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Analysis of Juno perijove 1 magnetic field data using the Jovian paraboloid magnetospheric model

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Abstract. One of the main features of Jupiter's magnetosphere is its equatorial magnetodisc, which significantly increases the field strength and size of the magnetosphere. Juno measurements of the magnetic field during the perijove 1 pass have allowed us to determine optimal parameters of the magnetodisc using the paraboloid magnetospheric magnetic field model, which employs analytic expressions for the magnetospheric current systems. Specifically within the model we determine the size of the Jovian magnetodisc and the magnetic field strength at its outer edge.

1 Introduction

In this paper we consider magnetic field measurements made during the Juno perijove 1 pass (the first since the orbit insertion pass numbered "0"), paying particular attention to the middle magnetosphere measurements where Jupiter's magnetodisc field plays a major role. The structure and properties of the Jovian magnetodisc have been described in many papers starting from the first spacecraft flybys to Jupiter, as discussed, e.g., by Barbosa et al. (1979), and references therein. In particular, the empirical magnetodisc model published by Connerney et al. (1981), derived from Voyager-1 and -2 and Pioneer-10 observations, has been employed as a basis in numerous subsequent studies, including predictions for the Juno mission by Cowley et al. (2008, 2017). Detailed physical models have also been constructed, by Caudal (1986) who presented a steady-state MHD magnetodisc model in which both centrifugal and plasma pressure (assumed isotropic) forces were included, and by Nichols (2011) who incorporated a self-consistent plasma angular model. Nichols et al. (2015) have also included the effects of plasma pressure anisotropy, as observed in Voyager and Galileo particle measurements, which redistributes the azimuthal currents in the magnetodisc changing its thickness.

Here we model the magnetic field observations during Juno perijove 1 using the semi-empirical global paraboloid Jovian magnetospheric magnetic field model derived by Alexeev and Belenkaya (2005). We focus on the middle magnetosphere, for which the magnetodisc provides the main contribution to the magnetospheric magnetic field. In the model, in which the field

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contributions are calculated using parameterised analytic equations, the magnetodisc is described by a simple thin plane disc lying in the planetary magnetic equatorial plane. We thus search the paraboloid model input parameters to determine the best fit to the Juno perijove 1 measurements.

2 Jupiter paraboloid model

The paraboloid magnetospheric magnetic field model was developed for Jupiter by Alexeev and Belenkaya (2005), based on the terrestrial paraboloid model of Alexeev (1986). It contains the internal planetary field, $\boldsymbol{B}_{\mathrm{i}}$, calculated from the full order-4 VIP4 model of Connerney et al. (1998), the magnetodisc field, $\boldsymbol{B}_{\mathrm{MD}}$, the field of the magnetopause shielding currents, $\boldsymbol{B}_{\mathrm{si}}$ and $\boldsymbol{B}_{\mathrm{sMD}}$, screening the planetary and magnetodisc fields, respectively, the field of the magnetotail current system, $\boldsymbol{B}_{\mathrm{TS}}$, and the penetrating part of the interplanetary magnetic field (IMF), $k\boldsymbol{B}_{\mathrm{IMF}}$, where k is the IMF penetration coefficient. The magnetopause is described by a paraboloid of revolution in Jovian solar magnetospheric (JSM) coordinates with the origin at Jupiter's centre

$$\frac{x}{R_{\mathrm{ss}}} = 1 - \frac{y^2 + z^2}{2R_{\mathrm{ss}}^2} \tag{1}$$

where X is directed towards the Sun, the X-Z plane contains the planet's magnetic moment, and Y completes the right-hand orthogonal set pointing towards dusk. R_{ss} is the distance to the subsolar magnetopause, where $y = 0$ and $z = 0$. The magnetospheric magnetic field, $\boldsymbol{B}_{\mathrm{m}}$, is then the sum of the fields created by all these current systems

$$\begin{aligned}\boldsymbol{B}_{\mathrm{m}} = \boldsymbol{B}_{\mathrm{i}}(\Psi) + \boldsymbol{B}_{\mathrm{TS}}(\Psi, R_{\mathrm{ss}}, R_2, B_{\mathrm{t}}) + \boldsymbol{B}_{\mathrm{MD}}(\Psi, B_{\mathrm{DC}}, R_{\mathrm{DC1}}, R_{\mathrm{DC2}}) + \boldsymbol{B}_{\mathrm{si}}(\Psi, R_{\mathrm{ss}}) + \\ + \boldsymbol{B}_{\mathrm{sMD}}(\Psi, R_{\mathrm{ss}}, B_{\mathrm{DC}}, R_{\mathrm{DC1}}, R_{\mathrm{DC2}}) + k\boldsymbol{B}_{\mathrm{IMF}}\end{aligned} \tag{2}$$

