Saturn’s Planetary Period Oscillations During the Closest Approach of Cassini’s Ring-Grazing Orbits

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Abstract Saturn’s planetary period oscillations (PPOs) are ubiquitous throughout its magnetosphere. We investigate the PPO’s azimuthal magnetic field amplitude interior to the field-aligned currents, during the closest approaches of Cassini’s ring-grazing orbits (October 2016 to April 2017), with periapses at ~2.5 Rs. The amplitudes of the northern and southern PPO systems are shown to vary as a function of latitude. The amplitude ratio between the two PPO systems shows that the northern system is dominant by a factor of ~1.3 in the equatorial plane, and it is dominant to ~ −15° latitude in the southern hemisphere. The dayside amplitudes are approximately half of the 2008 nightside amplitudes, which agree with previous local time-related amplitude observations. Overall, there is clear evidence that the PPOs are present on field lines that map to the outer edge of Saturn’s rings, closer to Saturn than previously confirmed.

Plain Language Summary During the closest approaches of the Cassini spacecraft’s ring-grazing orbits at Saturn, the magnetometer instrument observed magnetic field oscillations associated with two systems, one from the northern hemisphere and the other from the southern hemisphere. The amplitude of each oscillation system was determined and shown to vary with latitude. From this, at the equatorial crossing, the larger amplitude oscillation was found to be the northern hemisphere oscillation, meaning in the region where both systems are present, the northern one dominates. These observations of the oscillations just outside of Saturn’s rings are the closest to the planet at present. This discovery has important implications for the studies of Saturn’s magnetic space environment, in particular, the periodicities, coupling between the planet and surrounding environment, and dynamical processes. In addition, the presence of the oscillations just outside the rings has possible ramifications for ring observations, as well as the multiple data sets from the Grand Finale dives between the planet and the rings.

1. Introduction

Saturn’s magnetosphere is permeated with oscillations that have a period close to the expected planetary rotation of ~10.6 hr; these phenomena have been termed as “planetary period oscillations” (PPOs). The PPOs are present in many of the magnetospheric observations, namely, radio and magnetic field measurements, plasma data, and auroral emissions, and act to modulate the behavior of the magnetosphere (e.g., Carbary et al., 2017; Carbary & Mitchell, 2013; Cowley & Provan, 2017; Jackman et al., 2016; Ramer et al., 2017; Thomsen et al., 2017; Ye et al., 2016). From observations of both the Saturn kilometric radiation emission and magnetic field oscillations, it has been shown that there are two distinct periods, one associated with the northern hemisphere and the other with the southern hemisphere (Andrews, Coates, et al., 2010; Gurnett et al., 2009; Kurth et al., 2008; Southwood, 2011). These periods have been extensively monitored over the Cassini mission showing that they vary by ±1% over Saturn’s seasons, with good agreement generally being found between these data sets (e.g., Andrews et al., 2012; Lamy, 2011; Provan et al., 2016).

The magnetic field oscillations are due to two perturbation fields, one associated with the northern hemisphere and the other with the southern hemisphere. These result from two rotating field-aligned current systems thought to be driven from the polar atmospheres (e.g., Hunt et al., 2014; Jia et al., 2012; Jia & Kivelson, 2012; Smith, 2006, 2014). The relative phasing of the three spherical polar components of the magnetic field referenced to Saturn’s spin axis shows that in the equatorial quasi-dipolar core region (field lines inside the main field-aligned currents), the perturbation fields are quasi-uniform. In the polar regions (field lines outside the main field-aligned currents) the perturbation fields are quasi-dipolar (Andrews, Coates, et al., 2010; Cowley et al., 2006; Espinosa et al., 2003; Espinosa & Dougherty, 2000; Provan et al., 2009, Southwood &
Kivelson, 2007). In the polar regions the oscillations are mostly hemispherically pure to within ~10% by amplitude (Andrews et al., 2012; Hunt et al., 2015). In the equatorial region both the northern and southern signals are present, and the observed oscillations are a vector superposition of the two perturbations (Provan et al., 2011). The equatorial oscillations are beat modulated due to the difference in the northern and southern periods. From this the amplitudes of both systems can be measured, and therefore, the dominant system can be determined. The ratio between the northern and southern amplitudes is given by the parameter, $k$.

