Interplanetary magnetic field B_x asymmetry effect on auroral brightness

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[1] We derive Northern Hemispheric auroral brightness patterns using images from Polar Ultraviolet Imager Lyman-Birge-Hopfield long band emissions (~ 170.0 nm). Pixels of these images are binned by the X and Y components of the interplanetary magnetic field (IMF) under the combinations of two seasonal (summer and winter) and two IMF B_z (northward and southward) conditions. Hemispheric auroral power is estimated from these images by an integration of auroral brightness over 60° – 90° MLAT for all local times. It is found that the hemispheric auroral power is higher for negative B_x than for positive B_x under similar B_y conditions when the IMF is southward. This B_x asymmetry of the hemispheric auroral power is significant both in summer and winter. For the northward IMF the hemispheric auroral power is low and the B_x asymmetry is not statistically present in both summer and winter. Recent studies have shown that hemispheric auroral power for negative B_y is higher than that for positive B_y . In summary, hemispheric auroral power reaches its highest level when all the components of the IMF are negative. **INDEX TERMS:** 2407 Ionosphere: Auroral ionosphere (2704); 2455 Ionosphere: Particle precipitation; 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; **KEYWORDS:** aurora, interplanetary magnetic field orientation, seasonal variations, space weather

1. Introduction

[2] The morphology of the aurora in terms of the interplanetary magnetic field (IMF) has been extensively studied using a variety of ground-based and space-borne observations. *Lassen and Danielsen* [1978] used all-sky camera images to show the high occurrence rate of auroral arcs for southward IMF. *Elphinstone et al.* [1990] used Viking images to show that IMF B_y controls the occurrence rate of auroral arcs during the northward IMF. A recent study [*Liou et al.*, 1998] has shown that premidnight auroral power for negative B_y is higher than that for positive B_y . They interpreted this B_y asymmetry as being due to a partial penetration of IMF B_y from the solar wind into the magnetosphere [*Fairfield*, 1979; *Cowley and Hughes*, 1983; *Lui*, 1984; *Wing et al.*, 1995], leading to an interhemispheric current adding to or subtracting from existing field-aligned currents.

[3] Some studies addressed the IMF B_x effect on the center of the polar cap [*Meng*, 1979; *Cowley*, 1981; *Holzworth and Meng*, 1984] and the cusp latitude [*Newell et al.*, 1989; *Cowley et al.*, 1991]. As to the B_x effect on auroral brightness, *Elphinstone et al.* [1990] determined typical Northern Hemisphere auroral distributions for “northward” IMF using Viking images. They found that emissions of polar arcs at both dawn and dusk were weaker for B_x toward

the Sun than for B_x away from the Sun. *Liou et al.* [1998] estimated the auroral power in the postnoon and premidnight sectors from Polar UVI images to study the solar wind control of auroral emissions. They found no statistically significant B_x effect on the nightside auroral power for various ionospheric response times to the IMF.

[4] It is well known that IMF B_x and B_y are strongly anticorrelated owing to the classic garden-hose angle. Also, season plays an important role in auroral brightness owing to ionospheric conductivity feedback effects [*Newell et al.*, 1996; *Liou et al.*, 1997; *Shue et al.*, 2001a]. The increase in conductance reduces auroral brightness in the premidnight sector and enhances auroral brightness in the early morning sector. In this paper, we group pixels of auroral brightness by IMF B_x and B_y under different IMF B_z and seasonal conditions. To prevent the B_x effect from being contaminated by other B_y , B_z , or seasonal effects, we manage to derive auroral patterns for various B_x under similar B_y , B_z , and seasonal conditions.

