The internal structure and dynamics of Jupiter unveiled by a high resolution magnetic field and secular variation model

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Abstract

Jupiter possesses the strongest magnetic field of all planets in the solar system. Modelling and interpreting this field gives essential information about the dynamo process acting at some depth inside Jupiter. Here we use the fluxgate magnetometer measurements acquired during the first four years of the Juno mission to derive an internal magnetic field and secular variation model using spherical harmonic functions. We compute an internal field model to degree 13, and a secular variation model to degree 8. The power spectrum of the field model is used to infer that the dynamo convective region has an upper boundary at 0.845±0.015 Jupiter radius, confirming that the transition layer plays a role in the field generation inside Jupiter. The secular variation timescales indicate that the dynamo is dominated by advective effects while the secular variation pattern suggests that the flow at the interior is complex and involves non-zonal features.
The internal structure and dynamics of Jupiter
unveiled by a high-resolution magnetic field and secular
variation model

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Key Points:
• Magnetic field of Jupiter is modeled from Juno’s first four years of observations.
• A degree 16 static and degree 8 secular variation magnetic field model is derived.
• The model indicates complex motions deep inside Jupiter.

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Abstract

Jupiter possesses the strongest magnetic field of all planets in the solar system. Unique information about the dynamo process acting at Jupiter can be inferred by modelling and interpreting its field. Using the fluxgate magnetometer measurements acquired during the four years of the Juno mission, we derive an internal and secular magnetic field model in spherical harmonics. The static part is derived to degree 16 with a secular time variation to degree 8. We use properties of the power spectrum of the static field to infer the upper boundary of the dynamo convective region at $0.830 \pm 0.022$ Jupiter radius. This confirms the role of the transition layer in the field generation inside Jupiter. The secular variation timescales indicate that advective effects dominate the dynamo and the secular variation structures estimated at the dynamo radius suggest that the complex flow involves non-zonal features.

Plain Language Summary

The interior of Jupiter can be described broadly as a dense core surrounded by fluids, dominantly hydrogen and helium. The hydrogen rich metallic fluid generates the strongest planetary magnetic field in the Solar System. Modelling and interpreting this field gives essential information about the dynamo process inside Jupiter. We use the Juno mission data throughout four years to derive an internal magnetic field and secular variation (SV) model using spherical harmonic functions. We take the fluxgate magnetometer measurements acquired during the first 28 orbits to compute a magnetic field model to degree 16, and model its temporal variation to degree 8. The power spectrum of the magnetic field model is used to investigate the radius of the dynamo region. Using the non-zonal and quadrupole family spectra, we infer that the convective region has an upper boundary at $0.830 \pm 0.022$ Jupiter radius. The slope of the SV timescales indicates that the dynamo is dominated by advective effects. The SV displays a maximum near the equator with a bi-polar structure in agreement with zonal drift of the Great Blue Spot. However, numerous small scale SV structures suggest that the flow at the interior is complex involving both zonal and non-zonal features.

1 Introduction

The interior of the giant planets of our Solar System can be described in simple terms as consisting of a core of unknown composition surrounded by fluid envelopes (Guillot, 2005). For Jupiter, the core could be small and dense, but also large and dilute (Wahl et al., 2017). The overlying envelopes consist of an inner layer of metallic hydrogen and an outer layer of molecular hydrogen. Recent experimental results describe a transition H-He demixing layer, suggesting Helium rain between depths 0.68 and 0.84 $R_J$ (Jupiter's equatorial radius, $1 R_J = 71,492$ km) (Brygoo et al., 2021). The high temperature and pressure inside the planet renders it electrically conducting. Convection in the electrically conductive metallic hydrogen generates the strong Jovian magnetic field (Jones, 2011, 2014). In contrast to rocky bodies, Jupiter does not have an abrupt change between its metallic hydrogen (magnetic source) and molecular hydrogen (source free) regions. The change is expected to be gradual. The electrical conductivity profile of the different hydrogen layers at different depths from an ab-initio simulation (French et al., 2012) does not indicate a clear value of the dynamo region radius. Previous attempts to constrain this radius using the magnetic energy spectrum place it somewhere between 0.80 and 0.90 $R_J$ (Langlais et al., 2014; Tsang & Jones, 2020; Connerney et al., 2022).

Jupiter’s magnetic field has been measured by various flybys and orbiting satellites. The observations made by the flybys of Pioneer 10 and 11, Voyager 1 and 2 (during the seventies) and the Ulysses probe (early nineties) gave some initial information about the planet (Smith et al., 1974; Ness et al., 1979; Balogh et al., 1992). The first orbiting satellite, Galileo, was launched in 1989. It provided measurements from Jupiter and its moons.
from 1995 to 2003. Although these magnetic observations are spread over long periods of time, there have been only a few attempts to constrain or estimate the temporal variation of the field (Connerney et al., 1982; Yu et al., 2010; Ridley & Holme, 2016). Out of these studies, only Ridley and Holme (2016) co-estimated the secular variation (SV) with the main field (MF) using magnetic field measurements made between 1973 and 2003. However, due to the inhomogeneous temporal and geographical data distribution, most of the selected observations were from the Galileo mission at low latitudes. Ridley and Holme (2016) computed two models, one with only MF time averaged Gauss coefficients and one with time dependent MF and SV coefficients. The latter model was considered better because of its lower residuals and greater smoothness. Nevertheless, they considered their SV model to be reliable only up to degree 2.

