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Southern Hemisphere poleward moving auroral forms

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[1] This paper presents a statistical study of Southern Hemisphere poleward moving auroral forms (PMAFs) using optical data from the US Automatic Geophysical Observatory network in Antarctica. These Southern Hemisphere events are compared with Northern Hemisphere PMAFs, which have previously been observed during varied interplanetary magnetic field (IMF) configurations. The frequency of PMAF occurrence is studied as a function of IMF orientation and magnetic local time. Southern Hemisphere PMAFs are biased to $B_z < 0$ constituting 62% of events, but are frequently observed during conditions of $B_z > 0$ constituting 38% of events. Southern Hemisphere PMAFs share a similar IMF B_z dependence with Northern Hemisphere events [e.g., *Fasel*, 1995]. The primary modulator of PMAFs was found to be IMF B_y, which was negative for 81% of events. Although the average background IMF was biased to $B_y < 0$, we find significant enhancement during $B_y < 0$ after this bias was removed. In a statistical study of Northern Hemisphere events, *Fasel* [1995] found 77% of events occur during positive B_y. PMAFs appear to have an antisymmetric B_y dependence between hemispheres. We find $B_y < 0$ ($B_y > 0$) enhances the observation of PMAFs in the prenoon (postnoon) region, consistent with the release of magnetic stress. A morning bias of Southern Hemisphere PMAFs is observed, consistent with Northern Hemisphere events. *INDEX TERMS:* 2704 Magnetospheric Physics: Auroral phenomena (2407); 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers

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1. Introduction

[2] The mechanisms of solar wind energy and momentum transfer to the magnetosphere can be studied in the dayside cusp/cleft ionosphere where field lines map directly to the dayside magnetopause and boundary layers. Poleward moving auroral forms (PMAFs) are one of the most common features of the dynamic dayside cusp [*Horwitz and Akasofu*, 1977; *Rairden and Mende*, 1989; *Fasel et al.*, 1992; *Fasel*, 1995; *Sandholt et al.*, 1986, 1990, 1994, 1998a, 1998b; *Sandholt and Farrugia*, 1999]. These transient forms are initiated by a brightening at the equatorward boundary of the dayside auroral oval, then separate, and move antisunward (tailward), subsequently fading and disappearing several degrees from the auroral oval in the polar cap [*Fasel et al.*, 1992]. PMAFs are distinguishable from other transient forms initiated at or near the cusp by their mean lifetime (∼10 min [*Fasel*, 1995]), tailward velocity (∼1 km/s), and relatively large-latitudinal motion (∼5°).

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[3] Previous studies have suggested four magnetopause/boundary layer mechanisms leading to transient ionospheric forms in the cusp/cleft region: (1) Kelvin-Helmholtz instabilities caused by vortices at plasma flow shears, (2) plasma penetration (PTEs) of solar wind particles with irregularly high-momentum density, (3) solar wind pressure pulses leading to the expansion/contraction of the dayside magnetosphere, and (4) magnetic reconnection of terrestrial field lines with the solar wind field. Mechanisms (1) and (2) are not thought to produce ionospheric signatures consistent with the location, motion, and spatial/temporal scale of observed PMAF events.

[4] Dynamic pressure changes in the solar wind cause large motions of the magnetopause, leading to the expansion/compression of the dayside magnetosphere. The motion of the magnetopause may lead to ionospheric forms consistent with the spatial/temporal scale and location of PMAFs. Using case studies, *Lui and Sibeck* [1991] and *Sandholt et al.* [1994] found a correlation between PMAFs and transient pressure pulses. However, *Lockwood et al.* [1990] found no correlation between PMAFs and dynamic pressure pulses in their case study. *Fasel*'s [1995] statistical study of 189 PMAFs found the majority of events occurred

during steady solar wind density ($\Delta\rho/\rho \sim 0.1$), suggesting that pressure pulses were not responsible. Additionally, he found that the sign of (B_x/B_y) during events was invariant to MLT. If pressure pulses were responsible, he argued, one would expect to find a prenoon (postnoon) bias of events to a negative (positive) sign due to the fast mode wave initiated by the interplanetary magnetic field (IMF) impacting the postnoon (prenoon) magnetopause [*Fasel*, 1995]. If dynamic pressure variation is responsible for PMAF events, prenoon (postnoon) events in the Northern Hemisphere should have a similar dependence on IMF B_y with prenoon (postnoon) events in the Southern Hemisphere.

[5] *Vorobjev et al.* [1975] first suggested that PMAFs are the signature of dayside magnetic flux traversing the polar cap. Flux transfer events (FTEs) refer to the initiation of transient magnetic flux transfer. Previous studies have linked PMAFs with FTEs [*Sandholt et al.*, 1986], and associated their statistical periodicity (5–15 min recurrence time and 2–10 min duration) [e.g., *Fasel*, 1995]. FTEs are frequently observed by satellites in situ in the dayside magnetosphere [*Russell and Elphic*, 1978, 1979; *Kawano and Russell*, 1996, 1997]. These events consist of increased magnetic field intensity with a transient magnetic perturbation normal to the magnetopause, first outward (inward) then inward (outward) in the Northern (Southern) Hemisphere [*Russell and Elphic*, 1979; *Kawano and Russell*, 1996]. These magnetic field disturbances are proposed to initiate tailward convection of previously closed dayside magnetic field lines. *Kawano and Russell* [1997] correlated 240 FTE events with concurrent IMF data. They concluded that FTEs in the dayside magnetosphere are not likely to be caused by solar wind pressure variation. They found that the majority of dayside FTEs occurred during conditions of $B_z < 0$, but were relatively frequent during conditions of $B_z > 0$. The initiation of FTEs was linked to patchy reconnection [*Kawano and Russell*, 1997].

[6] The region of reconnection is theoretically located where the magnetosheath and magnetospheric field lines are antiparallel (referred to as the neutral line) [*Crooker*, 1979]. During conditions of negative B_z, the neutral line is located at low-latitude field lines near the subsolar point. The neutral line moves to open field lines in the northern and southern lobes during conditions of positive B_z. A significant component of IMF B_y will move the neutral line to the prenoon (postnoon) high-latitude region during $B_y < 0 (B_y > 0)$ in the Northern Hemisphere [e.g., *Cowley*, 1981]. This relation is reversed in the Southern Hemisphere. The neutral line is spatially modulated by IMF B_x primarily when $B_z > 0$, leading to a larger neutral line impacting the southern (northern) lobe given $B_x > 0 (B_x < 0)$. A simple model of reconnection requires antiparallel field lines, localizing reconnection to the location of the neutral line. Component reconnection has also been postulated for reconnection events occurring away from the neutral line, under conditions that are not exactly antiparallel.

[7] Previous papers have classified the ionospheric signatures of different reconnection locations. Given a purely southward IMF, ionospheric precipitation will begin as a brightening at the equatorward boundary of the dayside aurora and move poleward as the field line convects tailward. The reconnection of an open field line during a purely northward configuration will lead to a brightening at the poleward boundary of the cusp, followed by equatorward motion in the fading phase [*Sandholt et al.*, 1998b]. However, if there is a significant B_y component to the IMF, one of the lobe cells will be enlarged creating plasma flow shears which could generate poleward propagation for lobe connected field lines [*Reiff and Burch*, 1985]. High-latitude reconnection of dayside field lines in the postnoon (prenoon) regions will propagate field lines prenoon (postnoon) due to the release of magnetic field tension. This leads to enhanced observation of ionospheric events in the prenoon (postnoon) given $B_y > 0 (B_y < 0)$ in the Northern Hemisphere [*Karlson et al.*, 1996; *Provan et al.*, 1999]. The Southern Hemisphere dependence on B_y is similar after switching B_y sign.

