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# Multi-Periodic Auroral and Thermospheric Variations in 2006

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**ABSTRACT**

A data survey reveals multiple periodic variations in auroral hemispheric power (HP) and thermospheric composition ($O/N_2$) in 2006. The periods include 27, 13 - 14, 9, and 6.7 days. These periods of 13 - 14, 9 and 6.7 days are essentially the harmonics of the 27-day solar rotation. Similar multi-periodicities were found in the dayside magnetic merging rate (MMR) (Newell et al. 2007) which depends upon solar wind speed (V), magnitude ($B_T$) and clock angle ($\theta_c$) of interplanetary magnetic field (IMF). A high correlation coefficient (0.93) between MMR and HP indicates MMR is the driver of the periodic variations. While high solar wind speed associated with coronal holes plays an important role in the HP variations, IMF $B_T$ is equally important. The term [$B_T^{2/3}\sin^{8/3}(\theta_c/2)$] is even more important as its correlation coefficient with HP is higher than that for $B_T$ or solar wind speed. Nevertheless, MMR has the highest correlation with HP. Similar results were seen in the 2005 data where the 9-day variation is dominant. These results indicate that both solar wind speed and IMF conditions are required for accurate specification of periodic variations in aurora hemispheric power and thermosphere composition.

Key word: High speed solar wind, Aurora, Thermosphere, Periodic variation

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## 1. INTRODUCTION

Periodic re-occurrence of auroral and geomagnetic activities/storms during the declining phase of a solar cycle is well known (Tsurutani et al. 2006 and references therein). The strong 9-day variations in 2005 have attracted much attention recently and have been seen in thermospheric neutral density, composition ($O/N_2$ column density ratio) and auroral hemispheric power (Crowley et al. 2008; Lei et al. 2008; Thayer et al. 2008; Zhang et al. 2010). These 9-day variations are found due to the 9-day recurrence of fast streams in the solar wind arising from solar coronal holes which is distributed roughly 120° apart in longitude on the Sun (Temmer et al. 2007; Vršnak et al. 2007). The high speed streams increase the magnetic field merging rate on the dayside magnetopause (Newell et al. 2007) and enhance the energy input into the magnetosphere. This results in enhanced auroral particle precipitation, heating in the polar ionosphere and thermosphere. The consequence of the process is global neutral density increase and thermospheric $O/N_2$ decrease when the heated and disturbed polar thermosphere expands and transports to mid and low latitudes. Are there any 9-day or other periodic variations in other years? Understanding the auroral and thermospheric responses to the periodic variation in solar wind will improve our space weather forecast. In this paper, we extend the study (Zhang et al. 2010) for 2005 to 2006 and answer the above questions.

## 2. DATA

To address the questions regarding aurora and thermosphere response to the periodic variations in solar wind, various data sets are acquired. The solar wind speed, density and interplanetary magnetic field (IMF) data from Advanced Composition Explorer (ACE) satellite were used to calculate their periodic variations. Furthermore, Newell et al. (2007) developed a nearly universal solar wind-magnetosphere coupling function [$d\Phi_{MP}/dt = V^{4/3}B_T^{2/3}\sin^{8/3}(\theta_c/2)$, where V is the solar wind speed, $B_T$ is the magnitude of IMF, and $\theta_c$ is the IMF clock angle]. The function provides an estimate of the dayside magnetic reconnection or merging rate ($R_M = d\Phi_{MP}/dt$) which is better than the old ones [e.g., the ε parameter of

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Perreault and Akasofu (1978), $\varepsilon = vB_T^2\sin^4(\theta_c/2)$, the Kan-Lee electric field, $E_{KL} = vB_T^2\sin^2(\theta_c/2)$ (Kan and Lee 1979)] and provides the best correlation between the reconnection rate and nine out of ten indices of magnetospheric activity. Periodic variations in the magnetic merging rate are also examined as they provide a connection between the solar wind and the aurora activities.

The levels of auroral activities can be represented by auroral hemispheric power (HP), the total energy flux of precipitating electrons over one hemisphere. In this study, HP data from NOAA space weather center are used. Furthermore, thermospheric $O/N_2$ column density ratios based on GUVI data (Zhang et al. 2004) are examined for their response to the auroral variations.