where Ψ is Jupiter's dipole tilt angle relative to the Z axis. The magnetodisc is approximated as a thin disc with outer and inner radii R_{DC1} and R_{DC2}, respectively. B_{DC} is the magnetodisc field at the outer boundary, while the azimuthal currents in the disc are assumed to decrease as r^{-2}. R_2 is the distance to the inner edge of the tail current sheet, and B_{t} is the tail current magnetic field there. The magnetospheric current systems are thus described by nine input parameters, determining the physical size of the current systems, and their magnetic field (current) strength (Ψ, R_{ss}, R_2, R_{DC1}, R_{DC2}, B_{t}, B_{DC}, k, $\boldsymbol{B}_{\mathrm{IMF}}$).

Alexeev and Belenkaya (2005) and Belenkaya (2004) determined model parameters which approximated the magnetic field along the Ulysses inbound trajectory rather well. These parameters are $R_{\mathrm{ss}} = 100\,R_{\mathrm{J}}$, $R_2 = 65\,R_{\mathrm{J}}$, $B_{\mathrm{t}} = -2.5\,\mathrm{nT}$, $R_{\mathrm{DC1}} = 92\,R_{\mathrm{J}}$, $R_{\mathrm{DC2}} = 18.4\,R_{\mathrm{J}}$, and $B_{\mathrm{DC}} = 2.5\,\mathrm{nT}$. This set of parameters is used in the present paper as a starting point for fitting parameters for the Juno data. The angle dipole tilt angle Ψ changes during the observations and is calculated as a function of time in the paraboloid model. As the interplanetary field is unknown during the Juno mission, we neglect it here.

3 Magnetic field calculations along the Juno perijove 1 orbit

As indicated above, field calculations have been made using the paraboloid model for the Juno perijove 1 trajectory, for comparison with the observed data. The orbit was closely polar, with large eccentricity, and apoapsis located in the dawn

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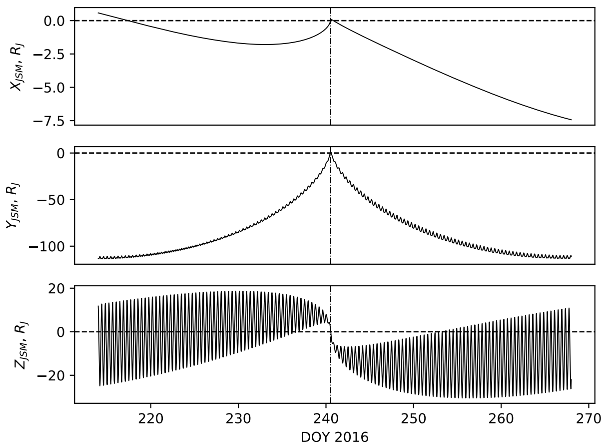

Figure 1. Juno perijove 1 trajectory in JSM Cartesian coordinates plotted versus time in DOY 2016, where the vertical dashed line shows the time of periapsis.

magnetosphere (see, e.g., Connerney et al. (2017)). We consider separately the inbound and outbound passes of the orbit. Figure 1 shows the perijove 1 trajectory versus time (in day of year (DOY) 2016) in JSM Cartesian coordinates, where the vertical dashed line shows the time of periapsis.

We first investigate the main factors which control the magnetic field along the Juno trajectory, and in Figure 2 show the magnitude of the modelled field from different sources along the inbound (left) and outbound (right) trajectory legs. The model parameters are those from Alexeev and Belenkaya (2005) as outlined in Section 2. The red line shows the internal JRM09 ("Juno Reference Model through perijove 9") planetary field (Connerney et al., 2018), while the black lines show the field of the various magnetospheric current systems in the paraboloid model as marked. The JRM09 model employed the magnetic field data from first nine Juno orbits, plus their disc model, to derive Jupiter's internally-generated field to degree 20 spherical harmonics. It can be seen from the figure that for $r < 60\,R_{\mathrm{J}}$ the contributions to the magnetospheric field from the magnetopause and tail current systems are negligible compared with the magnetodisc field.

