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On magnetopause inflation under radial IMF

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Abstract

Full understanding of the magnetosphere interaction with radial IMF structures embedded in the solar wind flow is far from completeness. In order to analyze the effects of radial IMF, we use THEMIS observations of the magnetopause and magnetosheath together with upstream data acquired from ACE and Wind monitors as well as from the OMNI data base. We demonstrate a prominent magnetopause inflation and low pressure magnetosheath (LPM) mode under long-lasting radial IMF. We propose that these phenomena result from a kinetic effect of energetic ions taking the energy away from the pressure balance at the magnetopause. We show that strict quantitative determination of the inflation and LPM mode as a function of the cone angle is difficult because of the problems with reliable determination of the upstream and magnetosheath conditions. The shortcomings are caused by such effects as ambiguous time delay for the solar wind propagation, THEMIS orbital bias and model-dependent estimations of the magnetopause inflation.

Keywords: Magnetopause inflation; Radial IMF; Low-pressure magnetosheath; Timing accuracy

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1. Introduction

Dynamics of the Earth's magnetopause during radial interplanetary magnetic field (IMF) orientations, whenever the cone angle between the IMF vector and the Earth–Sun line is small ($\theta < 30°$), significantly differs for short- and long-time events (Suvorova and Dmitriev, 2015). In the overall statistics, short-time events (<2 h) of radial IMF dominate, and a portion of long-time events is about 1% (Suvorova et al., 2010). The near radial IMF of short duration causes large-amplitude magnetopause variations around an average position established by the upstream solar wind (SW) dynamic pressure (e.g., Sibeck, 1995). The near radial IMF of long duration (several hours) may cause a significant long-lasting inflation of the magnetosphere by >1.5 Re (Suvorova et al., 2010). A magnetopause displacement ΔR is estimated from a difference between the distances determined from magnetopause crossings by a satellite R_O and predicted by a model R_M: $\Delta R = R_O – R_M$. The inflation has been assessed to be a manifestation of a special mode of a pressure balance at the magnetopause with establishing of low pressures in the magnetosheath, called the LPM mode (Suvorova et al., 2010).

Analysis of huge statistics of ΔR testifies to the global systematical inflation with an average positive ΔR value of about 1–1.7 R_E in the range of low θ (Dušík et al., 2010). Although the ΔR value has a broad scatter from -2 R_E to 4 R_E in both subsolar and flank regions. From case events and statistical studies, it is known that magnetopause oscillations within $\pm(1–2)$ R_E correspond poorly to fluctuations of the low cone angle (Sibeck et al., 2000; Suvorova et al., 2010; Dušík et al., 2010).

Although the cone angle is a very important factor of the magnetopause dynamics, any direct relationship between the cone angle and magnetopause distance was

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not found. One of the possible reasons of that is large difficulty in determining the timing between IMF and magnetosheath measurements. As a result, no one empirical model can predict the location of enlarged magnetosphere. Additionally, global MHD simulations underestimate the inflation effect significantly (e.g. Tang et al., 2013). As discussed by Suvorova et al. (2010), the problem of solar wind energy transformation in the LPM mode might be solved using kinetic approach or theory of turbulence.

The problem of large uncertainties in $\Delta R(\theta)$ motivated us to analyze their possible causes, which could be related to methodic shortcoming in mixing event durations, methodic errors of timing accuracy, systematic errors of the using a particular model, and observational limitations due to the orbital bias. In the previous work (Suvorova and Dmitriev, 2015) we considered the systematic errors by comparing 14 models and showed their large differences of 2–5 Re in predictions of the magnetopause standoff distance within the low pressure range (<2 nPa). In the current work we focus on the other factors: the accuracy of time delays determined for the solar wind propagation from far upstream regions to the Earth under radial IMF conditions, the duration of events and the effect of orbital bias.