## 3. MULTIPLE PERIODIC VARIATIONS IN 2006

Figure 1a shows the NOAA daily mean hemispheric power in 2006. Periodic variations are visible in the HP data. Lomb-Scargle Periodogram (Lomb 1976; Scargle 1982) of the HP data (Fig. 1b) clearly shows the spectral peaks at periods of 6.7, 9, 13 - 14, and 27 days. The spectra also show small peaks with periods around 4 - 5 days. The 6.7-day variation is the dominant one. These variations are significantly different from that of HP in 2005 (Zhang et al. 2010) where the 9-day variation is the only significant one. As enhanced auroral heating (and Joule heating too) causes depletion of thermospheric $O/N_2$ at sub-auroral latitudes, it is expected that $O/N_2$ will have similar periodic variations. Indeed, periodic variations are seen in the GUVI $O/N_2$ [daily mean at mid and high latitude (> 30°)] in 2006 (Fig. 2a). The Lomb-Scargle Periodogram (Fig. 2b) of the GUVI $O/N_2$ shows strong spectral peaks at periods of 6.7 days, followed by 27, 9, 13 - 14 days. Such a periodogram is nearly identical to that of HP, confirming the $O/N_2$ response to the HP changes. Note the 13 - 14, 9, and 6.7 days are essentially

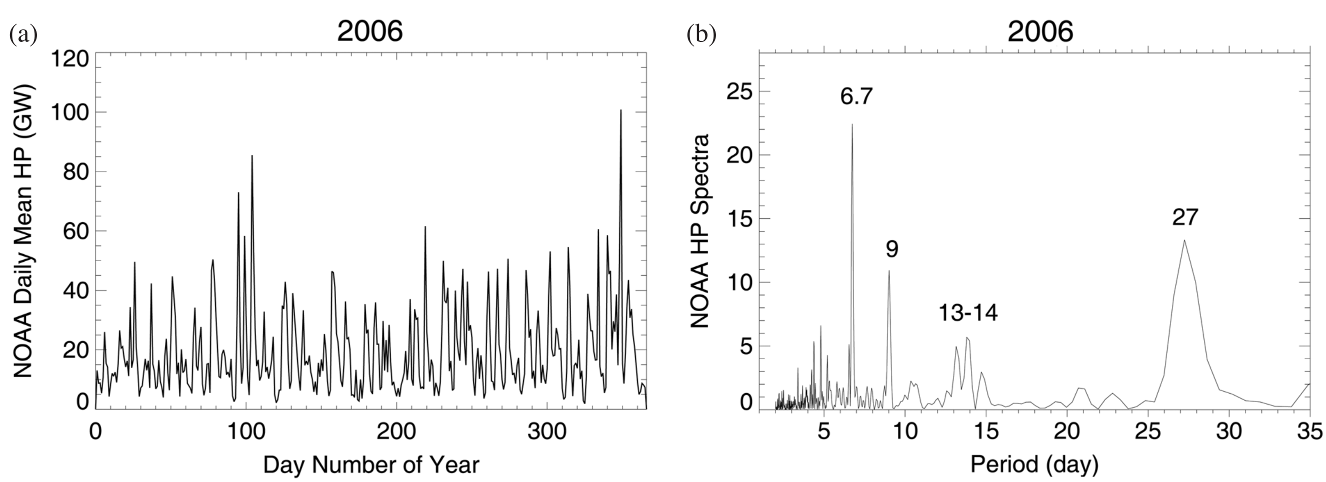


Fig. 1. NOAA hemispheric power daily mean (a) and their spectra (b) in 2006. In additional to a spectral peak at a period of 27 days, there are multi peaks at periods of 6.7, 9, 13 - 14, and 4 - 5 days in the order of their peak spectra.

