**Different response of dayside auroras to increases in solar wind dynamic pressure**

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Variations in the solar wind dynamic pressure can create changes in the auroral brightness, especially in the dayside region. In this study, mainly using Polar Ultraviolet Imager auroral images and NASA OMNI magnetic field and plasma data, we investigate the relationship between interplanetary parameters and dayside aurora intensification. We first identify the dayside aurora cases caused by the solar wind dynamic pressure increases from 1997 through 1999 and divide these cases into two types: one with intensification and the other without significant intensification following the increase in the solar wind dynamic pressure. Then, case by case, we examine the separate roles of the solar wind density and velocity on auroral brightness. Our result demonstrates that the dayside aurora intensification requires the contributions of both the density and solar wind velocity increases. The solar wind density increase alone (without velocity increase) could not create the dayside aurora intensification.


1. Introduction

The aurora is an interesting phenomenon resulting from the solar wind-magnetosphere-ionosphere coupling. Auroral features seen at the low-altitude ionosphere can be used to infer auroral processes taking place in high-altitude magnetospheric regions. As the magnetosphere responds to changes in the solar wind, the configuration of the magnetosphere changes, the energetic electrons in the radiation belt could be accelerated and decelerated [Zong et al., 2009], the ionospheric total electron content (TEC) enhances [Zong et al., 2010], and the ultralow-frequency (ULF) waves at geosynchronous orbit are excited [Zhang et al., 2010]. This may therefore change the configuration of aurora seen in the ionosphere. As is known, the interplanetary magnetic field (IMF) variations are the important source of geomagnetic disturbances detected on the Earth [Vorobjev and Yagodkina, 2009]. However, recent studies indicate that the solar wind dynamic pressure, in addition to IMF, also substantially affects the intramagnetospheric processes [Lyons, 2000; Lee et al., 2004; Boudouridis et al., 2005; Vorobjev and Yagodkina, 2009]. Liou et al. [1998] took advantage of the large database returned by Polar Ultraviolet Imager (UVI) to study the characteristics of dayside and nightside auroras under various solar wind plasma and IMF conditions.

Changes in the solar wind dynamic pressure can create variations in the auroral brightness. It has been found that solar wind dynamic pressure increase leads to intensification of the whole auroral oval. The intensification first occurs in the dayside and then propagates to the nightside [Boudouridis et al., 2003; Meurant et al., 2003; Zhou and Tsurutani, 1999]. Brittnacher et al. [2000] and Liu et al. [2002] studied the motion of the dayside auroral oval and its boundaries using cases of dayside auroras caused by the solar wind dynamic pressure increases.

The increase in the solar wind dynamic pressure causes different changes in the auroras under different IMF conditions, in particular the IMF \( B_z \). Boudouridis et al. [2003] have examined the effect of large solar wind dynamic pressure increases on the location, size, and intensity of the auroral oval under different IMF orientations. The auroral zone width increases and the auroral oval is intensified when the solar wind dynamic pressure increases under steady southward IMF conditions. A smaller response is seen when the IMF \( B_z \) has a simultaneous northward turning and when it is nearly zero before the pressure enhancement [Boudouridis et al., 2003]. Vorobjev et al. [2009] used the optical observations on Heiss Island to study the characteristics of auroras in the near-noon MLT sector after abrupt increases in the solar wind dynamic pressure at negative and positive polar of the IMF \( B_z \) component, and they found out that the auroral emission intensities in different bands and their boundaries at the different polarity conditions of the IMF \( B_z \) respond differently to the increases in the solar wind dynamic pressure.
[5] On the other hand, an increase in the solar wind dynamic pressure could strengthen the changes of the auroral oval. For intense substorm disturbances that occurred in association with magnetic storms, if the magnetosphere was impacted by a substantial solar wind dynamic pressure increase at the onset of these disturbances, the auroral brightening extends over about twice as broad an MLT range as did the auroral brightening of disturbances that did not have evidence of a solar wind dynamic pressure increase at onset [Lyons et al., 2005, 2008]. A sudden increase in the solar wind dynamic pressure, associated with an interplanetary shock, produces a short duration (~10 min) of the enhanced dayside auroral brightness [Craven et al., 1986; Spann et al., 1998; Zhou and Tsurutani, 1999; Tsurutani et al., 2001].

