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Solar cycle dependence of the seasonal variation of auroral hemispheric power

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Although much has been done on the hemispheric asymmetry (or seasonal variations) of auroral hemispheric power (HP), the dependence of HP hemispheric asymmetry on solar cycle has not yet been studied. We have analyzed data during 1979–2010 and investigated the dependence of HP hemispheric asymmetry/seasonal variation for the whole solar cycle. Here we show that (1) the hemispheric asymmetry of HP is positively correlated to the value of solar F10.7 with some time delay; (2) it is closely related to the coupling function between the solar wind and magnetosphere; and (3) the winter hemisphere receives more auroral power than the summer hemisphere for *K*p ~0 to 6. The statistic results can be partly understood in the framework of the ionospheric conductivity feedback model. The similarity and differences between our results and previous results are discussed in the paper.

auroral power, hemispheric asymmetry, coupling function, solar cycle, precipitation

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One of the major ways the solar wind transfers energy to the polar ionosphere is through precipitation of energetic particles from the magnetosphere to the ionosphere. The amount of auroral power in each hemisphere can be estimated by integrating the precipitating particle energy flux observed by in-situ satellites over the entire polar region. It has been known for a long time that there is a difference of auroral hemispheric power (HP) between the two hemispheres, called hemispheric asymmetry or seasonal variations of HP.

Several investigations have shown that the auroral power has seasonal and hemispheric dependences. For example, Barth et al. [1] used nitric oxide measurements from SNOE satellite (1998–2000) and reported a clear minimum in the electron energy flux (3 keV) at summer solstice in both hemispheres. Ridley [2] found seasonal dependence with the winter hemisphere receiving ~20% more power (~3.8 GW) than the summer hemisphere. Emery et al. [3] calculated the ratio of auroral power carried by electrons and ions. Electrons are found to contribute 30% auroral power during summer and 40% during the winter while the auroral power produced by ions is always higher during summer than winter. However, Luan et al. [4] used auroral images from TIMED/GUVI and found hemispheric asymmetry with summer hemisphere receiving more auroral power (10%–20%) when *K*p is ⩽3, while this asymmetry disappeared during moderate and active geomagnetic times.

Observations have also shown that auroral power is not distributed equally between day and night sides. Polar UVI observations in the northern hemisphere show that the auroral precipitation on the night side is stronger in the winter than in the summer [5].

These studies of auroral power between different hemispheres and/or seasons show that there is general agreement that HP hemispheric asymmetry and seasonal variations exist, but there is still disagreement as to which hemisphere or season receives more auroral power. Moreover, it is still not known whether this asymmetry and seasonal variations change from year to year and whether there is solar cycle

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dependence. We have used the NOAA estimated HP data set from 1979 to 2010 and here we report for the first time the HP hemispheric asymmetry and seasonal variations depending on solar cycle.

1 Data sets

The NOAA estimated HP data set can be obtained based on David Evans's formula and could be available at http://www.swpc.noaa.gov/ftpdir/lists/hpi/. The method of HP calculation is to combine the observed energy flux along the track of the satellite with a statistical model which is based on the database of NOAA/POES observations. The first step is to average the actual energy flux observations over one-degree intervals in dipole magnetic latitudes above 45° and 180° in longitude during a satellite pass over the polar region. A further summing of these averages yields a "zeroth order estimate of total hemispheric power". The second step is to match the zeorth order estimate to the statistical patterns repeatedly to get a final normalizing factor that multiplies the "zeroth order estimate" to obtain a final estimate of hemispheric power (personal communication with David Evans). The normalizing factor is an indication of how effectively a single pass samples the auroral oval. If the pass samples the major part of the auroral oval, a low value of normalizing factor can be expected. Otherwise, the normalizing factor tends to be large if the pass only cuts a small part of the auroral oval. In this paper, we only use data with normalizing factors less than 2.0 as recommended by Evans. The principal of NOAA HP calculation can be also explained by the formula HP=$\psi A(l)f(\text{MLT})$ where ψ is the measured energy flux observed along the trajectory of the spacecraft, A is the total area of the auroral oval when the geomagnetic activity level is "l" as determined from ψ, and f(MLT) is a factor to account for the variation of the energy flux as a function of the magnetic local time (MLT) (http://cedarweb.hao.ucar.edu/wiki/index.php/DMSP:ssj4_hp). It should be noted that there is another data sets available as NOAA/DMSP HP data [3], which was obtained by setting the ratio of south hemisphere HP to north hemisphere HP at 1.0 for the lifetime of each satellite. It implied that it discarded some inter-hemisphere differences of HP more or less. In addition, NOAA/DMSP HP has a different energy baseline and a narrower energy range compared to the original NOAA HP. We think it is more reasonable to use the NOAA HP in order to study the solar-cycle dependence of the hemisphere asymmetry of HP instead of NOAA/DMSP HP.

