

Where is the Io plasma torus? A comparison of observations by Juno radio occultations to predictions from Jovian magnetic field models

Phillip H. Phipps¹, Paul Withers^{1,2}, Marissa F. Vogt¹, Dustin R. Buccino³, Yu-Ming Yang³,
Marzia Parisi³, Drake Ranquist⁴, Peter Kollmann⁵, Scott Bolton⁶

¹Center for Space Physics, Boston University, Boston, MA, USA.

²Department of Astronomy, Boston University, Boston, MA, USA.

³Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.

⁴Laboratory for Atmospheric and Space Science, University of Colorado Boulder, Boulder, CO, USA.

⁵The Johns Hopkins University Applied Physics Lab, Laurel, MD, USA.

⁶Southwest Research Institute, San Antonio, TX, USA.

Key Points:

- The location of the Io plasma torus depends on longitude and radial distance.
- Observed torus locations are predicted better by the JRM09 model than by the VIP4 model.
- The predicted location of the “torus beyond $5.5 R_J$ ” improves if a current sheet model is included.

Corresponding author: Phillip H. Phipps, phhipps@bu.edu

Abstract

The Io plasma torus is thought to lie in Jupiter’s centrifugal equator, a location that depends on Jupiter’s rotation and magnetic field. Yet previous observations and predictions of the location of the Io plasma torus are inconsistent. Here we test the hypothesis that the Io plasma torus lies in the centrifugal equator by comparison of observations by Juno radio occultations to predictions derived from Juno-era magnetic field models. These observations determine the locations of two torus components: the cold torus, which is centered near $5.3 R_J$, and the “torus beyond $5.5 R_J$ ”, which is dominated by the warm torus and is centered near $5.9 R_J$. The observations deviate by 1–2 degrees from the planar centrifugal equator expected for a Voyager epoch dipolar magnetic field. In each observation, the locations of distinct torus regions differ by as much as 1 degree indicating significant radial structure. The root-mean-square error between observation and prediction is smaller for predictions from the JRM09 magnetic field model than for predictions from the VIP4 magnetic field model. Agreement between observations and predictions improves for the “torus beyond $5.5 R_J$ ” if the magnetic field contributions of a nominal magnetospheric current sheet model are included, but worsens for the cold torus. The current sheet affects the location of the “torus beyond $5.5 R_J$ ”, but not the cold torus at $5.3 R_J$. Improved knowledge of the torus location will help to understand how the torus affects the broader magnetosphere.

1 Introduction

The innermost Galilean satellite, Io, is the source of most of the material in Jupiter’s magnetosphere. This material, made mostly of sulfur and oxygen atoms, gets ionized and trapped by Jupiter’s magnetic field [Thomas *et al.*, 2004]. The ionized material is transported radially through the magnetosphere. The plasma is then lost via charge exchange with neutrals or transported to the outer magnetosphere. The highest density of the plasma lies between 5 and 10 Jovian radii (1 Jovian radius = 71,492 km, R_J) in what is called the Io plasma torus (IPT).

These charged particles are trapped on magnetic field lines. Yet this plasma does not drift freely along the full pole-to-pole extent of a field line. Instead, centrifugal forces caused by Jupiter’s rapid rotation confine plasma near the point of minimum centrifugal potential, which is the point on the field line that is farthest from Jupiter’s rotational axis [Hill *et al.*, 1974; Vasylunas, 1983; Khurana *et al.*, 2004; Thomas *et al.*, 2004]. The collection of the maximally separated points on Jupiter’s field lines is called the “centrifugal equator”.

If the magnetic field is dipolar, then the centrifugal equator is a plane. However, if higher-order moments contribute to the magnetic field, then the shape of the surface of the centrifugal equator is distorted from a plane [e.g., Schneider and Trauger, 1995]. Indeed, observations have suggested that the Io plasma torus appears “warped like a potato chip” [Herbert *et al.*, 2008], consistent with the centrifugal equator having a non-planar shape. Furthermore, ground-based imaging observations of the location of the Io plasma torus by Schneider and Trauger [1995] were reproduced better by centrifugal equator predictions based on high-order models of that time, the O4 and O6 models [Acuna and Ness, 1976; Connerney *et al.*, 1981; Connerney, 1993], than by a simple offset tilted dipole model. Using Voyager data, Bagenal [1994] showed that the predicted location of the torus inward of $5.5 R_J$ was very sensitive to the magnetic field model used and that the O4 and O6 models were not adequate.

Based on these results from the Voyager epoch, observations and predictions of the location of the Io plasma torus are inconsistent. This inconsistency is significant. In order to understand the behavior of Jupiter’s magnetosphere, the largest object in the Solar System, it is necessary to understand the behavior of the Io plasma torus, which is the source of most plasma in Jupiter’s magnetosphere. In order to understand the behavior

of the Io plasma torus, it is necessary to understand where in the magnetosphere the Io plasma torus is located.

Three main hypotheses exist that could resolve this problem: the observations are insufficient, the predictions are insufficient, or the basic premise that the Io plasma torus lies in the centrifugal equator is insufficient. Since the Voyager epoch, new information has been acquired by the Juno spacecraft that can be used to address this problem. Radio occultations by Juno have sampled the electron density distribution within the torus, yielding precise measurements of the location of the Io plasma torus. Magnetic field measurements by Juno have sampled closer to Jupiter and over a wider range of latitudes than before, yielding an improved model of the internal magnetic field of Jupiter. This leads to an improved prediction for the location of the centrifugal equator.

The aim of this article is to test the hypothesis that the Io plasma torus lies in the centrifugal equator. This aim is achieved by the comparison of observations by Juno radio occultations to predictions derived from Juno-era magnetic field models. Section 2 describes the available Juno radio occultation observations of the location of the Io plasma torus. Section 3 describes selected internal and external magnetic field models and their predictions for the location of the Io plasma torus. The internal field is generated within Jupiter. The external field is generated in the magnetosphere, primarily in the current sheet. Section 4 compares observed and predicted locations of the Io plasma torus. Section 5 assesses the impact of plausible variations in the poorly constrained parameters of the external field on the predicted location of the Io plasma torus. Section 6 interprets the results of Sections 4-5. Section 7 states the conclusions of this article.

2 Observations by Juno radio occultations

The Juno spacecraft entered orbit around Jupiter on 4 July 2016. Its orbital period has remained constant at approximately 53 days. During each perijove, the Juno–Earth line of sight sweeps through one sector of the IPT. Operations on some, but not all, perijoves have a gravity science focus. During the first two years of the Juno Mission gravity science observations were performed on Perijoves 1, 3, 6, 8, 10, 11, 13, 14, and 15. During those perijoves, Juno points its high-gain antenna towards Earth and maintains a two-way coherent radio link with a ground station of the NASA Deep Space Network (DSN) at X-band and Ka-band frequencies. These X-band and Ka-band radio signals pass through the Io plasma torus, which affects their observed differential Doppler shift. A time series of the total electron content along the Juno–Earth line of sight can be determined from such observations. As the path of the Juno–Earth line of sight through the IPT changes with time during each perijove, this provides information on the spatial distribution of plasma in the Io plasma torus. During the other Juno perijoves, radio signals are transmitted from Juno’s medium gain antenna and are thus much noisier and are unsuitable for the purpose of determining densities in the Io plasma torus. Thus, data from Perijoves 2, 4, 5, 7, 9, and 12 are not suitable for Io plasma torus studies.

As explained in detail in *Phipps et al.* [2018] and *Phipps et al.* [2019], the observed differential Doppler shift is integrated with respect to time to yield an initial time series of the total electron content (TEC) along the Juno–Earth line of sight. This contains several contributions from sources other than the Io plasma torus, such as Earth’s ionosphere and the solar wind, which should be removed from the initial time series of TEC. First, contributions from Earth’s ionosphere are subtracted from the initial time series of TEC to obtain the intermediate time series of TEC. This uses the line of sight total electron content of Earth’s ionosphere, which is provided by a routine DSN data product measured using radio links to GPS satellites visible above the DSN stations. Second, contributions from changes in the solar wind are subtracted from the intermediate time series of TEC to obtain the final time series of TEC. The intermediate time series of TEC still contains a contribution from changes in the TEC in the solar wind along the Juno–Earth line of

sight. This is not directly measurable. Instead, a high-order polynomial function of time is fitted to the intermediate TEC values at times outside the interval of the Io plasma torus occultation. This baseline function is subtracted from the intermediate time series of TEC to obtain the final time series of TEC. Note that the steady state value of the solar wind TEC does not affect the observations.

The final time series of TEC is expressed as a one-dimensional function of position, where the relevant position coordinate for each Earth received time is a distance above the nominal plane of the centrifugal equator. Specifically, the distance above the nominal plane of the centrifugal equator of the point on that ray path whose projected distance from Jupiter in the nominal plane of the centrifugal equator is $5.89 R_J$, the orbital distance of Io.

