No Evidence for Time Variation in Saturn’s Internal Magnetic Field

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Abstract

The time variation of a planetary magnetic field can reveal important aspects of a planet’s interior structure. Searching for time variation in planetary magnetic fields other than Earth has proved challenging owing to the small number of spacecraft missions flown to date, but such a detection may be possible given a sufficiently long baseline for comparison. Here we leverage 38 years of spacecraft magnetometer measurements to search for time variation in Saturn’s internal magnetic field. To isolate the possible signal of time variation, we remove a contemporary high-resolution internal field model, derived from Cassini data, as well as a best-fitting external magnetodisk field model from each of four past mission data sets: Pioneer 11 (1979), Voyager 1 (1980), Voyager 2 (1981), and Cassini Saturn Orbit Insertion (2004). We then attempt to fit the resulting signal with an axisymmetric internal field model. Overall, we find no evidence of time variation on a multidecadal timescale. Our results lend support to the existence of a stably stratified layer in Saturn and have comparative planetology implications for Jupiter’s interior structure and dynamics.

Unified Astronomy Thesaurus concepts: Saturn (1426); Jupiter (873); Planetary interior (1248); Planetary magnetosphere (997); Planetary science (1255); Magnetic fields (994); Geomagnetic fields (646); Magnetic anomalies (993)

1. Introduction

Spacecraft observations of Saturn over the past few decades have revealed surprising features such as the planet’s excess luminosity (Pollack et al. 1977; Fortney 2011; Lecointe & Chabrier 2013), deep zonal jets (Chachan & Stevenson 2019; Iess et al. 2019; Militiz et al. 2019), and its highly axisymmetric magnetic field (Acuña & Ness 1980; Connerney et al. 1982; Burton et al. 2009, 2010; Dougherty et al. 2018; Cao et al. 2020). One possible explanation for these intriguing observations is zonal flow in a stably stratified, electrically conducting layer at the top of the planet’s magnetic-field-generating region (dynamo; Stevenson 1982). Through processes such as differential rotation, this layer could axisymmetrize the field above the dynamo region and thereby resolve the paradox presented by Cowling’s theorem (Cowling 1934), which, in its original form, states that dynamos cannot generate a steady, perfectly axisymmetric magnetic field. We note that subsequent work has relaxed the condition that the field be steady (see, e.g., Kaiser & Tilgner 2014). Physically, such a layer could arise owing to the immiscibility of hydrogen and helium in a narrow range of interior conditions possibly found in Jupiter and Saturn (Lorenzen et al. 2009; Militiz & Hubbard 2013). This immiscibility would lead to a dissolution zone near the top of the dynamo region, with helium raining down and leaving a less dense, helium-depleted, stably stratified layer (Stevenson 1979).

Although ab initio computations suggest that Saturn should possess a stably stratified layer owing to helium dissolution, the existence and extent of this layer inside Saturn (and Jupiter) are still subjects of debate. First, there is significant disagreement regarding the equations of state for hydrogen and helium at planetary conditions (Saumon et al. 1995; Nettlemann et al. 2012), as well as the range of conditions where helium becomes insoluble in hydrogen (Nettleman et al. 2015). Second, observational studies show similar levels of disagreement. Some analyses of Voyager and Cassini spectrometer data report that Saturn’s atmosphere is depleted in helium (implying that the helium is sequestered deeper in the planet; Conrath et al. 1984; Sromovsky et al. 2016; Achterberg & Flasar 2020), but others draw the opposite conclusion (Conrath & Gautier 2000; Koskinen & Guerlet 2018), depending on the specific assumptions and methods used. Similarly, normal-mode seismology has successfully detected other proposed stably stratified regions in Saturn such as the planet’s eroded core (Fuller 2014), but current ring seismology data are less sensitive to a shallower stably stratified layer, due to the relatively small density jumps involved.