2 Statistic results

2.1 Seasonal variations in one hemisphere and north-south asymmetry for the local summer/winter

The term seasonal variation or hemispheric asymmetry of HP has been used in three different ways: (1) seasonal variations of HP in a given hemisphere, (2) differences of HP between northern and southern hemispheres for a same local season and (3) differences of HP between northern and southern hemisphere at the same time. Generally most publications have used the third one.

We have examined the seasonal differences of HP for both hemispheres and north-south differences for the local summer/winter and the results are summarized in Table 1. The column "North" indicates the difference of HP between summer and winter in the Northern Hemisphere: June solstice (summer in the Northern Hemisphere) minus December

Table 1 HP seasonal difference for each hemisphere and North-South difference in the same season (HP unit in GW)

Year	North (Jun–Dec)	South (Dec–Jun)	Summer	Winter
1979	−2.10	−3.42	−1.13	−2.45
1980	−4.88	−0.58	−2.36	1.94
1981	0.10	−5.14	2.09	−3.16
1982	1.15	−5.73	3.23	−3.65
1983	−3.54	1.73	−1.52	3.75
1984	−0.96	−1.75	−0.35	−1.14
1985	−2.59	2.12	−2.23	2.48
1986	1.36	−3.60	1.14	−3.82
1987	−0.97	1.71	−2.03	0.65
1991	6.35	−11.87	9.72	−8.51
1992	−3.24	−0.50	−0.46	2.28
1993	−6.69	1.90	−3.94	4.65
1994	−0.68	−3.19	2.32	−0.19
1995	−2.43	−0.55	−2.58	−0.70
1996	−1.44	0.36	0.05	1.85
1997	0.61	−0.72	1.96	0.63
1998	0.72	−1.35	1.84	−0.23
1999	−9.53	6.51	−6.20	9.84
2000	1.08	−5.02	3.92	−2.18
2001	−2.03	−2.77	−0.45	−1.19
2002	−5.99	0.48	−3.92	2.55
2003	0.41	−10.16	3.68	−6.89
2004	−9.42	5.71	−8.86	6.26
2005	2.29	−7.34	3.89	−5.74
2006	−4.63	2.32	−4.14	2.81
2007	−1.84	−1.18	−1.28	−0.62
2008	−1.17	−0.83	−1.31	−0.97
2009	0.99	−1.76	0.38	−2.37
2010	3.46	−5.14	2.95	−5.66
Average	−1.57	−1.72	−0.19	−0.34
Years(+)(+)	11	9	13	12
Years(−)	18	20	16	17

solstice (winter in the Northern Hemisphere). “South” indicates the differences of HP between summer and winter in the Southern Hemisphere: December (summer in the Southern Hemisphere) minus June (winter in Southern Hemisphere). The column “Summer” and “Winter” show the differences of HP between the two hemispheres at the same local season.

Table 1 shows that out of a total of 29 years, 18 have more HP in winter than in summer in the Northern Hemisphere, and 20 in the Southern Hemisphere. On average, the excess HP in winter for the Northern (Southern) Hemisphere was 1.57 GW (1.72 GW), indicating that HP favors winter most of the time for both hemispheres, which is consistent with previous observations. The difference of hemispheric asymmetry for the same local season is not significant, indicating that the difference between the hemispheres at a given time is mainly seasonal. Therefore, we will focus on studying the seasonal variations of HP based on the observations of both hemispheres at the same time period.

2.2 Dependence on the solar cycle indicated by F10.7

We define the daily value of HP as the mean value of a 3-d wide window from 1979 to 2010. As an example, we show variations of the daily HP values (top panels) in 1996 (solar minimum) and 2003 (after solar maximum, declining phase of SC23) in Figure 1. The dotted and solid lines correspond to the Southern and the Northern Hemisphere, respectively. The middle panels show the differences of daily HP values (north minus south) versus day of year and the bottom panels give the ratios of the daily HP values. Seasonal effect is especially prominent in 2003 showing that the winter hemisphere HP is higher than the summer hemisphere HP, while the auroral power is nearly the same around equinoxes.

