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

Z. Nemeth^{1}, K. Szego¹, L. Foldy¹, S.W.H. Cowley², G. Provan², and M. Thomsen³*

(1) MTA Wigner Research Center RMI, Budapest, Hungary,

(2) Department of Physics and Astronomy, University of Leicester, Leicester, UK,

(3) Planetary Science Institute, Tucson, AZ, USA.

(*) nemeth.zoltan@wigner.mta.hu

Abstract

Most of the phenomena that describe the magnetized plasma filling the huge magnetosphere of Saturn exhibit periodic behaviour. 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 behaviour 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.

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, roughly 10.6 hours. 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, 2013). 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 behaviour 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 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 behaviour 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 (*JGR*, 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.

Data and Methods

The distance from the sheet centre 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 Figure 1 a 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 centre. The azimuthal speed of the proton plasma component can be seen in the middle panel, while the bottom panel presents the proton density.

Figure 1. Quasi-periodic variations of the magnetic field (top panel,) the proton azimuthal speed (middle panel,) and the proton density (bottom panel) for two 4 day long time intervals around the T57 (left) and T59 (right) Titan encounters. Black, purple and blue lines in the top panel represent the radial, azimuthal and latitudinal components of the magnetic field respectively, while the thick green line is the field magnitude.

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 centre shows a quasi-periodic time dependence. As the sheet centre 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 Figure 2 shows the position of the sheet centre 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 centre. The particle density and azimuthal speed (among other parameters) can be described by even functions of d , maximum at the sheet centre 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 centre. 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 Figure 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 Figure 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 the density show a very similar time dependence. Their strong correlation has been documented before (Nemeth et al., 2015) while here we call attention to their identical periodic behavior. This being true for all the cases we studied, we used one of these parameters (v_ϕ) as the example for plasma parameters that peak at the sheet centre of the magnetodisk.

From d and the spacecraft trajectory it is easy to calculate the position of the sheet centre of the magnetodisk. As the first step in magnetodisk reconstruction we use a simple analytic model of the

magnetodisk position derived from the model of Arridge et al. (2011b), with only two slight modifications

$$z_{CS} = z_{bowl} + a \cos\left(\frac{2\pi}{T}t - \psi_0\right) \quad (1)$$

$$z_{bowl} = \rho - r_H \tanh\left(\frac{\rho}{r_H}\right) \quad (2)$$

$$a = a_0 \sqrt{(\rho - \rho_0)^2 + b} \quad \rho > \rho_0 \quad (3)$$

In these expressions z_{bowl} represents the static bowl shape of the current sheet, while the second cosine term in equation (1) corresponds to the flapping, with flapping amplitude a . Here r_H is the hinging distance, ρ is the radial distance from Saturn in the Saturn-centered SSQ system, in cylindrical coordinates, T is the planetary period, and ρ_0 is the distance from which the flapping amplitude starts

Figure 2. Magnetodisk position from a simple analytic model (red line top panel), the radial component of the magnetic field derived from the model (green line middle panel), and the azimuthal speed derived from the same model (green line bottom panel). The black lines on the two latter panels represent measurements, on the top panel the black line is the magnetodisk position reconstructed from the magnetic field data (see the text). The blue line in the top panel is the spacecraft position, the blue line in the inset is the distance of the spacecraft from the model magnetodisk.

to grow. Our two modifications compared with Arridge et al. (2011b) are as follows: First, since we are not interested here in the global longitude dependence, we fit the longitudinal phase ψ_0 of the cosine function for each orbit segment separately. Also we do not calculate the amplitude a_0 from the solar angle of incidence, but simply fit a_0 , ψ_0 and ρ_0 to match the shape of the B_r function. Second, instead of using $a=0$ for $\rho<\rho_0$ and $a\sim\rho$ for $\rho>\rho_0$ for the flapping amplitude, we use $a = a_0\sqrt{b}$ for $\rho<\rho_0$, and $a = a_0\sqrt{(\rho - \rho_0)^2 + b}$ for $\rho>\rho_0$. Taking $b=0$ retrieves the model in the literature exactly, $b\neq 0$ provides a small residual flapping amplitude for smaller ρ values and a smoother transition around ρ_0 . (As we only use data from the nightside outer magnetosphere of Saturn ($\rho>10R_S$), the validity of the model was only tested for that region; it tells nothing about the presence of flapping in the inner magnetosphere.) Using this the distance d can be written as $d = z_{s/c}-z_{CS}$, where $z_{s/c}$ is the z coordinate of the spacecraft.