The Io plasma torus consists of three distinct regions: the cold torus ($4.9\text{--}5.5 R_J$), ribbon ($5.5\text{--}5.7 R_J$), and warm torus ($5.7\text{--}8 R_J$) [Bagenal and Sullivan, 1981; Thomas *et al.*, 2004; Phipps, 2019]. Values of the peak total electron content, the offset of the location of peak total electron content from the centrifugal equator, and the scale height are found for two components of the torus by fitting a pair of Gaussian functions of position to the final TEC values. The location of peak total electron content can be expressed as an angular offset from an idealized planar centrifugal equator expected for a dipolar magnetic field. The two fitted components of the torus are the cold torus and the torus beyond $5.5 R_J$, where the latter includes contributions from the warm torus and the ribbon. Representative radial distances of the two fitted regions are $5.3 R_J$ and $5.9 R_J$. The “torus beyond $5.5 R_J$ ” region contains the ribbon and warm torus, but is likely dominated by total electron content contributions from the warm torus. The Juno observations are not able to discriminate between the warm torus and ribbon, which have similar scale heights.

Results of Juno radio occultation observations of the Io plasma torus have been reported by Phipps *et al.* [2018] and Phipps *et al.* [2019] for four Juno perijoves (PJ). These are PJ1 ($\lambda_{III} = 184$ degrees, 27 August 2016), PJ3 ($\lambda_{III} = 60$ degrees, 11 December 2016), PJ6 ($\lambda_{III} = 213$ degrees, 19 May 2017), and PJ8 ($\lambda_{III} = 10$ degrees, 1 September 2017). The locations of two components of the Io plasma torus were determined by Phipps and colleagues for these four observations. The fitted locations and their uncertainties from Phipps *et al.* [2018] and Phipps *et al.* [2019] are shown in Table 2. Io plasma torus properties from Perijoves 10, 11, 13, 14, and 15 have not yet been determined.

The dependence of the fitted locations on longitude is shown in Figure 1. The observed locations generally deviate by 1–2 degrees from the idealized planar centrifugal equator expected for a dipolar magnetic field from the Voyager epoch. This can be seen by the offset from zero of the observations in Figure 1. This confirms that the centrifugal equator is not planar. On any given perijove, the locations of the cold torus and the torus beyond $5.5 R_J$ differ by as much as 1 degree, indicating that significant radial structure is present in the centrifugal equator between 5.3 and $5.9 R_J$.

3 Predictions based on magnetic field models

Predictions for the location of the centrifugal equator rely upon magnetic field models. Jupiter possesses the strongest magnetic field of any planet in the solar system [Bagenal, 2013; Kivelson and Bagenal, 2014]. Although the planet’s internally-generated field is predominantly dipolar, significant spectral power is present in the higher-order moments [Connerney *et al.*, 2018]. Several models of Jupiter’s internal magnetic field have been generated by analysis of magnetic field measurements and other constraints [Acuna and Ness, 1976; Connerney, 1993; Connerney *et al.*, 1998; Grodent *et al.*, 2008; Hess *et al.*, 2011; Connerney *et al.*, 2018].

There are also external magnetic fields created by currents in the magnetosphere (e.g. ring current, magnetopause current, current sheet) [Khurana *et al.*, 2004]. For the re-

gion of the magnetosphere from $5 R_J$ to $40 R_J$, the most significant external field comes from the current sheet. Jupiter's magnetosphere is full of plasma which is confined in a sheet in the outer magnetosphere. Currents flow through this confined plasma leading to the creation of magnetic fields [see review by *Khurana et al.*, 2004]. These currents are closed in the ionosphere of Jupiter and lead to magnetosphere-ionosphere coupling and Jupiter's powerful aurora. This current sheet originates near the orbit of Io, the source of the bulk of the plasma in the magnetosphere. Despite the strength of Jupiter's internal magnetic field, the external magnetic field is not negligible in the regions outside of $5.5 R_J$. Previous studies have shown that these external magnetic fields have appreciable influence on the magnetic field environment around the Io plasma torus [*Connerney et al.*, 1981; *Khurana*, 1992, 1997]. Current sheet models have been developed to fit data from Voyager and Galileo [*Connerney et al.*, 1981; *Khurana*, 1992, 1997].

3.1 Internal field models

We consider two internal magnetic field models: the widely-used VIP4 internal field model [*Connerney et al.*, 1998], which is based upon Pioneer 11 and Voyager 1 magnetometer data, plus optical observations of the location of the Io auroral footprint; and the recent JRM09 internal field model [*Connerney et al.*, 2018], which is based upon the first nine orbits of magnetometer data acquired by the Juno magnetic field investigation.

Both the VIP4 and JRM09 models adopt a spherical harmonic representation of the field. The planetary magnetic field can be defined as the gradient of a scalar potential, $\vec{B} = \nabla V$. The scalar potential is defined by a spherical harmonic expansion of the following form [e.g. *Chapman and Bartels*, 1940; *Connerney et al.*, 1998, 2018]:

$$V = a \sum_{n=1}^{n_{max}} \left(\frac{a}{r}\right)^{n+1} \sum_{m=0}^n \{P_n^m(\cos \theta) [g_n^m \cos m\phi + h_n^m \sin m\phi]\} \quad (1)$$

where a is the equatorial radius of Jupiter, r is the radial distance to the planet's center, angle θ is the colatitude, and angle ϕ is the longitude. The $P_n^m(\cos \theta)$ are the Schmidt-normalized associated Legendre functions of degree n and order m . The coefficients g_n^m and h_n^m are the fitted internal field parameters called Schmidt coefficients.

Magnetometer data can be fitted to the scalar potential representation of the magnetic field to determine the coefficients for the field. The field models for Jupiter are found as a partial solution to a linearized system [*Connerney*, 1981]. The dipole parameters, dipole moment (M), dipole tilt (θ_M), and orientation (λ_M), are determined using the g_1^0 , g_1^1 , and h_1^1 coefficients as follows [*Khurana et al.*, 2004]:

$$M = \sqrt{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2} \quad (2)$$

$$\theta_M = \tan^{-1} \left(\sqrt{(g_1^1)^2 + (h_1^1)^2} / g_1^0 \right) \quad (3)$$

$$\lambda_M = \tan^{-1} \left(h_1^1 / g_1^1 \right). \quad (4)$$

The VIP4 internal field model stands for Voyager, Io, and Pioneer 4th order model [*Connerney et al.*, 1998]. The dipole parameters determined for this model are $M = 4.264$ Gauss, $\theta_M = 9.5$ degrees, and in System III (1965) West coordinates $\lambda_M = 200.8$ degrees. In this article we use System III (1965) West.

The JRM09 internal field model stands for "Juno Reference Model through Perijove 9" [*Connerney et al.*, 2018]. This model uses observations from the Juno spacecraft made within $7 R_J$ of Jupiter during the first 9 orbits. This model also calculates the spherical harmonic expansion through degree 20 but values are only well defined through degree

10. The dipole parameters determined for this model are $M = 4.170$ Gauss, $\theta_M = 10.31$ degrees, and in System III (1965) West coordinates $\lambda_M = 196.61$ degrees.

In this article, we use the VIP4 dipole parameters to define the idealized planar centrifugal equator expected for a dipolar magnetic field. This is used as the reference from which angular offsets are measured. This convention is adopted for consistency with the reference Io torus models of *Phipps and Withers* [2017], *Phipps et al.* [2018], and *Phipps et al.* [2019]. The JRM09 dipole parameters are stated for reference only.

Even though VIP4 ends at 4^{th} order and JRM09 truncates at 10^{th} order, further truncated versions of the VIP4 and JRM09 internal field models can also be generated in which coefficients above some threshold degree are ignored. For example, a dipole approximation to such a model arises from neglecting all coefficients above degree 1. Similarly, a fourth-order approximation arises from neglecting all coefficients above degree 4. The parameters for the dipole approximation to each model can be found in Table 1.

3.2 External field models

Previous studies have adopted two primary methods for modeling the external field produced by the magnetospheric current sheet. The first method to model the current sheet was applied by *Connerney et al.* [1981]. Similar to the internal field, they solved for an analytical solution for a potential to match Voyager 1 and 2 and Pioneer 10 observations of the current sheet. However, unlike the internal field, they solved for a vector potential $\underline{A}$ that satisfies the relation $\underline{B} = \nabla \times \underline{A}$. From this relation, *Connerney et al.* [1981] derived simple analytical functions, assuming the current sheet is azimuthally symmetric, which approximate the solution and allow fast computation of the field. This model does a reasonable job between $6 R_J$ and $30 R_J$. However, after $30 R_J$ there is hinging and lag behind co-rotation of the current sheet, which breaks the symmetric approximation [*Khurana et al.*, 2004]. The abrupt inner edge of this current sheet model at $5 R_J$ also leads to fringing effects inside $5 R_J$ [*Vasyliunas*, 1983]. Despite these issues, the model does a reasonable job matching measurements between 5 and $8 R_J$, where the Io plasma torus is located. An updated version of this current sheet has been published by *Pensionerov et al.* [2019]. The updated current sheet model of *Pensionerov et al.* [2019] starts from the same functional form as *Connerney et al.* [1981], then adds two additional terms to capture the deviations between observations and model beyond around $30 R_J$. It also updates the parameters that define the model.