Early in the Cassini mission (2004–2008) the periods were well separated, the southern being longer at ~10.8 hr and the northern at ~10.6 hr, with the southern system being dominant by a factor of ~2.5 relative to the northern system (Andrews et al., 2012). During the interval across equinox (2008–2013) the periods converge and diverge, but the southern period always remains the longer one. However, there were sharp changes in periods and amplitudes (Provan et al., 2014). In 2014 the northern period suddenly became longer by lengthening to ~10.8 hr, while the southern period remained at ~10.7 hr (Provan et al., 2016). The amplitude ratio also changed over this time interval such that the northern dominated by a factor of ~2. By September 2015 the southern signal in the equatorial core region could no longer be detected, thus implying strong northern dominance of a least $k > 5$, this was the case up to March 2016, after which the southern signal was detected in the southern polar region (Provan et al., 2016, 2018). The periods then remained very stable at ~10.79 hr for the northern systems and ~10.68 hr for the southern until the end of mission. However, $k$ decreased to ~1.4 during the 2016/2017 orbits indicating a change in the relative dominance (Provan et al., 2018). The energetic electron periodicities during 2016/2017 exhibit a very similar dominant period associated with the northern hemisphere. This is approximately equal to the summer southern hemisphere period from earlier in the Cassini mission (Carbary et al., 2017).

Andrews, Cowley, et al. (2010) showed the amplitude of the equatorial azimuthal field component varied with radial distance and local time with the nightside amplitude being ~2 times larger compared to the dayside at ~10 Rs. The decrease in amplitude of the azimuthal oscillation with decreasing radial distance suggested a region of field-aligned current at the Enceladus torus (~3.5 Rs) that would effectively shield out the PPOs inside that radial distance. This inner closure current has also been previously discussed by Hunt et al. (2014, 2015); Hunt, Cowley, et al. (2018); Hunt, Provan, et al. (2018); Southwood and Cowley (2014); and Southwood and Kivelson (2007). Analysis of 2008 nightside data by Hunt et al. (2015) showed that it was possible to track the amplitudes of the two PPO systems as function of latitude within a given field region and determine the amplitude ratio inside the main field-aligned current regions.

In this present study, we focus on the azimuthal component of the magnetic field, which is not influenced by the ring current whose spatial variations dominated the radial and theta components on these passes. The periapses were on the dayside at approximately noon and at distances just outside the Saturn’s F ring at ~2.5 Rs. These orbits are known as the “F-ring orbits” or “ring-grazing orbits.” We first describe the data set and procedures, then we investigate the northern and southern PPO modulations separately. Lastly, we determine the northern and southern amplitudes, and the $k$ parameter as functions of latitude. For discussion we compare these to nightside results from Hunt et al. (2015).

2. Data Set and Procedures

2.1. Data Set

In this letter we employ the data collected around the periapses of the Revs 251–270, inclusive. Figure 1a shows the segments of the orbits considered for this study in cylindrical $\rho$-$z$ coordinates, where $\rho$ is perpendicular distance from the spin/magnetic axis and $z$ is aligned along the spin axis. These orbits are color coded as shown at the top of the figure. We employ a magnetic field model based on the Burton et al. (2010) axisymmetric internal field model together with the ring current model from Bunce et al. (2007), where the subsolar magnetopause distance is set to 22 Rs. The gray shaded region shows a field region between 20° (22.1°) and 40° (44.7°) ionospheric colatitude in the northern (southern) hemispheres, which in the equatorial plane maps to between ~6.6 Rs and ~1.9 Rs. Data from within this region are employed in this study. The fanned straight and dashed lines indicate 15° bins of latitude, which overlap by 7.5°; these bins will be used in section 4. The light green shaded region indicates where the typical PPO-related field-aligned currents flow (Hunt, Provan, et al., 2018). The three dotted trajectories are from the 2008 high-latitude orbits, specifically Revs 65, 75, and 85. The portions of the orbits shown are from the minimum northern ionospheric...
75, and 85. Figure 1b shows the azimuthal magnetic rents shaded region shows the field region considered. The green shaded region shows the field region where the PPO-related field-aligned currents flow. The dotted trajectories are from the 2008 interval, specifically Revs 65, 75, and 85. Figure 1b shows the azimuthal magnetic field data, $B_\phi$, from the trajectory sections shown in Figure 1a as a function of time from periapsis. The gray shaded region corresponds to the field region in Figure 1a. The vertical dotted line marks the time of periapsis, and the vertical dashed line is the equator crossing.

