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Periodic motion of the magnetodisk as a cause of quasi-periodic variations in the Kronian magnetosphere

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ABSTRACT

Most of the phenomena that describe the magnetized plasma filling the huge magnetosphere of Saturn exhibit periodic behavior. The fundamental period reflected in many magnetospheric phenomena is the rotational period of the planet, but the relationship is not at all trivial. In most cases clear periodic behavior can be found only for relatively short time intervals, and often even in these intervals abrupt phase-shifts occur and non-rotational frequencies appear. Several sophisticated methods have been developed to filter out interfering fluctuations and find the basic periodicity and phase of the variations. Although these methods proved to be very useful, some information is inevitably lost in the process. To recover this otherwise lost information we follow a different strategy to analyse the quasi-periodic variations of the plasma properties. We assume that the motion of the magnetodisk is periodic and that the observed quasi-periodic variations are due to the interplay of this periodic motion and the effects governing the spatial dependence of the plasma parameters (F), especially their dependence on the distance (d) from the central sheet of the magnetodisk. We found that relatively simple $F(d)$ functions are able to reproduce the observed complex temporal dependence of the plasma properties.

1. Introduction

Saturn has an extended spinning magnetosphere. As the planet rotates, it drags around the magnetic field and plasma filling the magnetosphere. As Saturn is a gas giant, its rotation period cannot be defined by the motion of solid landmarks; the longitude system and the rotational period can only be derived from observations of periodically recurring phenomena of the Kronian system. One possibility, which is commonly used in magnetospheric studies, is the Saturn Kilometric Radiation (SKR). It gives a slowly varying rotation period (Gurnett et al., 2005), roughly 10.6 h. Further investigations revealed some peculiarities of the SKR periodicity. For example, the northern and southern hemisphere exhibit slightly different periods, the difference changing with the Kronian seasons (Gurnett et al., 2009). It turned out that many magnetospheric phenomena can be organized around the SKR periodicity. The magnetic field shows similar periodicities (Espinosa and Dougherty, 2000; Andrews et al., 2008, 2012; Provan et al., 2009), and southern-northern duality was even discovered in the magnetic field variations (Andrews et al., 2012; Provan et al., 2012). Burch et al. (2009) have shown that the heavy (water group) ion population of the Kronian plasma exhibit a cam-like feature (the plasma cam) in a longitude system fixed to SKR. The same periodicity can be observed in the variations of the proton and heavy ion density moments as well (Nemeth et al., 2011; Szego et al., 2011, 2012, 2013; Arridge et al., 2011a). Although the planetary rotation period evidently plays a very important role in these phenomena this relationship is not at all trivial. In most cases coherent periodic behavior can be found only for a few periods long time intervals, and often even in these intervals abrupt phase-shifts occur and higher frequencies appear. Different methods can be used to find the periodicity. In the simplest way it can be observed "by eye", using apparent features (zero crossings, minimum–maximum pairs etc.), which reappear for several consecutive planetary periods. A more sophisticated method uses the statistical distribution of a plasma parameter in an SKR based longitude system. As other effects also influence the plasma, it is hard to find this type of relationship, and the details can be completely washed out. Burch et al. (2009) used this method for example by applying very strong data filtering constraints to lessen the influence of other effects. Another method to find an approximately known periodicity is to apply a band-pass filter to the time series. Andrews et al. (2008, 2012) and Provan et al. (2009, 2012) used this method. Although the periodicity and its variation

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is very clear in the filtered data, some information is inevitably lost in the process.

A strong longitudinal asymmetry of electron densities was also observed in Saturn's magnetosphere by Morooka et al. (2009). Due to this asymmetry, periodic electron density variations appear in the measurements throughout the magnetosphere including the lobe regions. Based on their statistical investigation they constructed a model of the electron density featuring a rotating asymmetry. For the magnetic field (also using electron and energetic neutral atom data) Khurana et al. (2009) performed a similar statistical investigation, which explains the observed periodicity by a rotating anomaly, due to asymmetrical lift of the magnetosphere by the solar wind. None of these papers attempt to provide accurate fits to the quasi-periodic variations observed during individual orbit segments. Statistical studies, as well as methods which use filters to enhance the data, by their very nature hide interesting non-permanent features and non-periodic variations, which nonetheless can provide important insights into the mechanisms governing the phenomena. We believe that this lost information is also important to understand the cause of the periodic behavior and the process that leads to these variations. To recover this information we investigate the periodicities by applying and fitting a simple model to the quasi-periodic data sets of several measured plasma properties.