The second method uses Euler potentials to derive the magnetic field. This method uses two scalar functions to represent the magnetic field. *Goertz* [1976] derived a scalar potential f that is dependent on radial distance and height above the plane and a scalar potential g that is dependent on radial distance and azimuthal angle. This method was improved upon by *Khurana* [1997] to allow the internal and current sheet models to be linked. This model was created using dawn side data and thus does a reasonable job in that sector. The *Khurana* [1997] model included the hinging and lag of the magnetic field beyond $30 R_J$ to better map the field in the outer magnetosphere.

Here we adopt the current sheet model of *Connerney et al.* [1981] (called CAN). It provides reasonable agreement with magnetic field measurements at the radial distances of the Io plasma torus. The current sheet model of *Pensionerov et al.* [2019] has the same functional form as CAN at the radial distances of the Io plasma torus. *Pensionerov et al.* [2019] updated the model parameters given by *Connerney et al.* [1981], but the conclusions of our analysis are not sensitive to the precise values of the model parameters that are adopted (Section 5). The model of *Khurana* [1997] is optimized for the dawn sector, whereas Juno radio occultation observations sample the noon sector. Furthermore, its sophisticated representations of hinging and associated behavior are primarily relevant for the outer magnetosphere, not the radial distances of the Io plasma torus.

The parameters of the CAN current sheet model are listed at the bottom of Table 1. Figure 2 shows the relationship between the total magnetic field strength of the JRM09, JRM09 dipole, JRM09 greater than dipole (quadrupole and above), the CAN current sheet, and the JRM09 plus current sheet models in the magnetic equator at a System III West longitude of 196.6 degrees.

3.3 The Centrifugal Equator

If the magnetic field is perfectly dipolar, then the location of the centrifugal equator at a given longitude satisfies [Hill *et al.*, 1974; Vasyliunas, 1983; Khurana *et al.*, 2004; Phipps, 2019]:

$$\tan \theta = \frac{-4/3 \tan \alpha \cos \phi}{1 \mp \sqrt{1 + 8/9 \tan^2 \alpha \cos^2 \phi}} = \frac{-4/3 \tan \alpha \cos (\lambda_{III} - \lambda_M)}{1 \mp \sqrt{1 + 8/9 \tan^2 \alpha \cos^2 (\lambda_{III} - \lambda_M)}} \quad (5)$$

where θ is the angle from the rotational equator to the centrifugal equator, α is the tilt of the magnetic dipole axis from the planet's rotational axis, and ϕ is the right-handed magnetic longitude. Jovigraphic longitude, λ_{III} , is the left-handed System III longitude and λ_M is the jovigraphic longitude of the magnetic prime meridian. These are related by $\lambda_{III} - \lambda_M = 360^\circ - \phi - \lambda_M$. Note that Equation 5 predicts that the angular location of the centrifugal equator is independent of radial distance for a dipolar magnetic field. The theoretical expression shown in Equation 5 is a useful benchmark for assessing predictions of non-dipolar magnetic field models for the location of the centrifugal equator, which may vary with radial distance. As discussed in Section 3.1, in the dipolar approximation to the VIP4 internal field model, α is 9.6 degrees, λ_M is 200.8 degrees, and the predicted location of the centrifugal equator is as shown in Figure 3. The greatest absolute value of θ is 6.4 degrees or $2\alpha/3$, consistent with the approximation to Equation 5 that $\tan \theta = -2/3 \tan \alpha \cos \phi$ in the limit of small α . A schematic of the centrifugal equator relative to the rotational and magnetic equators in the dipolar approximation is shown in Figure 4.

We find the centrifugal equator of a given magnetic field model by tracing a set of model field lines using the model parameters and identifying the point on each field line that is farthest from Jupiter's rotational axis. The field line is traced starting at a latitude of 0 degrees and moving toward the planet along the magnetic field. The tracing is done for longitudes from 0 to 360 degrees incrementing by 10 degrees and radial distances from 5 to 10 R_J incrementing by 0.1 R_J . The implementation of this approach is verified by reproduction of the analytical result shown in Figure 3 for the dipolar approximation to the VIP4 internal field model. Note that all subsequent descriptions of the location of the centrifugal equator are referenced to the dipolar approximation to the VIP4 internal field model, not to the rotational equator. This convention is adopted in order to highlight small differences effectively and to maintain consistency with previous work. Figure 5 shows the offsets from the dipolar approximation to the VIP4 internal field model for the VIP4 full model, the JRM09 dipolar approximation, the JRM09 truncated at 4th order, and the full JRM09 model.

The offsets of the centrifugal equator predicted by the full VIP4 internal field model from the dipolar approximation to the VIP4 model are shown in panel A of Figure 5. Deviations of this predicted centrifugal equator from the predicted centrifugal equator of the dipolar approximation to the VIP4 internal field model have a magnitude on the order of 1 degree. The longitudinal structure of these deviations is characterized by two maxima and two minima, each separated by 90 degrees in longitude. This shows that this predicted centrifugal equator is not planar. This predicted shape is similar to the “potato chip” shape seen in Io plasma torus observations [Schneider and Trauger, 1995; Herbert *et al.*, 2008]. Neither the two maxima nor the two minima of the tilt angle offsets are identical; slight asymmetries between them are present. Furthermore, slight variations with radial distance

are also apparent. No such variations with radial distance are possible in a purely dipolar field model.

The offsets of the centrifugal equator predicted by the dipolar approximation to the JRM09 internal field model from the dipolar approximation to the VIP4 model are shown in panel B of Figure 5. In this instance, α is 10.31 degrees and λ_M is 196.61 degrees, slightly different from the corresponding values above for the VIP4 internal field model. Results are shown for different radial distances even though no dependence on radial distance exists in this dipolar case. This is done for consistency with the other panels of Figure 5 and later figures. The basic shape of the difference between the centrifugal equators of the dipolar approximations to the JRM09 and VIP4 internal field models is consistent with the difference between two tilted planes. The maximum value of the difference, 0.72 degrees, is consistent with the difference between tilts of 6.4 degrees and 6.9 degree (two-thirds of the respective values of α). Note that this is not equivalent to the difference in magnetic dipole axis tilt due to a shift in longitude between the models.

The offsets of the centrifugal equator predicted by a JRM09 internal field model that is truncated at degree 4 from the dipolar approximation to the VIP4 model are shown in panel C of Figure 5. The offsets of the centrifugal equator predicted by the full JRM09 internal field model from the dipolar approximation to the VIP4 model are shown in panel D of Figure 5. Differences between these two are negligible, which shows that terms above degree 4 can be neglected in this analysis. Hence we focus on interpretation of the JRM09 internal field model truncated at degree 4 in the remainder of this article, setting aside the full JRM09 internal field model which is computationally more difficult to run due to the higher order terms. This predicted centrifugal equator is qualitatively similar to that of the full VIP4 internal field model (panel A). However, differences between the centrifugal equators predicted by these two degree 4 models are present. For example, the asymmetry between the two tilt angle offset minima is greater in the JRM09 internal field model than in the VIP4 internal field model. These differences can be attributed to the differences in the fitted dipolar tilt and tilt longitude values for the two models. These fitted dipole values differ between the VIP4 and JRM09 models due to the different data used in the two models. Figure 6 shows the dependence of offset on longitude for each of the four models in panels A–D of Figure 5. Values are shown for a distance of $6 R_J$.

4 Comparison of observations and predictions

The top panel of Figure 7 shows how the four observed locations of the cold torus and the four observed locations of the torus beyond $5.5 R_J$ compare to the locations of the centrifugal equator predicted by the full VIP4 internal field model. The error bars are the one sigma uncertainties on the measurements from *Phipps et al. [2018]* and *Phipps et al. [2019]*. They are also listed in Table 2. The observed locations generally deviate from the plane of the dipolar approximation to the VIP4 internal field model and (not shown) the plane of the dipolar approximation to the JRM09 internal field model by 1–2 degrees, confirming that the centrifugal equator is not planar. On any given perijove, the locations of the cold torus and the torus beyond $5.5 R_J$ differ by as much as 1 degree, indicating that significant radial structure is present in the centrifugal equator between 5.3 and $5.9 R_J$. Yet neither the cold torus observations nor the torus beyond $5.5 R_J$ observations lie close to the VIP4 prediction for the centrifugal equator.

