Substorm onset location and the equatorward boundary of the proton auroral oval

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[1] An examination of the substorm onset location inferred from Polar UVI and the location of the equatorward boundary of the proton auroral oval inferred from ground based SuperDARN radars is presented. A study of 96 individual substorm events reveals that the substorms can be initiated either near the equatorward boundary of the proton auroral oval or far poleward of the equatorward boundary of the proton auroral oval depending on the preceding interplanetary conditions. When the Interplanetary Magnetic Field (IMF) is predominantly southward prior to the substorm onset, the onset location is near the equatorward boundary of the proton auroral oval; when the IMF is predominantly northward prior to the onset, the onset location is far poleward of the equatorward boundary of the proton auroral oval. The latitudinal separation (ΔΛ) between the onset location and the equatorward boundary of the proton auroral oval shows a linear dependence on the IMF.

INDEX TERMS: 2403 Ionosphere: Active experiments; 2455 Particle precipitation; 2704 Magnetospheric Physics: Auroral phenomena (2407); 2788 Storms


1. Introduction

[2] One of the fundamental questions in magnetospheric substorm research is: ‘Where in the magnetotail is substorm onset initiated?’ Different observations and substorm models based on these observations have shown that the substorm onset is initiated anywhere between geosynchronous orbit and far tail regions of the magnetosphere [Lyons and Nishida, 1988; Lui, 1991; Lyons, 1995; Maynard et al., 1996; Erickson et al., 2000]. In terms of particle precipitation or their optical manifestations this can be in the region of proton precipitation (proton aura) [Samson et al., 1992], poleward of the peak of the proton aurora [Deehr and Luhmann, 2001], and near the poleward edge of the auroral electron precipitation [e.g. Elphistone et al., 1996]. Present knowledge therefore indicates that substorms can be initiated on the nightside, anywhere from inside of geosynchronous orbit and distant central plasma sheet (CPS).

[3] By its classical definition, an auroral substorm begins with a sudden brightening of the most equatorward part of an existing discrete arc system (auroral breakup) [Akasofu, 1964]. This does not necessarily mean that the onset arc is at the equatorward edge of the auroral oval itself since there exists ion precipitation (proton aura) equatorward of the discrete aura (electron precipitation) in the dusk-midnight sector [Akasofu, 1974; Feldstein and Galperin, 1985; Gus-senhoven et al., 1986]. The most equatorward boundary of the proton auroral oval is where high-energy ions stop precipitating, i.e. the transition region between bounce trapping and strong pitch angle scattering. This boundary is also called the ion isotropy boundary [Sergeev et al., 1983] and is clearly related to the b2i boundary identified by DMSP spectrograms [Newell et al., 1998]. Recently Jayachandran et al. [2000, 2002a, 2002b] have shown that the SuperDARN E region backscatter in the dusk-midnight sector is from the region of ion precipitation/proton aurora and that its equatorward boundary coincides with the b2i boundary and can be used as a tracer of the equatorward boundary of the proton auroral oval in the dusk-midnight sector.

[4] The location of the equatorward edge of the proton auroral oval (meaning, hereafter, the equatorward edge of the keV ion precipitation) is the earthward limit of strong pitch angle diffusion, and, ostensibly the equatorward boundary of strongly curved field lines [Sergeev et al., 1983; Donovan et al., 2002]. Identifying where the substorms are initiated relative to this boundary can provide valuable information about where in the magnetotail the onset occurs and the base level conditions in the magnetosphere for the substorm to occur. In this paper we present a study of the location of the substorm onset region with respect to the equatorward edge of the proton auroral oval. We use simultaneous data from ground-based SuperDARN radars to identify the location of the equatorward boundary of the proton auroral oval and Polar UVI to identify the substorm onset location.