None of these spacecrafts provided data near the poles. This was overcome by the recent Juno measurements. Juno space probe was launched on August 5th, 2011 and entered Jupiter’s orbit in July 2016. Its magnetic measurements have already been used to propose recent models of the Jovian field. Connerney et al. (2018) provided a spherical harmonic (SH) internal field model up to degree 10 using the first 9 orbits. This initial model was improved by Connerney et al. (2022) who calculated a static model up to degree 30 for internal and degree 1 for external, using the first 33 orbits, using a generalized inversion technique to damp the unresolved parameters. They state that the Gauss coefficients are well resolved until degree 13 though useful information can be retained until degree 18 for some coefficients. Jupiter’s internal field is characterized by a very high magnitude, showing both dipole and non-dipole parts. The non-dipole field is dominantly observed in the northern hemisphere. Field change over a 45-year time span was observed and zonal drift was invoked to explain the temporal change of an intense magnetic flux patch near the equator (Moore et al., 2018, 2019). An updated external magnetodisk field model for Juno is also available (Connerney et al., 2020). None of the existing models based on Juno data attempt to model explicitly the current global temporal variation of the field.

In this study, we use the high quality Juno measurements to derive a SH model of the Jovian field, simultaneously describing its MF and SV up to SH degrees 16 and 8, respectively. Section 2 details the data and the selection criteria we use for this study. Section 3 describes the method used to derive the models and their spectra that was assessed with a thorough synthetic analysis (Supplementary Information, Text S1). In Section 4 we analyze the model and discuss our results. We first determine the dynamo radius assuming white spectrum of specific parts of the field. We also calculate the SV correlation times of the Jovian field. We finally downward continue the field into Jupiter’s interior to the estimated dynamo radius and infer kinematic properties. We conclude in Section 5.

2 Data

Juno has a near polar, highly elliptical orbit with apojove exceeding over 100 times the Jupiter’s radius. The prime mission lasted five years and provided data for 33 orbits with one complete orbit taking about 53 days. The space probe was initially planned to undergo a reduction maneuver for achieving 14-day science orbits but Juno entered safe mode for its second orbit, thereby remaining in its initial 53-day capture orbit for the entire mission. The spacecraft aims to obtain a global coverage of the planet. For the first eight orbits, the shift between successive orbits was 45 degrees in longitude. The subsequent shifts reduce the longitudinal spacing by half to obtain data from the gaps left previously.

Juno uses two fluxgate magnetometers, located on one of the three solar arrays to measure the vector magnetic field. Magnetic field measurements acquired by Juno are available under two versions. The version 1 data provides measurements across the en-
tire orbit, whereas the version 2 data gives only near planet measurements from the orbit, denoted as perijove hereafter. Both version 1 and 2 data are provided in three Cartesian coordinate systems - planetocentric, sun-state and payload. Since planetocentric system is body-fixed, it is the most appropriate to study the internal field. We use the version 2 one-second data in planetocentric coordinates from the first 28 perijoves (data available for only 27 perijoves, excluding the second one). As discussed later, synthetic tests inversion including the latest perijoves from 29 to 33 leads to an increase in polar gaps that degrades some model coefficients. Perijove 19 was also dismissed because spurious oscillations were later observed.

The periapsis reaches altitude as low as 2500 km, or radius $1.03 R_J$, and precesses about $1^\circ$ in latitude northward, starting from the equator, after each orbit. In order to minimize external field contributions and to increase the signal to noise ratio of high internal magnetic field harmonics, we select measurements near the planet’s surface, i.e., the vector data below an arbitrarily chosen altitude of 300,000 km (or radius $\sim 5.2 R_J$).

Moreover, due to geometric attenuation with the altitude, high-altitude measurements are less sensitive to small spatial scales than the ones at comparatively lower altitudes. The vector data range from August 2016 to July 2020 giving 628,828 data locations, that are plotted in Supporting Information (Figure S1). Minimum measured field intensity is of the order of 3000 nT at maximum altitude while the maximum intensity reaches above $10^6$ nT.