[5] Using auroral images obtained by the Polar Ultraviolet Imager (UVI), we are able to study the IMF effect on global auroral brightness. *Shue et al.* [2001b] have studied the influence of IMF clock angle (the Y and Z components) on global auroral brightness. The whole study will not be complete if we do not also consider the possible role of the X component of the IMF in the global auroral brightness. As a continuation study of *Shue et al.* [2001b], this paper thus focuses on global auroral patterns in terms of the X

Figure 1. Interplanetary magnetic field (IMF) distribution in GSM XY coordinates for different combinations of season and IMF orientation. Pluses indicate the corresponding IMF conditions for 1-hr averaged Polar UVI data points. Radial lines show the division of the data points according to IMF azimuthal angle (ϕ). The zero azimuthal angle is defined in the direction of $+X$. The value is positive when the angle rotates counterclockwise. An upper limit of $B_T = 6$ nT and a lower limit of $B_T = 1$ nT (the two concentric circles) are set to avoid a bias of sampling.

component of the IMF. Here we will also summarize the effects of IMF B_x , B_y , and B_z , and season on global auroral brightness. This study is useful to us for an understanding of interactions between the solar wind, the magnetosphere, and the ionosphere. Derived auroral patterns can be used as input to a global circulation model dedicated to the study of the coupling of the thermosphere and the ionosphere and can be used for forecasting auroral activities for space weather.

2. Data

[6] The Polar UVI instrument carries four major optical filters with different wavelength bands at ~ 130.4 and ~ 135.6 nm for atomic oxygen lines, and at Lyman-Birge-Hopfield short (LBH-short, ~ 150.0 nm) and long (LBH-long, ~ 170.0 nm) bands for molecular nitrogen lines [Torr *et al.*, 1995]. In this study we use the LBH-long band because auroral emissions from this band are approximately proportional to total energy flux [Strickland *et al.*, 1993; Germany *et al.*, 1994], which is more suitable to estimate hemispheric power than the other bands. Images collected from summer and winter between January 1997 and August 1998 are used in this analysis. Overall, $\sim 27,000$ images in winter and $\sim 31,000$ images in summer were taken. Since the images include emissions from both aurora and sunlight illuminated dayglow [Germany *et al.*, 1997; Lummerzheim *et al.*, 1997], a series of calibration steps have been taken to subtract background emissions, convert counts to photon

fluxes, correct flat field and nadir-looking platform effects, and subtract dayglow emissions before we analyze the auroral images [Brittnacher *et al.*, 1997; Liou *et al.*, 1998]. High-resolution pixels of images are binned and averaged over a 1-hour interval in a grid system of 0.5 hours in magnetic local time and 1° in magnetic latitude.

[7] The IMP 8 satellite was in an orbit with geocentric distances from 25 to $48 R_E$, providing us with reliable solar wind observations of the near-Earth environment. We use 1-hour averaged IMP 8 data with a 1-hour delay as the corresponding IMF conditions for 1-hour averaged UVI image pixels, because nightside auroras respond to a southward IMF turning with a peak time delay of ~ 1 hour [Liou *et al.*, 1998]. Shue *et al.* [2001b] have shown that the general characteristics of auroral patterns derived from hourly average solar wind data are consistent with results derived by Liou *et al.* [1998], who used 5-min resolution Wind interplanetary data. For example, the aurora for southward IMF is brighter than that for northward IMF, and the auroral power for negative B_y is higher than that for positive B_y . This consistency indicates that hourly averaged data are appropriate to this statistical study for average auroral patterns in terms of IMF conditions. Note that hourly average IMP 8 data we used are from NASA OMNI web. These hourly data were averaged in a way, for example, for 0100 UT, it covers from 0100 to 0200 UT. Thus we average the UVI data in the same way when the hourly IMP 8 measurements are available.