An additional way to address this long-standing ambiguity is by analyzing the time variation (secular variation) of Saturn’s magnetic field. Stanley & Bloxham (2016) showed that for the general case of axisymmetric magnetic fields, the requirement to preserve the field’s axisymmetry places strong constraints on the internal fluid flow and will lead to extremely small time dependency of the magnetic field. Specific to Saturn, the axisymmetric nature of the planet’s magnetic field has long been suggested to be due to a stably stratified layer. The presence of such a thick, stably stratified layer atop the dynamo (not necessarily differentially rotating) will result in extremely small time dependency of the magnetic field through diffusive damping of the secular variation (Cao et al. 2011). In this study, we take advantage of 38 yr of Saturnian exploration—culminating with the recently concluded Cassini Grand Finale—to place the firmest constraints on Saturn’s magnetic time variation to date. In Section 2, we describe our methodology
for data processing, as well as internal and external field modeling. We then describe the new constraints placed on possible time variation in Saturn’s magnetic field (Section 3) and their implications for the interiors of Saturn and Jupiter (Section 4).

2. Methods

Previous studies have searched for time variation in Saturn’s field by comparing internal magnetic field models made from spacecraft measurements during different epochs to each other (Cao et al. 2011). This method, however, suffers from the relatively large uncertainties present in the models at each epoch. Recently, Moore et al. (2019) developed a new method of examining the time variation of a planetary magnetic field by directly comparing a recent high-resolution spherical harmonic model based on accurate and well-distributed data from a recent mission to spacecraft data from past missions. They applied this method to Jupiter’s field, using a spherical harmonic model (Connerney et al. 2018) based on recent Juno measurements and data from a number of past missions. This method can also be thought of as using the field model to calculate what a spacecraft at present (e.g., Juno or Cassini) would have observed had it flown the trajectory of, for example, Pioneer 11, and comparing that to what Pioneer 11 actually observed.

Here, we apply the method of Moore et al. (2019) to search for time variation in Saturn’s magnetic field. We start by using the Cassini11+ model from the Cassini Grand Finale orbits (Cao et al. 2020) as our modern-day Saturn field model (taken here to represent 2017). This model updates the previous Cassini Grand Finale model (Dougherty et al. 2018) to include data from the spacecraft’s final 12.5 orbits, as well as enhanced spatial resolution. Thus, it provides us with the longest baseline with which to look for time dependency in the field. The model itself is a degree 14 spherical harmonic model composed of only the axially symmetric coefficients (see Table A1 in the Appendix for a list of coefficients).

We then compare the Cassini11+ model to the spacecraft data from past missions, as well as the early phase of Cassini: Pioneer 11 (1979), Voyager 1 (1980), Voyager 2 (1981), and Cassini Saturn Orbit Insertion (SOI; 2004). However, each past measurement ($B_{OBS,PAST}$) has contributions from both Saturn’s internal magnetic field ($B_I$) and the external magnetic field associated with currents in the magnetosphere and ionosphere ($B_E$). We wish to isolate the changes in Saturn’s internal magnetic field between past spacecraft missions and Cassini’s Grand Finale ($\Delta B$):

$$\Delta B = B_{I,CAS} - B_{I,PAST}$$

(1)

$$\Delta B = B_{I,CAS} - (B_{OBS,PAST} - B_{E,PAST}).$$

(2)

We describe our data processing methods and external field modeling below.

2.1. Data Processing

For this study, we use magnetometer data from all four missions that have visited the Saturn system in order to provide the longest possible baseline. Specifically, we use data from the vector helium magnetometers aboard Pioneer 11 (1979) and the fluxgate magnetometers aboard Voyager 1 (1980), Voyager 2 (1981), and Cassini (2004–2017) (Smith et al. 1975; Behannon et al. 1977; Dougherty et al. 2004). For the Cassini mission in particular, we focus on the SOI phase in 2004. This presents a long baseline when compared to the Cassini11+ model, which represents Saturn’s field in 2017.

For each mission, we use the highest-resolution data available in Saturn-centered coordinates (1-minute data for Pioneer 11, 1.92 s data for Voyager 1 and 2, and 1 s data for Cassini SOI). We use only data within $r \leq 15$ Saturn radii ($R_S = 60,268$ km) from Saturn’s center. This allows us not only to isolate variation in the internal field close to the planet but also to accurately fit and remove a model of Saturn’s magnetodisk currents. The location of Saturn’s magnetopause varies greatly but typically occurs beyond $15R_S$.