[8] Papers have tested these models by comparing cusp auroras to the local IMF geometry [*Øieroset et al.*, 1997; *Sandholt et al.*, 1998a, 1998b, 2001]. A two quadrant clock angle regime (CAR) is frequently used to define the projection of the IMF on the *z-y* plane: $\theta = \arctan\{B_y\}/B_z$ ($B_z > 0$), and $\theta = 90° - \arctan\{B_y\}/\{B_z\}$ ($B_z < 0$) Northern Hemisphere studies observe a latitudinal separation of the dayside aurora, dependent on clock angle, leading to the definition of the two distinct auroral cusps: (1) type 1 cusps at latitudes of 72°–75° magnetic latitude (MLAT) and (2) type 2 cusps at latitudes of 77°–79° MLAT. It has been argued that the type 1 cusp is the ionospheric signature of particle precipitation following reconnection with previously closed dayside field lines and that the type 2 cusp is the signature of precipitation following reconnection with previously open lobe field lines. During clock angles of $\theta <$ 45° only type 2 cusps are observed; during clock angles of $45° < \theta < 90°$ a superposition of types 1 and 2 cusps are often observed; and during clock angles of $\theta > 90°$ type 1 cusps are observed [*Øieroset et al.*, 1997; *Sandholt et al.*, 1998a, 1998b, 2001]. The concurrent observation of two cusp latitudes corresponding to open and closed field line reconnection suggests either that dynamic solar wind structure rotates into antiparallel configurations as it propagates to the sites of reconnection or that component reconnection is occurring.

[9] The majority of Northern Hemisphere studies report enhanced PMAF occurrence during conditions of southward IMF, consistent with enhanced dayside reconnection [*Fasel et al.*, 1992; *Fasel*, 1995; *Karlson et al.*, 1996; *Sandholt et al.*, 1990, 1992, 1996, 1998a, 1998b; *Provan et al.*, 1999]. Many case studies have observed PMAFs initiating from latitude of 72°–75° MLAT consistent with dayside reconnection [*Lockwood et al.*, 1989; *Sandholt et al.*, 1986, 1990, 1998a, 1998b]. However, PMAFs are frequently observed during conditions of $B_z > 0$ [*Fasel*, 1995; *Provan et al.*, 1999; *Sato et al.*, 1999], and are frequently observed to initiate from latitudes greater than 75° MLAT [*Sato et al.*, 1999]. These observations question the one-to-one correspondence of PMAFs with dayside reconnection, given the simple model of antiparallel merging.

[10] Previous Northern Hemisphere studies show that PMAFs occur more frequently during conditions of $B_y > 0$ than $B_y < 0$ [*Murphree et al.*, 1990; *Sandholt et al.*, 1992; *Fasel*, 1995; *Provan et al.*, 1999]. In addition, an increase in ionospheric green line emission has been correlated to $B_y > 0$ [*Øieroset et al.*, 1997]. However, dayside reconnection should not show a statistical preference to B_y sign [*Kawano*

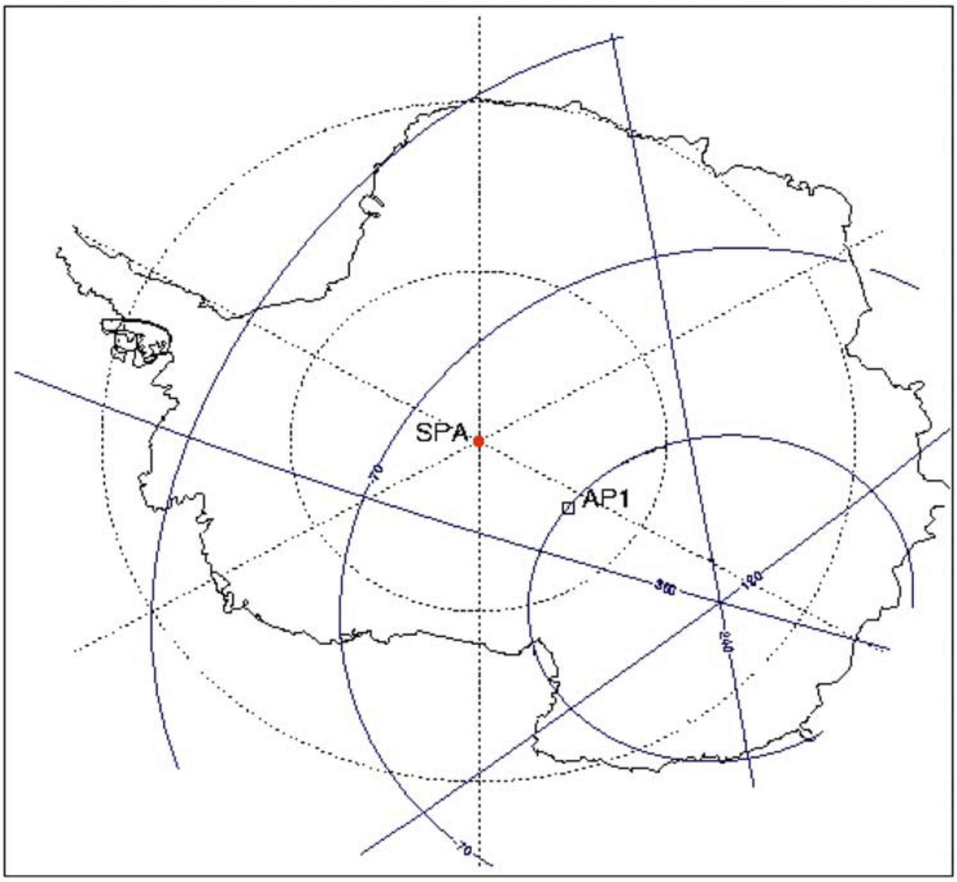

Figure 1. Geographic and geomagnetic orientation of South Pole Station and AGO P1.

and Russell, 1997]. A B_y-dependent, field aligned current sheet (FAC) proposed by *Saunders* [1989] may lead to the enhanced visibility of PMAFs during Northern Hemisphere conditions of $B_y > 0$. Given conditions of negative B_z, $B_y > 0$($B_y < 0$) will modulate reconnection to the postnoon (prenoon) high-latitude dayside region. The merged dayside field lines from the postnoon (prenoon) region propagate to the morning (afternoon) sector by the release of magnetic stress. The field lines undergo shortening and rotation as their motion is changed from the initial magnetic stress force to the viscous magnetosheath drag, inducing an upward (downward) FAC sheet poleward of the morning (afternoon) cusp. Accordingly, precipitation is enhanced in the Northern Hemisphere morning sector for $B_y > 0$ and in the Southern Hemisphere morning sector for $B_y < 0$. The induced FAC sheet is located just poleward of the cusp to ~80° MLAT in the polar cap [Figure 2, *Saunders*, 1989]. This model of FAC enhanced precipitation requires high-latitude dayside merging.

[11] Northern Hemisphere statistical studies have previously been used to correlate PMAFs to preferred IMF orientations [*Fasel*, 1995; *Karlson et al.*, 1996; *Provan et al.*, 1999]. *Fasel* [1995] completed the most comprehensive statistical study of Northern Hemisphere PMAFs using data from Longyearbyen (74.3° MLAT). He used Meridian Scanning Photometer (MSP) and all-sky camera data to identify 189 PMAF events with concurrent solar wind data [*Fasel*, 1995].

[12] This study presents a significant body of auroral observational data collected in the southern auroral zone using the chain of US Automatic Geophysical Observatory (AGO) observatories, covering a latitude range of 68°–86° MLAT. The intent of this study is to statistically establish the properties of Southern Hemisphere PMAFs, and to compare their IMF and MLT dependence with Northern Hemisphere PMAFs. If FAC enhanced high-latitude dayside merging is responsible, the Southern Hemisphere events should share a similar dependence on B_z with Northern Hemisphere events, as well as a morning bias. The B_y dependence of Southern Hemisphere events should be antisymmetric to the B_y dependence of Northern Hemisphere events.