We then use a simple odd function $F(d)$ to model the d dependence of the magnetic field. The exact form of $F(d)$ is not critical. Good fits by eye were obtained with either $F(d)\sim\text{atan}(d)$ or $F(d)\sim\tanh(d)$. The radial dependence of the lobe field (Jackman and Arridge, 2011), which serves as the asymptotic value of our $F(d)$ function must also be taken into account. For example, the function $B(r,d) = B_0(r)\tanh(d)$ with $B_0(r) \sim r^{-p}$ fits also the data very well (see Figure 2, where we used $r_H=15R_S$, $\rho_0=17.5R_S$, and $b=2$ for the fit, and slightly tuned values of the Jackman and Arridge lobe field model). We use this function to fit the magnetic field data, and thus to determine our model $d(t)$ function. After that we insert this $d(t)$ into the model $F(d)$ functions for the other plasma parameters. The model fit for the magnetodisk position (red curve) and spacecraft-magnetodisk distance in the vicinity of the T59 Titan flyby (blue curve) are shown in the top panel and inset of Figure 2. We note that this method only enables us to determine d up to a scale factor (D), which is the scale height of the plasmashet for the parameter in question. So in reality we determine $d(t)/D$.

With this we can reconstruct the time dependence of, e.g., v_ϕ using a simple even function of the quasi periodic spacecraft magnetodisk centre distance, for example a simple Gaussian $v_\phi\sim\exp(-(d(t)/D)^2)$. When we assumed that the velocity scale-height remains constant for the whole time interval the fit was not accurate, but it showed the qualitative properties of the measured time series. As the spacecraft travels from $30R_S$ to $10R_S$ in this time, it is reasonable to assume that the width of the plasma sheet changes significantly. If the velocity scale-height of the proton plasma sheet was assumed to change linearly from $1R_S$ at $r=15R_S$ from Saturn to $2R_S$ at $30R_S$ the results reproduce the measured v_ϕ fairly well. The fit is very good in the outer magnetosphere, but becomes poor for radial distances smaller than $18R_S$ (i.e., after day 206 in Figure 2). We have repeated this process for several other orbit segments as well and found that this simple model can reproduce the quasi-periodic variation of the density and velocity moments of the nightside outer magnetosphere fairly well.

The results in this paper show that the quasi-periodic variations of several plasma parameters in the nightside outer magnetosphere of Saturn are governed by the same underlying quantity, namely the distance from the flapping magnetodisk centre. Until now we have done that by using a simple model of the magnetodisk, calculating the distance from that model, and using simple odd and even functions of the distance to describe the variations of the parameters. We can use a different approach as well, in which it is not necessary to construct a model magnetodisk as a first step. If we assume that simple functions of the same $d(t)$ time series describe various parameters, we can choose one of the parameters and apply the inverse function to get $d(t)$. At this point we don't need any assumptions about the shape of the magnetodisk, only that the same $d(t)$ will appear in the time dependence of the other parameters as well. If the radial component of the magnetic field is $B_r=F(d)$, and $v_\phi=G(d)$, we can calculate $d(t)$ as $d(t)=F^{-1}(B_r)$, and thus $v_\phi=G(F^{-1}(B_r))$. This means that we can

calculate one parameter from the other, using only the simple F and G functions, even the calculation of $d(t)$ is unnecessary.