We then remove obvious outliers and known intervals of poor data quality due to spacecraft operations. The Voyager 1 and 2 spacecraft in particular performed several roll maneuvers during their Saturn approaches. Precise attitude knowledge was unavailable while the spacecraft rolled, leading to large errors in each component of the vector magnetic field data (see Figure A1 in the Appendix). We remove data during these rolls in accordance with prior studies (Connerney et al. 1983). Although Saturnian longitudes are not well defined owing to uncertainties in the interior rotation rate (Mankovich et al. 2019), our analysis is not affected by this since both the internal and external field models in our analysis are axisymmetric.

2.2. Estimation of Error Sources

Quantifying the level of uncertainty is essential for interpreting any possible inferences of time variation in Saturn’s field. Here we discuss the uncertainty present in past mission data sets, as well as in the Cassini11+ model.

Spacecraft measurements of planetary magnetic fields have many sources of uncertainty, from both the instrument and the main spacecraft; one source of uncertainty is the data quantization error. Spacecraft instruments can only record and transmit data with a finite precision owing to a limited number of memory bits, affecting the uncertainty of a measurement. Magnetometers typically operate in “ranges” chosen based on the field magnitude, such that the quantization error increases when the field reaches the set threshold for the next range. Assuming a random spread, this error corresponds to approximately $3\sigma$. (We note that, unlike modern data sets, the archived data for past missions do not always list the specific magnetometer range used for each individual data point. Thus, the quantization errors shown here represent our best analysis based on the published range change algorithms, as well as transitions in the properties of the data quantization noise.)

Beyond the quantization error, additional measurement and spacecraft-related errors must also be considered. For example, fluxgate magnetometer instruments have initial uncertainties associated with the gains, offsets, and orthogonalities, as well as the possibility for changes in these values over time. The spacecraft itself will also generate a weak magnetic field. The uncertainty due to this contaminating signal can be strategically reduced (but not fully eliminated) by placing the magnetometer instrument at the end of a long boom far from the main spacecraft electronics, by the use of inboard and outboard magnetometers, and through measurements of the spacecraft field on the ground before launch.

Finally, imprecise knowledge of the spacecraft and instrument attitudes (pointing orientations) can add additional uncertainty to the vector components of the field. We take
the upper bound of this attitude error as $|B| \sin(\psi)$, where $\psi$ is the attitude uncertainty. In reality, however, attitude errors are nonisotropic and may be significantly smaller in some vector components than the maximum bound used here; see Holme & Bloxham (1996) for more details. The scalar magnitude of the field should conceivably be unaffected by attitude errors, as an attitude error is equivalent to a rotation of coordinates.

Extensive and sophisticated calibration procedures are used to reduce these sources of data uncertainty as much as possible. These procedures may vary from mission to mission, depending on factors such as the intended orbital trajectory, spacecraft and instrument design, ground calibration setup, and calibration philosophy. For some missions, individual sources of error have been estimated and reported separately. For other missions, the calibration parameters for multiple error sources were solved for simultaneously, and so only a total uncertainty estimate is reported (as assigning individual error quantities would be inappropriate in this case). We refer the interested reader to the corresponding mission instrument papers for more details on the specific spacecraft magnetometer instrument design and calibration procedures used in each case.

We summarize the estimated $3\sigma$ uncertainty levels for each magnetometer data set below, as well as the Cassini11 + model. To find the total $3\sigma$ error, we take the rms of all of the above effects:

$$\text{rms} = (\sigma_{\text{quantization}}^2 + \sigma_{\text{SC field}}^2 + \sigma_{\text{baseline}}^2 + \sigma_{\text{attitude}}^2 + \sigma_{\text{SH model}}^2)^{1/2}, \quad (3)$$

or for the Cassini mission, where uncertainty sources are co-reported,

$$\text{rms} = (\sigma_{\text{quantization}}^2 + \sigma_{\text{overall}}^2 + \sigma_{\text{SH model}}^2)^{1/2}. \quad (4)$$

For most data, the total uncertainty is dominated by the attitude knowledge (see Figure A2 in the Appendix for a visual comparison). We note that our total uncertainty estimate is based on a list of known error sources and that there is a possibility that this list may later be revised; for example, a 2010 reanalysis of Galileo magnetometer data at Jupiter discovered that the magnetometer’s gain had drifted, requiring a small correction (Yu et al. 2010). Cataloging the extent of these “unknown unknowns” for the data sets used here, however, is beyond the scope of this study. In any case, given the excellent agreement between the Cassini11 + model and past magnetometer data (see Results), any such effects are likely to be small.