The mapping acts to normalize the $B_\phi$ data for $\rho$, thus allowing comparison between measurements over varying $\rho$. For the F-ring orbits $\rho$ is almost constant at $\sim 2$ $R_S$ as shown in Figure 1a. Thus, the gross features of the field orbit to orbit remain unchanged relative to each other.

To determine the PPO modulation of the field, we organize the data relative to the PPO phase systems. For this we employ the northern and southern phases, $\Phi_{N,S}(t)$, derived by Provan et al. (2018), where $\Phi_{N,S}(t)$ is the angle between the radially outward quasi-uniform field and noon. The position of the observation relative to either the northern or southern PPO perturbation fields is given by

$$\Psi_{N,S}(\varphi, t) = \Phi_{N,S}(t) - \varphi,$$

where $\varphi$ is the azimuthal angle of the observation point from noon. Both $\Phi_{N,S}(t)$ and $\varphi$ increase with planetary rotation. The quasi-uniform field points radially outward at $\Psi_{N,S} = 0^\circ$, and as the PPO system rotates the $B_\phi$ component varies as $\sim \sin \Psi_{N,S}$ at any fixed near-equatorial point. We analyze the PPO modulations by fitting either a constant plus single sinusoidal function or a constant plus the sum of two sinusoidal bands; both approaches are described below.

Figure 1b shows the $B_\phi$ data as a function of time from periapsis, each colored profile corresponding to a trajectory segment shown in Figure 1a. The gray shaded region corresponds to the inner field region shown in Figure 1a. This region of field is interior to the gradients in $B_\phi$ which are associated with the main field-aligned currents at $\sim 4$ hr prior to and $\sim 2$ hr after periapsis. The $B_\phi$ field changes gradually from negative to positive within the shaded region. The change of sign of $B_\phi$ across the magnetic equatorial plane (vertical dashed line) indicates the presence of a lagging or "swept back" field configuration in both hemispheres. We envisage that this field deflection is associated with a quasi-steady axisymmetric field-aligned current system, which transfers angular momentum from the ionosphere to the subcorotating magnetospheric plasma (Hunt et al., 2014, 2015; Hunt, Cowley, et al., 2018; Hunt, Provan, et al., 2018). The main variation of $B_\phi$ from orbit to orbit is due to the PPOs, which vary the field in a sinusoidal manner. We will determine the variation of amplitudes for both northern and southern PPO systems with latitude across this field region and to compare with previous results.

2.2. Data Procedures

In this section, we describe the method to determine the PPO amplitudes from the Cassini $B_\phi$ data shown in Figure 1b. To begin, the $B_\phi$ data are mapped to the ionosphere to estimate the ionospheric azimuthal field, $B_\phi$ given by

$$B_\phi = B_\psi \left( \frac{\rho}{\rho_i} \right),$$

where $\rho_i$ is the perpendicular distance of the field line foot in the ionosphere to the spin/magnetic axis. The basis of equation (1) comes from Ampère’s law that $B_\psi$ varies as $1/\rho$ for an axisymmetric current system. Moreover, this is also approximately true for a nonaxisymmetric situation, provided that the longitudinal scales of the current systems are much longer than the latitudinal, as for the PPO current system. In section 4 we will discuss results from orbits during 2008, their ($\rho$ greek symbol) values varied, as shown by the dotted trajectories in Figure 1a.