However, if we further suppose that the $d(t)$ we obtain as a middle product of this procedure is the distance from the sheet centre of the magnetodisk, then we can use one of the measured parameters (preferably the magnetic field) to reconstruct the shape of the magnetodisk more accurately. This means that we do not suppose an analytic form for the $d(t)$ function a priori, but instead invert the odd $F(d)$ function, and filter the magnetic field through this inverted function to get the distance which would result in the actual measured magnetic field value at the position of the measurement. This way we get a magnetodisk position function $d(B(t))$, which is similar to the analytic model, but shows more irregular variations as well. This reconstructed position is the black line of the top panel in Figure 2. It is possible that this method translates magnetic field fluctuations caused by other processes into distance variations. However, we cannot eliminate them, but can use the reconstructed $d(t)$ function to fit the other parameters, and check the quality of the fit. Examination shows that using this shape model to determine d , we get even better fits for the other parameters. Figure 3 shows the modelled $v_\phi = G(d(B(t)))$ functions computed from the reconstructed magnetodisk position (thick green line) together with the measured values (black line). The reproduction of the measurements is even better than that shown in Figure 2. Both the phase and the shape of the peaks are more accurate, and some double-peaked structures missing in the model

Figure 3 Black: azimuthal speed measurements; green: model results using a simple Gaussian d dependence, and the distance d as reconstructed from the magnetic field data.

line of Figure 2 appear here as well.

One can argue that this $d(t)$ function is not necessarily the distance from the sheet centre,. However we found that several parameters of the plasma in the outer magnetosphere of Saturn (e.g., B_r , n , V_ϕ) can be described as simple functions of the same $d(t)$ quasi-periodic signal. We can also find supporting arguments that this quantity is really the distance. First, if we subtract the position of the spacecraft from $d(t)$, we can eliminate the linear latitudinal variation, and the remaining time series can be fitted fairly well with the analytic z_{CS} function. The theories describing these plasma parameters also support this view. If we think of the magnetic field as either a dipole, or a stretched dipole, the radial component is necessarily an odd function of the distance from the magnetic equator. Centrifugal forcing of the plasma leads to density distributions with the properties we used in our reconstruction (Persoon, 2009). It was shown recently by Nemeth et al. (2015) that the azimuthal speed is an even function of d decreasing rapidly with the distance. It should be noted that our method only determine the dimensionless distance d/D , so we cannot determine the absolute scale heights (D) of the various plasma properties. Thus if the thickness of the plasma sheet also shows periodic variations (Provan et al., 2012; Ramer et al., 2013) the function we determine is

$d(t)/D(t)$, i.e. the dimensionless distance. Still we can understand all these variations as the results of the flapping of the magnetodisk filtered through very simple distance dependence functions, and we can reconstruct the time dependence of the density and velocity with a simple model refined by using the magnetic field measurements.

Conclusions

In this paper we explored the relationships between the quasi-periodic variations of several plasma properties of the Kronian magnetosphere on a case-by-case basis. We aimed at providing accurate fits for several day long time series data sets (e.g. for the radial magnetic field, the density and the azimuthal speed) measured by the Cassini spacecraft along orbit segments approaching and crossing the Kronian magnetodisk. These data sets feature recurring peaks or dips of varying amplitude, sometimes grouped together (in doublets or triplets) but usually spaced quasi-periodically with their recurrence time close to the planetary rotation period. It is a wide-spread opinion that these quasi-periodic signals somehow stem from an underlying periodic phenomenon, which most likely is the flapping motion of the magnetodisk. Here we clarified the relationship of the observed quasi-periodic behaviour with the underlying periodicity. We have shown that the changing amplitude, varying period, multiple peaks and apparent phase-shifts of the quasi-periodic signals can all be explained by an underlying periodicity if we take into account the spacecraft motion, and assume that the plasma properties are simple odd or even functions of the distance from the magnetodisk. Although models for the magnetodisk position as well as models describing the dependence of these parameters on the distance from the magnetodisk were present in the literature for some time, they were never combined this way to explain the strange quasi-periodic signals of the observations. With this simple method we were able to produce the best analytic fits to this date for the three plasma properties we studied. The fits minutely reproduce all the peculiarities of individual orbit segments.