To quantify the seasonal effect and show deviations between the two hemispheres, we define a parameter D to describe the asymmetry, D=mean (D_w)−mean (D_s), for each year. Here, D_w is the difference of HP value (north minus south) in the 90-d wide window centered at winter solstice (December) and D_s is for the 90-d wide window centered at summer solstice (June). D_w, D_s and D are calculated for 1979–2010, which covers SC22, SC23 and the declining phase of SC21. The middle panel of Figure 2 shows the variation of D (solid line) and the annual mean value of solar flux F10.7 (dashed line), respectively. The D value tends to decrease with an increase of solar activity (1985–2005) and the maximum (minimum) of D peaks ~1–2 years after solar maximum (minimum), suggesting the seasonal variation of HP lags the solar cycle by 1–2 years. The correlation coefficient between F10.5 and the yearly value of D reaches 0.67 with a time delay of 1 year.

The bottom panel of Figure 2 shows the variations of summer HP (red) and winter HP (blue) from 1979 to 2010, respectively. The black dash line is the yearly averaged

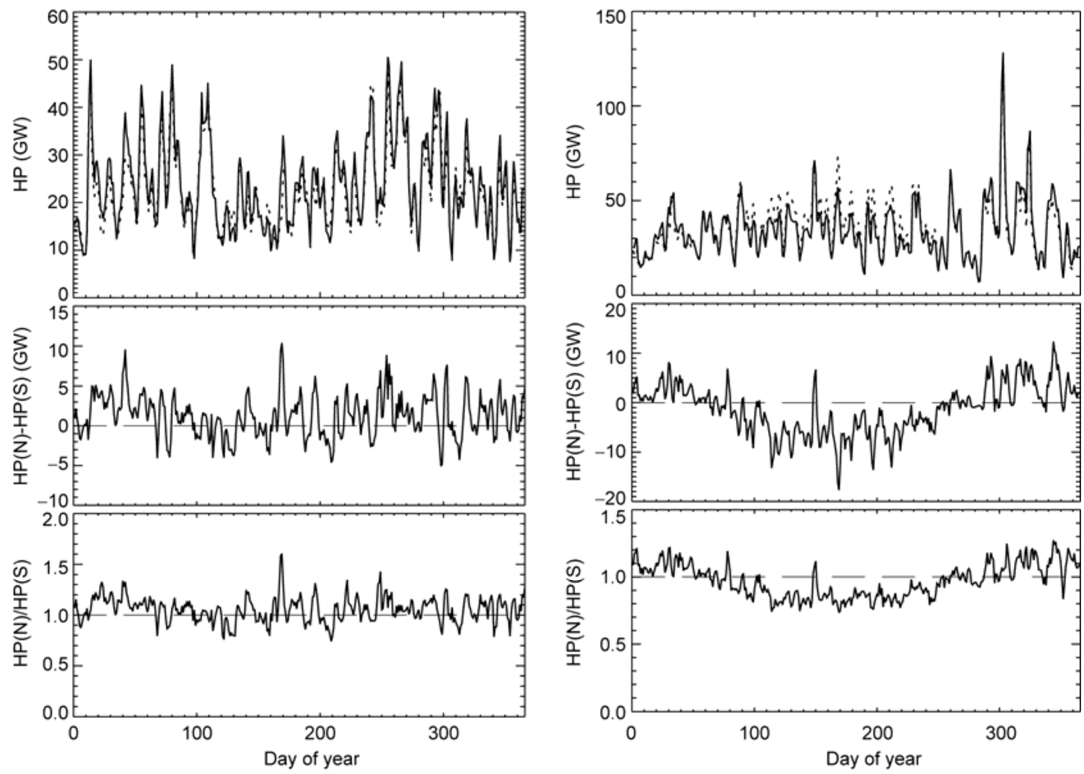

Figure 1 HP and its hemispheric asymmetry for the year 1996 (left) and 2003 (right). The top panels show daily HP variations in southern hemisphere (HP(S), dotted line) and northern hemisphere (HP(N), dashed line), respectively. The middle panels indicate the differences of daily HP between the Northern and the Southern Hemisphere (HP(N)-HP(S)). The bottom panels show the ratio of daily HP of the Northern and the Southern Hemisphere (HP(N)/HP(S)).