The middle panel of Figure 7 compares the observed locations to the centrifugal equator predicted for the truncated JRM09 internal field model. The observed cold torus locations are consistent with the centrifugal equator predicted for the truncated JRM09 internal field model. Yet the observed locations of the torus beyond $5.5 R_J$ are not consistent with these predictions.

Two interpretations are possible: either the torus beyond $5.5 R_J$ does not lie in the centrifugal equator or the JRM09 internal field model does not accurately predict the location of the centrifugal equator at distances of $5.9 R_J$, despite being successful at the nearby distance of $5.3 R_J$. In fact, neither the VIP4 internal field model nor the JRM09 internal field model predicts a ~ 1 degree change in location of the centrifugal equator as observed on PJ8 (10 degrees longitude) and on PJ1 (184 degrees longitude) at any longitude. This suggests that the problem is more subtle than some coefficient values being incorrect. It is inherently difficult for models of this type to yield variations over such short spatial scales far from the currents that generate the fields.

That realization points to a likely resolution of this problem. The VIP4 and JRM09 internal field models represent the internally-generated magnetic field of Jupiter. They do not include representations of contributions from the magnetospheric current sheet [Connerney *et al.*, 1981]. Therefore we add a model of currents in Jupiter’s magnetosphere to the truncated JRM09 internal field model. Jupiter’s magnetospheric current sheet is mostly confined to equatorial latitudes and hence can be represented by a “current sheet” model. Jupiter’s magnetosphere and the currents therein are inherently variable, which poses challenges for developing a suitable model. For simplicity, we initially adopt a widely-used model of the “nominal” current sheet. This is the parameterized model of Connerney [1981] which considers an axisymmetric disc of azimuthal currents in the magnetic equator. This model is defined by a half-width of $2.5 R_J$, inner radius of $5 R_J$, and current sheet current density of 225 nT ($\mu_0 I_0/2$, where μ_0 is the permeability of free space and I_0 is a reference current per unit length). An outer radius of $50 R_J$ is also specified, but the centrifugal equator at the $5\text{--}10 R_J$ radial distance of the Io plasma torus is essentially the same for any plausible value of the outer radius.

The bottom panel of Figure 7 compares the observed locations of the centrifugal equator to the locations predicted by the combination of the truncated JRM09 internal field model and the nominal current sheet model. The observed locations of the torus beyond $5.5 R_J$ are now consistent with predictions. Furthermore, at the longitudes of each of the four perijoves, the predicted locations of the two torus regions are separated by an amount and direction comparable to the observed separations. However, the observed locations of the cold torus, which were predicted well prior to the inclusion of a current sheet model, are now predicted acceptably, but not as well as before. Inclusion of the nominal current sheet model has improved some aspects of the data-model comparison, but worsened other aspects. On the whole, the agreement between observations and predictions for the combination of the truncated JRM09 internal field model and the nominal current sheet model is promising.

We conclude that addition of a current sheet contribution to an internal magnetic field model is necessary in order for a model to accurately predict the location of the centrifugal equator for the “torus beyond $5.5 R_J$ ”. The current sheet is not needed to explain the the cold torus location. This suggests that the current sheet model should not penetrate into $5 R_J$. The combination of the truncated JRM09 internal field model and the nominal current sheet model of Connerney [1981] provides a promising, but imperfect, prediction of the location of centrifugal equator. This is not unreasonable as the current sheet is known to vary spatially and temporally in ways that are not represented by the idealized current sheet model of Connerney [1981] [Vogt *et al.*, 2017].

5 Effects of variations in current sheet model parameters

The parameters of the nominal current sheet model are listed in the bottom of Table 1. However, the real current sheet is likely more complex and variable than suggested by this model, which would cause errors in the predictions of the nominal current sheet model. To assess the degree to which changes in the values of the parameters of the nom-

inal current sheet model change the predicted location of the centrifugal equator, we perform a series of simulations in which the values of these parameters are varied.

First, we vary the current sheet inner radius of $5 R_J$ to 6, 7, and $8 R_J$ while keeping the half-width and current sheet density fixed at their nominal values. This step through the values of the inner radius from the inner density boundary of the IPT (around $5 R_J$) through the outer density boundary (around $8 R_J$). Results are shown in the top row of Figure 8. Changes in the location of the centrifugal equator due to the simulated variations in the current sheet inner radius are relatively small. In this idealized model, the current sheet has limited effects on the location of the centrifugal equator within the inner radius. Therefore, if the inner radius is moved out from $5 R_J$ then the combination of JRM09 and current sheet will better represent the data. *Pensionerov et al.* [2019] found that a better match to the data was found using an inner radius of $7 R_J$. *Ridley and Holme* [2016] found an inner radius of around $4 R_J$ was a better fit. At small radial distances, the centrifugal equator effectively remains at the location predicted by the internal field model only.

Second, we vary the current sheet density ($\mu_0 I_0/2$) of 225 nT to 125, 325, and 425 nT while keeping the inner radius and half-width fixed at their nominal values. The values are varied from 125 nT through 425 nT counting by 100 nT. This range was chosen to contain the values for the current sheet found by *Vogt et al.* [2017] from fitting to the Galileo data. Results are shown in the middle row of Figure 8. In this idealized model, as the current sheet density increases, the displacement of the predicted location of the centrifugal equator from the location predicted by the internal field-only model increases. Changes are most apparent at radial distances greater than the inner radius of the current sheet. For the values simulated here, these changes in location can be on the order of one degree, which is substantial.

Third, we vary the current sheet half-width of $2.5 R_J$ to 1.5, 3.5, and $4.5 R_J$ while keeping the inner radius and current sheet density fixed at their nominal values. These values were chosen to be between 1 and $5 R_J$ counting by $1 R_J$ where the list of values would include the initial value of $2.5 R_J$. Results are shown in the bottom row of Figure 8. In this idealized model, changes in the location of the centrifugal equator due to simulated variations in the current sheet half-width are relatively small. A comparison of all the test cases at $6 R_J$ is shown in Figure 9. Although we test the parameters independently, *Ridley and Holme* [2016] have shown that the values of D and $\mu_0 I_0/2$ are covariant and thus should be treated as a single parameter. This covariance does not change the results of this work, but it would be more physically realistic to vary $D\mu_0 I_0/2$, rather than to vary both D and $\mu_0 I_0/2$.

In this idealized model of the current sheet, the predicted location of the centrifugal equator is sensitive to the assumed value of the current sheet density, but is only weakly sensitive to the assumed values of the current sheet inner radius and half-width. At this stage, it is premature to consider the “best” set of parameters for this particular current sheet model, which would be the set that gives the best agreement between observed and predicted locations of the centrifugal equator. However, we note that none of the model adjustments explored in Figure 8 yields what visual inspection would identify as an appreciably better agreement between observations and predictions than the nominal model shown in Figure 7.

6 Discussion

Ground-based imaging of the Io plasma torus has shown that the centrifugal equator of Jupiter’s magnetic field is warped from the idealized shape of a plane. Analysis of four Juno radio occultation observations of the total electron content distribution in the Io plasma torus has confirmed this finding. A dipolar magnetic field would produce a planar

centrifugal equator and cannot produce the observed structure. Furthermore, both ground-based imaging and radio occultation observations show that the location of the centrifugal equator at fixed longitude depends on radial distance. For example, the angular location of the centrifugal equator has been observed to change by one degree between the cold torus at $5.3 R_J$ and the “torus beyond $5.5 R_J$ ” (ribbon and warm torus) at $5.9 R_J$.

We modeled the location of the centrifugal equator using the VIP4 internal field model of Jupiter’s internal magnetic field and compared these predictions to locations observed in Juno radio occultation observations of the Io plasma torus. To determine the fit of the model to the data we calculate the Root-Mean-Squared Error (RMSE). The RMSE is calculated using the model output for a radial distance of $5.3 R_J$ for the cold torus and $5.9 R_J$ for the torus beyond $5.5 R_J$. This is repeated for each longitude. The RMSE for predictions of the location of the centrifugal equator is 0.54 ± 0.20 degrees for the cold torus while it is 1.35 ± 0.50 degrees for the torus beyond $5.5 R_J$.

Next, we modeled the location of the centrifugal equator using the JRM09 internal field model of Jupiter’s internal magnetic field and compared these predictions to locations observed in Juno radio occultation observations of the Io plasma torus. Terms beyond degree 4 did not affect the predicted location of the centrifugal equator significantly. The RMSE of the predictions of the location of the centrifugal equator is 0.17 ± 0.20 degrees for the cold torus and 0.82 ± 0.50 degrees for the torus beyond $5.5 R_J$. Based on these findings, we conclude that the JRM09 internal field model is an improvement over the earlier VIP4 internal field model.