[8] We divide the whole data set into four categories in terms of two IMF B_z orientations (positive and negative) and two seasons (summer and winter). Figure 1 shows IMF distributions in the GSM XY plane for these four categories. Pluses represent a running hourly average of all the UVI images when IMF measurements are available. We further bin the data in each category into eight groups, as indicated by radial lines. The width of each group is 90° wide centered at a multiple of 45° . For example, the group with $\phi = 0^\circ$ covers pluses from $\phi = 45^\circ$ to -45° ; the group with $\phi = 45^\circ$ covers pluses from $\phi = 0^\circ$ to 90° . The distribution of pluses shows that IMFs are mostly in a garden-hose distribution (opposite B_x and B_y signs). Also, the distribution is not uniform in ϕ , that is, more data points with a large B_T value at some ϕ , where $B_T = \sqrt{B_x^2 + B_y^2}$. As we know, a large negative B_y may also contribute more power to the Northern Hemisphere aurora than a large positive B_y . To avoid such an effect from the large negative B_y , we set a criterion $B_T < 6$ nT, as marked by the outer circle. A lower limit of $B_T = 1$ nT, as marked by the inner circle, has also been set, because the field direction may be meaningless if $|B|$ is too small.

[9] It is well known that the orientation of the IMF is a main controlling factor for auroral activity. We also set a criterion of $-4 < B_z < -1$ nT for southward IMF and $1 < B_z < 4$ nT for northward IMF to have relatively constant average B_z values for each azimuthal angle (ϕ). This criterion ensures that average auroral patterns will not be biased by the B_z effect when we sort out the B_x effect.

3. Results

[10] In Figure 2 we show distributions of 1-hour averaged IMF B_x , B_y , and B_z , solar wind velocity (V_p), solar wind

Figure 2. Average solar wind and geomagnetic conditions in eight azimuthal orientations for summer and northward IMF. The azimuthal angle (ϕ) is defined in Figure 1. Error bars represent the uncertainties of the average values.

density (N_p), geomagnetic indices (K_p and Dst), and dipole tilt angle (λ) as a function of ϕ for summer and northward IMF. Average IMF B_z , V_p , and N_p are relatively constant for all the ϕ bins. The absolute magnitude of average K_p and Dst shows small values for this northward IMF, as expected. The largest data number of data points, in the $\phi = 135^\circ$ bin, will give the smallest uncertainty. Note that the uncertainty used here is defined as the standard error of the mean for the bin. Under this definition the more the data number in a bin, the less the uncertainty of the mean. The uncertainty is marked by a error bar for each average value in the figure. Figure 3 is in the same format as Figure 2, but for winter and northward IMF. Similarly, average IMF B_z , V_p , and N_p are relatively constant for all ϕ bins, and the absolute magnitude of average K_p and Dst are small in this category, indicating that the energy coupling between the solar wind and the magnetosphere is weak during the northward IMF.

[11] Similarly, Figure 4 (summer) and Figure 5 (winter) show distributions of 1-hour averaged solar wind parameters and geomagnetic indices, but for southward IMF. Like the distributions for the northward IMF, average IMF B_z , V_p , and N_p are relatively constant. However, the absolute magnitude of average K_p and Dst for southward IMF are larger than those for northward IMF.

[12] Although this study focuses on the B_x effect on auroral brightness, for a good visualization effect we

arrange auroral patterns in terms not only of B_x but also B_y . Figure 6a shows auroral patterns in terms of IMF azimuthal angle for summer and northward IMF. As expected, the auroral activity is low for northward IMF. The afternoon bright spot and late morning auroral activity are seen during the summer. IMF B_x effects on auroral brightness under various B_y conditions are not statistically present. We also estimate the uncertainty of the brightness in each latitude-local time bin by dividing the standard deviation in the bin by the square root of the data number (the standard error of the mean). The distribution of uncertainty in terms of IMF azimuthal angle is shown in Figure 6b. The overall uncertainty in auroral brightness is less than 10% of the auroral brightness. Note that effects of background subtractions and flat field corrections may contribute some uncertainty to the data (less than 14%). The total uncertainty is an summation of the square root of these uncertainties (less than 17%). The uncertainty in the bins at $\phi = 0^\circ$, 45° , and -135° are largest owing to a small number of data points in these bins.