3 Methodology

The magnetic field in a source free location can be expressed as the gradient of a scalar potential $V$ that satisfies the Laplace equation:

$$\nabla^2 V = 0$$ (1)

The potential for internal and external sources can be written as an expansion of SH functions:

$$V(r, \theta, \phi, t) = R_J \sum_{n=1}^{n_{\text{max}}} \sum_{m=0}^{n} \left\{ \left( \frac{R_J}{r} \right)^n \left( g_n^m(t) \cos m\phi + h_n^m(t) \sin m\phi \right) P_n^m(\cos \theta) \right\}$$

$$+ R_J \sum_{n=1}^{n_{\text{max}}} \sum_{m=0}^{n} \left\{ \left( \frac{r}{R_J} \right)^n \left( q_n^m(t) \cos m\phi + s_n^m(t) \sin m\phi \right) P_n^m(\cos \theta) \right\}$$ (2)

where $(r, \theta, \phi, t)$ are the planetocentric spherical coordinates (radius, co-latitude and longitude) and time, respectively. $R_J$ is the reference radius equal to Jupiter’s equatorial radius (71,492 km). $g_n^m(t)$ and $h_n^m(t)$ are the time-dependent internal field Gauss coefficients of degree $n$ and order $m$ while $q_n^m(t)$ and $s_n^m(t)$ are the external field coefficients. $P_n^m$ are the Schmidt quasi-normalised associated Legendre functions. $n_{\text{max}}^i$ and $n_{\text{max}}^e$ are the maximum degree for the internal and external field coefficients respectively.

To calculate the SH coefficients, we apply a weighted least-squares inversion approach based on a singular value decomposition (SVD) algorithm. The weights are defined in nT by the instrument error and intrinsic noise for each Juno data location (Connerney et al., 2017). The temporal variation of the internal field is calculated using B-splines of order 2, which are piece-wise polynomials describing the time derivatives between defined knots. We use three knots, at the beginning, middle and final epoch of the measurements (spacing is about 1.95 years). This parameterization was extensively tested on the selected set of Juno’s data location with a synthetic time-varying internal magnetic field mimicking the strength and the power spectrum of the actual internal field of Jupiter. The inversion on synthetic measurements does not require regularization with
this parameterization and it is stable with random noise (Details of the method, tests and assessments are provided in the Supporting Information, Text S1).

Once the Gauss coefficients and their time variation are estimated, several statistical quantities can be computed. The Lowes-Mauersberger spectrum represents the magnetic field power spectrum per SH degree (Mauersberger, 1956; Lowes, 2007). For a given time, and at a given radius \( r \), it can be defined as

\[
\mathcal{R}_n = (n + 1) \left( \frac{R_J}{r} \right)^{(2n+4)} \sum_{m=0}^{n} [(g_m^m)^2 + (h_m^m)^2]
\]

(3)

at SH degree \( n \). Similarly, for the SV, it can be defined as

\[
\mathcal{S}_n = (n + 1) \left( \frac{R_J}{r} \right)^{(2n+4)} \sum_{m=0}^{n} [(\dot{g}_m^m)^2 + (\dot{h}_m^m)^2]
\]

(4)

where \( \dot{g}_m^m \) and \( \dot{h}_m^m \) are the Gauss coefficients of the SV.

The main field and its spectrum \( \mathcal{R}_n \) can be upward or downward continued, provided there are no magnetic field sources present in between. This property has been used to derive estimates of the radius of the dynamo region, or of the liquid core, in the case of the Earth. This is also known as the white noise hypothesis: immediately outside the dynamo region, the part of the magnetic spectrum associated with the dynamo is assumed flat, and the depth to the dynamo can thus be grossly estimated (Lowes, 1974). However some terms \((n=1 \text{ and } n=2)\) have to be ignored in order for this approximation to match the radius of the Earth’s core (Cain et al., 1989; Voorhies, 2004). Langlais et al. (2014) found that certain parts of the spectrum \( \mathcal{R}_n \), namely the non-zonal and quadrupole families, are independent of \( n \) at some radius \( r \) (see Supporting Information, Text S2 for details). On Earth, these approaches return the value of the core or dynamo radius with a combined relative error lower than 0.3%. In the following, we refer to the dynamo radius at Jupiter, estimated from the non-zonal and quadrupole families of coefficients, as \( R_{sf} \). It can be interpreted as the radius of the top of the source region, or the bottom of the source free region.

The correlation times as a function of degree \( n \) can also be defined combining the quantities \( \mathcal{R}_n \) and \( \mathcal{S}_n \). The correlation times, also referred to as the SV timescales, give a measure of how long it takes for the field of a particular degree to get reorganized, or become uncorrelated to its former state at that degree (Hulot & Le Mouël, 1994; Christensen & Tilgner, 2004; Amit et al., 2018). It is expressed as

\[
\tau_n = \sqrt{\frac{\mathcal{R}_n}{\mathcal{S}_n}}
\]

(5)