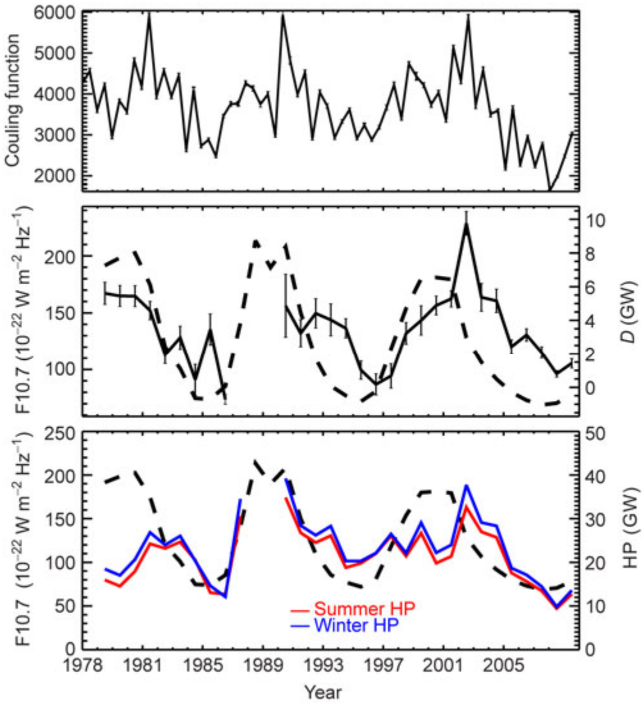

Figure 2 Solar-cycle dependence of hemispheric asymmetry/seasonal variation of HP. The top panel is the coupling function described by Newell [6]. The second panel shows the annual mean values of F10.7 (dash line) and *D* (solid line) defined in the text. The bottom panel shows the solar flux F10.7 (dash line) and HP values for summer (red) and winter (blue), respectively.

solar flux F10.7. The winter HP value for each year is the mean value of daily HP value around the December solstice in the Northern Hemisphere and June solstice in the Southern Hemisphere, while the summer HP is the mean value of daily HP around June solstice in the Northern Hemisphere and December solstice in the Southern Hemisphere. The solar wind-magnetosphere coupling function based on Newell et al. [6] is shown in the top panel of Figure 2. It is clear that the variation of the hemispheric HP follows the trend of the coupling function quite well. The correlation coefficient between Newell's coupling function and NOAA HP, with a 1.5 h time lag, is 0.73 (Southern Hemisphere) and 0.70 (Northern Hemisphere), respectively. Both summer and winter HP are better correlated with the coupling function rather than with F10.7, suggesting the dominant factor for the auroral power is the total energy input from the solar wind by particle precipitation.

2.3 Dependence on the geomagnetic activity level indicated by *K*p index

We next investigate the dependence of HP hemispheric asymmetry and seasonal variations for different *K*p bins. The *K*p 0 includes all data when *K*p equals 0 or 0+. *K*p 7 covers all data points when *K*p is ⩾7. Other samples are for *K*p equals N−, N and N+ (N from 1–6). In order to separate the geomagnetic effects from solar activity, we have categorized the data from 1978–2010 into three groups by different solar activity (F10.7<100, 100<F10.7<150, F10.7>150), and the results are shown in Figure 3. For each group of the plots, the upper two panels show the number of data samples. The middle panels show the difference of HP (north minus south) around Summer solstice (Jun) and Winter solstice (Dec). The bottom presents percentage difference of HP for summer and winter, respectively. The hemispheric difference dHP increases as *K*p increases for both hemispheres and dHP is larger in the winter by as much as ~20%. We can see that the trend of the curves are similar for all the solar activity level, except for the result of high solar activity and high magnetic activity level (*K*p=6). There appears to be a turning point for *K*p>6 when the auroral power appears to favor the summer hemisphere. However, we should note that the data sample for large *K*p are very small and the corresponding error bars are large, which will lead to an uncertainty of the results for high *K*p. Therefore, it is difficult to reach a definite conclusion about the cases of largest *K*p values.

