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A close-up view of Jupiter's magnetic field from Juno: New insights into the planet's deep interior

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Key Point:
- New insights into Jupiter's deep interior

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Abstract The first results from the Juno mission magnetometer have recently become available. Juno provides us with the closest view of any planetary dynamo, flying to within 1.25 of the radius of the dynamo region, whereas for the Earth, we cannot get closer than 1.83 of the core-mantle boundary radius. We compare the Juno results with those from first principles dynamo simulations of Jupiter's magnetic field. Intense flux patches at Jupiter's surface are found in both the data and the simulations, though the simulations have them mainly at slightly higher latitudes than the observations. We consider the prospects for determining more accurately the location of the top of the metallic hydrogen region and the implications of possible weak flux patches at the poles.

1. Introduction

The results from the Juno mission magnetometer have been eagerly awaited by scientists studying Jupiter's magnetic field. The data gathered by six previous missions, combined with information arising from observations of the magnetic foot point of Io, have given us an overview of the main features of its magnetic field [*Connerney*, 1993; *Connerney et al.*, 1998; *Ridley and Holme*, 2016], but all these data constrained its spherical harmonics only up to at most degree 7, giving a very broad brush view of the field. Jupiter has the strongest magnetic field of any planet in our solar system, and it is mainly dipolar, with the dipolar axis inclined by about 10° to the rotation axis. The shape of the field is therefore broadly similar to that of the Earth, though its dipole moment is 19,000 times larger. The paper by *Moore et al.* [2017] in this issue of *Geophysical Research Letters* interprets the data from the first flyby which had the instrumentation working, on 27 August 2016. It is clear from the results and the analysis that the magnetometer data are not going to disappoint. Data quality is high, and even from this single pass (30 flybys are planned) our picture of Jupiter's field has changed in important ways. The first perijove pass, PJ1, flew along a pole to pole track, reaching down to only 4200 km above Jupiter's cloud tops, and subsequent passes will be similar. It is the closeness of the approach which is particularly exciting for people interested in how planetary magnetic fields arise. These fields are generated in the dynamo region, above which the electrical conductivity rapidly falls to zero. In the Earth, the dynamo occurs in the liquid outer core, so the dynamo region extends to the core-mantle boundary, located at $R_{\rm dyn} = 3480$ km, and the mean radius of the Earth, where the observations are made, is at $R_s = 6371$ km. The geomagnetic data from space missions such as Swarm are of course taken farther from the center of the Earth.

Above the dynamo region (and below the ionosphere) currents are negligible, and the magnetic potential for the internally generated field **B** is

$$V = R_s \sum_{n=1}^{\infty} \sum_{m=0}^{m=n} \left(\frac{R_s}{r}\right)^{n+1} P_n^m(\cos\theta)\left(g_n^m \cos m\phi + h_n^m \sin m\phi\right) \quad (1)$$

where $\mathbf{B} = -\nabla V$; r, θ, and ϕ are spherical polar coordinates; $r = R_s$ is the planetary surface; and P_n^m are Schmidt normalized associated Legendre functions. The Gauss coefficients g_n^m and h_n^m are defined at the Earth's surface, $r = R_s$. The Lowes-Mauersberger spectrum,

$$R_n = \left(\frac{R_s}{r}\right)^{2n+4} (n+1) \sum_{m=0}^{n} \left[\left(g_n^m\right)^2 + \left(h_n^m\right)^2\right] \quad (2)$$

is quite flat at $r = R_{\rm dyn}$ [*Lowes*, 1974], and indeed it is expected to be flat at the outer boundary of any high magnetic Reynolds number natural dynamo, until the dissipation cutoff is reached at very large n. So g_n^m and h_n^m have to become very small at large n, reduced by a factor $(R_{\rm dyn}/R_s)^{n+2}$. Unfortunately, in the case of the Earth this means that the signal from the internal dynamo field is lost in the noise from crustal magnetism for n larger than about 12 or 13. This means that the geomagnetic field coming from the core cannot be accurately determined above $n = 13$ no matter how accurate the magnetometers used are. Our view of the Earth's field is inevitably fuzzy, because direct observation of the field is denied to us.