2. Instrumentation

[13] The optical imaging data presented in this study were collected from South Pole station (geographic coordinates: 90.00°S, 0.00°E; CGM: 74.02°S, 18.35°E) and the US AGO station P1 (geographic coordinates: 83.86°S, 129.61°E; CGM: 80.14°S, 16.75°E) (See Figure 1 for visual orientation). P1 station lies approximately on the geomagnetic meridian of South Pole station enabling observation of poleward moving aurora beyond the poleward horizon of South Pole. These stations have a combined imaging range of 68°–86° MLAT. The imaging instrumentation used were dual wavelength (427.8 and 630.0 nm) all-sky cameras with

a field of view of 170°, run at an imaging rate of one exposure per two minutes. A brief description of the instrument is included in Appendix A.

3. Observations

[14] We analyzed all-sky data from April through August in 1997. We required concurrent imaging at both stations (South Pole and P1) giving 67 days of data where both instruments were operating and the sky was clear enough to see PMAFs. Correlated IMF data from the magnetic field experiment aboard the WIND spacecraft was collected. We limited our use of WIND data to times when it was sunward of bow shock ($Wind_x > 15$ Re), giving 63 days of PMAF imaging with IMF data. A time lag calculation (T_{offset}) was applied to the Wind data where $T_{offset} \sim (Wind_x - 10Re)/v_x +$ 5 min.

[15] To familiarize the reader with our data set, we have included a period of all-sky images (Figure 2) and a Keogram (Figure 3). Figure 2 shows a PMAF event imaged at P1 station, with the blue (427.8 nm) and red (630.0 nm) wavelengths to the left and right, respectively. The process of brightening at the cusp (Figures 2a and 2b), separation from the cusp (Figure 2c), poleward motion (Figures 2d and 2e), and subsequent fading several degrees latitude into the polar cap (Figures 2f and 2g) is clearly seen. Keograms are obtained by extracting pixels along the magnetic meridian of all-sky data and plotting them progressively, creating a latitude versus time plot. The Keogram in Figure 3 represents an average day where the following characteristics of the dayside cusp aurora can be seen: (1) PMAFs are relatively common, beginning in the early morning and continuing through the day; (2) the cusp moves poleward during an average dayside period, peaking around geomagnetic noon (1530 UT), and (3) swirling forms dominate in the afternoon which have been attributed to Kelvin-Helmholz instabilities [*Wei and Lee*, 1993].

[16] The following is the method used to define a PMAF event and obtain our statistics. We limited our analysis to the dayside aurora occurring 3 hours before and after geomagnetic noon (1530 UT). We separated the Keogram data into 10-min bins to minimize the errors in identifying individual PMAF events given the limited time resolution of the instrument (one exposure per 2 min). We define a PMAF event as a bin in which a PMAF occurred. Therefore a 6-hour dayside period will have 36 ten-minute bins, which are sorted depending on whether PMAF(s) occurred within. This method provides a suitable data set because IMF data were also averaged for each 10-min bin.

[17] This method gave us a data set of 2282 total bins from April through August period in which both cameras were operating and IMF data were available. Three hundred twenty-six bins were found to have positive sloped PMAF events (14.3% occurrence). One event was found to have a negative slope, which is the signature of a sunward propagating auroral form.

4. Statistical Results

[18] The following is a summary of the IMF conditions accompanying PMAF events. Fifty-four percent of events (176) occurred during $B_z < -1$nT, 32.5% (106) with $B_z >$ +1nT and 13.5% (44) with -1nT $< B_z <$ +1nT. A total of 81.3% of events (265) occurred for $B_y < -1$nT, while the events for $B_y >$ +1nT and -1nT $< B_y$ were 15.9% (52) and 2.8% (9), respectively. A total of 24.8% of events (81) were found with $B_x < -1$nT, 14.1% (46) with -1nT $< B_x <$ 1nT and 61.1% (200) with $B_x >$ 1nT. A prenoon-postnoon asymmetry was also found, with 59.3% of events (193) occurring prenoon and 40.7% (133) occurring postnoon.

[19] The statistical distribution of IMF configurations and MLT characteristics of Southern Hemisphere PMAFs are derived from two data sets. The first set consists of the 2282 ten-minute bins which constitute the distribution of the background field composed of times during the 5-month period when the stations were operating and IMF data were available. The second data set is a subset containing 326 ten-minute bins in which PMAFs occurred. We analyze the dependence of the 326 PMAF bins after normalizing to the average background field (2282 bins) where it would have been possible to see PMAFs.

[20] Figures 4, 5, and 6 study the distribution of PMAF events related to B_z, B_y, and B_x components. Each component contains three plots, the first of which illustrates PMAF event distribution (326 bins). The second plot illustrates the overall background distribution (2282 bins). The third plot illustrates the normalized frequency of events, which corresponds to the frequency that one might expect to see a PMAF during a 10-min interval of the 1-nT wide IMF orientation. If PMAF occurrence were invariant to IMF orientation, one would expect the event distribution to resample the background distribution, which would lead to a constant expectation frequency for all values of IMF in the third plot. The occurrence frequency plots were truncated at ±5 nT for B_z and B_x, and at ±7 nT for B_y, where the $(n)^{-1/2}$ deviation is on the order of measurement for less frequent, large-IMF magnitude events.

[21] The dependence of PMAFs on IMF B_z is plotted in Figure 4. There is a bias of PMAF events toward $B_z < 0$ seen in Figure 4a, however, a significant number of PMAFs occur during $B_z > 0$. The average B_z distribution (Figure 4b) forms a relatively symmetric Gaussian, with a slight shift toward $B_z < 0$. The normalized distribution (Figure 4c) illustrates the weak bias of events to conditions of negative B_z.

[22] The dependence of PMAFs on IMF B_y is plotted in Figure 5. There is a strong bias of events to conditions of $B_y < 0$ seen in Figure 5a. However, the background field was more often negative than positive during the 5 months of our study seen in Figure 5b. A portion of the bias in Figure 5a represents a resampling of the background distribution. Figure 5c illustrates that the strong bias to negative B_y remains in the occurrence frequency after normalizing to the background field. The event distribution is shifted to a large component of negative B_y sign, with a mode of -4 nT (Figure 5a) and a peak in occurrence frequency at -5 nT (Figure 5c). After normalization, events are found to be much more frequent during conditions of $B_y < 0$ than $B_z < 0$.

[23] The dependence of PMAFs on IMF B_x is plotted in Figure 6. The background distribution of B_x was found to be more often positive than negative during our study. This is expected given the strong $B_y < 0$ bias, because it corresponds to the Parker spiral structure of the solar wind. We