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Figure 1. Overview of the Cassini spacecraft trajectories and data selection for the present study. Figure 1a shows the trajectories of Revs 251–270 in the $\rho$–$z$ plane, by Rev number color-coded at the top of figure, where $\rho$ is the perpendicular distance from the spin axis and $z$ is aligned with the magnetic/spin axis. The fanned solid and dashed lines mark 15° bins of latitude, which overlap by 7.5°. The gray shaded region shows the field region considered. The green shaded region shows the field region where the PPO-related field-aligned currents flow. The dotted trajectories are from the 2008 interval, specifically Revs 65, 75, and 85. Figure 1b shows the azimuthal magnetic field data, $B_\phi$, from the trajectory sections shown in Figure 1a as a function of time from periapsis. The gray shaded region corresponds to the field region in Figure 1a. The vertical dotted line marks the time of periapsis, and the vertical dashed line is the equator crossing.
To a first approximation, we can examine the modulation of the field data by $\Psi_N$ or $\Psi_S$ separately. Figures 2a and 2b show the northern hemisphere $B_{\phi i}$ data as calculated from equation (1), from the northern section of the field region in Figure 1 plotted as functions of $\Psi_N$ and $\Psi_S$, respectively. Figures 2c and 2d similarly show the southern hemisphere data plotted as functions of $\Psi_S$ and $\Psi_N$, respectively. To these data we least squares fit the following function,

$$B_{\phi i} = B_{\phi i 0} \sin(\Psi_S - \Delta),$$

where $\langle B_{\phi i} \rangle$ is the mean ionospheric azimuthal field, $B_{\phi i 0}$ is the amplitude of the oscillations in the data, and $\Delta$ is the relative phase, which based on the expectations outlined in section 2 should be $\Delta = 0^\circ/360^\circ$; that is, $B_{\phi i}$ varies by $\sim \sin(\Psi_N, \Psi_S)$. The resulting fitted parameters for equation (3) are shown in each figure with estimated uncertainties of the fit parameters from a statistical resampling method. We use the “jackknife” method, in which the fit is computed $N$ times, where $N$ is the number of orbits. For each fit a different orbit is removed from the data set, as to create a resampled data set of $N-1$ orbits. We then multiply the standard deviation of the ensemble of fit parameters by $\sqrt{N-1}$ to account for the $N-1$ resampling (e.g., Efron, 1982). This modified standard deviation gives an estimated error on each fit parameter, as it shows the variability for the best
fit parameter given by the data set. We also performed “bootstrap” resampling, where one randomly selects the orbits, allowing the same orbit to be picked multiple times to create a new data set with the same size as the original set. The fit is performed on the resampled data set and repeated a large number of times (~1,000). The standard deviation of these fit parameters is taken. We found that the bootstrap method yielded very similar fit uncertainties to the jackknife; therefore, we employed jackknife results due to its smaller computation need. This method of fit uncertainty estimation was used by Hunt et al. (2015).

There is a fair amount of scatter around the fits; however, Figures 2a and 2c show that the $B_{p}$ is well organized by that hemisphere’s PPO system. In both, the fitted amplitudes and phases are well constrained, and the root-mean-square (RMS) values are less than the peak-to-peak amplitudes. For the northern hemisphere data in Figure 2a the amplitude of the northern PPO oscillation is $\sim 12 \pm 2$ nT, while for Figure 2c the amplitude of the southern PPO oscillation is $\sim 9 \pm 2$ nT. However, in both cases, the $\Delta$ values are displaced somewhat from $0^\circ/360^\circ$ with the northern hemisphere data being $\sim 46^\circ \pm 7^\circ$ “earlier” and the southern hemisphere where the phase deviation is $\sim -23 \pm 18^\circ$ early. A similar effect was found by Hunt et al. (2015) for the northern hemisphere (see their Figure 5b) and was thought to reflect where the phase model best represented the data used to construct it due some possible radial and latitude phase structure of the PPOs.

Examining Figures 2b and 2d where the northern and southern $B_{p}$ data are plotted as a function of the other hemisphere’s PPO phase system, the data and fits show some organization, with nonzero amplitudes within errors, which are approximately half the amplitude values in the Figures 2a and 2c. The phase deviations are not well constrained, however, with errors up to an eighth of a cycle. In Figure 2b $\Delta = 350^\circ \pm 23^\circ$ is consistent, within errors, with $\Delta = 0^\circ/360^\circ$, while in Figure 2d $\Delta = 291^\circ \pm 42^\circ$ is inconsistent with the expected $\Delta$ value. These fits therefore show evidence of dual PPO modulation along the field lines into the opposite hemisphere. However, it should be noted that the RMS values are comparable to the peak-to-peak amplitudes. In these cases, to investigate the dual PPO modulation, further, a more rigorous fitting method using both phases is needed.