4 Results and Discussion

We calculate the main field model up to degree 20 and the SV to degree 8. The external field is estimated up to degree 2. Suspicion of power leakage from unresolved small and rapid spatial scales leads us to reject 29 out of the 608 eigenvalues in the weighted least-squares inversion. As a consequence, the terms beyond SH degree 16 are damped, and the final model is truncated to \( n_{max}^m = 16 \). We estimate a posteriori standard error on the coefficients from the covariance matrix and the inversion misfit for the three vector components. The misfits for each vector component are given in Supporting Information (Table S1). This table also shows the statistics for a model to SH degree 20 derived without SV. The misfit difference between these two cases supports the fact that a statistically significant and global SV is present in the measurements. The secular variation improves data fit better than increasing field complexity (see Ridley and Holme
(2016) for a similar conclusion). Note that Connerney et al. (2022) also indicates strong
evidences for local secular variation in the vicinity of Jupiter’s Great Blue Spot between
Juno perijoves 9 and 33. Figure 1a displays the main field (and the SV) power spectra
with the 99 percent error bars. For comparison, the power spectrum of the model of Connerney
et al. (2022) is also shown, which falls within the error bars down to SH degree 15-16.
The increase of the power between \( n = 16 \) and 18 of our model probably arises because
of the spectral aliasing of remaining signal in the measurements. We also note that with
increasing orbits the satellite goes lower in altitude near the north pole while increas-
ing the size of a gap at similar latitude ranges over the south pole area. This results in
high degree, low order terms being less resolved (i.e., zonal and near zonal terms). The
Supporting Information (Figure S2) shows the root mean square differences between Juno’s
dataset and predictions by our model, a model calculated without SV, the model by Connerney
et al. (2022), considering different truncation degrees for each model. At SH degree 16,
our model and the model by Connerney et al. (2022) have a root mean square misfit to
data equal to about 800 nT.

### 4.1 Inferences on the internal structure

We estimate the dynamo radius \( R_{sf} \) for varying truncation degrees of the main field
model \( n_{\text{max}}^\text{I} \) seeking in a minimum least-squares sense the depth at which the power spec-
tra from the non-zonal (\( m \neq 0 \)) and quadrupole (\( n + m \) even) families of coefficients
are statistically flat (Langlais et al., 2014). The error bars on the estimated dynamo ra-
dius decrease up to truncation degree \( n_{\text{max}}^\text{I} = 16 \) for both families (Supporting Infor-
mation, Figure S8). It is also the truncation degree for which the maximum likelihood
estimates from the non-zonal and quadrupole families of power spectra coincide. This
again supports the choice of truncating the present model to the maximum degree 16.
The maximum likelihood value from the non-zonal field is equal to 0.831 \( R_J \) and that
from the quadrupole family is equal to 0.829 \( R_J \). We use their mean and combine their
standard errors to provide a single estimate for \( R_{sf} = 0.830 \pm 0.022 R_J \). Previous stud-
ies such as the one by Connerney et al. (2018) estimate the dynamo radius ‘near 0.85
\( R_J \’ while Connerney et al. (2022) estimate it to 0.81 \( R_J \) and Tsang and Jones (2020)
between 0.82 and 0.87 \( R_J \) using a numerical model. However, all these studies use the
white noise hypothesis as discussed above, which ignores the \( n = 1 \) and even \( n = 2 \)
terms.

For a dynamo to exist in a planet, two main criteria are required: an electrically-
conducting fluid and an energy source, which is often convection within a spherical shell
in rotation. For Jupiter, the metallic hydrogen is the fluid, and its convective motion drives
the dynamo. Convection can also take place in the source free region, without contribut-
ing to the dynamo. Wicht and Gastine (2020), through numerical simulations, suggested
the possibility of two distinct dynamo regions inside Jupiter. The primary region would
be at depth, and is responsible for the dipole dominated field geometry. The secondary
one would be shallower, and operates where the equatorial jets encounter conductive ma-
terial in the transition layer. However, surface jets motion decays rapidly with depth and
are unlikely to extend at depths larger than about 3,000-3,500 km or \( \sim 0.95 R_J \) (Kaspi
et al., 2018; Guillot et al., 2018). Christensen et al. (2020) suggested that a stratified layer,
close to the surface, could quench the jets at depth and play a role in the secondary dy-
namo. Our study points towards a source free region extending deeper, with a radius placed
at 0.830 \( R_J \). This radius could correspond to the upper limit of the dynamo region. We
note that it also matches well the radius of the transition layer in between the meta-
lic and molecular hydrogen (Brygoo et al., 2021), rendering this layer part of the dynamo
region (Figure 2). Our results do not provide constraints on the bottom radius of the
dynamo and do not indicate a shallower secondary dynamo (Gastine & Wicht, 2021) above
0.830 \( R_J \).
Figure 1. (a) The power spectra with error bars for the main field (shown in blue, units - nT^2) and secular variation (shown in red, units - (nT/year)^2) of the model at the surface (dashed line) and at $R_{sf}$ (solid line). The main field terms for $n > 16$ are not downward continued to $R_{sf}$. The black line is the main field power spectrum of the model of Connerney et al. (2022), which lies within the 99% bound of our model. (b) The secular variation timescales of the model. The red line is the linear best fit to the non-dipole part.
Figure 2. Schematic view of the interior of Jupiter. The bold violet line depicts our result $R_{sf}$. The grey area depicts the core ($0.2 R_J$) and the possible dilute core region (Wicht & Gastine, 2020; Wahl et al., 2017). The violet area between the dotted lines ($0.68$ and $0.84 R_J$) depicts the H-He phase separated layer (Brygoo et al., 2021). The top dotted line at $0.95 R_J$ depicts the depth where the jets decay down to the minimum (Kaspi et al., 2018). The arrows represent possible convection area with unknown origin depth.