[13] We also show auroral patterns in terms of IMF azimuthal angle for winter under the same northward IMF polarity in Figure 7a. The afternoon bright spots and late morning auroral activity are not seen for any IMF azimuthal orientations. *Fujii and Iijima* [1987] suggested that field-aligned currents in the afternoon and late morning sectors

Figure 3. Average solar wind and geomagnetic conditions in eight azimuthal orientations for winter and northward IMF. The format is the same as that for Figure 2.

are mainly driven by voltage generators in the magnetosphere. Thus the field-aligned currents increase as the conductance increases. The enhanced field-aligned currents result in an increase in auroral luminosity. IMF B_x effects on auroral brightness under various B_y conditions are also not statistically present in these patterns. The associated uncertainties in these auroral patterns are shown in Figure 7b. The uncertainty is the highest for the bin at $\phi = -135^\circ$ due to the smallest number of data points in the bin.

[14] Figure 8a shows auroral patterns for southward IMF and summer. The afternoon bright spot and late morning aurora are not seen, suggesting that these two types of aurora are associated with northward IMF. However, aurora is seen in the early morning sector. This sector is most likely mapped to region 2 field-aligned currents [Iijima and Potemra, 1978]. The source of precipitating electrons associated with the aurora is mainly from the plasma sheet. The electrons in the plasma sheet convect earthward, drift eastward, scatter into the loss cone, and precipitate into the upper atmosphere in the early morning sector, colliding with molecules and atoms and creating auroras. In the left column of Figure 8 ($B_y > 0$) it is clearly demonstrated that auroral brightness for negative B_x is larger than that for positive B_x . However, for the other B_y polarities the B_x effect is not statistically significant. Figure 8b shows uncertainty estimations for these patterns. The uncertainty in general is larger than those under the northward IMF, suggesting that

the variations of the aurora are high for southward IMF. The total uncertainty, including averaging, background subtraction, and flat field correction, is within 17% of the brightness of the auroral patterns.

[15] Figure 9a shows auroral patterns for southward IMF and winter. Aurora is prominent in the premidnight sector where substorms occur most frequently. The auroral brightness is higher for $B_y < 0$ than that for $B_y > 0$. It should be noted that this B_y effect is not found for northward IMF. Stenbaek-Nielsen and Otto [1997] and Liou et al. [1998] attributed this B_y effect on auroral brightness to a penetration of IMF B_y into the magnetosphere, resulting in an interhemispheric current that favors the auroral production in the Northern Hemisphere. Figure 9b shows uncertainty for these patterns. The uncertainty is slightly larger than those for summer under the same southward IMF polarity, indicating that the variations of auroral activity is higher for winter than for summer.

[16] In figure 9a we find that auroral brightness for negative B_x is higher than that for positive B_x when we compare auroral patterns under similar B_y conditions (bins at $\phi = -45^\circ$ and -135° , 0° and 180° , and 45° and 135°). To show this effect more quantitatively, we estimate the total Northern Hemispheric auroral power by an integration of auroral brightness over 60° – 90° MLAT for all local times. Figure 10 shows the relation between Northern Hemispheric auroral power and IMF azimuthal angle for the four

Figure 4. Average solar wind and geomagnetic conditions in the eight azimuthal orientations for summer and southward IMF. The format is the same as that for Figure 2.