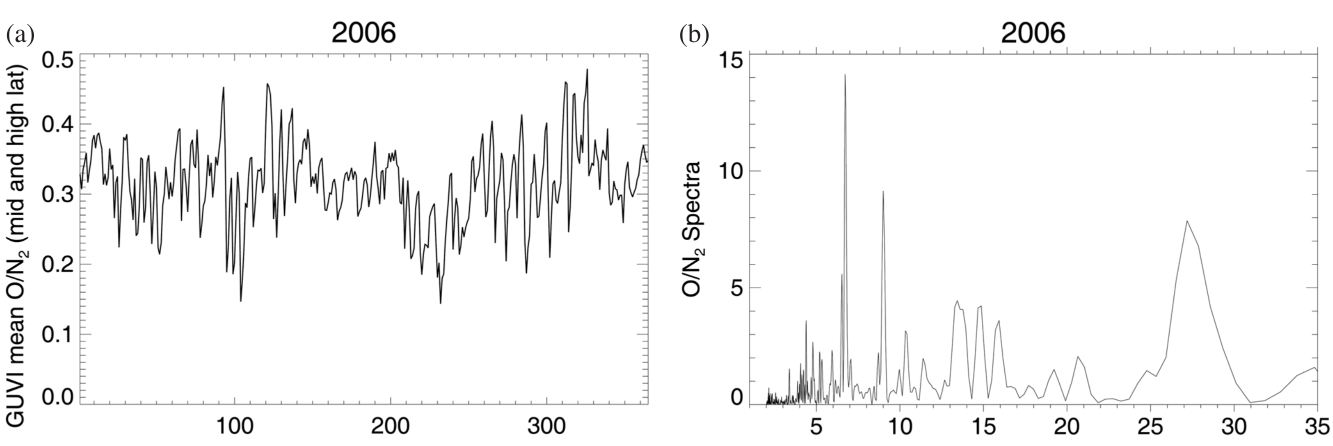


Fig. 2. GUVI daily mean of $O/N_2$ at mid and high latitudes (> 30°) (a) and their spectra (b) in 2006. The $O/N_2$ spectra are similar to that of HP.

the harmonics of the 27 day solar rotation, suggesting the periodic variations are related to the solar rotation.

As solar wind and IMF are the main drivers for auroral activities and the dayside magnetic merging rate (MMR) (Newell et al. 2007) is closely related to HP in 2005 (Zhang et al. 2010), the daily mean MMR in 2006 and its periodogram are calculated and shown in Fig. 3. Again, there are four major peaks in the MMR spectra: 6.7, 9, 13 - 14, and 27 days. These spectral features in MMR are similar to that in HP and $O/N_2$. The correlation coefficient between MMR and HP coefficient is 0.93. All these data suggest that the multiple periodic variations observed in HP and $O/N_2$ are driven by the magnetic merging rate. Note that the periodogram of solar EUV flux (Qeuv) from SOHO (Judge et al. 2000) in 2006 peaks at 22.5, 27.5, and 31.5 days. This rules out the possible contribution of solar EUV flux to the HP and $O/N_2$ variations with periods of 13 - 14, 9, and 6.7 days.

## 4. DISCUSSION

The dayside magnetic merging rate explains the multiple periodic variations in HP and $O/N_2$ well in 2006 (this study) and the strong 9-day variations in 2005 (Zhang et al. 2010). There is still a question to be answered: what are the relative contributions of solar wind speed and IMF to the MMR or HP variations? To answer this question, HP, scaled MMR, and scaled terms in the MMR [$V^{4/3}$, and $B_T^{2/3}\sin^{8/3}(\theta/2)$] between DOY 280 and 300 in 2006 are plotted in Fig. 4. It is clear that HP and MMR have almost