Reproduction of the observed large changes in the location of the centrifugal equator over short radial distances far from the planet with an internal magnetic field requires considerable power in the high degree components of the magnetic field. This is inconsistent with plausible internal magnetic field models — not only their specific coefficient values, but also their general spectral shape [Connerney *et al.*, 2018]. As previously suggested by Herbert *et al.* [2008], magnetic fields induced by the flow of plasma in Jupiter’s magnetosphere could cause variations in the location of the centrifugal equator over the short length-scales required to reproduce the observations. We added the nominal current sheet model of Connerney [1981] to the JRM09 internal field model, then modeled the location of the centrifugal equator. The root-mean-squared error of predicted locations of the centrifugal equator for the cold torus, which was 0.17 ± 0.20 degrees prior to the addition of the current sheet model, worsened to 0.41 ± 0.20 degrees. The RMSE of predicted locations of the centrifugal equator for the torus beyond $5.5 R_J$, which was 0.82 ± 0.50 degrees prior to the addition of the current sheet model, improved to 0.49 ± 0.50 degrees. As can be seen in the bottom panel of Figure 7, the inclusion of the current sheet model increases the magnitude of the rate of change of angular offset with radial distance. This characteristic explains why inclusion of the current sheet model is able to improve data-model agreement for the torus beyond $5.5 R_J$, but worsen it for the cold torus.

On the whole, the combination of the truncated JRM09 internal field model and the nominal current sheet model of Connerney [1981] provides promising, but imperfect, predictions of the location of centrifugal equator for the radial distances of the Io plasma torus. By implication, this combination of internal and induced field models provides an accurate description of the magnetic field environment in the equatorial regions of Jupiter’s inner magnetosphere. The improvements obtained in predictions of the location of the centrifugal equator by advancing from the VIP4 internal field model to the JRM09 internal field model, and from adding the nominal current sheet model to the JRM09 internal field model, are strikingly illustrated in the top panel of Figure 10.

Overall, it appears that magnetic field conditions around $5.3 R_J$ (representative radial distance of the cold torus) are adequately represented by an internal field model without the need for appreciable contributions from the external field generated by the magnetospheric current sheet. Yet magnetic field conditions around $5.9 R_J$ (representative radial

distance of the torus beyond $5.5 R_J$) require contributions from both an internal field and an external field. This pair of results places constraints on the properties of the magnetospheric current sheet during the Juno epoch.

The nominal current sheet model has three significant parameters: half-width, inner radius, and current sheet density. The predicted location of the centrifugal equator is most sensitive to the adopted value of the current sheet density, but is relatively insensitive to the adopted values of half-width and inner radius. However, the effects of the current sheet on the location of the centrifugal equator are weak at distances closer to Jupiter than the inner radius of the current sheet. Limited exploration of the consequences of varying the parameters of this current sheet model did not yield predicted locations of the centrifugal equator that appeared appreciably better than the predictions generated using the nominal set of parameters.

Impressive similarities exist between the structure of the centrifugal equator observed by ground-based imaging and by Juno radio occultation observations of the Io plasma torus, as shown in the bottom panel of Figure 10. For the ground-based imaging results of *Schneider and Trauger* [1995], this panel shows the observed offset of the ribbon from the location of the centrifugal equator predicted by their offset tilted dipole (OTD) model of the internal magnetic field. For Juno radio occultation observations, this panel shows the observed offsets of the cold torus and the torus beyond $5.5 R_J$ from the location of the centrifugal equator predicted by the dipolar approximation to the VIP4 internal field model of the internal magnetic field. The correspondence between the ribbon offsets found by ground-based imaging and the cold torus offsets found by Juno radio occultation observations is remarkable. It is also somewhat challenging to interpret as the ribbon is a distinctive feature in ground-based imaging, but not in Juno radio occultation observations, whereas the cold torus is a distinctive feature in Juno radio occultation observations, but not in ground-based imaging. We defer further interpretation of this intriguing result to future work.

7 Conclusions

Several predictions concerning the magnetosphere of Jupiter arise from the results of this work.

1. Future Juno radio occultation observations of the Io plasma torus should yield locations of the cold torus and the torus beyond $5.5 R_J$ that agree with the locations of the centrifugal equator that are predicted by the combination of the JRM09 internal field model and the nominal current sheet model.
2. Future Juno radio occultation observations of the Io plasma torus at longitudes already sampled by previous Juno radio occultation observations should yield the same locations of the cold torus and the torus beyond $5.5 R_J$ as in those previous observations.
3. By adjusting values of model parameters to optimize agreement between predictions and observations for the location of the centrifugal equator, it should be possible to place constraints on the properties of the current sheet in Jupiter's magnetosphere, particularly the current density.
4. The combination of the JRM09 internal field model and a current sheet model should provide an accurate description of the Io plasma torus in the equatorial regions of Jupiter's inner magnetosphere.
5. The effect of the current sheet on the centrifugal equator should increase substantially from 5 to $6 R_J$. For instance, the ribbon feature of the Io plasma torus, which is thought to be associated with the change in the radial temperature gradient, may be the boundary between inner regions that are primarily affected by the inter-

nal field and outer regions that are significantly affected by flows of hot magnetospheric plasma.

Several potentially fruitful avenues for further research arise from the results of this work.

1. Synthesis of findings on the location of the Io plasma torus from ground-based imaging and Juno radio occultation observations. This would improve understanding of the Io plasma torus' structure and role in Jupiter's magnetosphere. However, differences in the detectability of the distinct torus regions between these two measurement techniques presents both challenges and opportunities.
2. Investigation of the predicted location of the centrifugal equator for different current sheet models and different sets of model parameters. The Juno radio occultation observations present an opportunity to indirectly test proposed current sheet models, to reject unsuccessful models, and to place constraints on plausible parameter values for successful models. This would support a range of investigations into plasma dynamics in the inner magnetosphere and associated topics.
3. Assessment of the effect of temperature anisotropy on torus location. If the plasma temperature is highly anisotropic ($T_{\perp} \gg T_{\parallel}$) then plasma in the torus will be centered around the magnetic equator, not the centrifugal equator [Vasyliunas, 1983; Khurana *et al.*, 2004]. Current sheet effects and temperature anisotropy effects can both alter the torus location from that predicted by an internal field model.
4. Acquisition and analysis of additional Juno radio occultation observations of the Io plasma torus. Additional observations will fill in gaps in the observed longitudinal structure, as well as provide repeat coverage at some longitudes. This would better characterize the spatial structure of the Io plasma torus, as well as its temporal variability.

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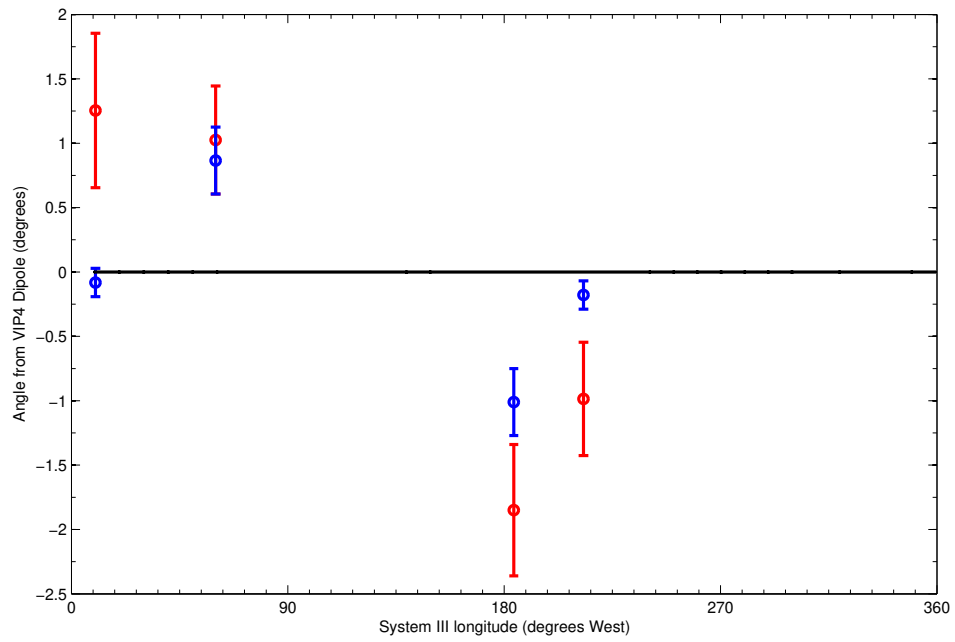


Figure 1. Observations of the centrifugal equator from Juno radio occultations of the Io plasma torus. Blue symbols and red symbols are Juno radio occultation observations of the cold torus and the torus beyond $5.5 R_J$, respectively.