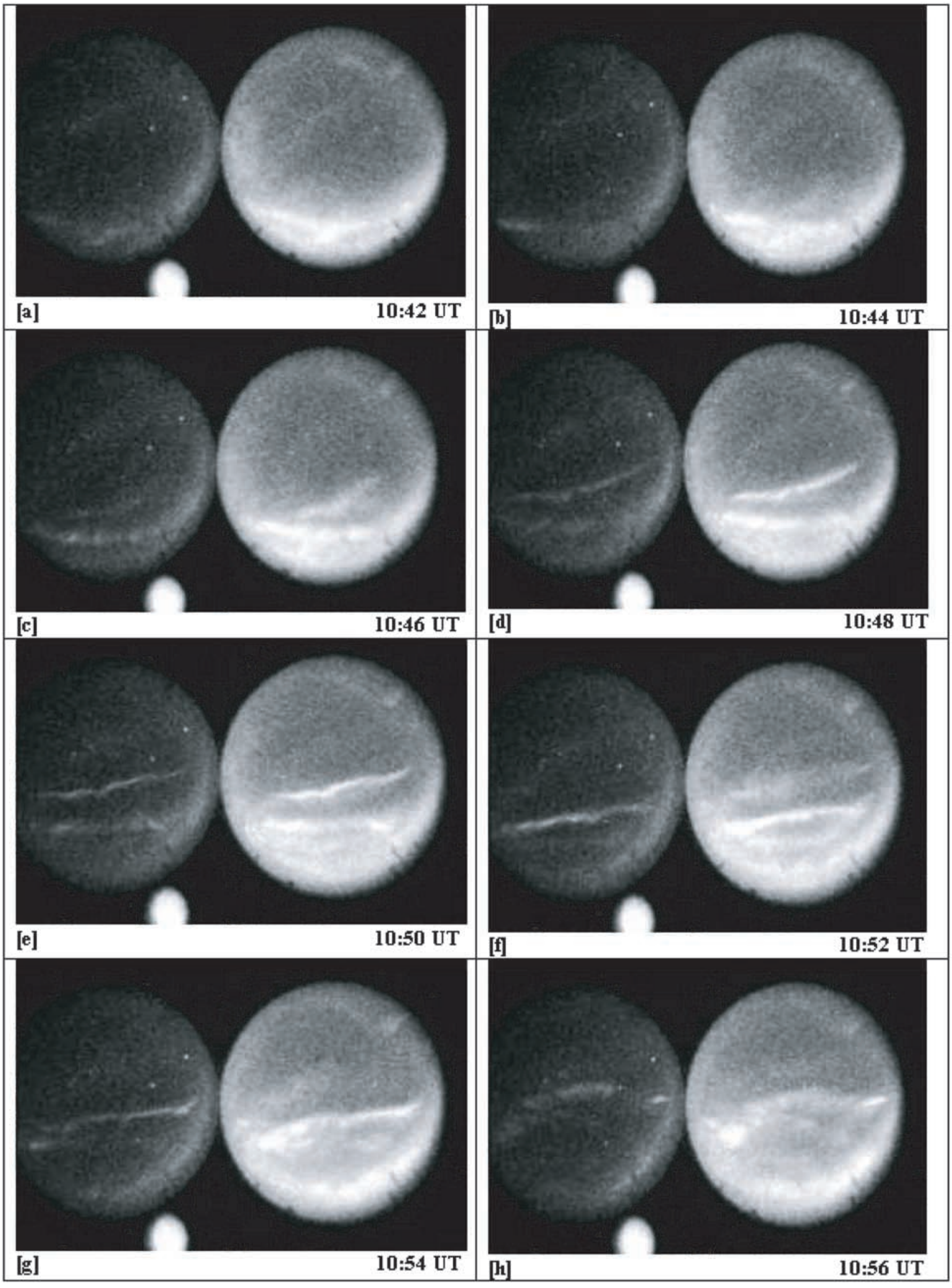

Figure 2. A typical series of dual wavelength (427.8 nm left, 630 nm right) all sky imagers taken at U.S. Atomatic Geophysical Observatory (AGO) P1 on May 8, 1997.

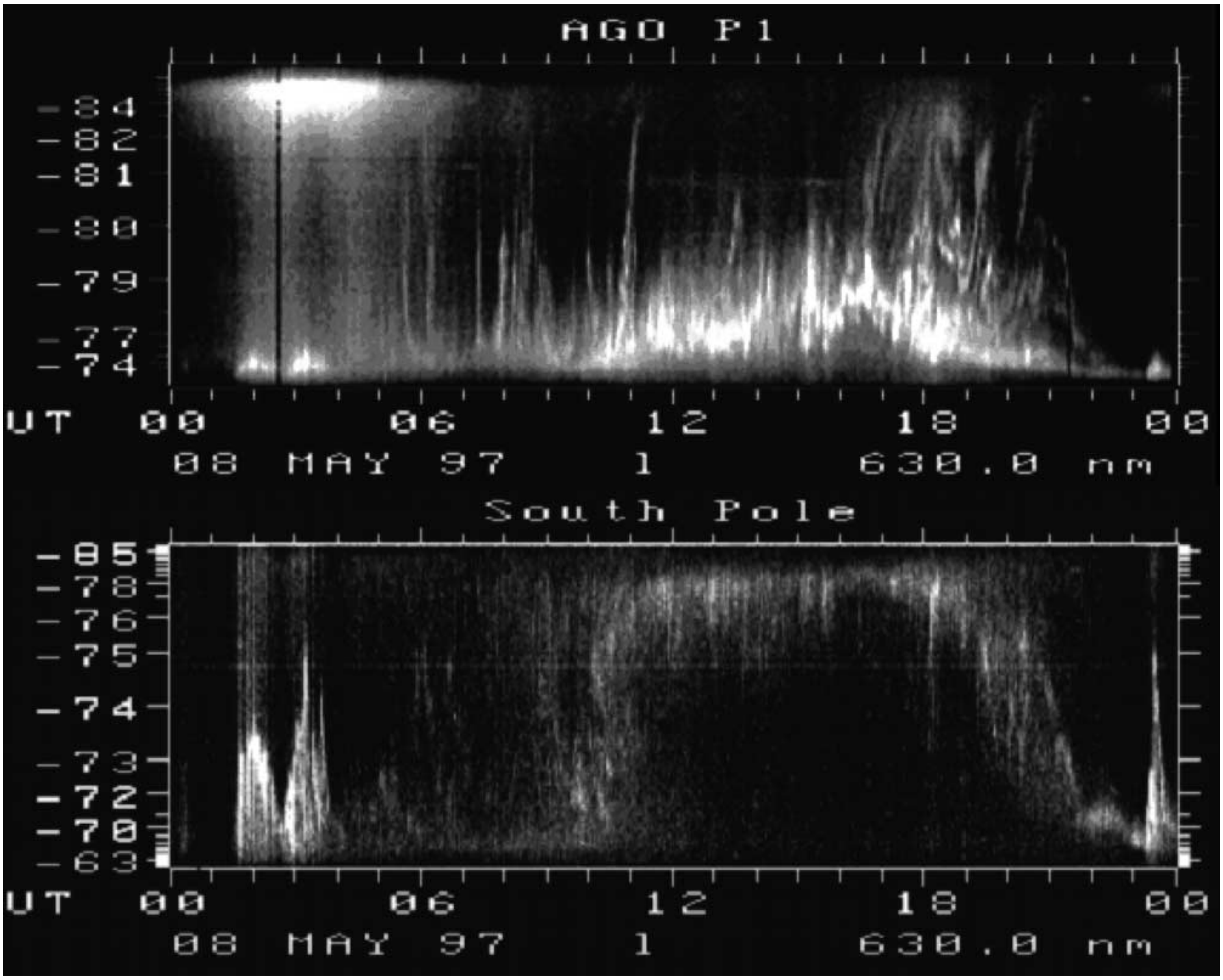

Figure 3. 630 nm keograms from AGO P1 and South Pole pair for the entire day of May 8, 1997. Geomagnetic noon occurs at 1530 UT. The keograms are produced by selecting a region including the central meridian of the images.

seem to have sampled more toward than away sectors during our study. Figures 6a and 6c show that PMAF events occurred more frequently during conditions of positive B_x.

[24] Figure 7 sorts the events by B_y sign and plots them as a function of MLT. Given $B_y < 0 (B_y > 0)$, PMAFs are more frequently observed in the morning (afternoon). Events were much more frequent during conditions of $B_y < 0$, and the majority of early afternoon events have negative sign. A significant trend of B_y modulated longitudinal motion is evident, however, the strength of the trend should not be misunderstood.

[25] Figure 8 plots the prenoon bias of PMAFs seen in the nearly monotonic decay of events from morning to afternoon. We have included events from the entire dayside period (6°–18° MLT) to illustrate that this trend is not limited to the near-noon dayside region (9°–15° MLT) of this study.

[26] A plot of IMF clock angles accompanying Southern Hemisphere PMAFs is given in Figure 9. Previous use of clock angle defined two quadrants, $B_z > 0 (0° < \theta < 90°)$ and $B_z < 0 (90° < \theta < 180°)$. This description of the IMF lacks information on B_y sign which seems significant in the study of PMAFs. Hence we defined a four-quadrant clock angle configuration which follows: (1) $B_z > 0$ and $B_y > 0$, $\theta_{\text{clock}} = \arctan(B_y/B_z)$; (2) $B_z < 0$ and $B_y > 0$, $\theta_{\text{clock}} = \arctan(\{B_y\}/B_z) + 90°$; (3) $B_z < 0$ and $B_y < 0$, $\theta_{\text{clock}} = \arctan(\{B_y\}/\{B_z\}) + 180°$, (4) $B_z > 0$ and $B_y < 0$, $\theta_{\text{clock}} = \arctan(B_z/\{B_y\}) + 270°$. Figure 9a plots the number of events per 15° of clock angle. Figure 9c plots the frequency of events after normalizing to the asymmetric background field seen in Figure 9b. The background distribution illustrates that the IMF contained a larger average B_y component than B_z component during the study.