In the present paper we mainly consider the middle part of the magnetosphere where the magnetodisc is the dominant magnetospheric contributor to the field. The solar wind influence is mainly important in the outer magnetosphere, which we do not study here, as the solar wind conditions are unknown while Juno is inside the magnetosphere. Thus, we cannot analyse the field in the outer magnetosphere correctly, and the use of averaged parameters is not adequate in this region. For this reason, we fit only magnetodisc parameters, while for the other parameters we use the Ulysses values from Alexeev and Belenkaya (2005) and Belenkaya (2004), i.e., $R_{\mathrm{ss}} = 100\,R_{\mathrm{J}}$, $R_2 = 65\,R_{\mathrm{J}}$, $B_{\mathrm{t}} = -2.5\,\mathrm{nT}$. The use of the Ulysses magnetodisc parameters is found to lead to a systematic underestimation of the field along the perijove 1 trajectory, and thus need to be modified. We retain use of the Ulysses value of the outer radius of the magnetodisk, $R_{\mathrm{DC1}} = 92\,R_{\mathrm{J}}$. The deep and sharp field decreases due to the equatorial current sheet encounters continue to be observed on the Juno trajectory even at large radial distances $r > 90\,R_{\mathrm{J}}$,

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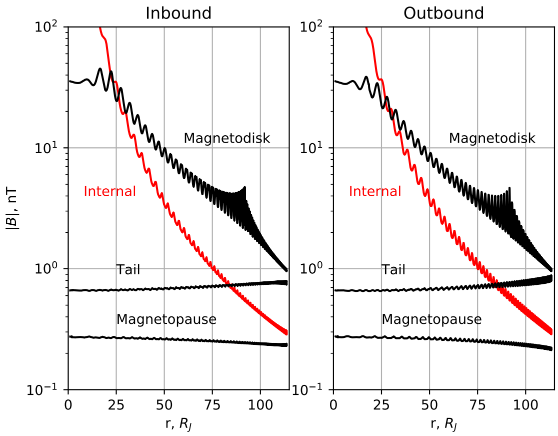

Figure 2. Magnitude of the model magnetic fields for the Juno perijove 1 inbound (left) and outbound (right) trajectories, due to the internal planetary field (JRM09, red), and the various model magnetospheric currents (magnetopause, tail, and magnetodisc, black).

but at such distances the precise radius of the outer boundary has little effect on the field at radial distances $r < 60\,R_\mathrm{J}$. Thus, only two parameters, R_DC2 and B_DC, need to be fitted.

To optimize the model we choose the approach of minimizing function S given by

$$S^2(B_\mathrm{DC}, R_\mathrm{DC2}) = \frac{1}{N}\sum_{n=1}^{N}\left(\frac{\boldsymbol{B}^{(n)}_\mathrm{mod} - \boldsymbol{B}^{(n)}_\mathrm{obs}}{|\boldsymbol{B}^{(n)}_\mathrm{mod}|}\right)^2 \tag{3}$$

where $\boldsymbol{B}^{(n)}_\mathrm{mod}$ and $\boldsymbol{B}^{(n)}_\mathrm{obs}$ are the values of the modeled and observed magnetic field vectors, respectively, and n is the index number of the data point along the trajectory; the total number of points is N. S represents a root-mean-square relative deviation of the modelled magnetic field from the observed field vectors. We used a relative deviation instead of an absolute value to equalize the influence of all the data points, noting that the magnetic field varies in magnitude significantly along the part of the trajectory examined here. Use of the absolute deviation would result in the region closer to the planet, where the field magnitude is greater, having a much stronger influence on the optimal values of parameters than the outer region, which is undesired.

With regard to the choice of interval employed to minimize S, we note that use of data from the innermost region is not optimal. The JRM09 internal planetary field model differs from observations at periapsis ($1.06\,R_\mathrm{J}$) by $0.3\cdot10^5\,\mathrm{nT}$ (Connerney et al., 2018), which is a reasonable accuracy for describing the observed field of roughly $8\cdot10^5\,\mathrm{nT}$ in magnitude, but does not allow us to distinguish the magnetodisc field in order of $100\,\mathrm{nT}$ on this background. We thus restricted the inner border of the interval to consider only $r > 5\,R_\mathrm{J}$. This is an arbitrary value, but the specific position within a range $\sim 5-10\,R_\mathrm{J}$ of the inner border of the fitting interval does not significantly affect the location of the minimum in S. On the other hand, the location of the minimum of the root-mean-square absolute deviation does depend strongly on the position of the inner fitting interval boundary, which is another reason not to use it for the present problem. A further limitation on the region of calculation of