categories. Error bars indicate the total uncertainties estimated by an integration of the uncertainties of all latitude-local time bins multiplying areas of the latitude-local time bins. Note that each bin has its own average value and uncertainty. When we integrate the average auroral brightness (in units of photons $\text{cm}^{-2} \text{s}^{-1}$), we need to multiply the auroral brightness by the area of the bin and a conversion factor ($1 \text{ photons cm}^{-2} \text{s}^{-1} \simeq 0.27 \text{ erg cm}^{-2} \text{s}^{-1}$, estimated by *Brittnacher et al.* [1997]) to obtain auroral energy in a unit of gigawatts (GW). Similarly, we also need to multiply the uncertainty of the bin by the area of the bin and the conversion factor when calculating the total uncertainty of the integrated auroral power. In Figure 10d, for the negative B_y category ($\phi < 0$), the auroral power is 36 GW for $\phi = -135^\circ$ ($B_x < 0$). The auroral power for $\phi = -45^\circ$ ($B_x > 0$) is 8 GW (22%) smaller than that for $B_x < 0$. The power difference is outside the uncertainties of the two bins. Thus this B_x asymmetry is statistically present. This B_x asymmetry also shows on the two points for the positive B_y ($\phi = 45^\circ$ and 135°) category and for the small B_y ($\phi = 0^\circ$ and 180°) category. The auroral power comparison for the summer category is shown in Figure 10c. It is seen that the same B_x asymmetry is found in the power for positive B_y , but it seems not statistically significant for negative B_y . However, in Figure 4b, the average B_y for $\phi = -45^\circ$ is $\sim 1 \text{ nT}$ smaller than that for $\phi = -135^\circ$, indicating that the former bin has been influenced by large negative B_y . Therefore the actual

hemispheric power for the former bin is overestimated; that is, auroral power for positive B_x is smaller than that originally estimated. This indicates that the B_x asymmetry may also be valid for negative B_y . In Figures 10a and 10b, the B_x asymmetry in hemispheric power is not statistically present for either summer or winter under northward IMF conditions.

4. Discussion

[17] In this study we have simply done an arithmetic average on pixels in each bin. Some uncertainty may have already been included in the UVI instrument or may be produced by averaging the pixels. For example, brighter aurora is usually more confined than dimmer aurora. Brighter aurora tends to occur in narrow curtains and small filaments that are orders of magnitude below the pixel resolution of the UVI instrument. This means that pixels covered by the aurora is overestimated by the UVI instrument. However, this does not matter when we consider the total integrated brightness. We have estimated uncertainties for these auroral patterns and have shown that the total uncertainty is generally within 17% of the average values.

[18] Figure 9a clearly shows a B_x effect, in which auroral luminosity is higher for negative B_x than for positive B_x . This B_x effect on auroral brightness may be the principal

Figure 5. Average solar wind and geomagnetic conditions in the eight azimuthal orientations for winter and southward IMF. The format is the same as that for Figure 2.

Figure 6. (a) Average auroral patterns in terms of the eight azimuthal orientations for summer and northward IMF. White areas on the top of the patterns indicate missing auroral brightness due to limited field of view of the UltraViolet Image. (b) Uncertainty distributions corresponding to the average auroral patterns shown in Figure 6a. The uncertainty is defined as the standard error of the mean.

Figure 7. (a) Average auroral patterns in terms of the eight azimuthal orientations for winter and northward IMF. The format is the same as that for Figure 6a. (b) Uncertainty distributions corresponding to the average auroral patterns shown in Figure 7a. The format is the same as that for Figure 6b.

signature of a penetration of IMF B_x into the magnetosphere [Cowley, 1981]. His Figure 2 illustrates the magnetospheric configuration for $B_x > 0$ in a magnetically open magnetosphere ($B_z < 0$). The northern magnetopause intersection point of an open field line for $B_x > 0$ will be displaced tailward from its southern hemisphere counterpart. For positive B_x the flux will be larger in the northern lobe.

The feet of the field lines at midnight are shifted to lower latitudes in the Northern Hemisphere. Similarly, the feet of the field lines at midnight are shifted to higher latitudes in the Northern Hemisphere for $B_x < 0$. Since the effect is most marked on field lines at greater distances in the magnetosphere, the effect will be greatest on the poleward border of the precipitation, with little effect at lower latitudes.

Figure 8. (a) Average auroral patterns in terms of the eight azimuthal orientations for summer and southward IMF. The format is the same as that for Figure 6a. (b) Uncertainty distributions corresponding to the average auroral patterns shown in Figure 8a. The format is the same as that for Figure 6b.