5. Discussion

[27] Previous case studies have attributed the initiation region of PMAFs to the type 1 cusp aurora which is associated with a latitude of 72°–75° MLAT [*Øieroset et al.*, 1997; *Sandholt et al.*, 1990, 1998a, 1998b, 2001; *Sandholt and Farrugia*, 1999]. Southern Hemisphere PMAFs are frequently observed initiating from a wider MLAT region of 72°–78° (See Figure 3). The AGO chain of stations used in this study were able to observe a wider

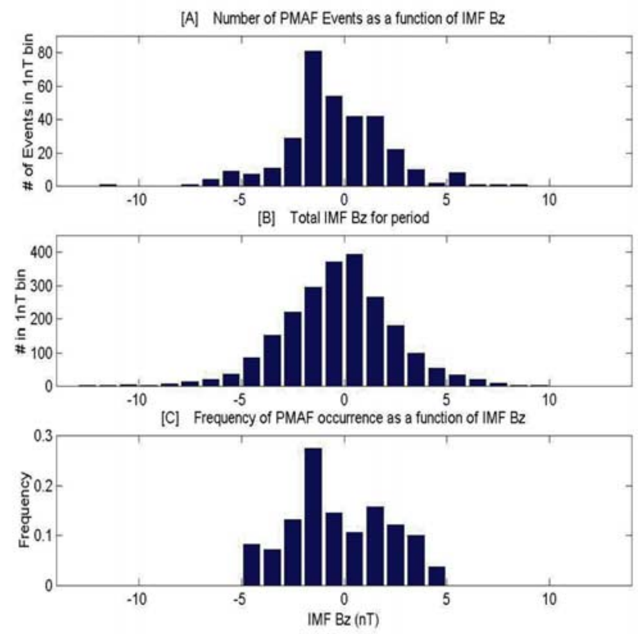

Figure 4. Plot [a] shows the number of PMAF events per 1-nT bin of IMF B_z. Plot [b] shows the total dayside IMF B_z distribution for the 4-month period studied. Note that plot [b] shows a nearly symmetric Gaussian distribution which we expect. Plot [c] shows the normalized frequency of PMAF occurrence as a function of IMF B_z (Plot [a]/Plot [b]).

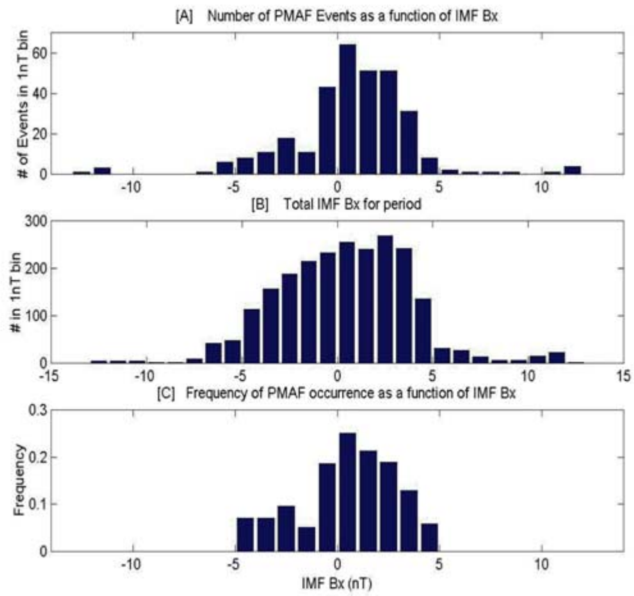

Figure 6. Plot [a] shows the number of PMAF events per 1-nT bin of IMF B_x. Plot [b] shows the total dayside IMF B_x distribution for the 4-month period studied. There is a bias of the background field to values of $B_x > 0$. Given the bias of the background field to $B_y < 0$, we seemed to have sampled more toward sectors (Parker spiral orientation) than away sectors during the study. Plot [c] shows the normalized frequency of PMAF occurrence as a function of IMF B_x (Plot [a]/Plot [b]).

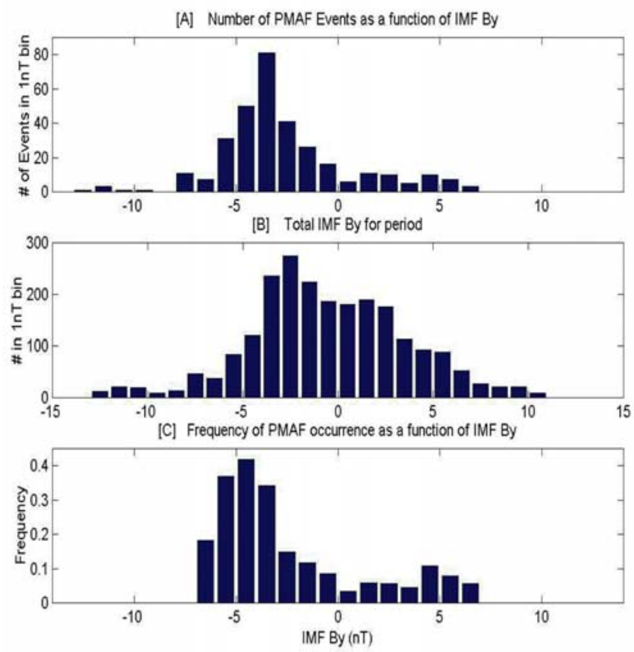

Figure 5. Plot [a] shows the number of PMAF events per 1-nT bin of IMF B_y. Plot [b] shows the total dayside IMF B_y distribution for the 4-month period studied. Note that it does not show the symmetrical Gaussian distribution which is seen for B_z. Plot [c] shows the normalized frequency of PMAF occurrence as a function of IMF B_y (Plot [a]/Plot [b]).

range of polar cap latitudes (68°–86° MLAT) enabling imaging of higher-latitude events than previous studies using stations located at ∼75° MLAT [*Fasel et al.*, 1992; *Fasel*, 1995; *Øieroset et al.*, 1997; *Sandholt et al.*, 1986, 1990, 1998a, 1998b; *Sandholt and Farrugia*, 1999]. This increased range is particularly important during times of positive B_z, where the auroral oval often contracts poleward of 78°. Under such conditions, the visibility of PMAFs is questionable from the lower-latitude (∼75° MLAT) Northern Hemisphere stations.

[28] The majority of Northern Hemisphere studies have attributed PMAFs to the ionospheric signature of pulsed magnetic reconnection at the dayside magnetopause. The evidence supporting this association includes the statistical bias of events to southward IMF [*Fasel*, 1995; *Provan et al.*, 1999], the concurrent equatorward motion of the cusp during a PMAF event [*Sandholt et al.*, 1998b], the B_y-dependent longitudinal motion of events consistent with the release of Maxwell stress from previously closed field lines [*Karlson et al.*, 1996; *Provan et al.*, 1999], the correspondence with upward FAC enhancement [*Provan et al.*, 1999], and a close match between the periodicity of FTE events and PMAF events [*Fasel*, 1995; *Kawano and Russell*, 1997; *Provan et al.*, 1999].

