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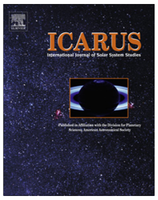

Probing the depth of Jupiter's Great Red Spot with the Juno gravity experiment

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ABSTRACT

Jupiter's Great Red Spot (GRS) is the most dominant and long-lived feature in Jupiter's atmosphere. However, whether this is a shallow atmospheric feature or a deeply rooted vortex has remained an open question. In this study, we assess the possibility of inferring the depth of the GRS by the upcoming *Juno* gravity experiment. This is achieved by an exploration of the possible gravitational signature of the vortex by systematically extending the surface winds into the interior and analyzing the resulting gravity signal. The gravity anomaly is then compared to the expected accuracy in the retrieval of the surface gravity at the GRS location obtained with numerical simulations of the Doppler data inversion based on the expected trajectory of the spacecraft. Starting from observations of the atmospheric velocity at the cloud level, we project the wind using a decay scale height along coaxial cylinders parallel to the spin axis and explore a wide range of decay scale heights in the radial direction. Assuming the large scale vortex dynamics are geostrophic, and therefore thermal wind balance holds, the density anomaly distribution due to Jupiter's winds can be derived from the velocity maps. The novelty of this approach is in the integration of thermal wind relations over a three-dimensional grid, and in the inclusion of the observed meridional velocity as measured during the Cassini flyby of Jupiter. The perturbations in the mean zonal flow give rise to non zero tesseral spherical harmonics in Jupiter's gravitational potential. We provide an estimate of this asymmetric gravity coefficients for different values of the wind decay scale height. We conclude that the mass anomaly associated with the GRS is detectable by the *Juno* gravity experiment if the vortex is deep, characterized by a vertical height larger than 2,000 km below the cloud level of Jupiter, and that the large mass involved with deep winds does not render much the ability to measure the feature.

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1. Introduction

The Great Red Spot is a perpetual anticyclone that has become an icon of Jupiter's atmosphere ever since it was first observed in 1665 by Gian Domenico Cassini. For this reason, the study of this perpetual vortex remains a crucial driver and scientific objective for future space missions to the giant planet. In this regard, *Juno* has the earliest possibility of observing the spot and answering some fundamental questions about its interior structure. Telescopic and spacecraft observations in the last decades not only suggest that the anticyclone evolution moves towards a more circular shape, but also show that it is shrinking. Asay-Davis et al. (2009) show that, between 1996 and 2006, the surface extension of the vortex has diminished by 15%, while its peak velocity remained constant. More recently, analysis of 2014 Hubble spectral imaging data has highlighted that the GRS size has reached its historical minimum (Simon et al., 2014). It is not known whether this condition is due to the damping of the vortex intensity or to periodic oscillations. In any case, the fortunate timing underlines the necessity for the *Juno* mission to collect as much data as possible.

Choi et al. (2007) have measured the surface velocity vectors of the GRS using an automated cloud tracking algorithm applied to *Galileo* images. They report measurements of the high velocity collar of the vortex, with peak velocities of 170 $\mathrm{m\,s^{-1}}$. Although observations of Jupiter's winds at the cloud-level are largely available, the penetration of the flow motion at depth, including the GRS, is unknown and object of a long-lasting controversy. The argument, extensively reviewed by Vasavada and Showman (2005), can be summarized as whether the jets are shallow and therefore involve only the upper layers of the atmosphere, or extend deeply into Jupiter's interior, organizing in differentially rotating coaxial deep-rotating cylinders (Busse, 1976; Ingersoll

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and Pollard, 1982). The only existent *in situ* measurements of the deep wind dynamics come from the *Galileo Entry Probe* which penetrated the jovian atmosphere at 6.5°N latitude (Young, 1998). The probe reached pressure levels down to 22 bar, detecting strong eastward zonal winds characterized by velocities of up to 160 $\mathrm{ms^{-1}}$. Yet, these data only reach down to about 0.2% of Jupiter's mean radius, excluding information about the underlying layers. Furthermore, the vertical structure of the vortex might be decoupled from that of the jets, reaching deeper or shallower layers of Jupiter's atmosphere than the surroundings.

Using *Voyager* imaging observations, Dowling and Ingersoll (1988) calculate the absolute vertical vorticity on Jupiter's GRS by looking at the horizontal velocity field. Using conservation of shallow-layer potential vorticity, they conclude that, since the ratio of relative vorticity to local thickness must be conserved, there must be deeper circulation beneath the GRS, although still constrained to very surficial layers. In the same study, the authors argue for the shallow vertical extension of the vortex by pointing out that in the proximity of the GRS, the absolute vorticity, and thus the thickness density, varies by a factor of two along closed streamlines. Dowling and Ingersoll (1989) use a two-layer model in which a deeper, zonally symmetric steady atmosphere is overlaid by a thin weather-layer, and show that it is possible to produce long-lasting vortices, such as the GRS. Morales-Juberias and Dowling (2013) show that coherent stable GRS-like features, with an appearance very similar to the observed GRS, appear in a 3D atmospheric general circulation model (GCM), which extends only down to 10 bars. These models all assume that instabilities generating vortices are confined to the upper layers of the gaseous planet. However, as shallow geostrophic turbulence is characterized by an inverse cascade to large-scale coherent structures (Rhines, 1979), the existence of such vortices in these models does not rule out the possibility that in reality the GRS is deeply rooted.