Figure 9. (a) Average auroral patterns in terms of the eight azimuthal orientations for winter and southward IMF. The format is the same as that for Figure 6a. (b) Uncertainty distributions corresponding to the average auroral patterns shown in Figure 9a. The format is the same as that for Figure 6b.

[19] Diagrams shown in Figure 11 provide a simple, reasonable explanation of the B_x effect on auroral brightness under southward IMF. Figure 11a shows the flow and field-aligned current for the symmetrical case ($B_x \approx B_y \approx 0$). The brightest auroras are associated with region 1 upward field-aligned currents at dusk and region 2 upward field-aligned currents at dawn. This tendency can be seen from the auroral patterns shown in Figures 8a and 9a, with the center of the auroral oval shifted to the dawnside. From Figure 3c of Cowley [1981], for $B_x > 0$ the antisunward flows at noon are strengthened, while those at midnight are weakened and vice versa for $B_x < 0$. The “perturbation” flows and field-aligned currents in the Northern Hemisphere are shown in Figures 11b ($B_x > 0$) and 11c ($B_x < 0$). For $B_x > 0$ the perturbation flows and field-aligned currents weaken the main flows and field-aligned currents on the nightside and hence auroras dim. In contrast, for $B_x < 0$ the perturbation flows and field-aligned currents strengthen the main flows and field-aligned currents on the nightside and hence auroras brighten. Thus, as we found, the strongest auroras on the nightside occur for $B_x < 0$ under southward IMF, and the weakest for $B_x > 0$. It is the other way around in the Southern Hemisphere.

[20] We admit that selection of a 1-hour delay is simplistic. Clearly, the varying location of IMP 8 in the solar wind will not introduce a significant variation on the scale of an hour. We have examined results derived from using a different time shift. Figure 12 shows integrated hemispheric auroral power for the auroral patterns without a 1-hour delay. By comparing to Figure 10 it is found that the overall variations of the auroral power with a 1-hour delay are similar to those without a 1-hour delay except for the summer and southward IMF category. The difference between auroral power for $\phi = 45^\circ$ and for $\phi = 135^\circ$ is outside the error bars of the two bins for the case with a

1-hour delay. However, for the case without a 1-hour delay the power difference is within the error bars. This indicates that the B_x asymmetry becomes less significant for the case without a 1-hour delay. In contrary, the difference between auroral power for $\phi = -45^\circ$ and for $\phi = -135^\circ$ is within

Figure 10. Northern Hemispheric auroral power in the eight azimuthal orientations for different combinations of season and IMF orientation. We use 1-hour averaged IMP 8 data with a 1-hour delay as the corresponding IMF conditions. Error bars represent the uncertainties of the average values.

Figure 11. Flows and field-aligned currents for (a) $B_x \approx 0$, and perturbation flows and field-aligned currents for (b) $B_x > 0$, and (c) $B_x < 0$, under the $B_y \approx 0$ and $B_z < 0$ condition. Figures 11b and 11c indicate the perturbation flows and field-aligned currents associated with the two B_x conditions, to be added to the symmetrical pattern shown at Figure 11a. Circles with a dot (cross) at the center denote upward (downward) field-aligned currents. Arrows indicate flow directions.

the error bars of the two bins for the case with a 1-hour delay. However, for the case without a 1-hour delay the power difference is outside the error bars. This indicates that the B_x asymmetry becomes more significant for the case without a 1-hour delay. Overall, this examination of using different time delay suggests that the time delay does not significantly affect the B_x asymmetry.

[21] One may argue that *Liou et al.* [1998] found no statistically significant B_x effect on the nightside auroral power. A possible reason to explain the difference is that they did not bin pixels of the UVI images under different

Figure 12. Northern Hemispheric auroral power in the eight azimuthal orientations for southward IMF and different seasons. The main difference from Figure 10 is that we calculate them using the solar wind data “without” a 1-hour time delay. The format is the same as that for Figure 10.