The key parameter for observing magnetic fields is $R_{\rm dyn}/R_{\rm obs}$, where $R_{\rm obs}$ is the radius at which the observations are made. It is here that the Juno mission scores so well. For the Earth, we are restricted to $R_{\rm dyn}/R_{\rm obs} = 3480/6371 = 0.546$ (except in Hollywood movies!). The value of $R_{\rm dyn}$ for Jupiter is not yet certainly known, but both observational and theoretical arguments suggest that it is between 0.85 R_{jup} and 0.9 R_{jup}. Since Juno approached to within 4200 km above its nominal radius of 71,398 km, $R_{\rm obs}/R_{jup} = 1.06$ only, so with even the most pessimistic lower value of $R_{\rm dyn}$, $R_{\rm dyn}/R_{\rm obs} = 0.8$, allowing a much better view of Jupiter's dynamo than is possible for the Earth. Of course, 4200 km is the closest point of the flyby, and though $R_{\rm dyn}/R_{\rm obs}$ is well within two radii at the north pole, it is larger at the south pole. Also, the noise levels from Jupiter's ring current may make it difficult to resolve very high n, but the data so far look very promising.

Interestingly, Jupiter gives us the best view (largest $R_{\rm dyn}/R_{\rm obs}$) of any natural high magnetic Reynolds number dynamo. It is clearly the optimal solar system planet (Saturn's metallic hydrogen region reaches up to $\sim$0.64 R_{sat}, but the dynamo region appears to extend only to $R_{\rm dyn}/R_{sat} \approx 0.4$ [*Cao et al.*, 2012]). Despite many attempts, laboratory dynamos can currently only reach magnetic Reynolds numbers just above critical for dynamo action, so they have no high n components in their magnetic fields. The solar dynamo is believed to be generated near the tachocline [*Tobias and Weiss*, 2007], $R_{\rm dyn}/R_{\rm obs} \approx 0.71$, but there is 200,000 km of current carrying plasma above the tachocline, so (1) does not apply. It is only by indirect observations of waves [e.g., *McIntosh et al.*, 2017] that we have any chance of probing the solar dynamo region. The Juno observations may therefore give us new information about how all natural dynamos work, and this may change our views of the dynamics of the deep interior of the Earth and other planets.

2. Jupiter's Deep Interior: The Metallic Hydrogen Transition

When we have further perijove flyby data available, it should be possible to improve our estimates of $R_{\rm dyn}$, by constraining the Lowes spectrum (2) for Jupiter. Our current view is that there is a continuous but rapid decline in the electrical conductivity as we move up out of the metallic hydrogen region. Density functional theory can be used to evaluate the electrical conductivity under Jupiter-like conditions [e.g., *French et al.*, 2012]. The result is a superexponential decline of conductivity with r, setting in at about $r \approx 0.85\ R_{jup}$. Some high pressure experiments have suggested that the dropoff in conductivity may occur farther out, at $r \approx 0.90\ R_{jup}$ or even $r \approx 0.95\ R_{jup}$. However, our knowledge of Jupiter's actual conductivity is far from complete, because in the density functional theory there is an uncertainty about the exchange potential term, and in the experiments it is very hard to reproduce Jupiter's temperature and pressure conditions. A combination of the new observational data with the results from dynamo models based on a range of conductivity models may well constrain the electrical properties of metallic hydrogen much more reliably than we can at present.

A notable feature of the *Moore et al.* [2017] results is the existence of strong patches of magnetic flux near the equator. These have not been seen in previous models of Jupiter's magnetic field, because the resolution to detect them was not available. Strong flux patches do show up in high-resolution Jupiter dynamo simulations [*Jones*, 2014; *Gastine et al.*, 2014]. In Figure 1 we compare the Juno data analyzed by *Moore et al.* [2017] with a snapshot from a dynamo simulation run. *Moore et al.* [2017] overcome the difficulty that the single flyby data are only useful to evaluate the magnetic field near the flyby path by using a new data analysis technique. Figure 1a shows the radial component of the magnetic field which they derive at $r = 0.85\ R_{jup}$, while Figure 1b shows it at $r = R_{jup}$. Only near the path are the data sufficient to require updating of the previous models. The intense near-equatorial negative flux patch just east of the flyby path (solid line) is robust, as are some of the smaller flux concentrations. At $r = R_{jup}$ the peak field in the patch is comparable to the peak positive field in the northern hemisphere. Figures 1c and 1d are taken from the run I simulation of *Jones* [2014]. This used a fixed flux outer boundary condition, rather than a fixed entropy condition. It is known from geodynamo simulations that the thermal boundary conditions can affect field morphology [*Sakuraba and Roberts*, 2009], and the fixed flux condition appears to fit slightly better with the Juno data. The dimensionless unit of field in