2.2.1. Pioneer 11 Data

For the Pioneer 11 investigation at Saturn, the quantization error ranged from $\pm0.026$ nT in the lower-field regimes to $\pm44.1$ nT in the highest range encountered within our chosen distance cutoff from Saturn (15 $R_\odot$). This is the instrument’s second-highest range overall; see Table 1 in Smith et al. (1974). The error due to unmodeled spacecraft fields is estimated to be $\leq0.01$ nT, and the error due to magnetometer baseline uncertainty is estimated to be $\leq0.05$ nT (Behannon et al. 1977). As the earliest of the four missions used in our study, the vector pointing accuracy of Pioneer 11 was particularly poorly determined. Estimates range from 1.5 deg (Connerney et al. 1984) to 5.5 deg (Smith et al. 1974); we take $\psi$ as 2.5 deg (Smith et al. 1974) and treat this bound as the $3\sigma$ attitude error.

2.2.2. Voyager 1 and 2 Data

Voyager 1 and 2 were created as twin spacecraft. For both spacecraft, the quantization error ranged from $\pm0.0063$ to $\pm0.513$ nT in the vicinity of Saturn. The error due to unmodeled spacecraft fields for each mission is estimated to be $\leq0.2$ nT, and the error due to magnetometer baseline uncertainty is estimated to be $\leq0.2$ nT (Behannon et al. 1977). We take the estimated attitude error for the Voyager 1 and 2 missions as 0.25 deg (Behannon et al. 1977; Ness et al. 1979).

2.2.3. Cassini Data

The Cassini magnetometer instrument quantization error ranged from $\pm0.00245$ to $\pm0.6nT$ during the SOI mission phase (Dougherty et al. 2004). A series of spacecraft roll maneuvers about different axes and with different periods were performed for calibration; relevant parameters such as magnetometer offsets, gains, and potential misalignments were simultaneously estimated through observations of spin tones in the magnetic field signal. Cross-calibration with the scalar helium magnetometer constrained the remaining free parameter, the absolute gain (Dougherty et al. 2004). Any remaining misfits after calibration were found to be smaller than the quantization error. We note that the orbital nature of the Cassini mission allowed for longer-term exploration of the planet’s magnetic field compared to previous flyby missions. In particular, the $B_y$ field was extensively studied (see, e.g., Southwood et al. 2020) and found to be consistently lower than $\pm2$ nT across many orbits. Out of a total field of 15,000 nT, this combined uncertainty from all sources translates to an effective equivalent attitude uncertainty of 0.01 deg. We use this approximate attitude uncertainty as our “overall” estimate for the nonquantization error in the Cassini SOI vector data set. For the magnitude-fitting portions of this study, we use a slightly lower bound on the calibration uncertainty equal to half the quantization error (since attitude errors should not apply to scalar data).

2.2.4. Cassini11 + Internal Magnetic Field Model

Finally, we address the uncertainty in our present knowledge of Saturn’s magnetic field. The Cassini11 + model (Cao et al. 2020) is a degree 14 spherical harmonic model. Formal ($3\sigma$) error estimates were available for each coefficient up to degree 11 (see Table A1 in the Appendix). We use these error estimates as the input values for a new spherical harmonic model and calculate the resulting magnetic field along the spacecraft trajectory. Since the exact combination of coefficient signs (+, −) will change the value of the field at a given location, we simulate all possible combinations ($2^{11} = 2048$). The results yield a range of values; we use the maximum value at each data point as our upper bound on the $3\sigma$ error due to uncertainty in the spherical harmonic model of Cassini’s modern-day field.

