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Interplanetary magnetic field structure at Saturn inferred from nanodust measurements during the 2013 aurora campaign

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ABSTRACT

Interactions between the solar wind and planetary magnetospheres provide important diagnostic information about the magnetospheric dynamics. The lack of monitoring of upstream solar wind conditions at the outer planets, however, restrains the overall scientific output. Here we apply a new method, using Cassini nanodust stream measurements, to derive the interplanetary magnetic field structure during the 2013 Saturn aurora campaign. Due to the complex dynamical interactions with the interplanetary magnetic field, a fraction of fast nanodust particles emerging from the Saturnian system is sent back into the magnetosphere and can be detected by a spacecraft located within. The time-dependent directionality caused by the variable interplanetary magnetic field enable these particles to probe the solar wind structure remotely. Information about the arrival time of solar wind compression regions (coupled with the heliospheric current sheet crossings) as well as the field direction associated with the solar wind sector structure can be inferred. Here we present a tentative identification of the interplanetary magnetic field sector structure based on Cassini nanodust and radio emission measurements during the 2013 Saturn aurora campaign. Our results show that, the interplanetary magnetic field near Saturn during 2013-080 to 176 was consistent with a two-sector structure. The intensifications of aurora and the radio emission on 2013-095, 112 and 140 coincide with the IMF sector boundaries, indicating that the encounter of the compressed solar wind is the main cause of the observed activities.

1. Introduction

Planetary magnetospheres respond differently to changing solar wind conditions, which provides diagnostic information about the magnetospheric dynamics as well as magnetosphere–ionosphere coupling mechanisms (Kurth et al., 2009). Phenomena such as optical aurora and radio emissions resulting from the magnetosphere-interplanetary magnetic field (IMF) interactions can be observed remotely by Earth-bound observatories or spacecraft in orbit. However, unlike at Earth, upstream solar wind measurements at the outer planets are mostly unavailable except for rare occasions, such as mission cruise phases or during orbits with large apoapses. Spacecraft orbiting outer planets spend most of the time inside the magnetosphere and cannot measure the solar wind directly. Solar wind propagation modeling (e.g., Zieger and Hansen, 2008), or using the radio emission as a proxy for the solar wind activities (e.g., Kurth et al., 2005) are the common alternatives to direct upstream solar wind measurements.

Nanodust observations provide an alternative method to measure the solar wind properties (Hsu et al., 2013). Acquiring electric charges and being accelerated in the magnetosphere of Saturn, nanometer-sized dust particles (radius 2–8 nm), so-called stream particles, escape into interplanetary space with high speeds (50–200 km/s). These particles have been monitored by the orbiting Cassini spacecraft since 2004 (Kempf et al., 2005a; Hsu et al., 2010a, 2011b, 2012). After entering interplanetary space, their dynamics are governed by the IMF. While being picked-up in the solar wind, a fraction of the emitted particles are in fact sent back into Saturn's magnetosphere because of their dynamical interactions with the time-variable IMF (Hsu et al., 2013).

IMF measurements during Cassini's Saturn approach phase in 2003 and 2004 show a two-sector structured IMF with recurrent Coroating Interaction Regions (CIRs) at the boundary between the inward and outward sectors (Jackman et al., 2005). Resulting from the interaction between the slow and the fast solar wind

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originating from different latitudes of the tilted solar dipole field, a CIR is characterized by a compressed, high magnetic field strength solar wind region (Jackman et al., 2005). The boundary between the outward and inward pointing IMF sectors, the Heliospheric Current Sheet (HCS), is often embedded within the solar wind compression region at Saturn's orbit (Crooker et al., 1999). The IMF at Saturn's orbit is dominated by the tangential component, consistent with the Parker spiral model (Jackman et al., 2008). The IMF strength varies between ~ 0.1 nT to > 1 nT in the rarefaction and the compression regions, respectively (Jackman et al., 2005).

The observations described by Jackman et al. (2005, 2008), were made during the declining phase of the solar cycle, whereas the interval examined in this paper (Spring 2013) was approaching solar maximum as indicated by the sunspot number. While the solar magnetic field is known to be significantly more disorganized at solar maximum, Ulysses observations around the previous solar maximum (2000-1) demonstrated that the two sector structure was present in both the solar wind velocity and IMF angle throughout the interval, with occasional disruptions, although with the HCS inclined to higher latitudes (Balogh and Smith, 2001; McComas et al., 2003; Smith, 2011). The disruptions were generally associated with transients such as Coronal Mass Ejections, which are expected to occur relatively more frequently around solar maximum. We therefore expect that during our interval of study the solar wind will generally exhibit a two-sector structure, with some transient disruptions superposed.

The consequence of the recurrent two-sector IMF structure on the stream-particle dynamics is an extended dust sheet, which is warped, depending on the IMF direction, toward north or south (with respect to the ecliptic plane). In interplanetary space, the dynamics of nanodust particles are modified by IMF as:

$$\dot{\mathbf{v}}_\mathbf{d} = \frac{q}{m} \cdot [\mathbf{v}_\mathbf{d} \times \mathbf{B}_\mathbf{IMF} + \mathbf{E}_\mathbf{co}], \quad (1)$$

where q/m is the dust charge-to-mass ratio, $\mathbf{B}_\mathbf{IMF}$ is the IMF vector, and $\mathbf{E}_\mathbf{co} = (\mathbf{v}_\mathbf{d} - \mathbf{v}_\mathbf{sw}) \times \mathbf{B}_\mathbf{IMF}$ is the co-moving electric field, induced from the relative motion between the solar wind and stream particles. $\mathbf{v}_\mathbf{d}$ and $\mathbf{v}_\mathbf{sw}$ are the dust and solar wind speed vectors, respectively. Since $|\mathbf{v}_\mathbf{sw}|$ is usually higher than $|\mathbf{v}_\mathbf{d}|$, $\mathbf{E}_\mathbf{co}$ is the dominant term that governs the nanodust trajectory evolution.