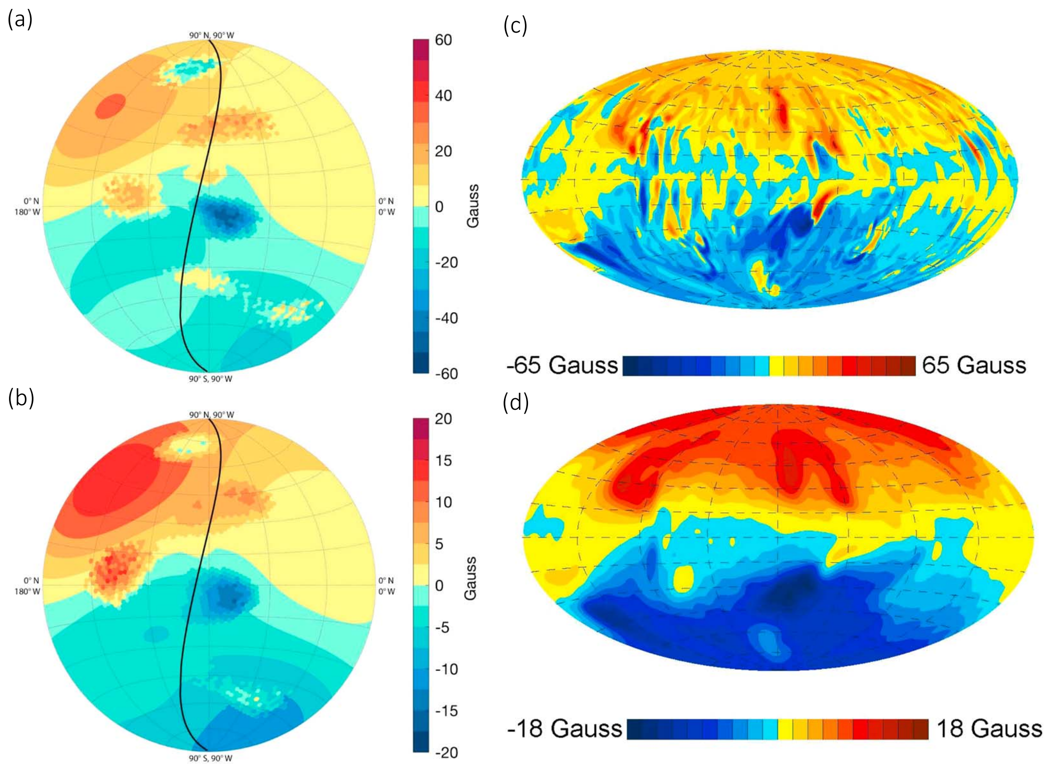

Figure 1. (a) The radial component of Jupiter's magnetic field at $r = 0.85\,R_{jup}$ taken from *Moore et al.* [2017]. (b) The same but at $r = R_{jup}$. (c) Output from a dynamo simulation from *Jones* [2014], showing the radial component of Jupiter's magnetic field at $r = 0.85\,R_{jup}$, and (d) the same at $r = 0.96\,R_{jup}$, the upper cutoff level of the simulation.

the simulation is converted to 13 G, the same conversion factor as used in *Jones* [2014]. The snapshot shows a rather similar negative flux patch at about latitude 30° S, which is displayed to have the same longitude as the Juno equatorial flux patch. Figure 1c is at $r = 0.85\,R_{jup}$, and Figure 1d is at $r = 0.96\,R_{jup}$, which is the computational cutoff in the simulation. The field at $r = R_{jup}$ will be similar to Figure 1d but with a slightly weaker amplitude. As with the *Moore et al.* [2017] data, the peak intensity of this flux patch is comparable with the peak positive field in the northern hemisphere at $r = R_{jup}$. There is still some uncertainty in the Juno data peak intensity, because a small very intense patch gives a similar signal to a broader less intense patch, but hopefully future flybys will resolve this uncertainty. There is an interesting difference between the simulations and the data, though. While the simulations do have intense flux patches of a similar magnitude to those showing up in the Juno data, they do not often occur inside latitude ±30°, whereas there is a strong patch in the Juno data almost at the equator. It seems that Jupiter's magnetic equator is more wavy than the simulations predicted, and if confirmed it will be interesting to study possible reasons for this.