2. Data and Method of Analysis

[5] Recently Liou et al. [2001] have identified 648 well-defined substorm onset events using Ultra Violet Imager (UVI) aboard Polar satellite. We have used these substorm onset times and locations as our initial database and used Saskatoon, Kapuskasing, and Goose Bay radars of SuperDARN array [Greenwald et al., 1995] to identify the equatorward boundary of the auroral oval using the method of Jayachandran et al. [2002a, 2002b]. As we are interested in determining the substorm onset locations relative to the equatorward edge of the SuperDARN E region backscatter, we are restricted to the substorm onset, which satisfies the following criteria: (1) E region backscatter should be present for the identification of the equatorward boundary.
of the proton auroral oval. (2) Since the identification of the equatorward boundary of the proton auroral oval is possible only in the dusk-midnight sector, we have selected substorm onsets occurred between 21:30–07:30 UT when any or all of the above mentioned three SuperDARN radars were in the dusk-midnight sector of the auroral oval (MLT midnight is at 03:30, 05:30 and 07:30 UT for Goose Bay, Kapuskasing and Saskatoon radars respectively). (3) The substorm onset locations need to be at magnetic latitudes greater than 62° owing to the inability to identify the equatorward boundary at lower latitude with the radars available. A total of 96 individual substorm onsets, which satisfies the above criteria have identified and studied in detail.

![Figure 1](image1.png)

**Figure 1.** Polar UVI image (top panel) sequence of a substorm onset and the simultaneous SuperDARN RTV image during the onset time from which, the equatorward boundary of the auroral oval is inferred for 31 May 1997. Date and time of each image is indicated in the figure. SuperDARN Saakatoon radar is used to identify the location of the equatorward boundary of the proton auroral oval. \( \Delta \lambda_{\text{on}} \) and \( \Delta \lambda_{\text{eq}} \) represents the onset latitude and equatorward boundary of proton auroral oval respectively.

![Figure 2](image2.png)

**Figure 2.** Same as in Figure 1 but for 10 December 1996. SuperDARN Saakatoon radar is used to identify the location of the equatorward boundary of the proton auroral oval.

3. Results and Discussion

[7] For each of the 96 individual substorm events the substorm onset latitude (\( \lambda_{\text{on}} \)) was identified using the polar UVI images. The corresponding equatorward boundary of the proton auroral oval (\( \lambda_{\text{eq}} \)) was identified from any of the three SuperDARN radars whose field of view covered the onset location, using the method of Jayachandran et al. [2002a, 2002b]. Since we are interested in the latitudinal separation between the onset location and equatorward edge of the proton auroral oval (i.e. how close or far the onset location is from the equatorward edge of the proton auroral oval) the latitudinal separation, \( \Delta \lambda = \lambda_{\text{on}} - \lambda_{\text{eq}} \) was computed and the distribution is shown in Figure 4. Even though the distribution shows that most of the substorm onset occurs near the equatorward boundary of the proton auroral oval (\( \Delta \lambda < 3\degree \)), there are a number of substorms whose onset is far poleward (\( >3\degree \)) of the equatorward boundary of the proton auroral oval. This clearly indicates that a substorm onset can be initiated near or far poleward of the equatorward boundary of the proton auroral oval. A recent study by Deehr and Lummerzheim [2001] using ground based Meridian Scanning Photometer (MSP) data of proton aurora and OI 557.7 nm have shown that the discrete auroral arc that brightens at the auroral substorm onset was poleward of the proton aura and the latitudinal separation between the

location was at 73° and the location of the equatorward boundary of the proton auroral oval identified from the Goose Bay radar was at 66.6°. For the event shown in Figure 2, the onset location was at 67° and the location of the equatorward boundary of the proton auroral oval identified using the Saskatoon radar was at 64.2°. These three examples clearly illustrates the variability in the location of the substorm onset region with respect to the location of the equatorward boundary of the proton auroral oval.
peaks of the proton aura and the onset discrete auroral arc (OI 557.7 nm) can be as high as $3.8 \text{ C24}$. The distribution shown in Figure 4 has much wider distribution since we are dealing with the equatorward boundary of the proton auroral oval instead of the peak of the proton aura and the difference between the peak of the proton aura and the equatorward boundary can be as high as $2 \text{ C176}$ and they are dependent on host of variables (local time, altitude of the emission, which is dependent on the particle energy, energy flux of the precipitating protons etc.) [Donovan et al., 2002].