2.3. Magnetodisk Modeling

As described in Section 2, past spacecraft magnetic field data record a combination of Saturn’s internal magnetic field, as well as the signal generated by any external current systems in Saturn’s magnetosphere, and any measurement uncertainty or
noise. Thus, in addition to quantifying the uncertainty estimates as described above (Section 2.2), we must also distinguish between internal and external magnetic field signals present in the data. One of the primary features generating external currents in Saturn’s magnetosphere is called the magnetodisk. This consists of an equatorial disk of current surrounding the planet, which generates a magnetic field in $B_r$ and $B_\theta$. We approximate this feature using the formula of Connerney et al. (1983) that models the disk with a square cross section (see Figure A3 in the Appendix for a visual illustration). We further incorporate the effect of additional bowl-shaped distortion of the current disk due to the solar wind (Arridge et al. 2008; not pictured). This gives us five free parameters: the inner and outer disk radii, $R_0$ and $R_1$; the radius at which it hinges (which is used to analytically parameterize the bowl-shaped deflection), $R_B$; the half-thickness of the disk, $D$; and a current density parameter, $\mu_0 J$.

For each mission data set, we perform a Monte Carlo analysis consisting of 10,000 different parameter combinations in order to find the best-fitting magnetodisk models. This allows us to place conservative estimates on the possible time variation of Saturn’s internal magnetic field. Although the magnetodisk is described by an axisymmetric mathematical model, we allow for the dayside and nightside parts of each mission flyby to be fit with separate magnetodisk models, in order to account for possible local-time variation of the magnetodisk. We use input parameter ranges of $R_0 = [6, 8]R_S$, $R_1 = [12.5, 22]R_S$, $R_B = [15, 30]R_S$, $D = [2, 3]R_S$, and $\mu_0 J = [30, 80]nT$ (where $R_S$ represents Saturn’s radius). These values are chosen in order to span the published range of estimates for Saturn’s magnetodisk parameters during different mission eras (see Table 1 in Bunce et al. 2007 for example values); our best-fitting models for each mission can be found in Table A2 in the Appendix. We have also applied highly accurate series approximations (Giampieri & Dougherty 2004) to improve our computational speed.

2.4. Linearized Inversions

After removing a best-fitting external field model (Section 2.3) from the processed magnetometer data (Section 2.1), we explore whether the inferred time variation signal can be explained by a purely axisymmetric internal field model. Our magnetodisk modeling (see above) featured data out to a cutoff distance of $15R_S$. However, in order to isolate the effect of any internal fields present and reduce the influence of the magnetodisk field, we only use data within $4R_S$ of Saturn’s center for the fitting of internal field models.

Since the vector components of the signal could be contaminated by large attitude uncertainties relative to the size of the time variation, we also only fit the field magnitude data for the purpose of our investigation. Fitting the change in field magnitude is a nonlinear problem, and so we seek the solution iteratively with an $L_2$-norm regularization. For each mission, we choose a solution near the knee of the trade-off curve. We also fit an additional model to all four data sets simultaneously (performing 1-minute averaging on the data to ensure that the missions are equally represented in the time domain).

3. Results

In Figures 1(e)–(t), we show the residual difference between the past spacecraft magnetic field measurements and the Cassini11+ model of Saturn’s internal magnetic field (black circles). The signal is depicted along the spacecraft flight trajectory (where time is the $x$-axis, and the corresponding $3\sigma$ error bars are marked in gray). If the differences here were entirely due to time variation of the planet’s internal magnetic field, then the rate of variation would appear to be typically $\sim0.01\%$ of the total field per year at close approach (see Figures 1(a)–(d) for the total field magnitude measured by each spacecraft, for comparison). This rate is similar to previous bounds placed on Saturn’s time variation based on earlier Cassini results (Cao et al. 2011), and at least two orders of magnitude smaller than the change in Jupiter’s magnetic field ($\sim1\%$ yr$^{-1}$; Moore et al. 2019). However, this value only represents an upper bound on Saturn’s magnetic time variation, because some portion of this signal may be due to contributions from external fields, as well as noise, rather than true time dependency of the internal magnetic field.

To place tighter constraints on the time dependency, we quantify the extent to which the observed differences could be due to external currents. Saturn’s magnetosphere contains external fields from a number of sources, the most prominent of which is the magnetodisk, a toroidal ring of current about the planet. For each past spacecraft mission, we model the external fields due to the magnetodisk current system (Connerney et al. 1983; Bunce et al. 2007; Arridge et al. 2008), creating separate models for the dayside and nightside of the planet (see Section 2 for details). Our results are plotted in Figures 1(e)–(t). We find that the magnetodisk models (red and pink lines) explain almost all of the residual between the past measurements and the Cassini11+ model (black circles).

