support from the Israeli Space Agency and from the Helen Kimmel Center for Planetary Science at the Weizmann Institute of Science. D. D., P. R., and L. I. were supported by the Italian Space Agency. TG acknowledges support from the Centre National de la Recherche Spatiale. The data plotted in the figures are available at <https://www.dropbox.com/sh/enef9c2z1lb5X1s/AABYea2T9Cx-oqtLYOfuvCjsa?dl=0>.

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