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Spatial and temporal dependence of the convective electric field in Saturn's inner magnetosphere

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ABSTRACT

The recently established presence of a convective electric field in Saturn's inner and middle magnetosphere, with an average pointing approximately towards midnight and an intensity less than 1 mV/m, is one of the most puzzling findings by the Cassini spacecraft. In order to better characterize the properties of this electric field, we augmented the original analysis method used to identify it (Andriopoulou et al., 2012) and applied it to an extended energetic electron microsignature dataset, constructed from observations at the vicinity of four saturnian moons. We study the average characteristics of the convective pattern and additionally its temporal and spatial variations. In our updated dataset we include data from the recent Cassini orbits and also microsignatures from the two moons, Rhea and Enceladus, allowing us to further extend this analysis to cover a greater time period as well as larger radial distances within the saturnian magnetosphere. When data from the larger radial range and more recent orbits are included, we find that the originally inferred electric field pattern persists, and in fact penetrates at least as far in as the orbit of Enceladus, a region of particular interest due to the plasma loading that takes place there. We perform our electric field calculations by setting the orientation of the electric field as a free, time-dependent parameter, removing the pointing constraints from previous works. Analytical but also numerical techniques have been employed, that help us overcome possible errors that could have been introduced from simplified assumptions used previously. We find that the average electric field pointing is not directed exactly at midnight, as we initially assumed, but is found to be stably displaced by approximately 12–32° from midnight, towards dawn. The fact, however, that the field's pointing is much more variable in short time scales, in addition to our observations that it penetrates inside the orbit of Enceladus ($\sim$4 R_s), may suggest that the convective pattern is dominating all the way down to the main rings (2.2 R_s), when data from the Saturn Orbit Insertion are factored in. We also report changes of the electric field strength and pointing over the course of time, possibly related to seasonal effects, with the largest changes occurring during a period that envelopes the saturnian equinox. Finally, the average electric field strength seems to be sensitive to radial distance, exhibiting a drop as we move further out in the magnetosphere, confirming earlier results. This drop-off, however, appears to be more intense in the earlier years of the mission. Between 2010 and 2012 the electric field is quasi-uniform, at least between the L-shells of Tethys and Dione. These new findings provide constraints in the possible electric field sources that might be causing such a convection pattern that has not been observed before in other planetary magnetospheres. The very well defined values of the field's average properties may suggest a periodic variation of the convective pattern, which can average out very effectively the much larger changes in both pointing and intensity over short time scales, although this period cannot be defined. The slight evidence of changes in the properties across the equinox (seasonal control), may also hint that the source of the electric field resides in the planet's atmosphere/ionosphere system.

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1. Introduction

Plasma circulation in the inner magnetosphere of Saturn is an interesting topic that has not been fully understood yet. What makes this system rather complicated and interesting to study is the fact that it is probably an intermediate case between the Earth's, where circulation is driven by the interaction with the solar wind, and Jupiter's magnetosphere, where the plasma circulation is driven by internal sources and the fast plasma rotation that is imposed by the planet (Gombosi et al., 2009). Specifically, although Saturn's magnetosphere is small enough to be controlled by the solar wind, it is also a fast rotating system, with its moon Enceladus acting as an internal source.

For the case of Earth, the inner magnetosphere is dominated by an electric field that is related to the rotation of the planet, also referred from now on as the corotation term. At larger radial distances, the corotation term becomes smaller and the convection term, which for the Earth is related to a sunward motion, becomes dominant. For Jupiter, on the other hand, the corotation dominates to all radial distances, and a similar behavior is also observed at Saturn (Kane et al., 2008; McAndrews et al., 2009; Thomsen et al., 2010).

Additionally, data that showed a dawn-dusk asymmetry in the temperature of low energy ions and electrons at the Io plasma torus region (Sandel and Broadfoot, 1982; Shemansky and Sandel, 1982) are consistent with the presence of a weak electric field that has a dawn-to-dusk orientation and a strength that was estimated to be ~4 mV/m at a distance of 6 Jovian radii. The origin of such an electric field can be associated with outflows of the plasma down the tail and has been attributed to plasma loading from Io (Barbosa and Kivelson, 1983; Ip and Goertz, 1983).