We sorted NOAA estimated HP data set from 1979 to 2010 by day numbers and obtained HPw (winter HP) and HPs (summer HP). Winter HP is approximately 1.65 GW (8.34%, difference of HPw and HPs divided by HPs) higher than summer HP. This observation result is consistent with the results shown by Ridley et al. [2].

3 Discussion

Our statistical study has shown that there is a dependence of HP hemispheric asymmetry on solar cycle. This result can be partially interpreted in the framework of the ionospheric conductivity feedback model [7–10]. The feedback model considers a fixed convective electric field in the magnetosphere that can be mapped into the polar ionosphere. When the background ionospheric conductivity is large, a small enhancement of Pederson conductivity produced by precipitating electrons in the upward Birkland current region will result in an increase of local electric field. This increased electric field mapped to the magnetosphere will reduce the convection electric field leading to less particle precipitation and Pederson conductivity in the ionosphere will then also be suppressed.

On the other hand, when the background ionospheric conductivity is low, the small enhancement of local conductivity by the downward electrons will produce an additional local field-aligned current, which could cause current-driven instability and anomalous resistance that can enhance the parallel potential drop. The intensified parallel potential drop and waves can then scatter more particles into the loss cone and further intensify the aurora, hence amplify the perturbation.

The summer hemisphere has much higher conductivity

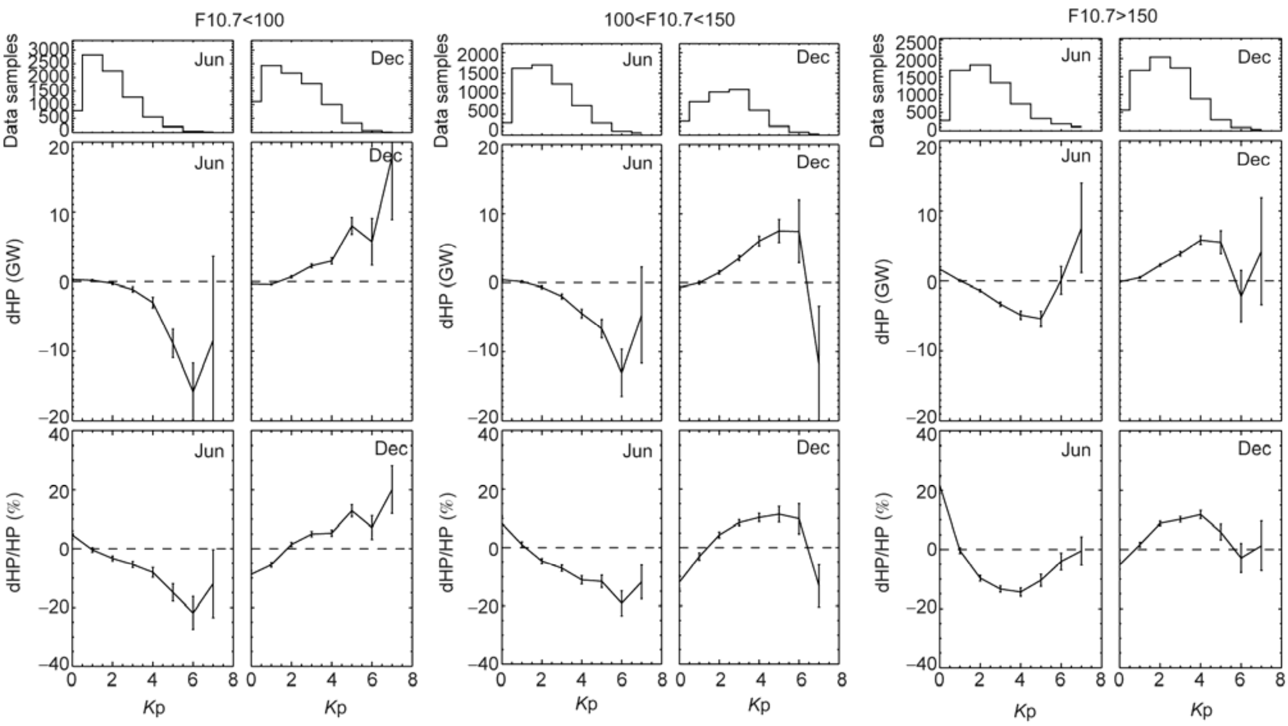

Figure 3 Hemisphere difference of HP (North minus South) under different *K*p levels from 1979–2007. The three groups of plots are refer to different solar activities (F10.7<100, 100<F10.7<150, F10.7>150). For each group of the plots, the upper two panels show the number of data samples for different *K*p. The middle panels show the difference of HP (north minus south) under different *K*p levels around summer solstice (Jun) and winter solstice (Dec). The bottom presents percentage difference of HP for summer and winter, respectively.