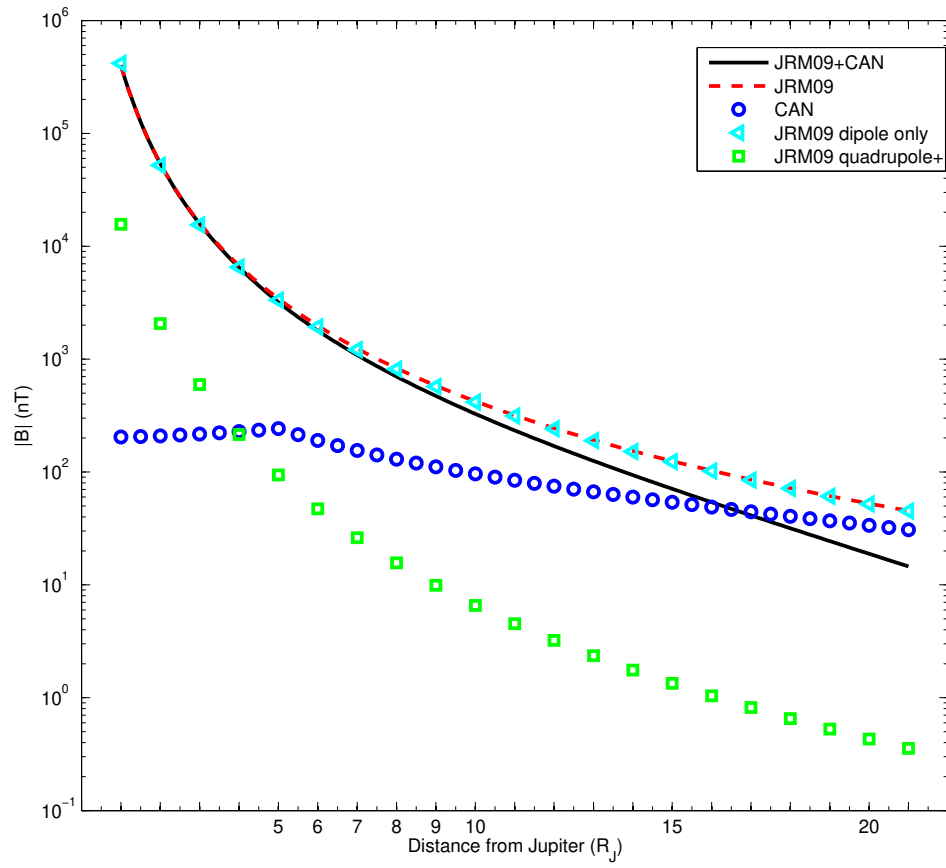


Figure 2. Model predictions for the magnitude of the magnetic field in the magnetic equator. Results are shown for the JRM09+CAN (black solid line), JRM09 (red dashed line), JRM09 dipole (cyan triangles), JRM09 quadrupole and above (green squares), and CAN-only (blue circles) models.

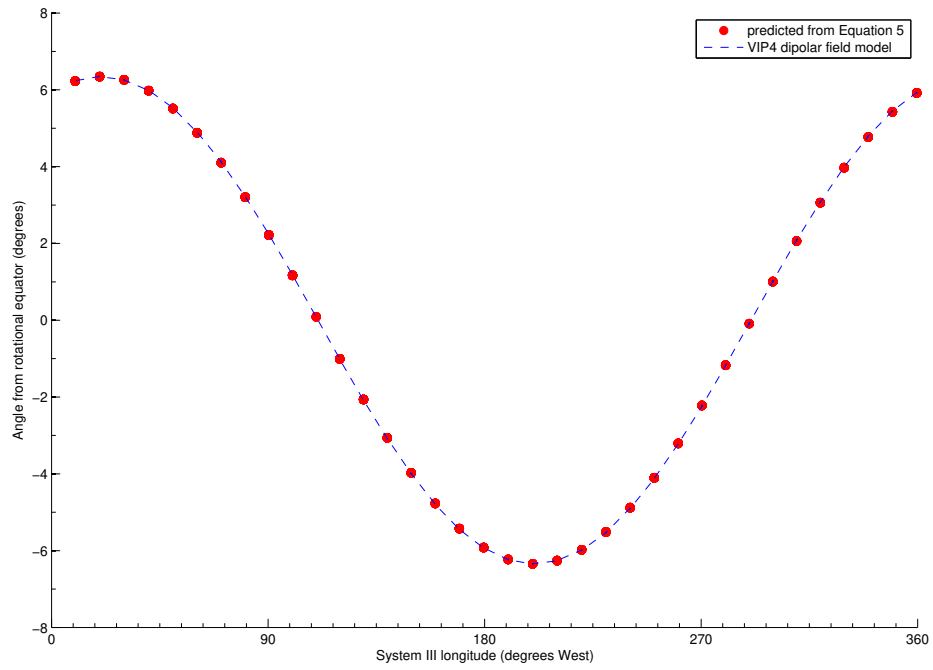


Figure 3. The predicted location of the centrifugal equator relative to the rotational equator. Red circles show the prediction from the dipolar approximation to the VIP4 internal field model by Equation 5. The blue dashed line shows the prediction from field line tracing using the dipolar approximation to the VIP4 model.

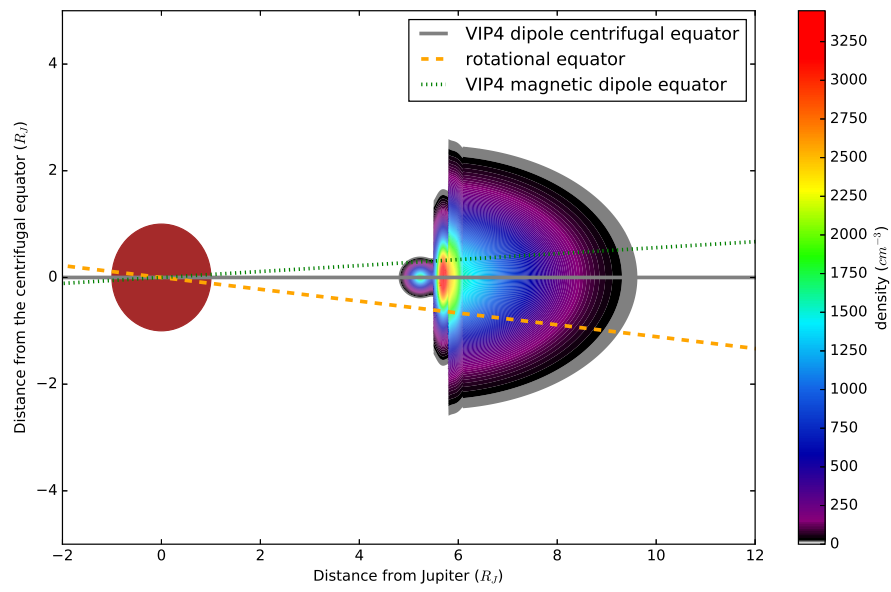


Figure 4. Schematic of the location of the centrifugal equator with respect to the rotational and magnetic equators in the dipole approximation. Colored regions show plasma density according to the model B from Phipps *et al.* [2018].

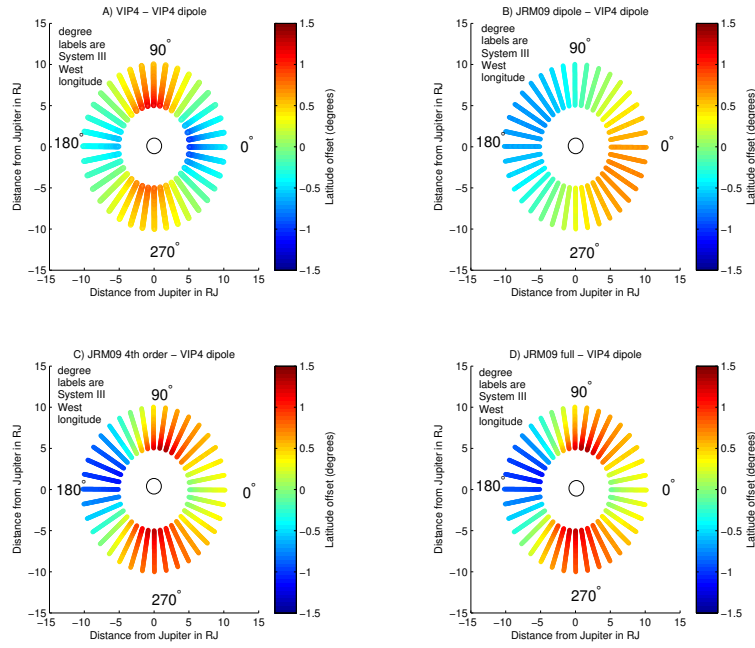


Figure 5. Model predictions for the centrifugal equator relative to the centrifugal equator of the dipolar approximation to the VIP4 internal field model. Results are shown between 5 and 10 R_J at intervals of 10 degrees in longitude as viewed from above Jupiter's south pole looking north. A. The full VIP4 internal field model. B. The dipolar approximation to the JRM09 internal field model. C. The degree 4 truncation of the JRM09 internal field model. D. The full JRM09 internal field model.