It is therefore possible that the GRS extent is tied to the surrounding zonal flows which might be very deep. One argument for this is that if the GRS was indeed a shallow feature, the vortex would have a much shorter life span since it would be sheared by the strongly turbulent atmospheric flows surrounding it (like storms on Earth). Yano and Flierl (1994) show in a parameterized deep QG model that in order to remain stable over long time scales the GRS must be deep, and therefore argue for a strong coupling between the GRS and the deep convective dynamics of the interior. Liu and Schneider (2010) generate long-lived coherent vortices in an idealized shallow GCM, and suggest that the life span of a vortex increases with the radiative time scale which, in turn, increases with pressure, whence with vertical extent. Therefore a scenario in which the phenomenon is deep-rooted is also plausible. In addition, it should be noted that shallow forcing can result in deep jets and vortices (Showman et al., 2006; Lian and Showman, 2008), and similarly deep forcing can result in shallow features (Kaspi et al., 2009), so the question of what is forcing the GRS may be decoupled from whether the GRS is deep or shallow. The *Juno* gravity experiment might hold the key to learning more about the depth of the GRS.

In this study we assess the possibility of detecting the gravitational signature of Jupiter's main cyclone by exploiting very precise measurements of the planet's gravitational potential (Finocchiaro and Iess, 2010; Finocchiaro, 2013), that can be linked to the amount of mass involved in the vortex and, by extension, to its depth. Furthermore, compared to previous studies looking at the gravity signature of dynamics on Jupiter (Kaspi et al., 2010; Kaspi, 2013; Liu et al., 2013; Kong et al., 2013), here we consider full three-dimensional maps of Jupiter's wind velocity without limiting the analysis to zonally axisymmetric profiles.

In Section 2 we report on the process of building three-dimensional maps of Jupiter's winds. We start from longitudinal mosaics of the planet's velocity vector retrieved by Choi and Showman (2011) by processing *Cassini* imaging data, and proceed by propagating the surface profile in the direction parallel to Jupiter's rotation axis (Busse, 1976; Hubbard, 1999). Since this propagation depth is unknown, we introduce a free parameter which is the e-folding decay scale height of the winds H, which then allows to cover a wide range of cases ranging from deep barotropic winds to winds that rapidly decay with radius (Kaspi et al., 2010, 2013). We continue in Section 3 by introducing the thermal wind balance as applied for a deep atmosphere (Kaspi, 2008; Kaspi et al., 2009), considering here the balance both in the zonal and meridional directions. Starting from the fundamental equations we obtain the expression for planetary density anomalies generated by zonal and meridional wind motions, assuming that a reference hydrostatic state is known.

In Section 4 we present numerical results for the density perturbations and contributions to the gravitational potential of the planet, and analyze the effects of varying the decay scale height on the redistribution of Jupiter's mass due to fluid dynamics. In Section 5 we investigate the gravity signature for cases where the vertical scales for the vortices and the background zonal velocity field are different. In Section 6 we discuss the possibility of detecting the gravitational signature of the GRS given the capabilities of the *Juno* gravity experiment, considering a varying scale height for the wind penetration. We compare the magnitude of the anomalies generated with our model of Jupiter's atmospheric dynamics to the expected uncertainties on the retrieved surface gravity resulting from numerical simulations of the experiment (Finocchiaro and Iess, 2010; Finocchiaro, 2013).

2. Jupiter's wind velocity

Multi-spectral observations of Jupiter's atmosphere during the *Cassini* Jupiter flyby in December 2000 have provided a large amount of atmospheric data that have been analyzed by Choi and Showman (2011) in terms of cloud patterns and kinetic energy. The data set contains observation sequences acquired by the Imaging Science Subsystem (ISS). In their work, the authors provide full longitudinal maps of Jupiter's surface wind vectors by using an automated cloud feature tracker (Choi et al., 2007). The results of the cloud tracking process are shown in Fig. 1 in terms of cloud-level wind velocity. The 2D maps are generated using the CB2 filter observations, which are sensitive to pressure levels down to 1.1 bar and are referenced to Jupiter System III (Choi and Showman, 2011). The zonal (azimuthal) component of the wind velocity (Fig. 1a) shows a mostly axisymmetric structure, positive and negative values indicate eastward and westward wind, respectively. As a result the flow organizes in wide rotating bands parallel to the equatorial plane, with peaks of nearly 150 $\mathrm{ms^{-1}}$. The equatorial region, comprised between 15°S and 15°N latitude, is superrotating and contributes the most to the total kinetic energy. The energetic contribution of the meridional component (Fig. 1b), is limited, except in correspondence to the main vortices and ovals, e.g., the GRS and Oval BA (28°S Lat., 82° Long.), where the meridional velocity is of order 65 and 60 $\mathrm{ms^{-1}}$, respectively. Due to the low contrast and resolution at high latitudes, related to the *Cassini* flyby geometry, wind vectors poleward of 50° are either replaced by the zonally symmetric average (Fig. 1a) or omitted (Fig. 1b). Where available, maps of the wind vectors are affected by measurement noise, leading to typical uncertainties of 5 $\mathrm{ms^{-1}}$, with peaks between 10 and 20 $\mathrm{ms^{-1}}$ (Choi and Showman, 2011). A close-up of the GRS reveals the high-speed collar of the vortex, where the magnitude of the velocity, after the removal of the zonal average, reaches values up to 95 $\mathrm{ms^{-1}}$ (Fig. 2), in contrast with the low-velocity inner region. The shape of the cyclone at the time of the observations is

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