Magnetopause models use the SW and IMF data as inputs. Because the interplanetary parameters are predominately measured in the L1 libration point (~230 Re upstream of the Earth), a timing procedure is applied to these data for characterizing SW-IMF structures, which impact the magnetosphere. However, characteristics of the upstream interplanetary parameters, especially in structures with radial IMF, can be different from those near the Earth (e.g. Paularena et al., 1998; Zastenker et al., 2000; Riazantseva et al., 2002) and hence, they might not affect the magnetosphere. Thus, the IMF cone angle is a crucial factor for timing accuracy, because it determines the degree of correlation between widely-separated spacecraft (e.g., Zastenker et al., 2000; Mailyan et al., 2008). The difference increases quickly with a spacecraft separation perpendicular to the Sun–Earth line. So, the propagation time of "radial" magnetic field structures is determined less accurately. A number of authors noted that the accuracy of delays in the OMNI data set can be very poor, especially for the radial IMF (Case and Wild, 2012; McPherron et al., 2013; Bier et al., 2014).

It is known that magnetic field structures are embedded in the solar wind in the form of flux tubes, also called spaghetti-like structures that contain distinct plasmas (Mariani et al., 1973; Thieme et al., 1989; Borovsky, 2008). It is shown that the SW plasma structures are elongated along the IMF, and hence, scale size of magnetic structure is smallest in the direction perpendicular to IMF. The median transverse size of the flux tube is comparable with the offset of the upstream monitors from the Earth–Sun line (Borovsky, 2008).

Duration of near-radial IMF structures reaches frequently several hours, but sometimes it is longer than a day, during which interplanetary conditions change slightly and smoothly (Wang et al., 2003; Watari et al., 2005; Suvorova et al., 2010; Pi et al., 2014). Also, it is known that the magnetopause can expand unusually during the stable radial-IMF conditions (Suvorova et al., 2010). Note that the accuracy of timing in such cases is not crucial because of the quasi-stable interplanetary conditions. Several prolonged magnetopause inflations have been found during the THEMIS mission in 2007–2008. These events are very interesting for investigation of the LPM mode and extreme outward displacement ΔR of the magnetopause. Here we analyze one of the long-lasting magnetopause expansions on 13 July 2007 and estimate the ΔR value using different magnetopause models and observations. A kinetic mechanism for the LPM mode is proposed.

2. Experimental data and a problem of timing

We used data from the ACE and Wind upstream monitors, rotating around the L1 point at geocentric distance of ~230 R_E, and the THEMIS near Earth's mission. We consider intervals of quasi-radial IMF in 2007 for comparison with data from five THEMIS probes (TA, TB, TC, TD, TE), which were located in the subsolar magnetosheath or foreshock regions (Lepping et al., 1995; Smith et al., 1998; Auster et al., 2008). To estimate the time delay for solar wind propagation, we compared the interplanetary conditions impinging upon the magnetosphere with those measured at L1 point by applying a cross-correlation method to magnetic field data. Also, we use ion spectrograms from THEMIS/ESA plasma instrument (McFadden et al., 2008) in order to identify the radial IMF conditions, which can be revealed in the dayside magnetosheath as enhancements of energetic ions with energies of >10 keV (e.g., Crooker et al., 1981).

Fig. 1 shows an interval of prolonged quasi-radial IMF observed by Wind, ACE and the TB probe from 10 to 13 UT on 9 June 2007. The positions of the satellites and solar wind propagation delays are shown in Fig. 2. Fig. 1a presents the ion spectrogram measured by the TB satellite along the pass from the magnetosheath to the magnetosphere in the postnoon sector (~15 LT) at geocentric distances $R \sim 14.5$–12.7 Re. The radial IMF resulted in formation of a foreshock, which can be revealed from the intensification of ion fluxes in the high-energy channels observed from 1010 UT to 1245 UT.

Association of energetic ions in the magnetosheath and foreshock with IMF orientation is well established (e.g., Gosling et al., 1978; Greenstadt et al., 1980; Crooker et al., 1981). Energetic ions originate from diffuse ion population accelerated at the quasi-parallel bow shock. They are observed both upstream (so-called foreshock region) and downstream (magnetosheath) from the quasi-parallel portion of the bow shock. During quasi-radial IMF ($\theta < 30°$), the subsolar bow shock is quasi-parallel such that energetic ions are observed everywhere on the dayside (Crooker et al., 1981).