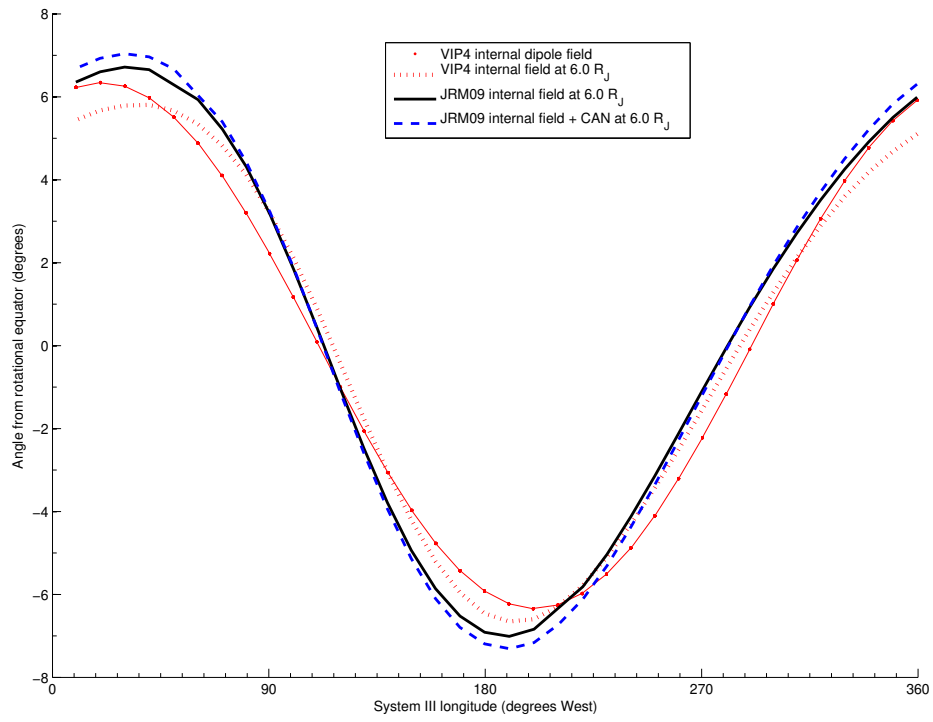


Figure 6. The location of the centrifugal equator at $6 R_J$ relative to the rotational equator, as predicted for the dipolar approximation to the VIP4 internal field model (red dots joined by solid red line), the full VIP4 internal field model (red dashed line), the JRM09 4th order internal field model (black solid line), and the JRM09 internal field plus current sheet model (blue dashed line).

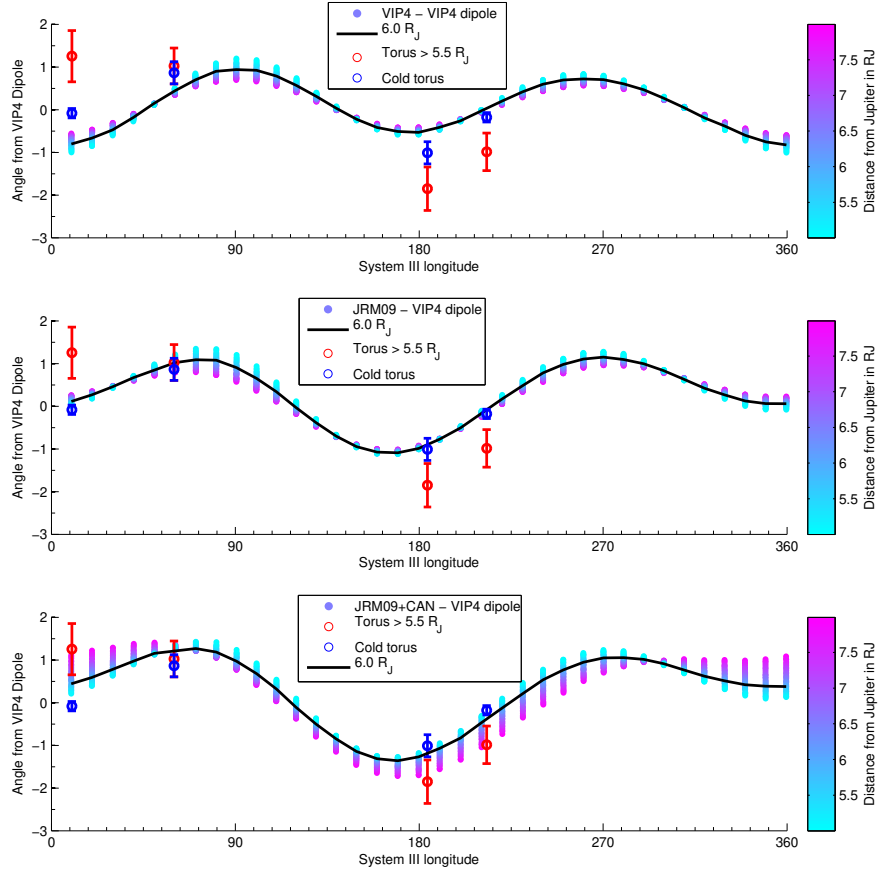


Figure 7. Comparison of observed and predicted locations of the centrifugal equator relative to the centrifugal equator of the dipolar approximation to the VIP4 internal field model. Blue symbols and red symbols are Juno radio occultation observations of the cold torus and the torus beyond $5.5 R_J$, respectively. Colored swaths are predictions made between 5 and $8 R_J$ at intervals of 10 degrees in longitude. The black line highlights the prediction for a radial distance of $6 R_J$. (top) Predictions from the full VIP4 internal field model. (middle) Predictions from the degree 4 truncation of the JRM09 internal field model. (bottom) Predictions from the combination of the degree 4 truncation of the JRM09 internal field model and the nominal current sheet model.