Within the inward IMF sector ($\phi > 0°$, see Fig. 1a), stream particles are accelerates by $\mathbf{E}_\mathbf{co}$ toward the south of the ecliptic plane and vice versa during the outward IMF sector ($\phi < 0°$). In the CIR compression regions, the field strength can increase by up to a factor of ten. The resulting strong $\mathbf{E}_\mathbf{co}$ and subsequent acceleration lead to enhanced stream-particle fluxes around the IMF sector boundaries and a simultaneous rotation for the stream orientation after the HCS crossing (Hsu et al., 2010b,a). In numerical simulations, particles can even reach speeds faster than the solar wind (Hsu et al., 2013). The kinetic energy gained in the compressed solar wind region is so high that the stream particles can re-enter and penetrate deeply into Saturn's magnetosphere. The dynamical fingerprint left from such interplanetary excursions allow the nanodust detection pattern to be used as a remote sensing tool to probe the IMF conditions when the spacecraft is inside the magnetosphere (Hsu et al., 2013).

2. Dust instrument and observation

2.1. Cosmic dust analyser

The dust measurements presented in this work were carried out by the Cosmic Dust Analyser (CDA) onboard the Cassini spacecraft (Srama et al., 2004). CDA is comprised of two subsystems, the Dust Analyser (DA) and the High Rate Detector (HRD). The DA is an impact-ionization type multi-incident dust detector and is

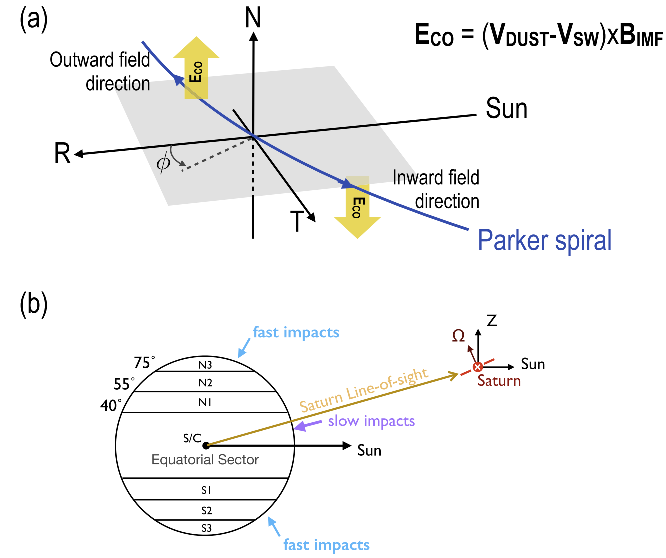

Fig. 1. Definition of coordinate systems used in this study. (a) The schematic shows the IMF RTN coordinate system, the azimuthal angle (ϕ), and the inward ($B_r < 0$) and outward ($B_r > 0$) Parker spiral field line at Saturn's orbit. In the inward IMF sector ($\phi \sim 90°$), the co-moving electric field ($\mathbf{E}_\mathbf{co}$) points toward the south of the ecliptic plane, and vice verse in the outward sector ($\phi \sim -90°$). (b) The grid system used for the stream particle measurement presentation. This system is comprised by three sectors at the spacecraft-centered frame. The equatorial plane of the system is parallel to the orbital plane of Saturn. The equatorial sector covers ±40° from the equator and is longitudinally divided into twelve segments. Each polar sector (north and south) is divided into three segments that cover the latitudes between 40° and 55°, 55° and 75°, and 75° and 90°, respectively. IMF-accelerated stream particles are expected to be detected from the polar sectors, as a consequence of the acceleration by $\mathbf{E}_\mathbf{co}$.

sensitive enough to detect nanoparticles via its mass spectrometer. Signals produced from the plasma generated upon an dust impact on the instrument target can provide the dynamical information of the incident particle. The integrated Time-of-Flight (TOF) mass spectrometer is capable of providing elementary composition information for impacts taking place on the inner, smaller rhodium Chemical Analyzer Target (CAT).

2.2. Particle identification

Because of their small sizes, in most cases the impact charge signals produced from a stream-particle impact are too small to trigger a measurement by all detectors except the TOF mass spectrometer, at the cost of missing the first mass line, i.e., H^+. As a consequence, most of them can only be identified manually by their mass spectral features. A typical stream-particle mass spectrum is governed by the target material ions, including Rh^+ (CAT material) and target contaminations such as C^+ and Na^+ (Kempf et al., 2005b; Postberg et al., 2009). H^+ only appears in the strongest stream-particle mass spectra, for which the target signals are sufficient to trigger a recording event. This also suggests that protons are in fact an abundant, most likely solar-wind-induced, target contaminant.

2.3. Observation limitation

Two factors that limit the stream particle measurements are (1) the spacecraft location and (2) the instrument pointing. For (1), composed of icy grains, Saturn's E ring extends from about 3 R_S all the way to Titan's orbit (20.3 R_S) with a thickness of a few R_S away from the ring plane (R_S, Saturn radius = 60,268 km) (Srama et al., 2011). Because of the DA instrument dead time (Srama et al., 2004), the dominance of ice grains strongly biases the detection statistics and thus excludes the detection of stream particles