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Magnetospheric cross-field currents during the January 6–7, 2011 high-speed stream-driven interval

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ABSTRACT

The cross-field current systems within a global, coupled geospace simulation of the January 6, 2011 high-speed stream-driven interval are analyzed to understand the flow and partitioning of energy within the magnetosphere. Even though this is a small storm with a minimum Dst of −41 nT, it is shown that the time-dependence of current system locations is very similar to that from a much larger storm (minimum Dst of −230 nT) driven by an interplanetary coronal mass ejection. That is, during the early part of the main phase, the tail current inner edge moves Earthward inside of geosynchronous orbit, but then retreats during the later part of the main phase, and by the peak of the storm interval, the ring/tail boundary is beyond $L=10$ in the nightside magnetosphere. It is also seen that a banana current (the part of the partial ring current that does not close through the ionosphere but rather with itself by flowing around the pressure peak entirely on the nightside) accounts for nearly all of the eastward current and the innermost portion of the westward current in the equatorial plane throughout the storm main phase interval.

1. Introduction

The interpretation of current systems within the nightside near-Earth magnetosphere has been a subject of much discussion for several decades. Early analyses of currents in this region often binned the measurements according to solar wind or geophysical parameters, such as Zanetti et al. (1984) and Lui et al. (1987, 1994). Statistical models of the magnetosphere rely on predefined current systems within specified location and intensity limits (e.g., Tsyganenko, 1989; Hilmer and Voigt, 1995; Alexeev et al., 1996; Antonova, 2004). Numerous physical models have also been used to investigate the partitioning of current among the various systems that flow in this region (e.g., Ebihara and Ejiri, 2000; Liemohn et al., 2001, 2011; Ganushkina et al., 2002, 2012; Chen et al., 2006). It is important to understand the partitioning of current among the classifications because each closure process results in a different feedback on the geospace system. For instance, the partial ring current, which closes through the ionosphere, will cause a distortion of the inner magnetospheric electric field, the symmetric ring current will inflate the dayside inner magnetosphere and distort the dayside magnetopause, and the tail current is directly involved in shaping the nightside magnetopause. A charged particle can carry current for many systems during its lifetime within the magnetosphere, yet individual charged particle motion is not equivalent to current flow (it is the net particle motion). This disconnect between particles and currents allows the current closure path to reconfigure faster than the particle drifts or pressure distributions, making current system dynamics a highly variable phenomenon within geospace.

Liemohn et al. (2011) analyzed the near-Earth current systems during an intense magnetic storm (specifically, that of 22 October 1999), concluding that, from the examined simulation, the ring current (partial and symmetric) dominated over the tail current throughout the main phase. They noted that the tail current moved inward during the early main phase, having an inner edge location inside of geosynchronous orbit. It retreated in the later portion of the main phase, however, and by the time of the storm peak (as identified by ground-based magnetometers and compiled in the Dst index), the nightside magnetosphere at $L=10$ was dominated by partial and symmetric ring current. Much of the cross-field current was identified as partial ring current, which closes through the ionosphere and therefore distorts the inner magnetospheric electric field (as well as the near-Earth magnetic field topology). This implies that geospace experienced significant nonlinear feedback to the intense driving conditions of the solar wind, fighting against additional build-up of the near-Earth hot ion population as the storm progressed.

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The October 1999 storm, discussed above, was driven by an interplanetary coronal mass ejection (ICME). It produced a peak Dst index of −230 nT, with strong sunward flows in the near-Earth nightside that brought plasma sheet material deep into the inner magnetosphere. Such a strong geospace response is typically only seen with this solar wind driving structure, but other geoeffective solar wind disturbances exist. In particular, there have been a number of recent studies investigating the magnetospheric response to different solar wind drivers, in particular comparing ICME-driven events to those caused by the passage of a corotating interaction region/high-speed stream (CIR/HSS) structure (e.g., Tsurutani and Gonzalez, 1997; Ji et al., 2012). Regarding the inner magnetosphere, there has been a concerted effort to identify the similarities and differences between the near-Earth plasma sheet and ring current region for ICME-driven events and CIR/HSS-driven storms (see, for example, the extensive list of geospace responses compiled by Borovsky and Denton, 2006). For instance, data analysis and modeling efforts have focused on the partitioning of energy dissipation in the ionosphere–magnetosphere system during these two types of storms (e.g., Huttunen and Koskinen, 2004; Lu, 2006; Turner et al., 2006, 2009; Pokhotelov et al., 2010), concluding that, even though CIR/HSS events are typically smaller in terms of current system intensity, they often have a larger portion of their total energy flowing into the auroral zone ionosphere. Furthermore, CIR/HSS events can have as much or more total energy dissipation in geospace when compared to ICME events because of the prolonged disturbed conditions and lengthy recovery phase typical of these events. Several other studies have focused on the plasma environment of near-Earth space during these two classes of storms (e.g., Denton et al., 2006, 2010; Zhang et al., 2006; Denton and Borovsky, 2008; Borovsky and Denton, 2009; MacDonald et al., 2010), concluding that the plasma entering the inner magnetosphere is typically colder and denser during ICME events than during CIR/HSS events. A few different near-Earth drift physics models have been used to probe the transport of hot ions during these two types of drivers (e.g., Jordanova, 2006; Liemohn and Jazowski, 2008; Jordanova et al., 2009; Liemohn et al., 2010; Ganushkina et al., 2012; Liemohn and Katus, 2012), finding that much of the geomagnetic disturbance during a CIR/HSS event is beyond geosynchronous orbit. Because such storms often have a significant portion of the energetic particle population outside of the simulation boundary for these models, such codes have a difficult time modeling these storm intervals; they are much more successful at reproducing ICME-driven events (for which the energetic particles are typically injected deeper into the inner magnetosphere). Global, coupled models have also been used to simulate geospace during both ICME and CIR/HSS storms (e.g., Huang et al., 2006, 2008; Zhang et al., 2007; Lopez et al., 2007; Toth et al., 2012; Glocer et al., 2009; Ilie et al., 2010a,b; Damiano et al., 2010; Welling and Ridley, 2010; Brambles et al., 2010; Liemohn et al., 2011; Welling et al., 2011). Most of these studies, however, consider only one storm or do not classify the events according to solar wind driving structure, and so little has been concluded from such studies regarding the differences between these two types of events.