We have also shown that the same $d(t)$ periodic signal provides very good fits for all three parameters simultaneously. This result strongly supports the idea that all of these plasma parameters are governed by the same underlying phenomenon, which was suspected but not commonly established earlier. This strong correspondence makes it possible to calculate these parameters from each other by inverting the simple functional dependence of one of the parameters to compute $d(t)$, and by that to predict the variation of other parameters. This technique gives, for these parameters, the best fits we are aware of, because it covers all the transient variations the statistical models cannot account for. Using this relationship, we can calculate e.g. the azimuthal speed and the proton density from the radial magnetic field. The radial magnetic field for example is an odd function of $d(t)$, where we find $\tanh(d(t)/D)$ and $\text{atan}(d(t)/D)$ work equally well. The logarithm of the proton density and the azimuthal velocity are both even functions of $d(t)$, thus $\exp(-(d(t)/D)^2)$ or $1/\cosh(d(t)/D)$ can serve as good approximating functions.

Similarly, the assumption that this $d(t)$ is the distance of the spacecraft from the sheet centre of the flapping magnetodisk agrees well with theoretical models of the various phenomena in question, i.e. of centrifugally confined plasma on the stretched field lines of a rotating and flapping magnetodisk. This suggests that the periodic variation of $d(t)/D$ is a dominant driving quantity behind the observed quasi-periodic variations of these plasma phenomena. It should be noted, however, that our calculations provide their $d(t)/D$ dependence only. If the scale height of the plasmasheet $D(t)$ also exhibits periodic behaviour (Provan et al., 2012, Ramer et al., 2013), the $d(t)/D(t)$ core function is determined by the flapping and breathing motions of the magnetodisk together.

Acknowledgements

The work of Z.N., K.Sz., and L.F. was supported by the Hungarian National Development Agency (NFÜ) under contract URKUT_1-2011-0011. SWHC and GP were supported by STFC grant ST/K001000/1. Work at PSI was supported by the NASA Cassini program through JPL contract 1243218 with Southwest Research Institute. In the US the Cassini project is managed by the Jet Propulsion Laboratory for NASA. The authors also thank M. Dougherty and the MAG team for providing the magnetic field data. Cassini MAG data and Cassini ion moments are available at the Planetary Data System (<https://pds.jpl.nasa.gov/>).

References

- Achilleos, N., P. Guio, and C. S. Arridge (2010), A model of force balance in Saturn's magnetodisc, *Mon. Not. R. Astron. Soc.*, 401, 2349–2371, doi:10.1111/j.1365-2966.2009.15865.x.
- Andrews, D. J., Bunce, E. J., Cowley, S. W. H. et al.: Planetary period oscillations in Saturn's magnetosphere: Phase relation of equatorial magnetic field oscillations and Saturn kilometric radiation modulation, *J. Geophys. Res.*, 113, 9205, 2008.
- Andrews, D. J., Cowley, S. W. H., Dougherty, M. K. et al.: Planetary period oscillations in Saturn's magnetosphere: Evolution of magnetic oscillation properties from southern summer to post-equinox, *J. Geophys. Res.*, 117, 4224, 2012.
- Arridge, C. S., C. T. Russell, K. K. Khurana, N. Achilleos, N. André, A. M. Rymer, M. K. Dougherty, and A. J. Coates (2007), Mass of Saturn's magnetodisc: Cassini observations, *Geophys. Res. Lett.*, 34, L09108, doi:10.1029/2006GL028921.
- Arridge et al, *J. Geophys. Res.*, 113, A08217, doi:10.1029/2007JA012963, 2008. // Arridge, C., Khurana, K., Russell, C. et al.: Warping of Saturn's magnetospheric and magnetotail current sheets, *J. Geophys. Res.*, 113, 2008.
- Arridge, C., Andre, N., Bertucci, C. et al.: Upstream of Saturn and Titan, *Space Sci. Rev.*, 162, 25–83, 2011a.
- Arridge, C. S., Andre, N., Khurana, K. K. et al.: Periodic motion of Saturn's nightside plasma sheet, *J. Geophys. Res.*, 116, 11205, 2011b.
- Burch, J. L., DeJong, A. D., Goldstein, J. et al.: Periodicity in Saturn's magnetosphere: Plasma cam, *Geophys. Res. Lett.*, 36, 14203, 2009.
- Carbary, J. F. and Mitchell, D. G.: Periodicities in Saturn's magnetosphere, *Rev. Geophys.*, 51, 1-30, 2013.
- Espinosa, S. A. and Dougherty, M. K.: Periodic perturbations in Saturn's magnetic field, *Geophys. Res. Lett.*, 27, 2785-2788, 2000.
- Gurnett, D. A., Kurth, W. S., Hospodarsky, G. B. et al.: Radio and Plasma Wave Observations at Saturn from Cassini's Approach and First Orbit, *Science*, 307, 1255-1259, 2005.
- Gurnett, D. A., Lecacheux, A., Kurth, W. S. et al.: Discovery of a north-south asymmetry in Saturn's radio rotation period, *Geophys. Res. Lett.*, 36, 16102, 2009.
- Jackman and Arridge, *J. Geophys. Res.*, 116, A05224, doi:10.1029/2010JA015973, 2011.