Figure 13. Northern Hemispheric auroral power in the eight azimuthal orientations for southward IMF and different seasons. The main difference from Figure 10 is that we relax selection criteria by including data points with large negative B_z and B_y . The format is the same as that for Figure 10.

IMF B_y and B_z conditions when they studied the B_x effect. In this way the B_y and B_z effects together may have obscured the B_x effect. In this study we do a controlled measure to sort out the B_x effect under similar B_y and B_z conditions. To test this hypothesis, we relax the selection criteria by including data points with large negative B_z and B_y and calculate the integrated hemispheric auroral power. Figure 13 shows the integrated hemispheric auroral power. It is apparent that the integrated power is higher than that shown in Figures 10c and 10d. Figure 14 shows average B_z conditions for bins with large B_z and B_y included. By comparing Figure 14 to Figure 5c, it is found that the higher integrated power is due to a larger negative B_z . The overall variations of the auroral power for the winter and southward IMF category have a significant difference from those with the stricter criteria. For example, the auroral power for $\phi = 45^\circ$ ($B_x > 0$) becomes larger than that for $\phi = 135^\circ$ ($B_x < 0$) after we relax the criteria. This change is due to larger negative B_z in the bin at $\phi = 45^\circ$

Figure 14. Average IMF B_z conditions in eight azimuthal orientations for the southward IMF and winter category. The format is the same as that for Figure 5c, but with a difference of including data points with large negative B_z and B_y .

than in the bin at $\phi = 135^\circ$. Therefore this hypothesis has been justified.

5. Summary

[22] Aurora is a manifestation of the energy flow generated by the interaction between the interplanetary magnetic field and the magnetosphere. Thus this study can help us to understand how the IMF changes auroral activity. We find that hemispheric auroral power is higher for negative B_x than for positive B_x when the IMF is southward. This B_x asymmetry is significant in both summer and winter. For northward IMF conditions, hemispheric auroral power is low and the B_x asymmetry is not statistically present. In summary, hemispheric auroral power in the Northern Hemisphere reaches its highest level when all components of the IMF are negative. This result is important to forecasting auroral activity for space weather. When a space weather forecaster finds the X , Y , and Z components of the IMF are all negative from solar wind data, a highest level of auroral activity can be expected. Furthermore, these auroral patterns can serve as input to space weather models.