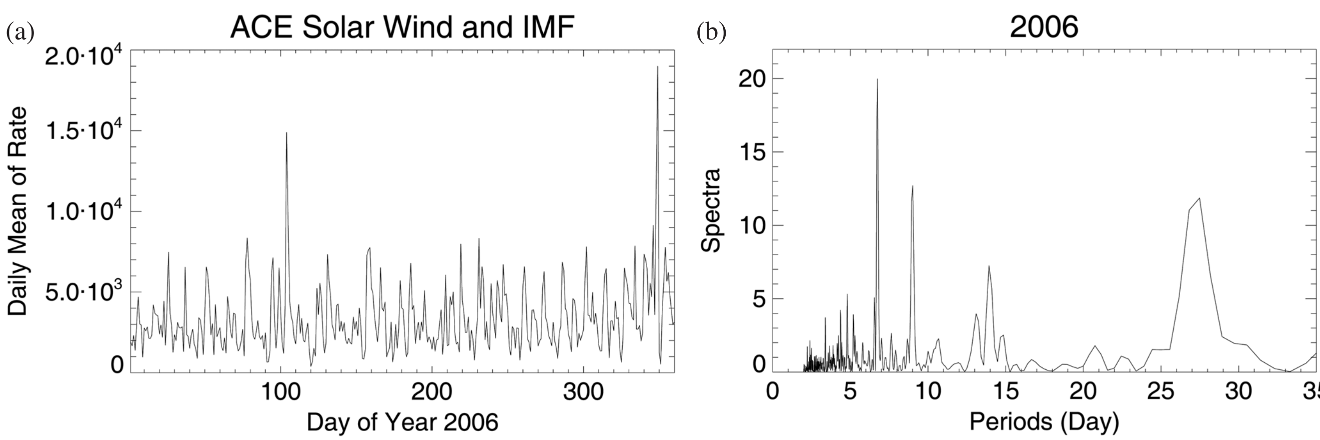


Fig. 3. Daily mean (a) of dayside magnetopause merging rate and their spectra (b). The merging rate is calculated using the Newell et al. (2007) formula and solar wind/IMF data from ACE.

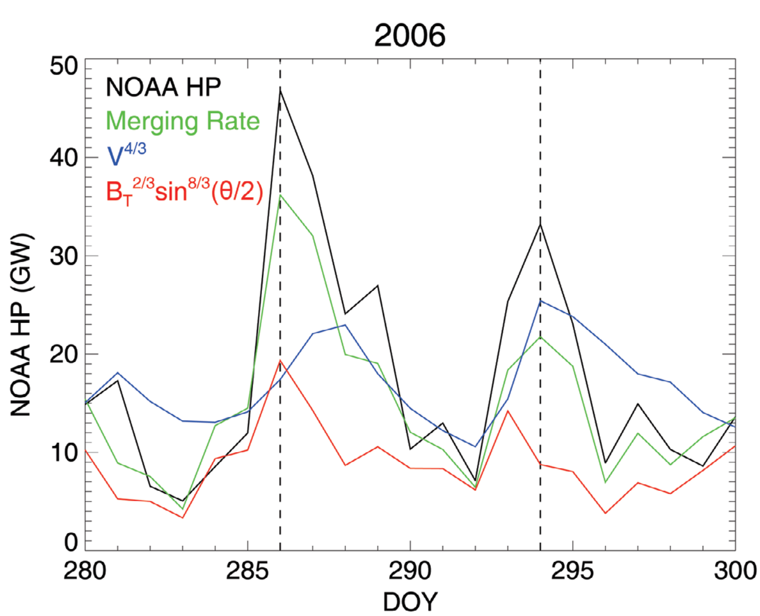


Fig. 4. NOAA HP (black), scaled merging rate (green), scaled $V^{4/3}$ (blue), and scaled $B_T^{2/3}\sin^{8/3}(\theta/2)$ (red) between DOY 280 and 300 in 2006.

identical shapes. They peaked at same DOYs (286 and 294, see the vertical dashed lines). On the other hand, the peak in $V^{4/3}$ on DOY 294 is at the same DOY of the HP or MMR peak. However, the peak in $V^{4/3}$ on DOY 287 occurred two days after the HP or MMR peak on DOY 286. The peak in $V^{4/3}$ (enhanced solar wind speed) on DOY 294 was closely related a coronal hole. The x component of solar wind speed on DOY 294 was -600 km $s^{-1}$. Assuming that the x component is roughly constant between the Sun and Earth. The high solar wind speed observed near the Earth was related to the Sun's condition about 2.9 days earlier or DOY 291.1 (beginning of October 18, 2006). Figure 5 shows solar Fe XII (195Å) images over three days: mid of October 15, late October 17, and late October 19, 2006. An elongated coronal hole was seen in the images and co-rotated with the Sun. The coronal hole was near the Sun's equator facing the Earth on late October 17 (Fig. 5b). This suggested the high solar wind speed seen on DOY 294 (October 21) was due to the coronal hole, consistent with earlier studies (Temmer et al. 2007).