When the Juno model data are evaluated at $r = 0.85\,R_{jup}$, smaller scale patches are also seen. The same is true in the dynamo simulation, and by comparing the relative intensity of these smaller scale patches, we can confirm (or disprove) the electrical conductivity model used in the simulations. These small flux patches are essentially the white noise expected when $r = R_{\rm dyn}$. First impressions are that the simulations are behaving similarly to the Juno data, supporting the *French et al.* [2012] conductivity model, but further work is necessary to confirm this. Until now, it seemed pointless to take into account the oblateness of Jupiter in dynamo models, because the observations were not good enough to distinguish between oblate and spherical dynamo models. The Juno data will change this situation, setting theoreticians a tough new challenge.

3. Weak Magnetic Flux at the Poles: A Signal of the Core?

A surprising feature of the radial component of the geomagnetic field, when plotted at the core-mantle boundary using (1), is that the maximum field occurs not at the poles but instead at latitudes ±70°. Indeed, the north polar patch inside latitude 70°N may even have reversed polarity, and the south polar patch is noticeably weak. The same effect is seen in dynamo simulations. There it is a clear signal of the solid inner core, whose radius $R_{icb}=0.35\,R_{cmb}$, where R_{cmb} is the radius of the core-mantle boundary. Columnar Busse convection rolls [*Busse*, 1970] collect just outside the inner core equator and contribute to the dynamo process [e.g., *Jones*, 2011]. This accumulates field aligned along the roll axis which comes out at the CMB at latitude $90° - \sin^{-1}(R_{icb}/R_{cmb}) = 70°$. So in the Earth, the weak polar patches are an indicator of a solid inner core.

It has been proposed [*Grodent et al.*, 2008; *Ridley and Holme*, 2016] that Jupiter also has a weak flux patch near its north pole. It is therefore very tempting to wonder whether this might be a signal of a solid core in Jupiter. The existence of a core has long been speculated, as it is difficult to see how Jupiter could form without one. To date there has not been much evidence of weak polar flux patches in Jupiter dynamo simulations, but this is not surprising as they have mostly used a small core radius. The *French et al.* [2012] model J11-8a had a core radius ratio of 0.092, so the polar cap would only be above $\pm 85°$, rather than $\pm 70°$ for the Earth. However, the size of the inner core is quite uncertain [e.g., *Guillot et al.*, 2004], so a larger inner core is possible. There is a further problem with the weak polar patch idea. Although the flow is columnar in low Rossby number anelastic convection, as it is in Boussinesq convection, the columns are typically not as robust in compressible simulations as in Boussinesq simulations, and the convection is more supercritical, as Jupiter's heat flux is much larger than the Earth's. Nevertheless, given the uncertainty about the convective Rossby number in Jupiter's interior, we cannot rule out the possibility that a solid core of radius say 10,000 km might be detectable from high quality magnetic data.

4. Secular Variation

The secular variation, the time dependence of the geomagnetic field, suggests that Earth's core flow is up to 10^{-3} ms^{-1}. This is a key figure that underpins our picture of core dynamics. *Ridley and Holme* [2016] found that the existing data on the Jovian field, which goes over a 44 year time span, could be better fitted by a time-varying field. Based on their models, Jupiter's interior velocity in the dynamo region is around 10^{-2} ms^{-1}. It is also possible to estimate core flow from the convective heat flux coming out of the planet, which for Jupiter is 5.4 Wm^{-2} [*Guillot et al.*, 2004]. An estimate by *Starchenko and Jones* [2002], taking into account the rapid rotation, gave 10^{-3} ms^{-1}, but subsequent work of *Christensen and Aubert* [2006], based on an extensive suite of dynamo simulations, increased this to 2×10^{-2} ms^{-1}. Convection in planetary cores is strongly influenced by rotation, and the desired parameter regime cannot be reached in simulations, so extrapolation is necessary to make these estimates, resulting in some uncertainty. Nevertheless, these estimates are at least in the same ball park as the Ridley and Holme values.

The Juno mission will last longer than originally planned, and it will be interesting to see if any evidence of magnetic features drifting relative to the planet emerges over time. A drift of about 1° over a 5 year period is expected from the 10^{-2} ms^{-1} estimate, so the secular variation is a challenging quantity to observe, but it could provide crucial information about the dynamics of Jupiter's deep interior.

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