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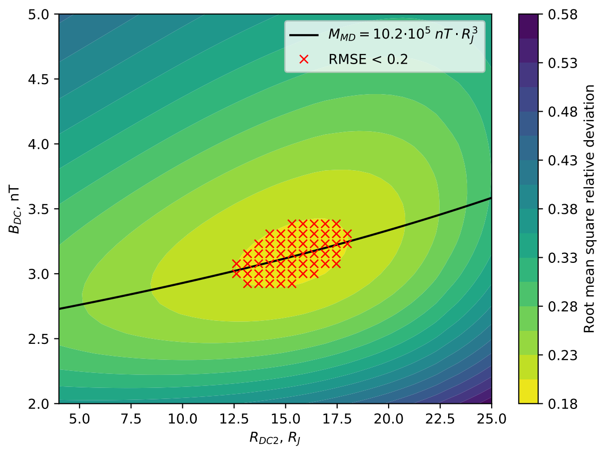

Figure 3. Contour plot showing the dependence of S given by equation 3 on magnetodisc parameters R_{DC2} and B_{DC} for field data in the radial range $5 < r < 60\,R_{\mathrm{J}}$.

S in the outer magnetosphere arises from the fact that the paraboloid model does not display regions of low field strength during intersections with the magnetodisc, as is observed in the field at larger distances, due to the use of the infinitely thin disc approximation (see Section 4). Thus, it is necessary to avoid these regions.

To minimize S in the radial range $5 < r < 60\,R_{\mathrm{J}}$ (excluding regions with current layer crossings), the optimum parameters are found to be $B_{\mathrm{DC}} = 3.15\,\mathrm{nT}$ and $R_{\mathrm{DC2}} = 15.8\,R_{\mathrm{J}}$. This is demonstrated in Figure 3, which shows the dependence of S on R_{DC2} and B_{DC} for the data in this radial range. The minimum is not very sharp, so it is necessary to provide some uncertainty intervals for the parameters. To do this, we choose a minimal reliable value of $S = 0.2$ and consider all the pairs of parameters, for which $S < 0.2$ as acceptable (marked in Figure 3 by red crosses). Resulting intervals for the two fitted parameters are then found to be as follows, $13 < R_{\mathrm{DC2}} < 18\,R_{\mathrm{J}}$ and $2.9 < B_{\mathrm{DC}} < 3.4\,\mathrm{nT}$. These parameters are not independent, of course, and not all pairs in this parameter rectangle are acceptable (see Figure 3). As shown by Alexeev and Belenkaya (2005), the effective magnetic dipole moment of the modelled current disk is equal to

$$M_{\mathrm{MD}} = \frac{B_{\mathrm{DC}}}{2} R_{\mathrm{DC1}}^3 \left(1 - \frac{R_{\mathrm{DC2}}}{R_{\mathrm{DC1}}}\right) \tag{4}$$

The black curve in Figure 3 corresponds to a constant M_{MD} value calculated using the optimum parameters with constant R_{DC1}, corresponding to a factor of 2.4 times the planetary dipole moment. Acceptable pairs of parameters are aligned with that line to some extent.

Figures 4 and 5 show comparisons of the observed (orange) and modelled (black and violet) residual field magnitudes plotted versus radial distance for the inbound and outbound perijove 1 trajectories, respectively. The JRM09 planetary field has been subtracted from the observed and modelled values. The violet curves show the Ulysses model while the black curves show the model derived here with optimum parameters. As can be seen the model with optimum parameters is in good accordance with the observations over the region $15 < r < 60\,R_{\mathrm{J}}$. As the distance from Jupiter decreases, a sharp increase in the residual field

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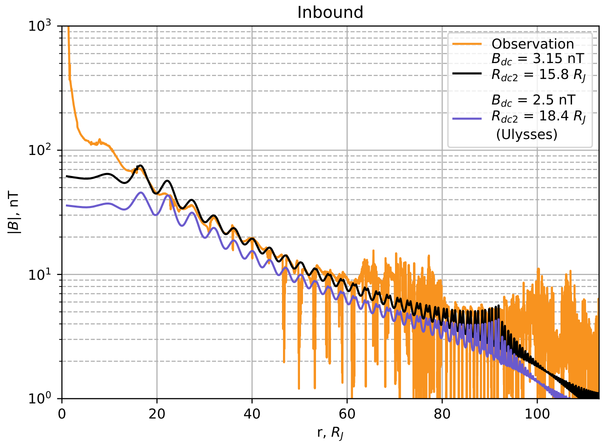