Therefore, one question that has not yet been addressed is the partitioning of current systems within a CIR/HSS event and how this compares to an ICME-driven storm. The study presented below addresses this issue by examining the January 6–7, 2011 storm interval. This will be compared against the results from Liemohn et al. (2011) for the ICME-driven event of October 21–23, 1999.

2. Numerical approach

The Space Weather Modeling Framework (SWMF) will be used for the numerical simulations in this study. The suite of models joined by the SWMF cover the solar surface to the Earth's thermosphere, including 10 different models representing 12 different physics domains (Toth et al., 2005, 2012). For this study, only three models will be used: the Block-Adaptive-Tree Solar Wind Roe-type Upwind Scheme (BATS-R-US) magnetohydrodynamic (MHD) model (Powell et al., 1999; Gombosi et al., 2002; Toth et al., 2006) for the global magnetospheric domain; the Rice Convection Model (RCM) (Harel et al., 1981; De Zeeuw et al., 2004) for the inner magnetospheric drift physics domain; and the Ridley Ionosphere Model (RIM) (Ridley and Liemohn, 2002; Ridley et al., 2004) for the solution of the ionospheric electric potential. The code configuration and numerical set-up for the models is the same as that used for the ICME-driven event, as discussed by Ganushkina et al. (2010) and Liemohn et al. (2011). The simulation used a Rusanov solver with an MC limiter with $\beta=1.2$ and a Cartesian grid with constant 0.25 R_E resolution everywhere in the inner magnetosphere.

The interval to be examined in this study is that of January 6–7, 2011. This was a weak storm event driven by a CIR/HSS solar wind structure. The plasma and magnetic field observations from the Advance Composition Explorer (ACE) satellite that were used as inputs to the SWMF are shown in Fig. 1. A large density enhancement began near 17 UT on January 6, with accompanying interplanetary magnetic field (IMF) perturbations. The density rose from a pre-CIR level of 10 cm^{-3} to a peak of 70 cm^{-3} at 20 UT. The solar wind temperature and velocity started to increase around 21 UT, with much larger IMF perturbations over the next few hours. The solar wind speed changed from its pre-CIR value of 350 km/s to the HSS peak speed of 600 km/s late on January 7. The IMF reached a magnitude of nearly 20 nT late on January 6, with the IMF Bz component dropping to −15 nT at 21 UT, recovering with a northward spike at 22 UT, and then plunging to −13 nT at 23 UT before abruptly rising again to northward values soon after 00 UT. The solar wind y and z velocity components were set to zero throughout the duration of the simulation. The numerical results to be discussed below are from a simulation beginning at 18 UT on January 6 and ending 30 h later at 00 UT on January 8.

3. Results

The CIR/HSS passage caused a weak storm with a long recovery phase at Earth. The observed Dst index is shown in green in Fig. 2. Note that this study will use Dst to define the phases of a storm, including the storm intensity and the timing of the storm maximum. Other measures of storm intensity and timing have been used, such as Kp (e.g., Borovsky and Steinberg, 2006) or the midnight boundary index (e.g., Denton and Borovsky, 2008), but we will limit the definition in this study to Dst. Dst rises from a pre-storm value of roughly +3 nT to a storm sudden commencement peak of +24 nT at 20 UT on January 6. The Dst index then dropped quickly to a first minimum value of −40 nT at 00 UT on January 7, followed by a slight recovery and the eventual storm peak of −41 nT at 06 UT. The observed Dst index includes a contribution from the conducting Earth. A crude method for removing this contribution is to divide the observed value by 1.3 (Langel and Estes, 1985). This corrected Dst is included in Fig. 2 (blue curve), giving a storm minimum of −31 nT.

Fig. 2 also shows the SWMF-simulated Dst time series (red curve) from a Biot–Savart integration of the currents within the entire BATS-R-US domain (assuming a virtual magnetometer at the center of the Earth). Because this calculation does not include the contribution from the conducting Earth, it is best compared to the corrected observed Dst. The code reproduces the initial phase very well, with a modeled maximum Dst of +23 nT, only a few nT away from the observed value. It also reproduces the first half of