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Research Paper

Auroral boundary movement rates during substorm onsets and their correspondence to solar wind and the *AL* index

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ABSTRACT

A statistical analysis of the equatorward and poleward auroral boundary movement during substorm onsets, the related solar wind activity, GOES 8 and 10 magnetic field, and the westward auroral electrojet (*AL*) index is undertaken, during the years 2000–2002. Auroral boundary data were obtained from the British Antarctic Survey (BAS). These boundaries were derived using auroral images from the IMAGE satellite. The timing of the onsets was derived from the Frey et al. (2004) database. Data were also classified based on the peak *AL* around the onset and the onset latitude, in order to analyze the differences, if any, in the rates of movement. It was found that the absolute ratio of the rate of movement of the mean poleward and equatorward boundaries was slower than the rate of mean movement around the midnight sector. The stronger the onset (in terms of the peak *AL* around the onset) was, the faster the rate of movement for both the boundaries. This implies that the stronger the *AL* signature around the onset, the weaker the magnetic field was prior to the onset and the faster it increased after the onset at GOES 8 and 10 locations. The stronger the *AL* signature, the thicker the latitudinal width of the aurora was, prior to the onset and higher was the increase in the width after the onset, due to large poleward and average equatorward expansion. Magnetotail field line stretching and relaxation rates as measured by GOES were also found to lie in the same order of magnitude. It is therefore concluded that the rates of latitudinal descent prior to a substorm onset and ascent after the onset, of the mean auroral boundaries, corresponds to the rate at which the tail field lines stretch and relax before and after the onset, respectively.

1. Introduction

Substorms are a fundamental geomagnetic process in the Earth's magnetosphere and have been a topic of intense research over several decades. During a substorm, an increased amount of solar wind energy is input into the dayside magnetosphere, which is then convected to the nightside and released explosively. Changes in ground magnetic field (Rostoker, 2000), auroral activity (Akasofu, 1963), magnetospheric plasma (Birn et al., 1997), and magnetic field properties (Lopez et al., 1988), are some of its signatures. The substorm is, therefore, a global reconfiguration of magnetospheric state, and can be observed through many measurements including magnetic field (McPherron et al., 1973), plasma distributions within the magnetotail (Machida et al., 1994), and electric currents and plasma convection in the ionosphere (Grocott et al., 2000). The most visible manifestation is the auroral evolution associated with the substorm cycle. Auroral activity is located at polar latitudes in an oval like region called the auroral oval. Observationally, a global picture of the evolution can be gained from either a synthesis of many ground based observations, e.g., Akasofu (1963) or by using satellite borne cameras to obtain global snapshots of the auroral distribution, e.g., Frank and Craven (1988) and Mende et al. (2003).

Satellite and ground observations of the auroral oval have been used to study various processes in the magnetosphere, due to the correspondence with the global magnetic field. Substorm dynamics can be deduced from the location, size, movement and brightening of the auroral oval. From auroral observations, Frey et al. (2004) noted that the onset statistically occurs in the nightside evening sector. Auroral boundaries expand and contract in response to solar wind activity and the internal dynamics of the magnetosphere. The poleward and equatorward boundaries of the oval move equatorward during the substorm growth phase, and the poleward boundary moves rapidly poleward during the substorm expansion phase (Newell et al., 1991; Lui et al., 1989; Meng and Lundin, 1986; Feldstein, 1973). The correspondence and timing between observations of solar wind forcing, auroral electrojet currents, and the boundary motion can be used to deduce

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substorm morphology because the stretching of the geotail magnetic field is related to the auroral boundary location and motion (Mende et al., 2003).

Boundary location and dynamics is driven by the geomagnetic activity and can be inferred either from ground based radar observations (Pinnock and Rodger, 2001; Aikio et al., 2006), low altitude satellites (Newell et al., 1996), or instantaneous snapshots of the global view of optical images obtained from high altitude satellites (Ostgaard et al., 2007; Newell et al., 2001). The equatorward boundary location is dependent on the existing magnetospheric magnetic and electric fields and also on the energy of the precipitating charged particles (Kauristie et al., 1999). The poleward boundary is often chosen to be the boundary that separates the open field lines that connect to the solar wind and the closed field lines that map to the plasma sheet. Automatic detection of auroral boundaries by analyzing images from Far Ultra Violet (FUV) instrument onboard the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite was accomplished by Longden et al. (2010). Using the DMSP F7 spacecraft data, Newell et al. (1996) studied the nightside precipitation structure during substorms.

Using data from the FUV onboard imager on the IMAGE satellite, Frey et al. (2004) observed more than 2400 substorm onsets during the years 2000–2002. They found a median onset location of 2300 h MLT at 66.4° latitude. According to Frey et al. (2004), brightenings were identified as substorm onsets if: (1) a clear local brightening of the aurora occurred, (2) auroral expansion happened in both the radial and azimuthal directions for at least 20 min. An onset was considered as isolated only if 30 min had passed after the previous onset. Pseudo-breakups were eliminated by the second criterion. Using this information, a list was created which contained onsets using either WIC or SI13 sensor.