Hill and Michel, J. Geophys. Res., 81, 4561 – 4565, doi:10.1029/JA081i025p04561, 1976.

Kivelson et al., Planetary Magnetodiscs: Some Unanswered Questions, Space Sci Rev., Volume 187, 2015

Nemeth, Z., Szego, K., Bebesi, Z. et al.: Ion distributions of different Kronian plasma regions, J. Geophys. Res., 116, 9212, 2011.

Nemeth, Z., K. Szego, L. Foldy, M. G. Kivelson, X. Jia, K. M. Ramer, S. W. H. Cowley, G. Provan, and M. Thomsen, The latitudinal structure of the nightside outer magnetosphere of Saturn as revealed by velocity moments of thermal ions, Ann. Geophys., 33, 1195-1202, 2015

Persoon et al, J. Geophys. Res., 114, A04211, doi:10.1029/2008JA013912, 2009. // Persoon, A. M., Gurnett, D. A., Santolik, O. et al.: A diffusive equilibrium model for the plasma density in Saturn's magnetosphere, J. Geophys. Res., 114, 4211, 2009.

Provan, G., D. J. Andrews, C. S. Arridge, A. J. Coates, S. W. H. Cowley, S. E. Milan, M. K. Dougherty, and D. M. Wright (2009), Polarization and phase of planetary-period magnetic field oscillations on high-latitude field lines in Saturn's magnetosphere, J. Geophys. Res., 114, A02225, doi:10.1029/2008JA013782.

Provan, G., Andrews, D. J., Arridge, C. S. et al.: Dual periodicities in planetary-period magnetic field oscillations in Saturn's tail, J. Geophys. Res., 117, 1209, 2012.

Ramer, K.M. et al, AGU Fall Meeting 2013, SM21A-2134, 2013. // Ramer, K.M., Kivelson, M., Khurana, K. et al.: Forces and Phases: An Investigation of Azimuthal Plasma and Field Periodicities in Saturn's Inner Magnetosphere, in: AGU Fall Meeting Abstracts, SM51B-2303, 2012.

Szego, K., Nemeth, Z., Erdos, G. et al.: Location of the magnetodisk in the nightside outer magnetosphere of Saturn near equinox based on ion densities, J. Geophys. Res., 117, 9225, 2012.

Szego, K., Nemeth, Z., Erdos, G. et al.: The plasma environment of Titan: The magnetodisk of Saturn near the encounters as derived from ion densities measured by the Cassini/CAPS plasma spectrometer, J. Geophys. Res., 116, 10219, 2011.

Szego, K., Nemeth, Z., Foldy, L. et al.: Dual periodicities in the flapping of Saturn's magnetodisk, J. Geophys. Res., 118, 2883-2887, 2013.

Thomsen et al, J. Geophys. Res., 115, A10220, doi:10.1029/2010JA015267, 2010. Thomsen, M. F., Reisenfeld, D. B., Delapp, D. M. et al.: Survey of ion plasma parameters in Saturn's magnetosphere, J. Geophys. Res., 115, 10220, 2010.