The wavy magnetodisk model originated in the work of Eviatar and Ershkovich (1976), when they derived plasma densities in the outer Jovian magnetosphere based on periodicity alone. Arridge et al. (2011b) pioneered this method for Saturn by applying a simple structural model of the magnetodisk to explain the variations found in the magnetic field data. Due to the fast rotation of the magnetosphere, the majority of the plasma is situated in the equatorial region, forming a disk-like structure. This plasma disk together with the centrifugally stretched field lines is called the magnetodisk (Arridge et al., 2007; Achilleos et al., 2010; Kivelson et al., 2015). The magnetodisk has a complex shape (Arridge et al., 2008), which depends on the radial distance, the local time, the Kronian season and also on external forces (solar wind pressure). It also exhibits an apparent periodic vertical motion (flapping) in the outer magnetosphere. This complex rotating and flapping structure together with the position of the spacecraft inside the magnetosphere can explain the quasi-periodic variation of the magnetic field. Szego et al. (2012) observed that the ion density moments derived by Thomsen et al. (2010) from Cassini CAPS measurements exhibit peaks around zero-crossings of the magnetic field. The proton peaks are broader, the heavy ion peaks are sharper. They found that the positions of these peaks can be explained by the simple structural model of Arridge et al. (2011b). Szego et al. (2013) modified the simple structural model to include the dual periodicity of the magnetic field, and found an even better agreement for the positions of the ion peaks.

In this paper we analyse the quasi-periodic variation of several plasma properties. The variation of the magnetic field is used to recover the position of the magnetodisk, and this information is further used to model the variation of the density and azimuthal velocity moments of the thermal ions. We assume that the motion of the magnetodisk is periodic and that the observed quasi-periodic variations are due to the interplay of this periodic motion and the effects governing the spatial dependence of the plasma parameters, especially their dependence on the distance (d) from the central sheet of the magnetodisk. This paper does not address the ultimate cause of magnetodisk flapping.

2. Data and methods

The distance from the sheet center of the flapping magnetodisk is a dominant factor in determining various periodic phenomena of the Kronian magnetosphere. We limit ourselves to analyzing orbit segments containing Titan encounters, because these segments provide the latitude scans together with relatively small radial motion needed to perform this study. In Fig. 1a few examples are presented, specifically two four day long intervals in the vicinity of two Titan encounters, T57 and T59. The upper panel shows the magnetic field measured by the Cassini magnetometer (MAG) instrument; where the black line represents the radial component of the field, which is the most sensitive indicator of the distance from the sheet center. The azimuthal speed of the proton plasma component can be seen in the middle panel, while the bottom panel presents the proton density. The density and speed moments were derived from Cassini CAPS data (Thomsen et al., 2010).

Due to the periodic motion of the magnetodisk and the motion of the spacecraft along its path, the distance (d) between the spacecraft and the sheet center shows a quasi-periodic time dependence. As the sheet center moves up and down, and the spacecraft moves towards lower latitudes, one finds that d approaches zero several times, then there are several crossing events, and after that as the spacecraft moves to larger latitudes in the other hemisphere, d repeatedly approaches the zero line from the other side.

The red line in the top panel of Fig. 2 shows the position of the sheet center of a model magnetodisk as a function of time for the T59 interval. The blue line represents the orbit of the spacecraft. The inset shows their separation distance d as a function of time. We will describe the details of the magnetodisk model later.

The radial component of the magnetic field is an odd function of this distance, saturating at the lobe value far away from the sheet center. The particle density and azimuthal speed (among other parameters) can be described by even functions of d, maximum at the sheet center and vanishing further away (Hill and Michel, 1976; Persoon et al., 2009; Nemeth et al., 2015). The quasi-periodic time dependence of d filtered through these simple odd and even functions results in very complex signal shapes, which can reproduce the measured behavior of many parameters of the Kronian plasma.

For example, as the spacecraft moves in latitude, we first see the asymptotic saturated value of the magnetic field. Later we experience deeper and deeper dips, which correspond to approaches to the current sheet center. Then come the zero crossings and even later the dips and asymptotic value on the other side. If the spacecraft velocity has a radial component as well, it also influences the picture. As indicated above, it is a reasonable assumption that the asymptotic values of the magnetic field are the northern and southern values of the lobe field. The lobe field, however, has a well-known radial dependence (Jackman and Arridge, 2011), which modifies the asymptotic value due to the radial motion of the spacecraft. We will show that these two effects (a saturating function of d with asymptotic values varying with radial distance) are enough to explain the features of the radial magnetic field shown in Fig. 1.

An even function of d would lead to higher and higher peaks, double peaked structures near shallow crossings and smaller peaks again on the other side, thus giving a reasonable qualitative description of the density and velocity data shown in Fig. 1.

We further tested the picture described above using additional Cassini magnetic field (MAG) measurements, and the numerical moments derived from Cassini CAPS/IMS data (Thomsen et al., 2010). These data were acquired in 2009, in the nightside outer magnetosphere. We verified through case studies that the behavior of the magnetic field, the density, and also the azimuthal speed can be qualitatively described by the above arguments. We investigated eight four day long time intervals around Titan encounters T55–T62. The azimuthal speed (v_φ) and the logarithm of