Some of the remaining differences can be further explained by inadequacies of the external field model. For example, the magnetodisk model is parameterized to have a sharp jump in current density at its inner boundary ($6 - 8R_S$, where Saturn’s radius is $1R_S = 60,268$ km), which creates a corresponding sharp signal in the external field near this region (Figure 1; most obvious for Voyager 1). Additionally, since Saturn’s internal magnetic field is perfectly axisymmetric to within the limits of the data, we would expect it to also have axisymmetric time variation. As all models used here (Cassini11+ magnetodisk) are axisymmetric and the internal time variation should also be axisymmetric, the signal in $B_r$ must be due to other external fields or noise/errors.

Could this residual signal nonetheless be due to time variation of Saturn’s internal, dynamo-generated field? An axisymmetric internal field must also have purely axisymmetric time variation if it is to remain axisymmetric. Accordingly, we attempt to fit the residual signal (past spacecraft data—Cassini11+ model—magnetodisk model) with an axisymmetric internal field model. Our resulting internal field models are plotted against the change in magnitude of Saturn’s magnetic field in Figure 2. It is clear that no single axisymmetric field model can fit all four data sets. Even for a relatively recent data set with small error bars, such as Cassini SOI, the peak in the predicted field from an axisymmetric field model is substantially offset from the real peak in the data. This suggests that the observed differences may not be internal in origin.

We also list the corresponding spherical harmonic coefficients for each data set in Table 1. These coefficients place an upper bound on the time variation of Saturn’s main dipole of $\sim0.0005$–$0.01\%$ yr$^{-1}$, depending on the model chosen.
However, upon close examination, individual coefficients appear to change in both sign and order of magnitude between missions that flew less than a year apart. Though this could imply that Saturn’s time variation is highly nonlinear and changes rapidly over time, that hypothesis is at odds with the extremely low rates of time variation observed overall. Rather, our inability to fit Saturn’s magnetic time variation signal with an axisymmetric internal field model further suggests the external nature of this signal.

4. Discussion and Conclusion

Using data from 38 yr of Saturnian exploration, we are able to place the firmest bounds on the time variation of Saturn’s...
magnetic field to date. Specifically, we examined the change in Saturn’s magnetic field between the recent Cassini1+ magnetic field model (Cao et al. 2020) and over 38 yr of past spacecraft measurements. Previous studies based on earlier results from Cassini suggested an upper bound on Saturn’s time variation on the order of 1 nT yr\(^{-1}\) (Cao et al. 2011). By extending our baseline of observation by several years and using a newly available, high-resolution model from Cassini, however, we find that this possible signal could be entirely external in origin and that no single time-varying internal field of this magnitude can fit all mission data simultaneously.

The absence of any time variation on a multidecadal timescale is in agreement with predictions from Cao et al. (2011) and Stanley & Bloxham (2016) and may support the hypothesis of a stably stratified layer above the planet’s dynamo region. For a dipolar magnetic field, time variation at timescales shorter than \(\tau \approx \pi L^2/\eta\) will be effectively eliminated by a stable layer atop the dynamo, where \(\eta\) and \(L\) are the magnetic diffusivity and thickness of the stable layer, respectively (Stevenson 1982; Cao et al. 2011; Christensen et al. 2018). Our linearized inversions place maximum bounds on the time variation of Saturn’s main dipole of 0.1–1 nT yr\(^{-1}\), corresponding to filtering frequencies of 20–200 kyr. Using a value of \(\eta = 4 \text{ m}^2 \text{s}^{-1}\) (Weir et al. 1996), this would suggest a minimum stable layer thickness of 900–2800 km based on the hypothesized mechanism of electromagnetic filtering, in good agreement with the layer thickness required to axisymmetrize Saturn’s magnetic field estimated from kinematic models (Stevenson 1982; Cao et al. 2011, 2020). However, as discussed in Stanley & Bloxham (2016), we note that a stably stratified layer is not necessarily required in order to explain low rates of magnetic time variation for the general case of planets with axisymmetric magnetic fields.