Figure 4. Magnitude of the residual magnetic field for the inbound pass of Juno perijove 1, from which the JRM09 model has been subtracted, plotted versus radial distance. The observed residual field is shown by the orange line, while the violet and black lines show modelled residual fields for different magnetodisc parameters as indicated, the violet curve being the Ulysses model of Alexeev and Belenkaya (2005), and the black from the present study with optimum parameters.

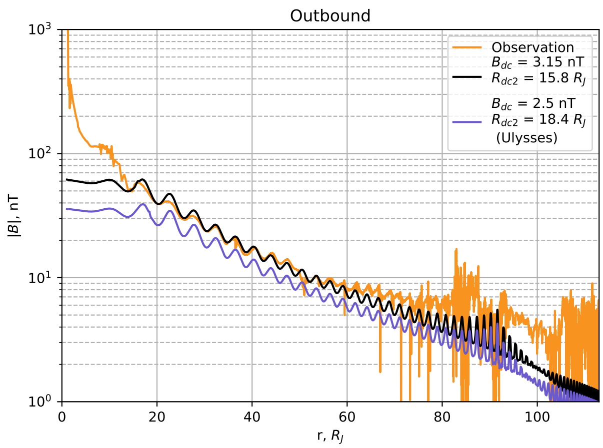

Figure 5. Same as Figure 4, but for the outbound pass of perijove 1.

is observed in the inner region to $> 100\,\mathrm{nT}$, while the model field plateaus at several tens of nT. At the closest distances from the planet the increase is probably due to inaccuracy of the JRM09 model of the internal field. But in the region $5 < r < 15\,R_\mathrm{J}$ it is hard to tell the reason for this increase. It is possibly also due to inaccuracy of the JRM09 approximation, or could be a consequence of a problem with the magnetodisc model applied in the paraboloid model. We note that the JRM09 model coefficients were obtained using a different model of the magnetodisc (Connerney et al., 1981, 2018).

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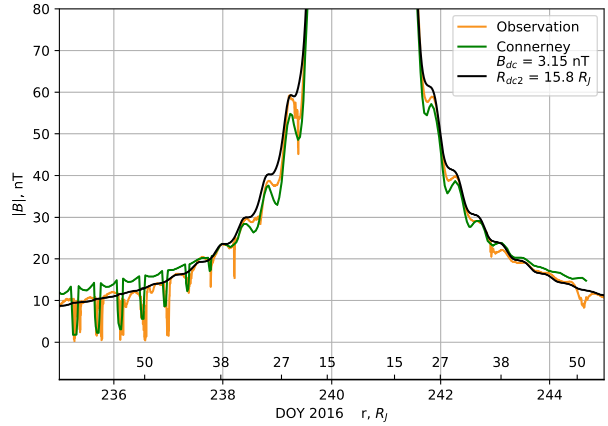

Figure 6. Magnetic field magnitude measured by Juno (orange curve), with model field calculated using the Connerney et al. (1981) model (green curve, taken from Connerney et al. (2017)) and the paraboloid model (black curve), using the optimum parameters determined here.

4 Approaches for future improvement of the Jupiter's paraboloid model

In the model of Jupiter's magnetodisc derived by Connerney et al. (1981) from Voyager-1 and -2 and Pioneer-10 field data, the current flows in a planet-centred annular disc of full thickness $5\,R_\mathrm{J}$, with inner and outer radii at 5 and $\simeq 50\,R_\mathrm{J}$, respectively. The azimuthal current in the disc is taken to vary as I_0/ρ, where ρ is the perpendicular distance from the planetary dipole magnetic axis. Figure 6 shows a comparison of the observed magnetic field magnitude (orange curve) with model results using the VIP4 internal field plus Connerney et al. magnetodisc model (green curve, taken from Connerney et al. (2017)), together with the paraboloid model with $B_\mathrm{DC} = 3.15\,\mathrm{nT}$ and $R_\mathrm{DC2} = 15.8\,R_\mathrm{J}$ (black curve). One important difference between the model results consists in the fact that the Connerney et al. (1981) model well reflects the observed periodic sharp drops of magnetic field strength during spacecraft intersections with the disc. The magnetodisc radial magnetic field component reverses sign above and below the disc, and at its centre becomes equal to zero. As indicated in Section 3, the paraboloid model having an infinitely thin disc certainly cannot reproduce this feature, and should thus be improved by use of a disc current of finite thickness. The Connerney et al. model demonstrates reasonable coincidence with observations near Jupiter, but at greater distances overestimates the magnetic field strength.