[8] One obvious factor to consider is the local time variation of $\Delta \Lambda$, since there is magnetic local time variation in the location of the auroral oval [Feldstein and Galperin, 1985] and the b2i boundary [Newell et al., 1998]. Figure 5 shows the scatter plot of $\Delta \Lambda$ with magnetic local time for all the 96 events studied here; the solid line in the figure is the mean curve. The figure shows that there is slight local time variation in $\Delta \Lambda$ with $\Delta \Lambda$ increasing slightly towards the midnight. However, this local time variation is much smaller than the scatter (standard deviation) of the data shown in Figure 5.

[9] A major factor that controls the substorm onset location, the location of the equatorward edge of the auroral oval, and, in some cases, the substorm trigger itself, should be the north-south component of the interplanetary magnetic field (IMF Bz) [Holzworth and Meng, 1984; Lyons, 1996; Liou et al., 2001]. Since it is clear from Figure 4 that there is a high degree of variability in $\Delta \Lambda$ the next obvious thing is to examine whether IMF Bz has any effect on $\Delta \Lambda$. For this purpose, one-minute values of IMF Bz from the WIND satellite were taken and corrected for the travel time of the IMF Bz detected at the satellite to the magnetopause using the solar wind velocity and the simple X-line method adopted by Ridley et al. [1998] and Jayachandran and MacDougall [2000]. The time delay between the instant that a change of IMF Bz first impacts the magnetopause and an ionospheric response can range anywhere from zero [e.g. Boralv et al., 2000] to tens of minutes or more [Meng et al., 1973; Bargatze et al., 1986; Jayachandran and MacDougall, 2000]. Therefore, for each of the 96 events studied here, we have computed a 30-minute average value of IMF Bz before the substorm onset. Figure 6 shows the scatter plot of the time averaged IMF Bz versus $\Delta \Lambda$. The figure shows a clear linear dependence of $\Delta \Lambda$ on the IMF Bz (as the value of IMF Bz increases, $\Delta \Lambda$ also increases). The correlation coefficient is 0.73 and the expression of linear best fit is $\Delta \Lambda (\text{Deg.}) = 2.65 + 0.4 \times \text{Bz (nT)}$. This shows that when the IMF Bz is negative $\Delta \Lambda$ is small, implying that the substorm onset is very near to the equatorward boundary of the proton auroral oval. Conversely, when the IMF Bz is northward $\Delta \Lambda$ is large, implying that the substorm onset is far poleward from the equatorward boundary of the proton auroral oval. The small number of data points when Bz $\neq 0$ is because of the reduced E region backscatter (from which the equatorward boundary of ion precipitation is derived) under these conditions.

[10] We have shown that substorms can be initiated anywhere near or far poleward of the equatorward boundary of the auroral oval depending upon the prevailing IMF conditions and $\Delta \Lambda$ is dependent on the strength of the IMF. This implies that the substorm onset location with respect to the equatorward boundary of the proton auroral oval moves poleward or equatorward depending on the preceding IMF conditions manifesting the tailward or earthward

**Figure 3.** Same as in Figure 1 but for 22 December 1996. SuperDARN Goose Bay radar is used to identify the location of the equatorward boundary of the proton auroral oval.

**Figure 4.** Distribution of the $\Delta \Lambda$ for the 96 substorm events.

**Figure 5.** Magnetic Local Time variation of $\Delta \Lambda$. The solid line shows the average.

**Figure 6.** Scatter plot showing the relationship between $\Delta \Lambda$ and the 1/2 hour average value of the IMF Bz before the onset.
motion of the onset region in the magnetotail. If the IMF is predominantly southward prior to the substorm onset, the onset location is far poleward of the proton auroral oval. Conversely if the IMF is predominantly northward prior to the substorm onset, the onset location is far poleward of the equatorward edge of the proton auroral oval.

4. Conclusions

A study of 96 events of the substorm onset location with respect to the equatorward boundary of the proton auroral oval has revealed that the substorm onset can be anywhere in the auroral oval depending upon the preceding IMF conditions. The latitudinal separation between the equatorward boundary of the proton auroral oval and the substorm onset location shows slight local time variation and depends dominantly on the IMF. When the IMF is predominantly southward prior to the onset the location of the substorm onset is near to the equatorward boundary of the proton auroral oval and when the IMF is predominantly northward prior to the onset the substorm onset location is far poleward of the equatorward boundary of the proton auroral oval.

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