The lack of observed time variation in Saturn’s magnetic field also has important implications for the interior structure of Jupiter. Nominally, the spatial morphologies of Jupiter and Saturn’s magnetic fields are distinctly different, with the former possessing a strong tilted dipole (Connerney et al. 2018) and the latter a perfectly axisymmetric field (Dougherty et al. 2018). The time variation of these two planetary magnetic fields, however, suggests a more nuanced comparison. A recent study of the time variation of Jupiter’s magnetic field using comparable methods and data sets to this work found that, unlike Saturn, Jupiter’s magnetic field has undergone notable time variation on a multidecadal timescale (Moore et al. 2019). But in that study, the observed time variation could be almost

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**Figure 2.** Fitting the change in Saturn’s field magnitude with asymmetric internal field models. We fit axisymmetric internal magnetic field models to the inferred change in the magnitude of Saturn’s magnetic field over time (black line), after the magnetodisk signal has already been removed: \(\Delta |B| = |B_{\text{INT,CAS}}| - |B_{\text{OBS,PAST}}|\). We fit separate models to each individual data set (Pioneer 11, pink; Voyager 1, red; Voyager 2, yellow; Cassini SOI, cyan), as well as a combined model to all four data sets (dark blue). See Table 1 for the corresponding model coefficients and Section 2 for more details. The 3\(\sigma\) error bars are shown in gray for reference.

**Table 1.** Modeling Saturn’s Inferred Time Variation

| Coefficient | Models Based on Individual Missions | Combined Model (All Missions) |
|-------------|-----------------------------------|-----------------------------|
|             | P11 (1979) V1 (1980) V2 (1981)   | PAST (2004) INT,CAS, CASI |
| \(\delta_{L,0}\) | -1.0 | -2.2 | 0.1 | -0.2 |
| \(\delta_{2,0}\) | -0.04 | -0.2 | -1.0 | -0.2 | 3.1 |
| \(\delta_{3,0}\) | 0.4 | 0.08 | -0.8 | 3.6 | 0.8 |

**Note.** We fit axisymmetric internal field models to the magnitude of the inferred time variation at close approach using a linearized inversion (see Section 2). All models are in units of nT yr\(^{-1}\) and use a reference radius of 60,268 km (1\(R_S\)). Each of the “individual models” is optimized to fit a single mission data set (compared to the Cassini1+ model), while the “combined” model is a simultaneous inversion of all four data sets.
the top of Jupiter may provide evidence in support of a stably stratified magnetic field, with much more slowly, comparable to our bounds on Saturn’s axial magnetic moments. We suggest that this weak time variation is due to its atmospheric winds, then the dynamo field itself may be changing much more slowly, comparable to our bounds on Saturn’s axial magnetic moments. We suggest that this weak time variation may provide evidence in support of a stably stratified layer near the top of Jupiter’s dynamo region as well (Moore et al. 2018).

Magnetometer and coordinate system data used throughout this work can be found on the Imperial College London MAGDA server (https://magda.imperial.ac.uk/) and the NASA Planetary Data System at the Jet Propulsion Laboratory (https://pds.jpl.nasa.gov/). We are grateful to Professor Stan Cowley and Dr. Gabrielle Provan at the University of Leicester and Dr. John E. P. Connerney at the NASA Goddard Spaceflight Center for providing independent use of Pioneer 11 magnetometer data. This research was supported by the Heising-Simons Foundation 51 Pegasi b Fellowship; the Royal Society Research Professorship; and the Royal Society UK grant RP 180014.

**Appendix**

This appendix contains several supporting figures and tables. Figure A1 shows example instances of attitude rolls which were removed from the data. Figure A2 compares the effect of different sources of data uncertainty. Figure A3 provides a

![Figure A1](image1)

**Figure A1.** Attitude uncertainty during spacecraft rolls (shown: Voyager 2). This figure shows examples of spacecraft roll maneuvers (pink), during which the attitude is poorly known. We have removed known intervals of spacecraft rolls from the Voyager 1 and 2 data as part of our data processing.