4. Dual Oscillation Fits

To fully assess the dual presence of the PPOs within the field region shown in Figure 1, the combined perturbations due to the two PPO systems can be considered as the sum of two sinusoidal functions. This is given by

$$ B_{pl} = B_{pN} \sin(\Psi_{N} - \Delta \Phi_{N}) + B_{pS} \sin(\Psi_{S} - \Delta \Phi_{S}), $$

where the five free parameters are ($B_{p}$) the mean field; $B_{pN}$ and $B_{pS}$ are the northern and southern amplitudes, respectively; and $\Delta \Phi_{N}$ and $\Delta \Phi_{S}$ are the northern and southern phase deviations.

We select $B_{p}$ data within the gray shaded region in Figure 1 (all mapped to the northern ionosphere). We split the data into $15^\circ$ bins of latitude, which overlap by $7.5^\circ$, and then minimize the RMS deviation between the data and the model given by equation (4). The method of the fitting is as follows: first, we fix a pair of the phase offsets, with the choice being informed by the fits shown in Figure 2. We then find the minimum RMS deviation in the 3-D parameter space of ($B_{pN}$, $B_{pS}$) in steps of $0.5$ nT. We then vary the phase offsets by $5^\circ$ to find the pair of values that give the smallest RMS deviation over the whole latitude range. These were found to be $\Delta \Phi_{N} = -55^\circ$ and $\Delta \Phi_{S} = -30^\circ$. Fixing these in equation (4) we then determine the remaining three parameters by repeating the RMS deviation minimization, also finding well-defined minima for these fits.

The results are shown as a function of latitude by the circles joined by solid lines in Figure 3, where Figure 3a shows the RMS deviation between the model and data; Figure 3b shows the average ionospheric azimuthal field ($B_{p}$); Figure 3c shows the northern ($B_{pN}$) and southern amplitudes ($B_{pS}$) in blue and red, respectively; and Figure 3d shows the “$k$” parameter. As in section 1, the latter parameter is the ratio of the northern and southern amplitudes, where $k = B_{pN}/B_{pS}$ and $k' = 1/k$. Such that $k \approx 0$ represents a southern PPO dominant case, while a $k \approx 0$ indicates a northern PPO dominant case, and $k \approx 1$ or $k \approx 1$ represents near-equal amplitudes. The uncertainties show here, as in Figure 2, are estimated using the “jackknife” resampling method, where data from one orbit are removed a time and the fitting repeated. These uncertainty values were again checked against the bootstrap method for several of the latitude bins, with little difference. For comparison...
we also plot similar fits using the 2008 (Revs 59–95) nightside periapsis data from Hunt et al. (2015) (see their Figure 11). These results are shown by the dashed lines in each panel. The RMS deviations for the F-ring fits are also smaller than for the 2008 fits (dashed crossed line), indicating that the data are less variable with respect to the model given by equation (4). In the majority of latitude bins the RMS values are less than half the amplitude. Only in the most poleward bins are the RMS and amplitudes comparable. However, these are still significantly less than the peak-to-peak amplitudes.

The average azimuthal field is shown in Figure 3b, with the F-ring fits showing a change in sign of \( \langle B_{\phi} \rangle \) about the equator from negative in the northern hemisphere to positive in the southern hemisphere. This is consistent with a lagging field geometry as discussed in section 2.1. This behavior is opposite to that derived from the 2008 data, where an approximately “leading” field configuration was observed. Previously, Hunt et al. (2014, 2015) and Hunt, Cowley, et al. (2018) suggested that a possible phase asymmetry in the PPO fields could result in an apparent “leading” background field. This would occur if the negative half cycle of the
The amplitudes $B_{\phi N}$ and $B_{\phi S}$ in Figure 3c show strong evidence for both PPO systems being present within both hemispheres. For the F-ring data set, starting in the northern hemisphere, $B_{\phi N}$ is $\sim 16 \pm 2$ nT, well separated from the weaker $B_{\phi S}$ $\sim 6$ nT $\pm 3$ nT. Moving toward the equator, both amplitudes remain separated until $\lambda = 0^\circ$ where the error bars cross, with the northern amplitude being the larger. The amplitudes converge to very similar values at $\sim 15^\circ$ in the southern hemisphere. Continuing southward they then diverge again with the southern amplitude becoming the larger. At the most southern latitude considered here $B_{\phi S}$ reaches $\sim 14 \pm 3$ nT while $B_{\phi N}$ decreases to $\sim 7 \pm 3$ nT.