[29] Southern Hemisphere PMAFs are also enhanced by conditions of $B_z < 0$. We find 61.7% of events occur during conditions of $B_z < 0$, corresponding to clock angles of $90° < \theta < 270°$ (Figure 9a). *Fasel* [1995] found 61.9% of Northern Hemisphere events occur during $B_z < 0$. However, these percentages may not accurately represent the total

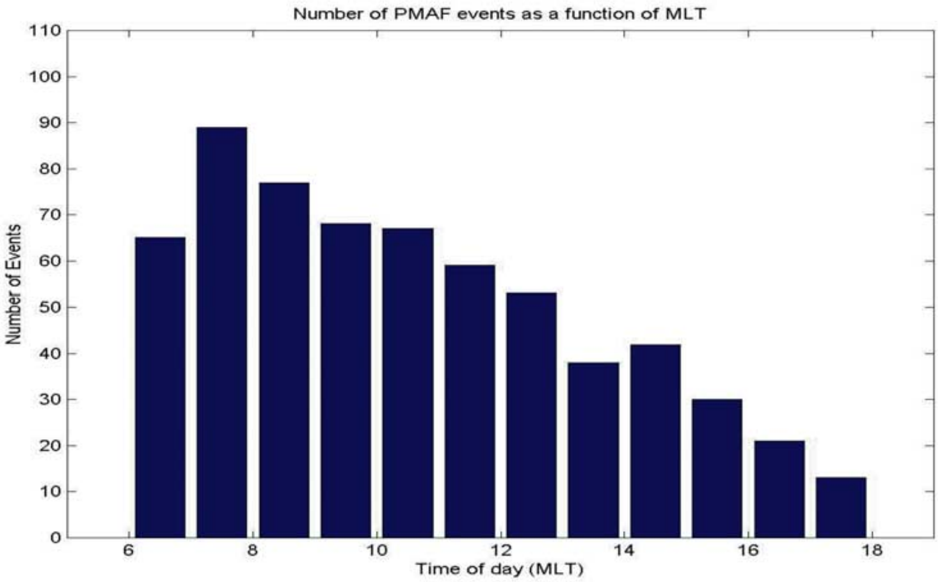

Figure 7. Plotted above is the number of PMAF events per 1-hour dayside interval as a function of MLT. A nearly monotonic decrease in events is seen across the entire dayside period, not just the study period of 0900–1500 UT.

number of antiparallel dayside configurations, because the IMF values were averaged over 10-min "bins." We find that the majority of $B_z > 0$ PMAF events occur within clock angles of 270°–290° (Figure 9). The IMF during many of these events contained a brief negative turn, although the averaged B_z value was positive. Fasel found 41 additional events with a brief turn of $B_z < 0$, although the 15-min average was positive. In total, 81% of Northern Hemisphere events [*Fasel*, 1995], and 72% of Southern Hemisphere events had at least a brief $B_z < 0$ component. However, a similar treatment of positive B_z shows at least a small component of $B_z > 0$ in 51% of Southern Hemisphere events, calling to question the strength of the one-to-one correlation of PMAFs to $B_z < 0$. It seems that either our method of averaging B_z over the duration of a bin may have weakened the correlation of PMAF events with transient $B_z < 0$ structure, or it may reflect that many studies are stretching parameters to strengthen the correlation of PMAFs to $B_z < 0$. It is possible that the strength of the statistical bias correlating PMAFs to $B_z < 0$ reflects the enhanced solar wind particle penetration into the boundary layers. Interestingly, many periods of steady IMF $B_z < 0$ are found with average solar wind speeds and particle densities, where conditions are ripe for reconnection, and no PMAFs are seen. This is particularly disconcerting during times of equatorward expansion of the auroral oval, without concurrent observation of PMAFs as magnetic flux is theoretically traversing the polar cap [*Mende et al.*, 1998].

[30] Southern Hemisphere PMAFs are frequently observed during conditions of $B_z > 0$. We find 38.3% of Southern Hemisphere events occur during clock angles of $\theta < 90°$ and $\theta > 270°$. Previous studies have also found that PMAFs are relatively frequent during conditions of $B_z > 0$ [*Fasel*, 1995; *Sato et al.*, 1999; *Provan et al.*, 1999]. *Fasel* [1995] found 38.0% of Northern Hemisphere PMAFs with $B_z > 0$. In addition, studies have observed other potential signatures of "residual" dayside reconnection during conditions of $B_z > 0$. A statistical study of FTEs found that dayside events were frequently observed during conditions of $B_z > 0$ [*Kawano and Russell*, 1997]. Also, the observation of type 1 cusps at clock angles as low as 45° [*Øieroset et al.*, 1997; *Sandholt et al.*, 1998a, 1998b, 2001] suggests that dayside reconnection occurs during relatively robust conditions of $B_z > 0$.

[31] The majority of Southern Hemisphere events (298) occurred during clock angles of $45° < \theta < 315°$ corresponding to the region capable of initiating dayside reconnection, inferred from Northern Hemisphere studies. It is surprising, however, that there are so many events during clock angles of 270°–315° (Figure 9), representing a significantly less efficient geometry for dayside reconnection than conditions of negative B_z. If we are to associate $B_z > 0$ PMAFs with residual dayside merging, it seems more frequent a phenomena than expected. It is also plausible that lobe reconnection is responsible for a portion of the observed $B_z > 0$ PMAFs. Poleward propagation of lobe-connected field lines is possible given a significant B_y component. This leads to the enlargement of one lobe cell, creating plasma flow shears capable of initiating tailward drifts [e.g., *Reiff and Burch*, 1985]. The majority of $B_z > 0$ PMAFs were found to have a large B_y component, which suggests lobe reconnection as a possible source. We also find that events occur more frequently during $B_x > 0$, where lobe reconnection is preferred in the Southern Hemisphere. However, given the Parker spiral structure of the solar wind and the strong bias of events to $B_y < 0$, it is unclear whether B_x directly enhanced PMAF occurrence.

[32] The merging of lobe field lines during purely northward configurations would lead to a brightening at the poleward cusp and equatorward drift [*Sandholt et al.*, 1998b]. Equatorward propagating auroral forms are very rare, as are purely northward IMF configurations, consisting of one event out of the 327 in our data set. This event