| Parameter | Cassini11+ (nT) | Formal Uncertainty (nT) |
|------------|-----------------|-------------------------|
| \( R_{1.0} \) | 21141           | 4.3358                  |
| \( R_{2.0} \) | 1583            | 5.0746                  |
| \( R_{3.0} \) | 2262            | 8.9612                  |
| \( R_{4.0} \) | 95              | 5.2436                  |
| \( R_{5.0} \) | 10.3            | 8.5742                  |
| \( R_{6.0} \) | 17.4            | 7.3446                  |
| \( R_{7.0} \) | –68.8           | 9.0676                  |
| \( R_{8.0} \) | –15.5           | 6.2590                  |
| \( R_{9.0} \) | –24.2           | 6.3578                  |
| \( R_{10.0} \) | 9.0             | 2.6660                  |
| \( R_{11.0} \) | 11.3            | 3.0746                  |
| \( R_{12.0} \) | –2.8            | N/A                     |
| \( R_{13.0} \) | –2.4            | N/A                     |
| \( R_{14.0} \) | –0.8            | N/A                     |

**Note.** This table contains the Schmidt seminormalized spherical harmonic coefficients for the Cassini11+ model of Saturn’s internal magnetic field. For a description of the derivation of this model and its associated 3σ uncertainty values, see Dougherty et al. (2018) and Cao et al. (2020). All coefficients use a reference radius of 60,268 km and are in units of nT.

| Input range | \( R_{6} \) \((\text{day})\) | \( R_{6} \) \((\text{night})\) | \( R_{11} \) \((\text{day})\) | \( R_{11} \) \((\text{night})\) | \( D \) \((\text{day})\) | \( D \) \((\text{night})\) | \( \mu J \) \((\text{nT})\) |
|-------------|-------------------------------|--------------------------------|-------------------------------|-------------------------------|-----------------|-----------------|----------------|
| 6 to 8      | 14.9                          | 13.8                          | 18.5                          | 16.9                          | 2.114           | 2.101           | 38.66           |
| 9 to 12     | 12.5                          | 11.8                          | 16.5                          | 14.8                          | 2.510           | 2.483           | 47.15           |
| 15 to 30    | 12.5                          | 11.8                          | 16.5                          | 14.8                          | 2.510           | 2.483           | 47.15           |
| 30 to 80    | 12.5                          | 11.8                          | 16.5                          | 14.8                          | 2.510           | 2.483           | 47.15           |
| Pioneer 11  | 13.9                          | 13.4                          | 18.8                          | 17.0                          | 2.142           | 2.117           | 41.56           |
| Voyager 1   | 15.8                          | 15.3                          | 20.3                          | 18.4                          | 2.915           | 2.876           | 55.06           |
| Voyager 2   | 15.7                          | 15.2                          | 20.2                          | 18.3                          | 2.915           | 2.876           | 55.06           |
| Voyager 3   | 15.6                          | 15.1                          | 20.1                          | 18.2                          | 2.915           | 2.876           | 55.06           |
| Cassini SOI | 15.5                          | 15.0                          | 20.0                          | 18.1                          | 2.915           | 2.876           | 55.06           |

**Table A2**

**Note.** This table provides the input parameters for our Monte Carlo analysis and the resulting best-fit values after 10,000 simulations. \( R_6 \) and \( R_1 \) are the magnetodisk’s inner and outer radii, respectively, \( R_h \) is the hinging radius, \( D \) is the half-thickness of the disk, and \( \mu J \) is the current parameter. See Section 2 for modeling details.

simplified illustration of the magnetodisk configuration. Table A1 provides the Cassini11+ Schmidt seminormalized Gauss coefficients and corresponding uncertainty values. Finally, Table A2 contains our best-fitting magnetodisk parameters from our Monte Carlo study. For more details, please see the corresponding figure and table captions below.
Figure A2. Comparing error magnitudes. This figure illustrates the relative magnitudes of the largest error sources considered here: the quantization error (red), attitude error (blue), and Cassini11+ model formal error (consisting of errors on $B_r$ and $B_\theta$; the combined error on $|B|$ is shown here in cyan). Note that attitude errors only affect vector measurements and do not apply to the field magnitude. See Section 2 for more details.
Figure A3. Magnetodisk configuration. This figure illustrates stylized overhead (top) and side (bottom) views of Saturn’s magnetodisk configuration based on the model of Connerney et al. (1983), depicting key parameters such as the half-thickness of the current sheet, $D$, and inner and outer radii $R_0$ and $R_1$. Our magnetodisk modeling also incorporates additional complexity as described in Arridge et al. (2008), which would further distort the flat disk-like shape portrayed here upward into a curved bowl, with curvature parameterized by the hinging radius, $R_H$. 

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