The superposed epoch analysis (SEA) method isolates signals that are difficult to detect against relatively large background noise through application of composites. This technique has been used extensively in understanding the geophysical processes related to the interaction of the Earth's magnetosphere with the solar wind (Milan et al., 2009; Lavraud et al., 2006; Partamies et al., 2009; Denton and Borovsky, 2008; Wang et al., 2005; Mende et al., 2003; Grocott et al., 2009). Using nearly 2000 onsets, Milan et al. (2009) performed a superposed epoch analysis of the auroral substorms by categorizing them based on the onset latitude. They found that the auroral brightness was enhanced with a larger open flux amount in the magnetosphere. Mende et al. (2003) performed a superposed epoch analysis on 91 onsets to study electron and proton auroras. They fitted double Gaussians to the intensity of images derived from the FUV instrument onboard the IMAGE satellite and concluded that the electron aurora expanded at a rate of .7° per min while the proton aurora expanded at .5° per min. Both the boundaries proceeded equatorward indicative of nightside field line stretching.

Partamies et al. (2009) performed a superposed analysis on solar wind, ground indices, and electron fluxes from geosynchronous satellites, to study the differences between sawtooth events, isolated substorms, and steady magnetospheric convection (SMC) events. They found that sawtooth events generally occurred with enhanced ionospheric activity and that this activity was driven by high solar wind radial speed, while SMCs occurred when the solar wind speed was the lowest on average. Grocott et al. (2009) analyzed the ionospheric convection in response to substorm activity using a superposed epoch analysis. The onsets were determined through the images obtained from the FUV instrument on board the IMAGE satellite and were binned based on the onset latitude. They found that high latitude onsets were associated with a considerable increase in the convection post-onset.

In this paper, utilizing the onset list of Frey et al. (2004), a superposed epoch analysis is performed and the mean rates of auroral boundary movement analyzed during substorms. This is accompanied by the study of solar wind conditions and the associated high latitude geomagnetic response as measured by the *AL* index. The emphasis of the work is to analyze and quantify the rate of boundary movement around the onset for various levels of geomagnetic response and the latitude at onset. The quantification of boundary movement rates is then reported and physical interpretation presented. The paper is divided into the following sections. In Section 2, we describe the data sources used for solar wind, magnetic field measurement at geosynchronous orbit as measured by geostationary operational environmental satellites (GOES) satellites, auroral oval boundary movement, and the geomagnetic response (*AL*). Section 3 elaborates on the procedure used to generate the mean epochs and rates of the various parameters. Sections 4, 5, and 6 discusses the results of superposed epoch analysis of all substorms, classification based on peak *AL*, and latitudinal onset, respectively. In Section 7, we discuss the rates and summarize the key results found in this work.

2. Data

The solar wind and geomagnetic response data used in this investigation was obtained from http://cdaweb.gsfc.nasa.gov/. Merged solar wind plasma, magnetic field measurements (from Advanced Composition Explorer, ACE and WIND satellites) and ground based magnetic activity index, during the years 2000–2002 at 1 min resolution were used. Solar wind interplanetary magnetic field (IMF B_y and B_z in nT, in geocentric solar magnetospheric system or GSM), solar wind flow speeds (V_x, V_y, and V_z in km/s, in geocentric solar ecliptic system or GSE), plasma density, N_p in particles cm^{-3}, and plasma temperature (T in K) were used. Plasma flow pressure was the only derived parameter used in the study. The intensity of substorm response was measured by the strength of westward electrojet currents through the *AL* index (nT).

The period, during the years 2000–2002, corresponded to high solar activity and fell in the solar cycle 23 which. The IMF B_z peaked at -47.8 nT indicative of strong IMF driving. IMF B_y also peaked around the same time with a value around -51 nT. Fast and slow wind structures were registered in the radial speed (V_x, km/s) with alternating fast (speeds above 700 km/s) and slow wind (below 350 km/s) structures. The solar wind speed averaged around 435 km/s during the whole period. Solar wind V_y ranged between 258 km/s and 329 km/s while V_z was measured between 310 and 452 km/s. Solar wind density peaked at around 72 particles cm^{-3}. Solar wind temperature and pressure peaked at 6.4×10 K and 99 nPa, respectively. The geomagnetic response as measured by *AL* was also strong, as indicated by a peak value of -3118 nT.

The auroral oval boundary data was obtained from the British Antarctic Survey (BAS). The procedure to determine the boundary locations from the imager onboard the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite is described in Longden et al. (2010). In this analysis, data from the WIC detector were used, the emissions in which are mainly due to the impact of secondary electrons on neutrals. These secondary electrons can be created by energetic particles (electron and ions). The WIC auroral images, specially the equatorward nightside boundaries, are impacted by proton/ion precipitations. From the images obtained by the FUV instrument on board the IMAGE satellite, Longden et al. (2010) created 24 averaged intensity profiles (for the 24 MLTs) as a function of latitude, by binning the emission intensities into bins of size 1° magnetic latitude by 1 h MLT. For latitudes ranging