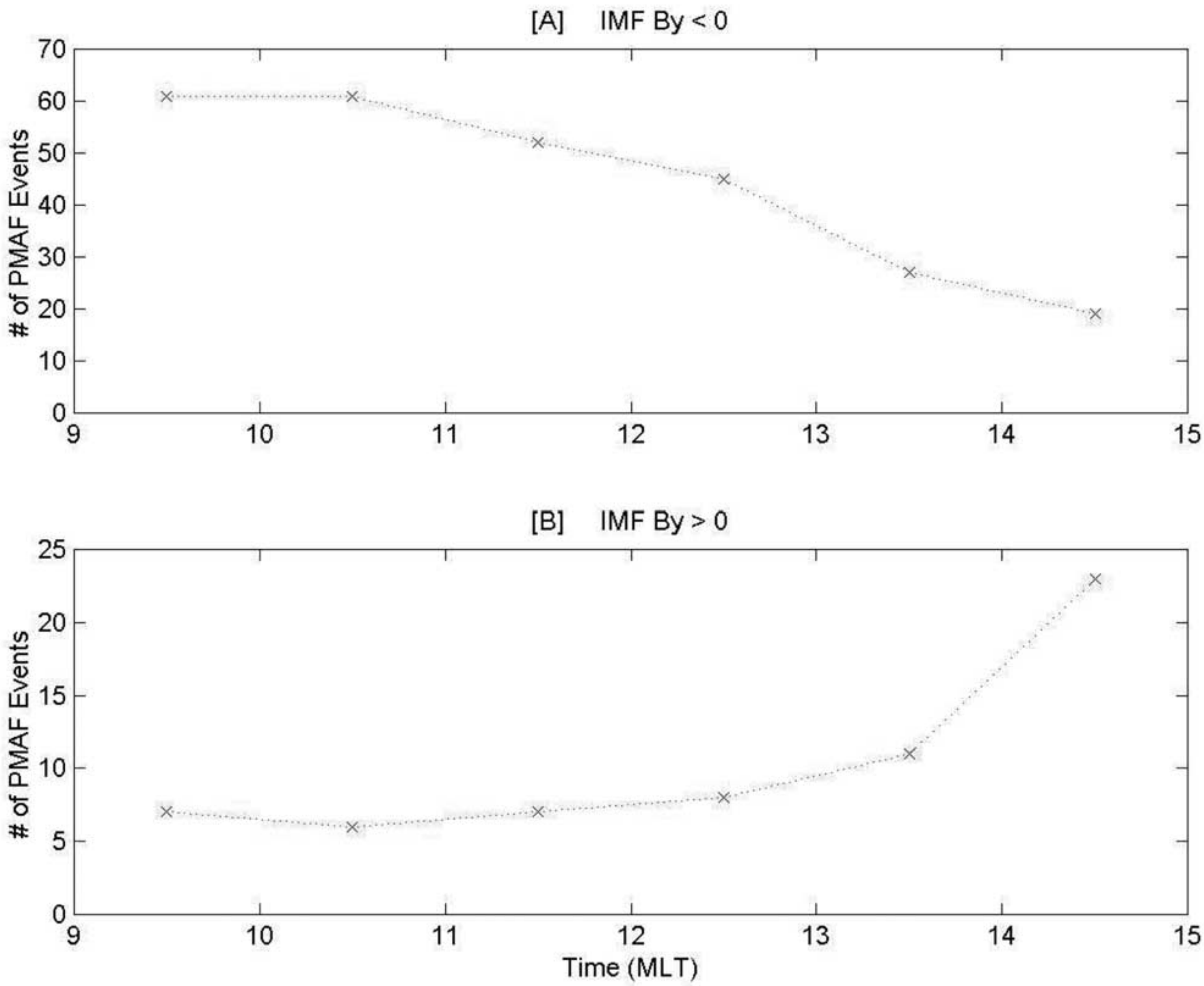

Figure 8. Plot [a] shows the time distribution of PMAF events with $B_y < 0$. Plot [b] shows the time distribution of PMAF events with $B_y > 0$. The time axis for both plots is corrected geomagnetic local time (MLT), where geomagnetic noon occurs at 1530 UT.

occurred during a purely northward configuration, as predicted [*Sandholt et al.*, 1998b].

[33] The most striking difference between the event distribution and the background distribution, in Figure 9, is the relative absence of events during $B_y > 0$. In total, 81% of Southern Hemisphere events occurred during $B_y > 0$. Southern Hemisphere PMAFs have a stronger correlation to $B_y < 0$ (81% of events) than to $B_z < 0$ (62% of events). *Fasel* [1995] found a similarly strong bias of Northern Hemisphere events to $B_y > 0$, constituting 77% events, and *Provan et al.* [1999] found 71% of pulsed ionospheric flow (PIF) events occurred during $B_y > 0$. These Northern Hemisphere statistical studies show a stronger correlation to $B_y > 0$ than to $B_z < 0$ (77–62% in Fasel's study, and 71–42% in Provan's study). The increased observation of ionospheric forms during $B_y > 0$ in the Northern Hemisphere polar cap has been documented by case studies as well [*Murphree et al.*, 1990; *Sandholt et al.*, 1992; *Sandholt and Farrugia*, 1999; *Øieroset et al.*, 1997].

[34] The bias of Southern Hemisphere PMAFs to negative B_y remains strong for $B_z > 0$ events. We find 76 events during clock angles of $270° < \theta < 315°$ ($B_y < 0$), as compared to 20 events found during clock angles of $45° < \theta < 90°$ ($B_y > 0$). This structure leads to B_y dominated high-latitude reconnection in the postnoon region of the Southern Hemisphere. A similar B_y trend of Northern Hemisphere $B_z > 0$ PMAFs has previously been documented [*Murphree et al.*, 1990; *Øieroset et al.*, 1997; *Fasel*, 1995], which is consistent with high-latitude postnoon reconnection.

[35] The MLT modulation of PMAFs by IMF B_y (Figure 8) is observed in Southern Hemisphere events. We find $B_y < 0(B_y > 0)$ events are more frequently observed in the prenoon (postnoon) region. Given our strong $B_y < 0$ bias of events, we find PMAFs are more frequently observed in the morning. Figure 7 shows a nearly monotonic decay of events with local time. The B_y modulated MLT trend has previously been observed in Northern Hemisphere studies where $B_y > 0(B_y < 0)$ events were more frequently observed in the prenoon (postnoon) region [*Karlson et al.*, 1996; *Provan et al.*, 1999]. In addition, the strong bias of events to $B_y > 0$ also led to a majority of morning events in the Northern Hemisphere [*Fasel*, 1995; *Provan et al.*, 1999].

[36] The B_y enhancement and morning bias of PMAFs is consistent with FAC enhancement. The bias of prenoon events with $B_y < 0$ in the Southern Hemisphere is predicted by *Saunder*'s [1989] argument that high-latitude dayside field lines will twist as they convect, inducing B_y-dependent FAC sheets in the polar cap. In the Southern Hemisphere, upward field aligned currents (region of auroral arcs) should occur prenoon, poleward of the cusp given $B_y < 0$ conditions of dayside reconnection. Similarly, prenoon high-latitude dayside reconnection during conditions of $B_y > 0$ in the Southern Hemisphere, will lead to downward FACs in the postnoon region. This relation is reverse for the Northern Hemisphere where precipitation will be enhanced in the morning during conditions of $B_y > 0$. Saunders discusses only the classic $B_z < 0$ reconnection events, and implies complete symmetry with B_y dependence.

[37] The fact that PMAFs are considerably more frequent in the prenoon sector in both hemispheres during antisymmetric B_y conditions, questions the one-to-one association of PMAFs with FTEs unless some mechanism can be proposed [e.g., *Saunders*, 1989] that makes the ionospheric signatures of FTEs highly asymmetric with local time. FTEs occurring on the front side of a symmetric magnetosphere ought to have a symmetric dawn/dusk distribution. If PMAFs were boundary layer phenomena, then the lack of symmetry could be explained based on the configuration of the upward field aligned currents (favoring precipitation) found only on the poleward side of the prenoon boundary layer auroras [e.g., *Lundin and Evans*, 1985]. In summary, correlating PMAFs with FTEs requires a B_y-dependent mechanism, which enhances the observation of prenoon events.

[38] In this study we did not find a systematic relationship between PMAFs and the enlargement/reduction of the polar cap. If PMAFs are the ionospheric manifestation of dayside reconnection, one would expect that increased FTE activity during periods of $B_z < 0$ would increase the flux in the tail with a concurrent enlargement of the polar cap and equatorward motion of the aurora. The equatorward motion of the initiation region is not seen during frequent PMAF occurrence (Figure 3).

6. Summary

[39] The frequency of Southern Hemisphere PMAF occurrence was studied as a function of IMF orientations and magnetic local time. Theoretically, the B_z dependence of Southern Hemisphere events should be similar to the B_z dependence of Northern Hemisphere events. We find 61.7% of Southern Hemisphere PMAFs occur during clock angles of $90° < \theta < 270°$, corresponding to times when $B_z < 0$. This compares favorably with a prior study of Northern Hemisphere PMAFs in which *Fasel* [1995] found 61.9% of the