4.2 SV Timescales

The SV timescales are shown in Figure 1b. For the Earth, the correlation time for the dipole is around 1000 years and the lowest value at $\sim \eta_{13}^{max}$ is of the order of 10 years. Field models and numerical dynamo simulations indicate that the non-dipole SV timescales are inversely proportional to the SH degree (e.g., Lhuillier et al., 2011; Bouligand et al., 2016). For Jupiter, the correlation time for the dipole ($\tau_1$) is 2210 years while the lowest value we obtain is 40 years for degree 7. We observe similar inverse proportionality for the Jovian SV timescales. The best fit slope for $n = 2 - 8$ is $-1.12$ with a standard deviation of 0.21. According to the scaling theory of the magnetic induction equation, a slope of -1 corresponds to advective SV, whereas -2 indicates diffusive SV (Christensen et al., 2012; Holme & Olsen, 2006). A -2 slope for our model is well outside 2 standard deviations and can be excluded. Therefore, our best fit value $-1.12 \pm 0.21$ suggests that the field change is dominated by advective effects, as is the case for Earth (Lhuillier et al., 2011; Christensen et al., 2012). In addition, the overall similarity between the non-dipole SV timescales of Jupiter and Earth suggests a similar magnetic Reynolds number (Christensen & Tilgner, 2004), i.e. $Rm_J \sim 1000$. In contrast, Wicht et al. (2019)
concluded that diffusive effects might govern the dynamo in the transition layer. Though
their transition region starts above $R_{sf}$, the SV timescales we compute are independent
of the radius, hence challenging the importance of diffusion. It thus remains an open ques-
tion as to what phenomenon drives the observed SV of Jupiter.

### 4.3 Implications to Jupiter’s dynamo

Using the four morphological criteria defined in Christensen et al. (2010) for Earth-
like dynamo models at the CMB, we compare our results with the geodynamo. For com-
parison purposes, we set $n_{\text{max}} = 8$ to calculate the different criteria, i.e. smaller than
that shown in Figure 3(a-f). The relative axial dipole power for our model is 0.86 at $R_{sf}$
while the standard value for Earth is 1.4, though the present-day value is about 1. This
indicates that Jupiter’s dynamo is either less dipolar or comparable to Earth’s (Figures
3a and 3b). The equatorial anti-symmetry for Earth is 1.0, whereas our model provides
a value of 0.52. A random equipartitioned non-dipole field ratio would give an equato-
rial anti-symmetry of 0.83 (Christensen et al., 2010). Thus, Jupiter’s non-dipole field is
more symmetric with respect to the equator than Earth’s (Figures 3c and 3d). The zonal
to non-zonal ratio for a random equipartitioned field is 0.10 (Christensen et al., 2010).
For Earth, the value is 0.15, while for our model the value is 0.20, which indicates a stronger
zonal contribution (Figures 3e and 3f). Lastly, the flux concentration for a purely dipole
field is 0.8 and that for the geomagnetic field is 1.50 (Christensen et al., 2010). The flux
concentration is considered low when flux exits one hemisphere and enters through the
other uniformly. Conversely, it is large when it exits from a concentrated spot and en-
ters the rest of the sphere uniformly. The concentration value for our model is 4.23. This
very large value reflects the dominance of the large intense flux patch in the northern
hemisphere.

Figure 4 shows the radial magnetic field and SV maps calculated using the model
at Jupiter’s surface and at $R_{sf}$. The large positive radial field patch in the northern hemi-
sphere and the intense negative patch near the equator (the Great Blue Spot) become
more concentrated with depth. SV is of the order of $10^4$ nT/year at the surface. This
corresponds to a 2.3% change over the course of four years of the dataset used, compared
to the 1.4% change over a similar duration for the Earth’s magnetic field. As for the Earth’s,
it should not be ignored when modelling the magnetic field over periods exceeding a few
years.

The spatial pattern of temporal variation of the field brings further dynamical con-
straints. The power spectrum of the SV calculated at $R_{sf}$ increases with degree (Fig-
ure 1a). Indeed, the SV reveals intense small scale structures (Figure 4). The strong neg-
ative radial field patch immediately south of the equator (the Great Blue Spot) coincide
with a pair of SV structures (Figure 4d), suggesting eastward drift (Amit, 2014; Livermore et
al., 2017). This is opposite to the westward drifting low- and mid-latitude patches ob-
served with Earth’s SV (Bullard et al., 1950; Finlay & Jackson, 2003; Aubert et al., 2013).
This eastward drift could relate to the zonal winds observed at the surface or until 0.95
$R_J$ (Moore et al., 2019). However, our model presents also other prominent SV struc-
tures which cannot be explained by zonal winds. There is some suggestion for a weak
eastward drift near 45°N latitude, which is the centre of the large positive radial field
patch (Figure 4b). But, it is not associated with particularly strong SV for most of its
structure, possibly indicating a region with dominantly field-aligned flow (Finlay & Amit,
2011). Livermore et al. (2017) gave similar explanation for the absence of strong SV at
southern high latitudes of Earth. Bearing in mind that the model is less constrained at
the south pole, the opposite signs of $B_r$ and $\dot{B}_r$ (Supporting Figure S3) suggest local fluid
upwelling (Amit, 2014), similar to the field and SV below Earth’s poles and in agreement
with a classic meridional circulation inside the tangent cylinder (Olson & Aurnou, 1999;
Cao et al., 2018). In addition, the southern hemisphere has many alternating sign SV
patches (Figure 4d) which are not correlated with particularly strong field structures (Fig-
Figure 4b). We note that the radial field and its SV from $R_{sf}$ to the surface are weakly sensitive to depth (Figure 4), making these kinematic interpretations robust.