The main goal of the current work is to investigate which are the processes that dominate the plasma circulation at Saturn and more specifically in the inner part of the magnetosphere. The most direct way to detect signatures of plasma circulation is to measure the plasma velocity vector (Sittler et al., 2006; Wilson et al., 2008). The problem with this method is that in the inner part of the fast rotating magnetospheres, such as the saturnian one, the velocity vector is dominated by the azimuthal component of corotation. Evidence for a convective pattern should therefore be sought in the radial velocity component, which for Saturn has only been recently extracted by Wilson et al. (2013). Such measurements, however, are limited by several factors that affect the respective instrument observations and reduce the size of the sample available for analysis (e.g. the Cassini attitude or penetrating radiation inside the orbit of Tethys at about 5 R_s). Furthermore, instantaneous and in situ radial velocity measurements can only be used to infer a convective pattern if they are observed at many different local times (and therefore different dates, given that Cassini samples a narrow range of local times for a given L-shell during a single orbit.). These measurements, therefore, allow only the average pattern of the flow to be resolved.

Prior to the Wilson et al. (2013) findings, we developed a very sensitive method to detect these weak radial flows in an effort to understand what is their driving mechanism. This method has been described and applied for the first time by Andriopoulou et al. (2012) and it uses the absorption effects that the saturnian moons have on energetic electrons. Particularly it studies the radial displacement of the resulting dropouts from their predicted location. The latter can be estimated if we ignore any possible effects of non-corotation convection patterns. The development of this method led to the detection of a convective pattern that is related to dawnward flows of a few km/s in the inner magnetosphere of Saturn. A big advantage of this method, is that the observed offset, apart from the fact that it can be measured very accurately, is representative of the radial flows over all the local times that the microsignature has crossed before its detection, allowing for properties of the global circulation pattern to be inferred from single events.

The presence of possible non-corotation convection patterns has been the topic of discussion in several previous works (Cooper et al., 1998; Goldreich and Farmer, 2007; Gurnett et al., 2007; Jia et al., 2012; Jia and Kivelson, 2012; Andriopoulou et al., 2012; Thomsen et al., 2012; Wilson et al., 2013). Cooper et al. (1998) discussed the possible presence of a weak electric field (magnitude of ~0.02 mV/m) with a dusk-to-dawn direction that would account for the solar wind penetration in the saturnian magnetosphere, similar to the case of the Earth. A possible corotating convective pattern has been proposed by Gurnett et al. (2007) to explain why the variations of the total electron density in the inner magnetosphere are synchronized with the observed, time-dependent modulation of the Saturn Kilometric Radiation (SKR). The plasma outflows were then assumed to be caused by a two-cell mode ($m = 1$) centrifugally driven instability. A similar pattern was also suggested by Goldreich and Farmer (2007) to account for the periodicities observed in the magnetic field observations of Saturn (Giampieri et al., 2006). The driver of such instabilities was assumed to be the centrifugal forces that act on the flux tubes, which are continuously loaded with heavy plasma that originates from the Enceladus neutral gas torus (Gurnett et al., 2007). Furthermore, a rotating inflow-outflow pattern due to ionospheric conductivity anomalies has also been suggested (Jia et al., 2012; Jia and Kivelson, 2012), arguing that the previously suggested corotating convective patterns are not consistent with magnetometer observations. Finally, another possible convection pattern that could be present at Saturn's inner magnetosphere and also related with plasma loading from Enceladus would be an electric field fixed in local time, similar to the one suggested for Jupiter (Barbosa and Kivelson, 1983; Ip and Goertz, 1983). The expected electric field pointing would be towards dusk and it would be related to tailward flows. However, none of the aforementioned convection patterns has been directly measured so far.

Recently another convection pattern fixed in local time, first pointed out by Roussos et al. (2007), was confirmed by Andriopoulou et al. (2012) and was further supported by the observational evidence presented in Thomsen et al. (2012) and Wilson et al. (2013). More specifically, using a large number of energetic electron microsignature events, i.e. longitude-dependent reductions in the electron fluxes that were caused by absorption by two saturnian moons that are located in the inner part of the magnetosphere, Tethys and Dione, Andriopoulou et al. (2012) observed a day-night asymmetry in the radial offsets of energetic electron microsignatures from the orbital distance of the respective absorbing moons. After confirming the fact that this systematic asymmetry is too large to be explained by the asymmetries of Saturn's magnetic field, the observed data were explained by requiring the presence of an average, assumed uniform, electric field with a noon-to-midnight orientation and strength around 0.2 mV/m. The presence of such an electric field is consistent with other observations, reported in Thomsen et al. (2012) and Wilson et al. (2013) (see also Section 2). Although the source of such a noon-to-midnight electric field is not yet clear to us, this convection pattern is a documented non-corotation convection component in Saturn's magnetosphere.

The continuously growing microsignature dataset is probably the best tool we have to derive additional properties of this electric field so that we can understand its currently unknown origin. For instance, our updated microsignature catalogues extend to a wider distance range in Saturn's magnetosphere and currently include events from two more saturnian moons, Rhea, which is located at an L-shell dipole distance of 8.74, and Enceladus, orbiting at an L-shell of 3.95. By assuming the field's orientation as a free,

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