than the winter hemisphere because of more solar EUV radiation. The conductivity feedback mechanism may rest in summer hemisphere but work in the winter hemisphere. Thus the conductivity feedback model is consistent with the summer-winter difference of HP. During solar maximum, solar radiation received in the Northern and the Southern Hemisphere increases with solar activity as indicated by F10.7, leading not only to higher ionosphere conductivity, but also to amplification of hemispheric asymmetry of ionospheric background conductivity due to the feedback effect. Since the ionospheric background conductivity is negatively related to the auroral power, it is reasonable to conclude that the difference of auroral power received by northern and southern hemispheres can be increased as well.

Our results are consistent with the results of Ridley [2], Emery et al. [3] and Barth et al. [1], however show some difference with the conclusions in Luan et al. [4] that HP favors summer hemisphere and *K*p dependency of HP hemispheric asymmetry. The inconsistency could come from three possibilities:

The first is that the detectors on NOAA and TIMED are measuring different energies. The NOAA estimated HP is derived from SEM-1 and SEM-2. SEM-1 measures electrons and ions 300 eV–20 keV and SEM-2, 50 eV–20 keV [3]. TIMED/GUVI LBHl and LBHs images used by Luan et al. [4] are sensitive to auroral particles with energies larger than ~500 eV as well as those energetic particles that SEM-1 and SEM-2 miss (>20 keV). In addition, the NOAA estimated HP includes contribution from both precipitating ions and electrons while GUVI measures aurora created primarily by electrons. Although both ions and electrons can produce secondary electrons, GUVI could miss a fraction of energy of precipitating ions. Hardy et al. [11] have estimated that ion energy can account for ~10%–15% of HP. The fraction of ion energy can be 19% during quiet times and 5% during active times [3]. Hubert et al. [12] showed ions can contribute ~10%–19% of HP during substorms and up to 30% during quiet times.

Second, the error and uncertainties associated with HP could contribute to the discrepancy. The NOAA estimated HP is obtained by matching the observed energy flux to a statistical pattern of global auroral precipitation that neglects seasonal variations and hemispheric asymmetry of HP. The estimated error of NOAA HP value can be 50% and even larger during geomagnetic disturbed times [3]. TIMED/GUVI estimation of HP is a conversion of UVI counts to energy flux, which is essentially based on Strickland's model [13,14]. Germany et al. [15] gave an uncertainty of ~45% about UVI counts conversion to auroral power. In addition, the lowest magnetic latitudes of the NOAA estimated HP and GUVI estimated HP are 45° and 50°, respectively, hence the two models covered slightly different regions.

Third, Liou et al. [5] and Luan et al. [4] showed that the dayside auroral power is enhanced while the night side auroral power is suppressed in summer, indicating that the relative contribution of dayside and night side auroral power to the total hemispheric power could contribute to the seasonal variation/hemispheric asymmetry of HP. For instance, the error of the dayside airglow correction model in GUVI estimated HP and correction of sunlit contamination in NOAA HP could enhance or lower the fraction of dayside auroral power in HP. In addition, the NOAA satellites preferentially crossed the auroral oval on the dayside of Northern hemisphere but had only sufficiently good nighttime coverage in the Southern Hemisphere [3].

4 Summary

Based on the NOAA estimated HP data set from 1979 to 2010, we investigated the dependence of HP hemispheric asymmetry/seasonal variation for the whole solar cycle. It is found that HP hemispheric asymmetry/seasonal variation does not only show annual variations but also changes from year to year over the solar cycle. But our analysis shows there is a few years delay (the significance of this delay is not understood at this time). For a given hemisphere, HP favors the local winter most of the time, while for the same local summer/winter, there is no significant hemispheric asymmetry. The auroral power favors winter hemisphere during moderate or active times. The hemispheric difference of HP increases with increase of *K*p when *K*p is <5. For large *K*p, it is difficult to reach a conclusion due to large statistical errors.

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