[6] The above results paid more attention to the changes in the auroral oval locations, their sizes and intensities caused by the solar wind dynamic pressure increases under various interplanetary conditions. In fact, it is not always true that the dayside aurora will obviously change when there is an increase in the solar wind dynamic pressure. To date, less attention is paid to under what kinds of conditions the dayside auroras will occur and be intensified by the increase in the solar wind dynamic pressure. Under the conditions of the average northward (southward) IMF $B_z$ of 2.4 (~2.6) nT for the summer and the average northward (southward) of 2.3 (~2.7) nT for the winter, Shue et al. [2002] statistically examine the role of the solar wind density and velocity separately on auroral brightness. However, their work averaged the high-resolution images to hourly ones, which may wash out some small-scale phenomena and may not show good relationships on the dayside. In this paper, we will use the high-resolution images and data to look for cases of the dayside auroras intensified by the solar wind dynamic pressure increases and look closely at the separate roles of the solar wind density and velocity on auroral brightness, especially for the dayside aurora intensification.

2. Data

[7] The UVI is one of three imagers aboard the Global Geospace Polar spacecraft [Torr et al., 1995]. By imaging in the far ultraviolet, UVI is capable of viewing both nightside and sunlit auroral features. It provides unprecedented opportunities to study global auroral phenomena under various solar wind conditions. In this study, we use the Lyman-Birge-Hopfield long (LBHL) band (~170.0 nm) because auroral intensity in this band is approximately proportional to the total energy flux [Strickland et al., 1993; Germany et al., 1994]. The spatial resolution of the Polar UVI images is ~20–40 km, while the altitudes of Polar were greater than 4 $R_E$ geocentric distance. Because the available data simultaneously observed for IMF, the solar wind parameters, and the auroral ovals, especially in the dayside sector, taken by Polar UVI are very limited and because UVI images of Polar from 2000 to 2005 are not good enough for this study, we choose to use the UVI images from 1997 through 1999 after checking the data from 1997 to 2005. A series of calibrations have been performed to subtract background emissions, correct flat field and nadir-looking platform effects, and subtract dayglow emissions from the images [Brittacher et al., 1997; Liou et al., 1998].

The interplanetary parameters used for this study are the three components of IMF, the solar wind density and velocity, and the solar wind dynamic pressure in 1 min resolution time provided by NASA OMNIWeb. The “High Resolution OMNI” (HRO) data set involves an interspersal of the Earth’s bow shock nose (BSN)–shifted ACE, Wind, IMP 8, and Geotail data (from http://omniweb.gsfc.nasa.gov). In order to determine the time of the variations of the solar wind more accurately, we also check the variations of magnetic field H component SYM-$H$. SYM-$H$ component variations correlate well with the solar wind dynamic pressure attached to the subsolar magnetopause. If the time determined by the OMNI data differs greatly from that by the SYM-$H$, we then use the original data of Wind.

[8] We select the ideal auroral images which have the whole auroral ovals when the solar wind dynamic pressure increases at least by 3 nPa within 10 min. The result of the selected images can be divided into two types: one is the dayside auroras intensified by the increase in the solar wind dynamic pressure; the other is the dayside auroras with no significant intensification after the increase in the solar wind dynamic pressure. When the ratio of the auroral intensity before and after the solar wind dynamic pressure increase is less than 2 or the brightening part is a region of less than 1 MLT within 10 min after the dynamic pressure increase, we find it hard to distinguish the auroral intensification very well, and thus we take it as a type of nonsignificant intensification following the increase in solar wind dynamic pressure. Here, the dayside auroras are defined as extending from 6 MLT through noon to 18 MLT, generally at dawn (6–9 MLT) and at dusk (15–18 MLT).