**Figure 3.** The radial field at $R_{sf}$. (a) Axial dipole field. (b) Non axial dipole field. (c) Non-dipole symmetric field. (d) Non-dipole anti-symmetric field. (e) Non-dipole zonal field. (f) Non-dipole non-zonal field. The maps are centered at $180^\circ$ longitude.
Figure 4. The (a, b) radial field and (c, d) its secular variation at (top) Jupiter’s surface and (bottom) $R_{sf}$. The maps are centered at 180° longitude. The lines in (a) show the orbit paths of the used data set.

5 Concluding remarks

We present a magnetic field model robust up to degree 16 and secular variation up to degree 8. The dynamo radius of 0.830 $R_J$ is more precise considering the method used and indicates that the transition region is part of the dynamo generation. The dominance of advective SV and the relative level of axial dipolarity of Jupiter exhibit similarity with the geodynamo. We find that the global secular variation is not weak enough to be neglected and the flow deep inside Jupiter involves zonal as well as complex non-zonal structures.

More insights into the dynamo regime could be gleaned by inferring the flow at Jupiter’s deep interior. Our field and SV model can be inverted for the flow at $R_{sf}$. Such an inversion, which is commonly performed for the flow at the top of Earth’s core (Holme, 2015), was performed for Jupiter by Ridley and Holme (2016), but using a very low resolution SV model. More data are also needed to increase the resolution of the field model and to confirm the temporal variation observed during the last four years. This will come from Juno during the upcoming extended mission, but also when the ESA’s JUICE mission enters Jupiter’s orbit at the end of this decade.

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Open Research

All Juno magnetometer data used here are publicly available on NASA’s Planetary Data System (PDS) at Planetary Plasma Interactions (PPI) node at https://pds-ppi.igpp.ucla.edu/search/?sc=Juno&t=Jupiter&i=FGM. The model coefficients and their standard deviation for the static field to degree 16 and its secular variation to degree 8 are available at: https://zenodo.org/record/6564162

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6 References for Supporting Information

(Finlay et al., 2020) (de Boor, 2001) (Aubert & Finlay, 2019) (Alken et al., 2021)
Supporting Information for "The internal structure and dynamics of Jupiter unveiled by a high-resolution magnetic field and secular variation model"
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2. Figures S1 to S8
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Text S1. Synthetic simulation

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The internal Jovian magnetic field and its temporal rate of change (secular variation, SV) is expanded in terms of Spherical Harmonics (SH). Above the magnetic sources, the magnetic field $B$ derives from the expression of a magnetic scalar potential $V$ by $B = -\nabla V$ and where in spherical coordinates it is approximated by the finite series

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

where $r$ denotes the radial distance from the center of Jupiter, $R_J$ is Jupiter’s equatorial radius equal to 71,492 km, $\theta$ the co-latitude, and $\phi$ the longitude. The functions $P_n^m(\cos \theta)$ are the Schmidt quasi-normalized associated Legendre functions of degree $n$ and order $m$. The Gauss coefficients $g_n^m(t)$, $h_n^m(t)$ are the time-varying parameters to be estimated by inversion of the measurements conventionally given in the units of nano-Tesla (nT). The mathematical series in Eq.(1) is truncated to $n_{i max}$ and $n_{e max}$, which are the maximum degrees for the internal and external field coefficients.

The three vector components of Jupiter’s magnetic field in the radial, southward and eastward horizontal directions ($B_r, B_\theta$ and $B_\phi$) are calculated from the negative gradient of Eq.(1) in the spherical coordinate system

$$B_r = -\frac{\partial V}{\partial r}, \quad B_\theta = -\frac{1}{r} \frac{\partial V}{\partial \theta}, \quad B_\phi = -\frac{1}{r \sin \theta} \frac{\partial V}{\partial \phi}.$$  

In order to test the data distribution and its adequacy with model determination, we compute a set of synthetic vector magnetic field predictions at the actual Juno locations.
and epochs using the CHAOS-7.8 Earth’s magnetic field model (Finlay et al., 2020). This time-dependent model is based on magnetic field observations collected by the low-Earth orbiting satellites between years 1999 and 2021. It is expanded to SH degree $n_{i}^{\text{max}} = 20$ for the time varying internal field with order 6 B-splines (de Boor, 2001) with a 6-month knot separation. The synthetic data we build therefore contains a significant amount of rapid secular variation, secular acceleration, and contributions of higher time derivatives, including some geomagnetic jerks or core pulses, which are sudden changes in the second time derivative of the Earth’s magnetic field (e.g., Aubert & Finlay, 2019).