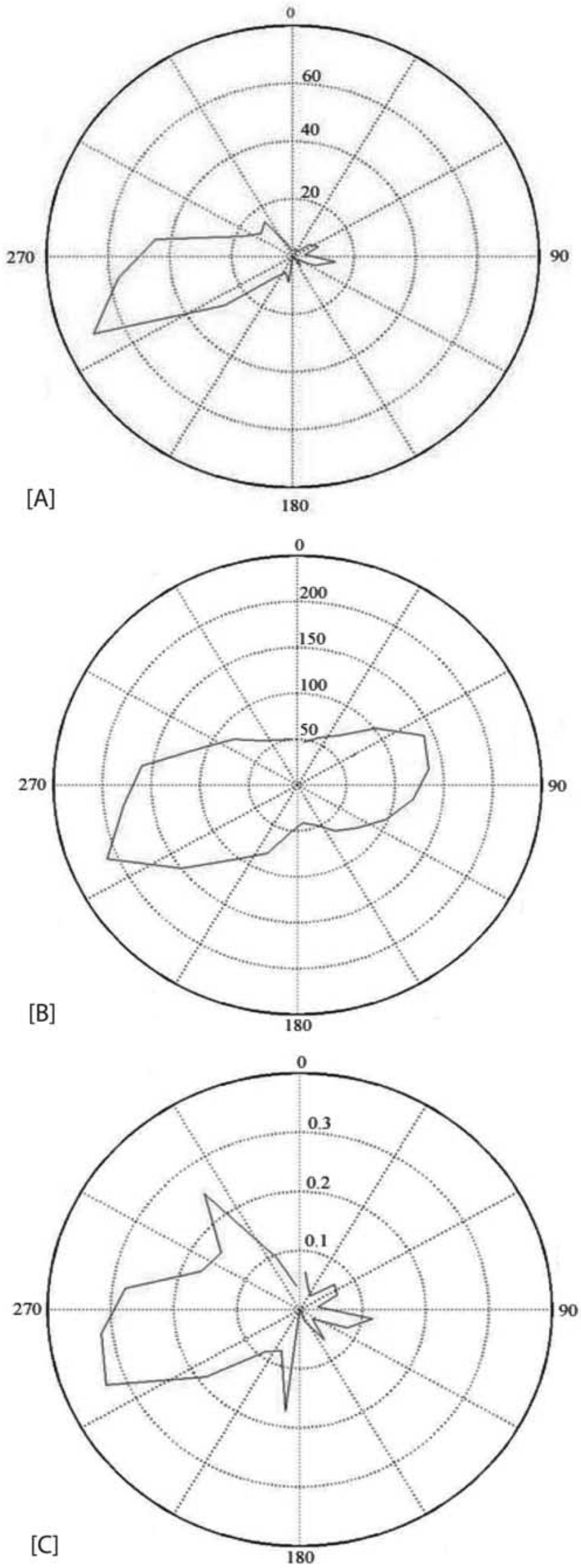

Figure 9. (opposite) Plot [a] shows the number of PMAF events per 15° of clock angle. Clock angle corresponds to the projection of the IMF onto the *z-y* plane where $\theta = 0°$ represents a purely northward IMF. Plot [B] shows the total number of 15° bins during the study. Plot [c] shows the frequency of PMAF occurrence normalized to the average IMF (plot [a]/plot [b]).

events occurred when B_z was negative. We find a significant number of PMAFs occur during conditions of $B_z > 0$, constituting 38% of events. Northern Hemisphere PMAFs are also frequently observed during conditions of $B_z > 0$, consisting of 38% of events in *Fasel*'s [1995] statistical study. Frequent residual dayside reconnection has been proposed for clock angles as low as 45°, possibly accounting for the large occurrence frequency of $B_z > 0$ PMAFs.

[40] Theoretically, the B_y dependence of Southern Hemisphere PMAFs should be antisymmetric to the B_y dependence of Northern Hemisphere events. We find 81% of PMAFs occurred during conditions of $B_y < 0$. Some of this bias is attributable to resampling the background distribution; however, the normalized frequency distribution retains a strong $B_y < 0$ enhancement (Figures 5 and 9). Statistical studies of Northern Hemisphere events have shown a similarly strong bias of events to $B_y > 0$. *Fasel* [1995] found 77% of PMAFs occur with $B_y > 0$, and *Provan et al.* [1999] found 71% of events occur during $B_y > 0$. The enhancement is antisymmetric between hemispheres as expected. Both Southern and Northern Hemisphere PMAFs show a stronger B_y enhancement than negative B_z enhancement.

[41] PMAF events in both hemispheres are enhanced prenoon (Figure 7) [*Fasel*, 1995; *Provan et al.*, 1999; this study]. The morning bias is not an expected consequence of the causal link to FTEs, which should have a symmetric dawn/dusk frequency. A mechanism leading to prenoon and B_y enhancement such as the induced FAC model proposed by *Saunders* [1989] is necessary to explain the observed event distributions of this and Northern Hemisphere studies [*Fasel*, 1995; *Provan et al.*, 1999].

[42] We did not find a systematic relationship between frequent PMAF occurrence and equatorward motion of the auroral oval.

Appendix A: Description of the US AGO All-Sky Imagers

[43] The instrument developed for use in the AGOs is illustrated in Figure A1. The camera is hermetically sealed under a dome (1) and a conventional all-sky lens (2) is used to form a 3-in. intermediate image in the vicinity of a special interference filter (4). The filter has two narrow (~4-nm wide) passbands at 427.8 and at 630 nm/s. This filter contains only the narrow band interference elements without blocking. This filter is in telecentric space provided by a lens (3) to ensure, given that the beam is at $F/4$, that the rays are as parallel with the optic axis as possible. The intermediate image is reimaged by lens groups (8) and (11) to form an image on the photocathode of the image intensifier (13). In collimated space between the two lenses (8) and (11), where the beams are less parallel, a set of blocking filters (9) is included which are constructed from two separate half filters. Each half filter selects and isolates one of the passbands of the narrowband filter. A prism (10) is included to bend each half image off the center of the image intensifier axis. Thus two images of the same sky are produced side by side on the image intensifier photocathode, which are separately filtered by the narrow band filters. The image intensifier (13) amplifies both images and the phosphor is reimaged on the CCD (15) by the lens (14).

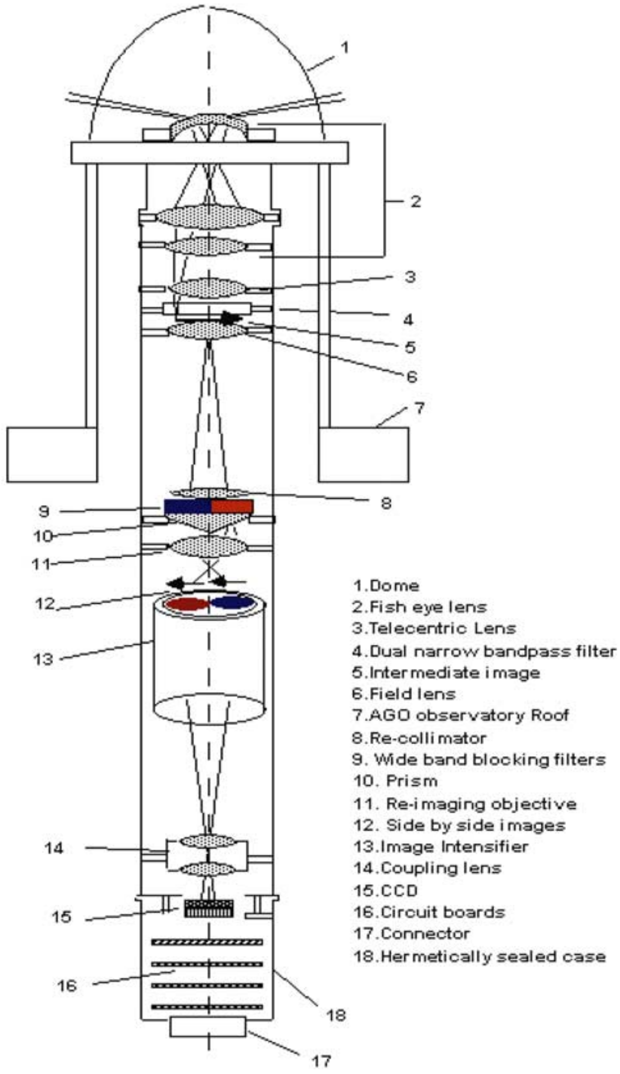

Figure A1. Optical imager at AGO stations.

The CCD electronics boards (16) provide the necessary signals to integrate the CCD for 8 s. This CCD signal is connected to the camera-controller electronics through connector (17) and the whole system is sealed in a hermetic container (18). The electronics consist of a single frame digital memory and a low power computer capable of compressing the images about 20:1 and transmitting them to the AGO data system. The domes are kept clear by wind scouring and perhaps benefit from waste heat, which passes from the AGO through the camera port to the dome. Since the AGO station power is limited the camera has an average power consumption of less than 5 W. These cameras have worked reliably for several years in unattended, unmanned environments.

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