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References

- Brittnacher, M., R. Elsen, G. Parks, L. Chen, G. Germany, and J. Spann, A dayside auroral energy deposition case study using the Polar Ultraviolet Imager, *Geophys. Res. Lett.*, **24**, 991, 1997.
- Cowley, S. W. H., Asymmetry effects associated with the X -component of the IMF in a magnetically open magnetosphere, *Planet. Space Sci.*, **29**, 809, 1981.
- Cowley, S. W. H., and W. J. Hughes, Observation of an IMF sector effect in the Y -magnetic field component at geostationary orbit, *Planet. Space Sci.*, **31**, 73, 1983.
- Cowley, S. W. H., J. P. Morelli, and M. Lockwood, Dependence of convective flows and particle precipitation in the high-latitude dayside ionosphere on the X and Y components of the interplanetary magnetic field, *J. Geophys. Res.*, **96**, 5557, 1991.
- Elphinstone, R. D., K. Jankowska, J. S. Murphree, and L. L. Cogger, The configuration of the auroral distribution for interplanetary magnetic field B_z northward, 1, IMF B_x and B_y dependencies as observed by the Viking satellite, *J. Geophys. Res.*, **95**, 5791, 1990.
- Fairfield, D. H., Average configuration of the geomagnetic tail, *J. Geophys. Res.*, **84**, 1950, 1979.
- Fujii, R., and T. Iijima, Control of the ionospheric conductivities on large-scale Birkeland current intensities under geomagnetic quiet conditions, *J. Geophys. Res.*, **92**, 4505, 1987.
- Germany, G. A., M. R. Torr, D. G. Torr, and P. G. Richards, Use of FUV auroral emissions as diagnostic indicators, *J. Geophys. Res.*, **99**, 383, 1994.
- Germany, G. A., G. K. Parks, M. Brittnacher, J. Cumnock, D. Lummerzheim, J. F. Spann, L. Chen, P. G. Richards, and F. J. Rich, Remote determination of auroral energy characteristics during substorm activity, *Geophys. Res. Lett.*, **24**, 995, 1997.
- Holzworth, R. H., and C.-I. Meng, Auroral boundary variations and the interplanetary magnetic field, *Planet. Space Sci.*, **32**, 25, 1984.
- Iijima, T., and T. A. Potemra, Large-scale characteristics of field-aligned currents associated with substorms, *J. Geophys. Res.*, **83**, 599, 1978.
- Lassen, K., and C. Danielsen, Quiet time pattern of auroral arcs for different directions of the interplanetary magnetic field in the YZ plane, *J. Geophys. Res.*, **83**, 5277, 1978.
- Liou, K., P. T. Newell, C.-I. Meng, M. Brittnacher, and G. Parks, Synoptic auroral distribution: A survey using Polar ultraviolet imagery, *J. Geophys. Res.*, **102**, 27,197, 1997.
- Liou, K., P. T. Newell, C.-I. Meng, M. Brittnacher, and G. Parks, Characteristics of the solar wind controlled auroral emissions, *J. Geophys. Res.*, **103**, 17,543, 1998.
- Lui, A. T. Y., Characteristics of the cross-tail current in the Earth's magnetotail, in *Magnetospheric Currents*, *Geophys. Monogr. Ser.*, vol. 28, edited by T. A. Potemra, p. 158, AGU, Washington, D. C., 1984.
- Lummerzheim, D., M. Brittnacher, D. Evens, G. A. Germany, G. K. Parks, M. H. Rees, and J. F. Spann, High time resolution study of the hemispheric power carried by energetic electrons into the ionosphere during the May 19/20, 1996 auroral activity, *Geophys. Res. Lett.*, **24**, 987, 1997.
- Meng, C.-I., Polar cap variations and the interplanetary magnetic field, in *Dynamics of the Magnetosphere*, edited by S.-I. Akasofu, p. 23, Reidel, D., Norwell, Mass., 1979.
- Newell, P. T., C.-I. Meng, and D. G. Sibeck, Some low-altitude cusp dependencies on the interplanetary magnetic field, *J. Geophys. Res.*, **84**, 8921, 1989.
- Newell, P. T., C.-I. Meng, and K. M. Lyons, Suppression of discrete aurorae by sunlight, *Nature*, **381**, 766, 1996.
- Shue, J.-H., P. T. Newell, K. Liou, and C.-I. Meng, The quantitative relationship between auroral brightness and solar EUV Pedersen conductance, *J. Geophys. Res.*, **106**, 5883, 2001a.
- Shue, J.-H., P. T. Newell, K. Liou, and C.-I. Meng, Influence of interplanetary magnetic field on global auroral patterns, *J. Geophys. Res.*, **106**, 5913, 2001b.
- Stenbaek-Nielsen, H. C., and A. Otto, Conjugate auroras and the interplanetary magnetic field, *J. Geophys. Res.*, **102**, 2223, 1997.
- Strickland, D. J., R. E. Daniel Jr., J. R. Jasperse, and B. Basu, Transport-theoretic model for the electron-proton-hydrogen atom aurora, 2, Model results, *J. Geophys. Res.*, **98**, 21,533, 1993.
- Torr, M. R., et al., A far ultraviolet imager for the international solar-terrestrial physics mission, *Space Sci. Rev.*, **71**, 329, 1995.
- Wing, S., P. T. Newell, D. G. Sibeck, and K. B. Baker, A large statistical study of the entry of interplanetary magnetic field Y -component into the magnetosphere, *Geophys. Res. Lett.*, **22**, 2083, 1995.

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