Figure 7 shows the observed azimuthal magnetic field component on the Juno perijove 1 inbound pass. The short-term modulations of the field between positive and negative values relate to crossings of the current sheet near the planetary rotation period, pointing to the well-known existence of radial currents in magnetodisc associated with sweepback of the field into a "lagging" configuration (e.g., Hill (1979)). Both models considered here, the Connerney et al. (1981, 2017) model and the paraboloid model of Alexeev and Belenkaya (2005) do not include these currents, but only the azimuthal current in the magnetodisc. Such radial currents have been included in the models by Khurana (1997) and Cowley et al. (2008, 2017), and could be a useful addition to the paraboloid model, together with their field-aligned and ionospheric closure currents.

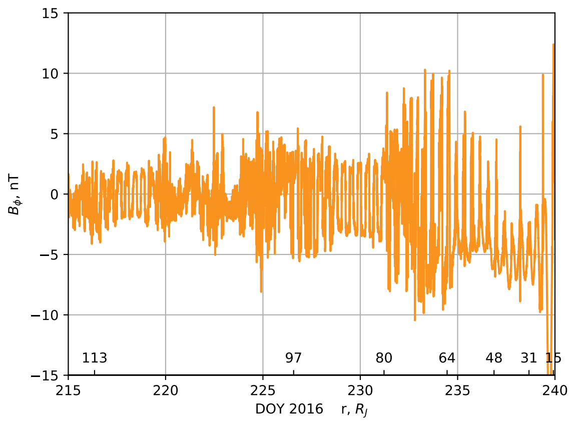

Figure 7. Azimuthal field component measured by Juno along the perijove 1 inbound pass.

We also note that the Jovian magnetosphere depends strongly on conditions in the solar wind, the influence of which increases at large distances from the planet, where the spacecraft moves relatively more slowly and hence spends most time. However, because we have no direct simultaneous information about the upstream solar wind, apart perhaps for the limited information obtained by computer modelling using data from near Earth orbit as input, it is very difficult to separate space and solar wind-modulated temporal field variations in these outer regions. For $r > 60\,R_\mathrm{J}$ in the outer magnetosphere, even our new parameters result in systematic underestimation of the magnetic field strength. Magnetodisc models with azimuthal current dependencies different from r^{-2} should also be investigated.

5 Discussion and Conclusions

As shown in Fig. 2, in the middle part of the Juno perijove 1 trajectory, selected for study here ($15 < r < 60\,R_\mathrm{J}$), the main contribution to the field due to the magnetospheric current systems is the equatorial magnetodisc. Here we have refined the magnetodisc parameters within the Jovian paraboloid model to best fit the Juno data in this region. Analysis of the field at very close radial distances requires better knowledge of the internal planetary field, while that at large distances is strongly influenced by the solar wind, whose simultaneous parameters remain unknown.

As a simplest approximation we took parameters found for the Ulysses mission data (Alexeev and Belenkaya, 2005; Belenkaya, 2004), and changed only R_DC2 and B_DC, the inner radius of the disc and the field strength at its outer radius. The profile of the magnetic field in the middle magnetosphere is then determined by a combination of these two parameters together with an unchanged outer radius $R_\mathrm{DC1} = 92\,R_\mathrm{J}$. These three parameters then determine the total current in the magnetodisc. Fitting of R_DC2 shows that a better result is obtained by decreasing its value to $15.8\,R_\mathrm{J}$ relative to the Ulysses value of $18.4\,R_\mathrm{J}$, with a simultaneous small increase of B_DC to $3.15\,\mathrm{nT}$ from $2.5\,\mathrm{nT}$.

To further refine the Jovian paraboloid magnetospheric model, it will be necessary to take into account the finite thickness of the magnetodisc current, and also to accurately determine its dependence on the radial distance from the planet. The existence of radial currents in the disc, as well as their closure via field-aligned currents in the planetary ionosphere, should also be incorporated.

Competing interests. The authors declare that they have no conflict of interest.

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