Before predicting the field over the four years of available Juno data, we note that the strength and shape of Earth’s and Jupiter’s magnetic fields are different. Figure S4 shows the power spectra of Earth’s main field CHAOS model, its secular variation, and the power spectrum of Jupiter’s magnetic field model derived by Connerney et al. (2022), both at the reference radius of each planet.

In a first step towards building a realistic synthetic data set, we estimate by standard least-squares the power law of Jupiter’s magnetic field model. For the CHAOS model, we estimate two power laws in order to account for the different internal field sources contributing to the model. Indeed, a distinct change of slope occurs around SH degree 13 that indicates that the field from the core dominates from SH degree 1 to 13, while the field from the crust dominates from SH degree 15 (Langel & Estes, 1982). For each part of the power spectrum we use the power law difference with Jupiter’s model to rescale the CHAOS internal field model to SH degree 20. In addition, we impose that the power spectrum of the rescaled secular variation keeps the same slope as the original CHAOS model.
Without this precaution, the synthetic secular variation power spectrum diverges at the dynamo radius of Jupiter. The power spectra of the rescaled CHAOS main field model, following now the general trend of the model by Connerney et al. (2022), and its secular variation are displayed in Figure S4.

The rescaling of the CHAOS model allows us to incorporate the a priori information provided with Juno data. In the database, each measurement is given with a precision index corresponding to the magnetometer operating range and an instrumental noise less than 1 nT. The uncertainties are defined for six different operating ranges and vary with the strength of the ambient magnetic field (Connerney et al., 2017). Each synthetic observation we build is therefore associated with a weight (with a minimum weight of 1 nT) and we further add a Gaussian random noise of 25 nT to each vector measurement. This Gaussian noise is the upper bound of the instrument error of Juno measurements.

We then set up the parameterization of the inverse problem. The internal static field is derived up to SH degree $n_{i}^{\text{max}} = 20$ and a static external field to SH degree 2. The maximum resolution of the internal time variation of the model is imposed by the time difference and the spatial coverage between Juno’s polar orbits. We choose to parameterize the time variation with splines of order 2 with a knot spacing of 2 years and for SH degrees 1 to 10 only. The examination of the covariance matrix indicates that we are not dealing with an ill-conditioned inverse problem that would require an explicit regularization. The 608 coefficients are then estimated by weighted least-squares and the inversion is performed with a singular value decomposition (SVD) algorithm, thus offering
the possibility at a later stage to solve the problem with the generalized truncated SVD technique.

The results of the synthetic inversion is assessed in the spatial and spectral domains using several criteria (see Alken et al. (2021) for a list of possible criteria). We show in Figure S5 the power spectrum of the estimated model with the power spectrum of the input rescaled CHAOS model for the main field and its secular variation. These are accompanied with the results of the spherical harmonic correlation analysis. Both power spectra for the main field agree in strength and correlate better than 0.99 over the full degree range. For the SV the correlation is better than 0.75. However, we observe an increase in the estimated power spectrum starting from SH degree 8. This overestimated energy compared to the rescaled CHAOS benchmark model is the sign of power leakage from the time-varying structures that are not accounted for in the estimated model. Figure S6 shows the input and output radial field and its difference at $R_{sf}$ (0.83 times Jupiter’s radius) to SH degree 20 for the static part and to SH degree 8 for the SV part. We observe no significant residuals for the static field while the SV residuals follow the SV structures. The residuals are one order of magnitude smaller than the input SV model indicating the presence of a small power leakage that is amplified at the dynamo radius.

**Text S2. Dynamo Radius Estimate**

For Earth, the geomagnetic field spectrum (Lowes, 1966) can be steadily interpreted in terms of magnetic source location. There is an apparent slope break near degrees 13-14 that distinguishes between the energy from the core and crustal field components, respectively. Ignoring the dipole term, the spectrum becomes almost flat when downward...
extrapolated to the CMB for the core part, while it shows an almost null slope at the surface for higher degrees. This property has been observed for a long time (Lowes, 1974) and has been suggested to provide a crude estimate of the core radius on other planets where seismological measurements are not available.

This crude estimate can be refined by using alternative expressions to the power spectrum. McLeod (1996) defined an expression using magnetic monopoles to estimate core radius. Langlais, Amit, Larnier, Thébault, and Mocquet (2014) defined two additional expressions, first using the non-zonal terms \( m \neq 0 \) and the second using the quadrupole terms \( n + m \) even). These two sub-families show flat spectra independent of degree \( n \) at a radius \( r \), interpreted as the CMB for Earth (Figure S7). The non-zonal spectrum has a null slope immediately above the dynamo area. This is expected because the geomagnetic field is axisymmetric on the long term, and the non-axisymmetric part is thought to be random. The flatness of the quadrupole family spectrum is explained by the dominance of rotational effects in the dynamo process. They can be defined as

\[
R_{nz}^n(r) = (n + 1) \left( \frac{a}{r} \right)^{(2n+4)} \sum_{m=1}^{n} [(g_m^m)^2 + (h_m^m)^2]
\]

\[
R_{qf}^n(r) = (n + 1) \left( \frac{a}{r} \right)^{(2n+4)} \sum_{m=0, n+m \ even}^{n} [(g_m^m)^2 + (h_m^m)^2]
\]

where \( a \) is the reference radius, equal to the planet’s radius.