Comparing the amplitude values from F-ring and 2008 data sets in Figure 3c, it is clear that for the latter data set, both the northern and southern amplitudes are considerably larger by a factor of $\sim 2$. Recent results from Hunt, Provan, et al. (2018) showed evidence that the strength of the PPO-related field-aligned currents during the F-ring orbits had decreased by a factor of $\sim 2$ compared to 2008 PPO current observations. In addition, Andrews, Cowley, et al. (2010) showed that $B_{\phi}$ oscillations were $\sim 2$–3 times weaker on the dayside compared to the nightside. Therefore, we suggest that the difference shown in Figure 3c between the 2008 and F-ring amplitudes could be due to a combination of the local time asymmetry observed by Andrews, Cowley, et al. (2010), the weaker PPO-related field-aligned currents, and secular change of the PPOs.

Figure 3d shows the ratio between the northern and southern amplitudes from Figure 3c for both the 2008 and F-ring orbits data sets. An important difference is in the $k$ value at the equator. For the F-ring epoch $1/k = 0.77 \pm 0.24$ or $k \sim 1.29 \pm 0.24$, which shows the northern system the dominant. This value of $k$ is consistent within errors with the $k$ value determined by Provan et al. (2018) from analysis of the beat modulations of data at larger distances in the magnetosphere but over the same time interval as studied here. It should be noted that during the F-ring epoch the dominant PPO system extends further into the opposite hemisphere compared to the 2008 observations. Similar behavior for the PPO currents was shown by Bradley et al. (2018) during the nightside high-latitude 2013 interval. These behaviors further support the seasonal changes of the PPO amplitudes and dominance (e.g., Gurnett et al., 2010), such that the summer hemisphere is the dominant one. It should be noted that while the northern PPO system is dominant, it is not to the same extent as the southern PPO system during the 2004–2008 southern summer epoch, implying that it is not just purely a seasonal effect.

The presence of the PPOs in the field region that maps to a radial distance in Saturn’s equatorial plane at $\sim 1.9$–$6.5\,R_S$ has significant consequences for the closing of the PPO-related current systems, and therefore for the extent the PPOs are still present at radial distances $<2.5\,R_S$. As discussed in section 1, it was previously thought that at the inner edge of the Enceladus plasma torus ($\sim 3.5$–$4\,R_S$), there would be a discrete field-aligned current region that would shield the PPOs from radial distances less than $\sim 3.5\,R_S$. The results presented here show no direct evidence of this inner discrete closure for the PPO-related current system. Instead we observe a distributed closure current throughout this region, as shown by the latitudinal variation of the PPO amplitudes and $k$. This implies that the PPOs still penetrate to radial distances less than $\sim 2.5\,R_S$, closer to the planet than previously thought.

5. Conclusions

We have presented observations of the PPOs in the $B_{\phi}$ field component in a field region that maps to between $\sim 6.5\,R_S$ and $\sim 1.9\,R_S$ in the equatorial plane. These observations show that the PPOs extend to smaller radial distances and are present on field lines at the outer edge of the F ring.

1. The ratio of the amplitudes shows that for the F-ring orbits epoch, the northern PPO system was the dominant system with $k \sim 1.3$. This is in agreement with the value of $k$ determined by Provan et al. (2018). While the northern system’s dominance has increased since the preequinox interval of 2008, the value is closer to unity than earlier data sets from 2015 and 2016 showed, thus implying that the northern system has either weakened and/or the southern system has strengthened (Provan et al., 2016, 2018).

2. These observations have direct implications for the closure of the PPO-related current systems. It is clear from the F-ring orbit data that the PPO-related current is not fully closed within the inner field region. These results imply that the PPOs could extend further over the rings of the Saturn.
3. Investigating the latitudinal variation along the flux tube, we have shown that both the northern and southern oscillation amplitudes are approximately a factor of 2 weaker than previous determined (Hunt et al., 2015). This difference could arise from a noon-midnight asymmetry and/or the seasonal change of the PPOs.

With the full set of Grand Finale orbits, now completed studies, it should be possible to determine the penetration of the PPO signals, smaller radial distances across the rings and within the D-ring gap.

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