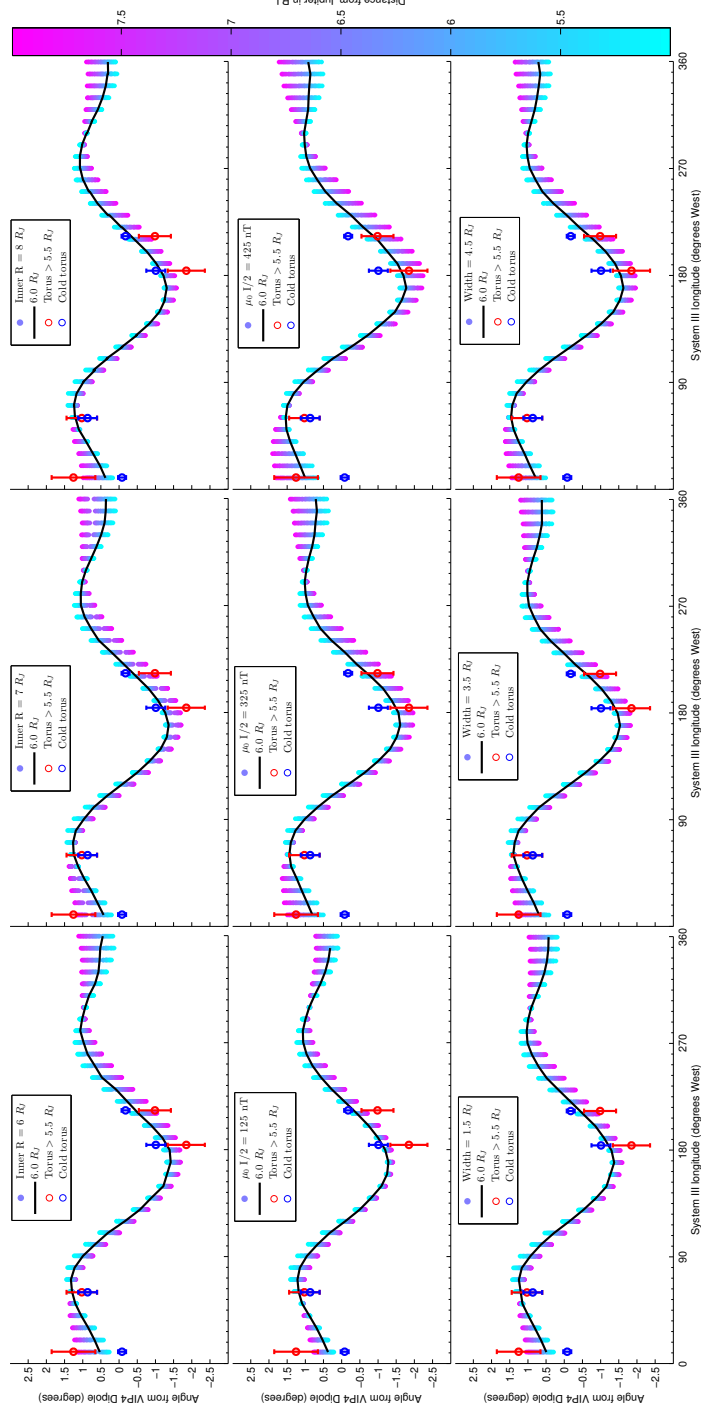


Figure 8. As the bottom panel of Figure 7 using JRM09 internal field model, but for different current sheet models. Note that the radial distances shown has expanded from 5–8 R_J in Figure 7 to 5–10 R_J here. In the top row, the current sheet model uses inner radial distances of 6, 7, and 8 R_J instead of the nominal 5 R_J . All other parameters have their nominal values. In the middle row, the current sheet model uses initial magnetic field values ($\mu_0 I_0 / 2$) of 125, 325, and 425 nT instead of the nominal 225 nT. All other parameters have their nominal values. In the bottom row, the current sheet model uses half-widths of 1.5, 3.5, and 4.5 R_J instead of the nominal 2.5 R_J . All other parameters have their nominal values.

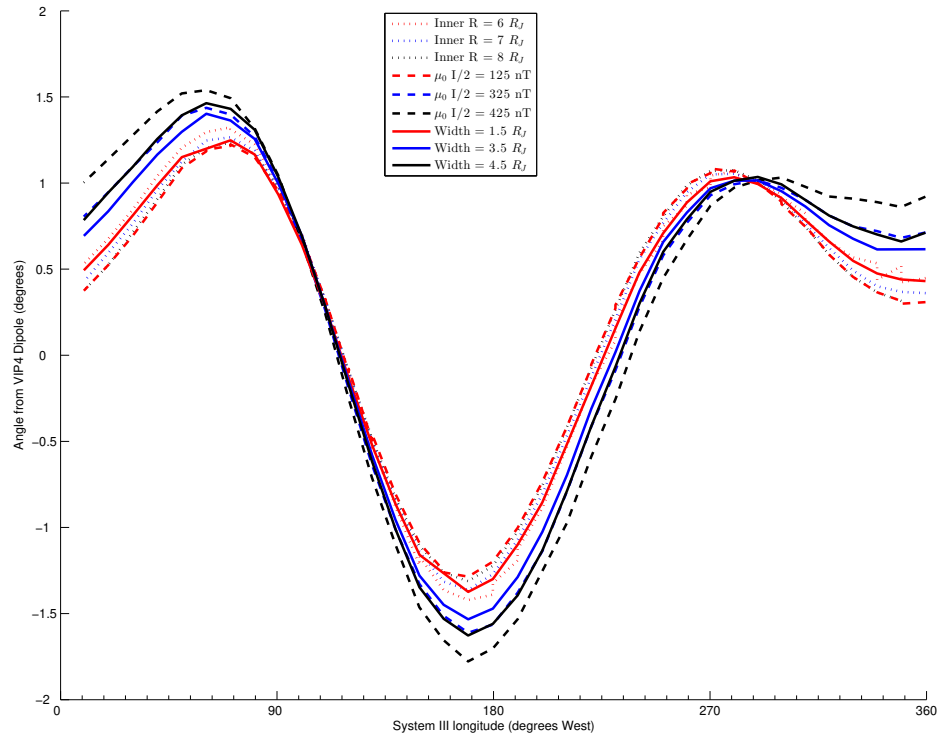


Figure 9. Dependence on longitude of values at $6 R_J$ for all nine CAN tests shown in Figure 8. The dotted lines show variation in the CAN inner radius, the dashed lines show variations in the CAN current density, and the solid lines show variation in the CAN half-width.

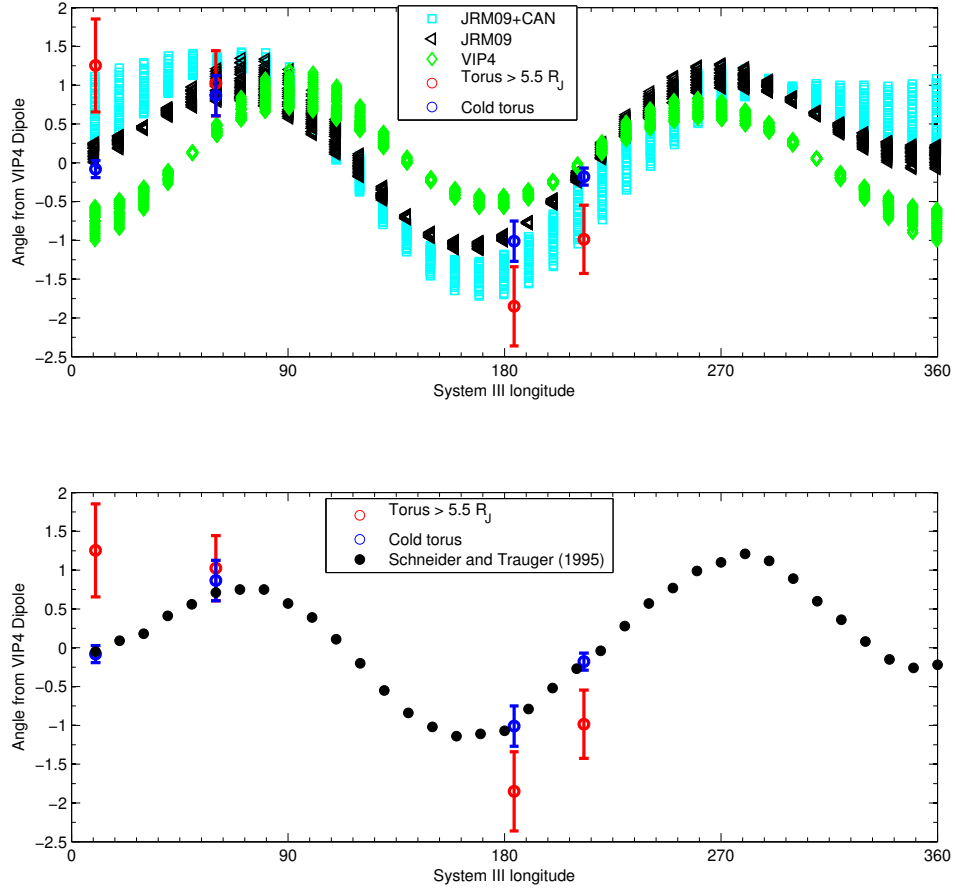


Figure 10. (top) Observed and predicted locations of the centrifugal equator. Blue symbols and red symbols are Juno radio occultation observations of the cold torus and the torus beyond $5.5 R_J$, respectively. Predicted values are from the full VIP4 internal field model (green), the truncated JRM09 internal field model (black), and the combination of the truncated JRM09 internal field model and the nominal current sheet model (cyan) as shown in Figure 7. Predictions are shown for radial distances of $5\text{--}8 R_J$. (bottom) Comparison of the location of the centrifugal equator as determined by ground-based imaging and Juno radio occultation observations. Blue symbols and red symbols are Juno radio occultation observations of the cold torus and the torus beyond $5.5 R_J$, respectively. These show location relative to the centrifugal equator of the dipolar approximation to the VIP4 internal field model. Black symbols are ground-based imaging observations of the ribbon by *Schneider and Trauger* [1995]. These show location relative to the offset tilted dipole (OTD) model used by *Schneider and Trauger* [1995].

Table 1. The top portion of this table lists parameters of the dipolar approximations to the VIP4 and JRM09 models. The bottom portion of this table lists the parameters of the CAN model.

Internal Model	M Gauss	θ_M degrees	λ_{III} degrees
VIP4	4.264	9.6	200.8
JRM09	4.170	10.31	196.61
External Model	$\mu_0 I_0/2$ nT	D R_J	Inner Radius R_J
<i>Connerney et al.</i> [1981]	225	2.5	5

Table 2. Offsets (α) of observed locations of torus regions from the centrifugal equator predicted by the dipolar approximation to the VIP4 model. Uncertainties are also listed (σ). Values are from *Phipps et al.* [2018] (PJ1) and *Phipps et al.* [2019] (PJ3, PJ6, and PJ8).

Perijove	cold torus		torus $> 5.5 R_J$	
	α degrees	σ degrees	α degrees	σ degrees
Perijove 1	-0.90	0.10	-1.70	0.20
Perijove 3	0.79	0.26	1.47	0.41
Perijove 6	-0.19	0.11	-0.91	0.44
Perijove 8	0.05	0.12	1.08	0.60