The \( R_{nz}^n \) and \( R_{qf}^n \) provide a close estimate of the core radius as was verified using four different geomagnetic models (Langlais et al., 2014). For CHAOS-4 field model at epoch 2005 and \( n = 13 \), the estimated core radius \( R_{nz} \) estimated from Eq.(3) is 3,486.6 km and the \( R_{qf} \) estimated from Eq.(4) is 3,496.7 km, which are similar to the accepted
The maximum likelihood value using the approach of Lowes (1974) gives $R_{\text{lowes}} = 3,294.5$ km and the one using the approach of McLeod (1996) provides $R_{\text{mcleod}} = 3,586.5$ km, both deviating significantly from the accepted seismic value. The core (or dynamo) radii for other planets were also estimated. Using the JSV model of Ridley and Holme (2016) for Jupiter up to $n = 5$, Langlais et al. (2014) provided the values 0.86 and 0.87 $R_J$ for $R_{nz}$ and $R_{qf}$ respectively. For our model, we estimate the dynamo radius for both the non-zonal and quadrupole families (Figure S8) by varying the truncation degree between 10 and 20, and observe that the slope is the most flat at $n = 16$. The radius starts to increase beyond it. The non-zonal spectrum gives a value of 0.831 $R_J$ with a standard deviation of 0.021 $R_J$, while the quadrupole family spectrum returns 0.829 $R_J$ with a standard deviation of 0.024 $R_J$. Both independent estimates therefore fall within each other’s error bars. The mean of the radii estimated using $n_i^{\text{max}} = 16$ corresponds to $0.830 \pm 0.022 R_J$.

References


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Figure S1. The data locations of Juno satellite below 300,000 km for the first 28
(without orbit 2 and 19) perijoves. The colour scale represents the altitude above the
mean radius. The map is centered at 180° longitude.
Figure S2. The residual misfits plotted as a function of the SH degree for the model by Connerney et al. (2022) (red), a model without SV (blue) and our model (black).
Figure S3. The (top) radial field and (bottom) radial secular variation at the estimated dynamo radius $R_{sf}$ for the (left) North Pole and (right) South Pole. The inner to outer circles represent latitudes $85^\circ$, $75^\circ$ and $60^\circ$ respectively.
Figure S4. (a) The initial power spectrum of the CHAOS-7.8 main field model (magenta), its SV (purple) and the spectrum of Connerney et al. (2022) main field (cyan). The red, orange and black straight lines are the power law rules estimated by least-squares fits for these models respectively. The power laws for the CHAOS main field model (red lines) are different from degrees 1 to 13 and from degrees 14 to 20 (Text S1 for details). The new rescaled CHAOS-7.8 main field and SV models are shown in blue and green respectively. The units for main field are nT^2 and (nT/year)^2 for SV spectra.
Figure S5. (a) The power spectrum of the main field (in blue with units of nT²) and secular variation (in red with units of (nT/year)²) of the estimated and input (black) magnetic field models at the Jovian surface. (b) The spherical harmonic correlation between the estimated and the input models for the main field (blue) and the SV (red).
Figure S6. The (a) radial field of the estimated model and the (b) difference of the radial field between the input and estimated model in the synthetic analysis. The (c) radial SV of the estimated model and the (d) difference of the radial SV between the input and estimated model in the synthetic analysis. The maps are centered at 180° longitude and plotted at $R_{sf}$. 
Figure S7. (a) Geomagnetic power spectrum of CHAOS-7.8 model at the CMB with linear regression from n=1-13 (black dashed line, slope = -0.0493) and 2-13 (black line, slope = -0.0245). (b) The non-zonal spectra with linear regression (black line) for the geomagnetic model (blue, slope = 0.0077) at CMB and for our model (red, slope = 0.0008) at the estimated dynamo radius $R_{sf}$. (c) The quadrupole family spectra with linear regression (black line) for the geomagnetic field (blue, slope = 0.0060) at CMB and for our model (red, slope = 0.0008) at the estimated dynamo radius $R_{sf}$. 

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Figure S8. The dynamo radius estimates with the error bounds calculated using the non-zonal (red) and quadrupole (blue) terms at different truncation degrees using the estimated Jovian magnetic field model.

Table S1. Inversion misfits (in nT) for models without and with secular variation \( (n_i^{\text{max}} = 20 \text{ and } 8 \text{ for the main field and } \text{SV respectively}). \)

<table>
<thead>
<tr>
<th>( n_i^{\text{max}} )</th>
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<th>( B_\theta )</th>
<th>( B_\phi )</th>
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