In contrast, the term $B_T^{2/3}\sin^{8/3}(\theta/2)$ has its peaks on DOY 285 (same as HP or MMR peak) and DOY 293 (one day earlier than HP or MMR peak). This indicates that neither $V^{4/3}$ nor $B_T^{2/3}\sin^{8/3}(\theta/2)$ can fully explain the variations

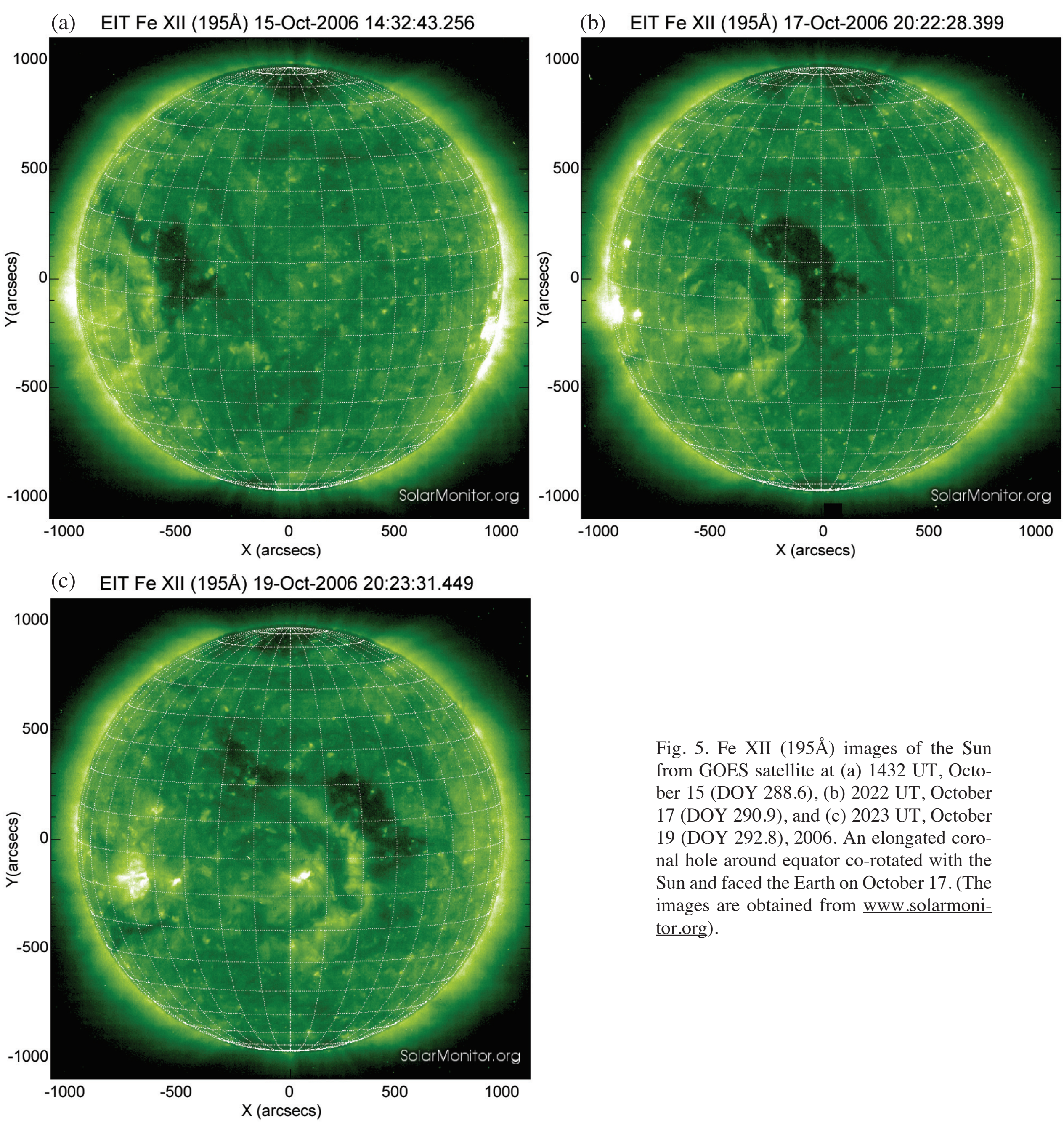


Fig. 5. Fe XII (195Å) images of the Sun from GOES satellite at (a) 1432 UT, October 15 (DOY 288.6), (b) 2022 UT, October 17 (DOY 290.9), and (c) 2023 UT, October 19 (DOY 292.8), 2006. An elongated coronal hole around equator co-rotated with the Sun and faced the Earth on October 17. (The images are obtained from www.solarmonitor.org).

in MMR or HP. To confirm such an idea, the correlation coefficients between HP and MMR, $V^{4/3}$, $B_T^{2/3}$, $\sin^{8/3}(\theta/2)$, $B_T^{2/3}\sin^{8/3}(\theta/2)$, $B_x$, $B_y$, or $B_z$ have been calculated for 2005 and 2006 and are listed in Table 1. As expected, HP and MMR are highly correlated with correlation coefficients of 0.92 and 0.93 for 2005 and 2006, respectively. Note the correlation coefficients in 2005 and 2006 are of the same order. The comparison is focused on the numbers for 2006 hereafter. The HP and $V^{4/3}$ correlation coefficient is just 0.56 which is similar to that (0.59) between HP and $B_T^{2/3}$, 0.51 between HP and $\sin^{8/3}(\theta/2)$, and -0.56 between HP and $B_z$. However, the correlation coefficient (0.82) between HP and $B_T^{2/3}\sin^{8/3}(\theta/2)$ is noticeably higher than 0.56, 0.59, 0.51, or -0.56. Finally, the correlation coefficients between HP and $B_x$ or $B_y$ are nearly 0. These correlation coefficients indicate that IMF magnitude and clock angle together plays an important role in determining HP or MMR. Solar wind speed played a relatively less important role. Nevertheless, these results also suggest that variation in solar wind speed alone does not necessary tell the whole story in periodic variations in auroral hemispheric power and thermosphere composition despite of similar periodograms in HP and solar wind speed. IMF conditions have to be considered for accurate specification of periodic variations in HP and thermosphere.

The different behaviors (dominant 9-day variation in 2005 and 6.7-day in 2006) are mainly due to different numbers of major coronal holes on the Sun. Earlier studies and the example in this study indicate that the three major coronal holes were evenly distributed in longitude on the Sun in 2005. The number of major coronal holes increased to 4 in 2006 during the transition from the 23rd solar maximum to the 23rd minimum. These coronal holes cause high solar wind speed which enhances energy input from the solar wind to the magnetosphere as well as the auroral activities (HP). The 27-day solar rotation modulate the variation in solar wind speed to the Earth and results in the dominant 9 (3rd harmonic of the 27 days) and 6.7 (4th harmonic of the 27 days) day variations in the magnetic merging rate, auroral hemispheric power and thermospheric $O/N_2$ ratio.

Table 1. Correlation coefficients between HP and solar wind/IMF parameters.

| | 2005 | 2006 |
|---|---|---|
| **Merging Rate** | 0.92 | 0.93 |
| **Solar wind speed$^{4/3}$** | 0.58 | 0.56 |
| **$B_T^{2/3} = [B_y^2 + B_z^2]^{1/3}$** | 0.65 | 0.59 |
| **$[\sin(\theta/2)]^{8/3}$** | 0.40 | 0.51 |
| **$B_T^* [\sin(\theta/2)]^{8/3}$** | 0.75 | 0.82 |
| **IMF $B_x$** | 0.06 | -0.01 |
| **IMF $B_y$** | -0.02 | 0.05 |
| **IMF $B_z$** | -0.40 | -0.56 |

## 5. SUMMARY

Observations in 2006 show clear multiple periodic (27, 13 - 14, 9, 6.7 days) variations in auroral hemispheric power and thermospheric column density $O/N_2$ ratio. The 13 - 14, 9 and 6.7 day variations are the harmonics of the 27 day solar rotation. The most intense variation occurred with a period of 6.7 days. These periodic variations are well correlated with the dayside magnetic merging rate which depends on both solar wind speed and IMF condition. There is evidence that the high solar wind in 2006 is associated with coronal hole. However, the solar wind speed alone is not sufficient to explain all features in observed auroral hemispheric power. IMF condition (magnitude and orientation) actually plays more important role than solar wind speed. Nevertheless, both IMF and solar wind speed data are needed to explain the periodic variations. The same conclusion applies to the data in 2005 with a dominant 9-day variation.

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