3. Observations

3.1. Dayside Auroral Intensification by the Solar Wind Dynamic Pressure Increases

[9] Let us look at the case on 5 July 1998 as the dayside aurora is intensified significantly by the increase in the solar wind dynamic pressure. Figure 1 shows the interplanetary condition for the period of 03:00–05:00 UT on 5 July 1998 for the magnitude and three components ($B_x$, $B_y$, $B_z$) of IMF in GSM coordinates. We use the component of the solar wind velocity along the direction of the Sun-Earth line because the solar wind velocity is almost along the direction of the Sun-Earth line. Figure 1 also shows the solar wind density ($D_p$), the dynamic pressure ($P_{dy}$), and the variations of SYM-$H$, which is consistent with the solar wind variation from OMNI. As seen in Figure 1, the solar wind dynamic pressure abruptly increases from 2 to 5 nPa with onset at 03:59 UT on that day. We can see from Figure 1 that the increase in the solar wind dynamic pressure comes from the contributions of both the solar wind velocity and density, and the IMF has no significant changes.

[10] Global auroral images from Polar UVI for this dynamic pressure increase are shown in Figure 2. We select one auroral image every 6 min because of the limits of the LBHL image data. Figure 2 (top) shows the auroral oval before the increase in the solar wind dynamic pressure. Just before the dynamic pressure increase, the dawn and midnight parts of the auroral oval at 03:58:30 UT have generally been restored from the previous intensification. After about 5 min, when the solar wind dynamic pressure increased
the whole auroral oval is intensified, especially the dayside aurora, by a factor of 2–4. The color bar shows the auroral intensity in photons cm\(^{-2}\) s\(^{-1}\). Although the time interval between every two auroral images after the dynamic pressure increase is a little long, by comparing the auroral images before and after the dynamic pressure increase, we can deduce that the dynamic pressure increase first intensifies the dayside aurora, and then the intensification propagates to the nightside as proposed by previous studies [Boudouridis et al., 2003; Meurant et al., 2003; Zhou and Tsurutani, 1999].

We examine all similar events as in Figures 1 and 2 from 1997 through 1999. Table 1 gives the interplanetary conditions of the events that have dayside auroral intensifications after the solar wind dynamic pressure increases. In Table 1, we provide the dates of the events as well as the times and the values of the solar wind dynamic pressure, in which \(t_0\) (UT) and \(t_1\) (UT) give the onset and the end time in UT for the dynamic pressure increase, respectively, and \(P_0\) and \(P_1\) give the values of the dynamic pressure at the corresponding times. In order to observe the IMF changes, we present the components of the IMF at 10 min before the dynamic pressure began to increase and 10 min after the dynamic pressure ended the increase as well as at \(t_0\) and \(t_1\), respectively. For the solar wind density and velocity, we only present their values at \(t_0\) and \(t_1\). In order to estimate whether the magnetosphere is compressed, we observe the variation of the magnetic field magnitude, which is listed in Table 1.

### 3.2. No Dayside Auroral Intensification by the Solar Wind Dynamic Pressure Increases

We then check the cases in which the dayside aurora has no obvious intensification following the increase in the solar wind dynamic pressure. Figure 3 shows the interplanetary condition for a period of 08:00–10:00 UT on 5 March 1998, illustrating a case of the dayside auroras with no significant intensification after the solar wind dynamic pressure increase. The format is the same as that for Figure 1. Here the variation of SYM-H comes a few minutes later after the solar wind dynamic pressure increase, and this is understandable because the magnetosphere variation usually does not immediately occur following the solar wind dynamic pressure increase. In this event, the solar wind dynamic pressure increases from 4 to 8 nPa during the period of 08:44–08:48 UT on 5 March 1998, and the IMF
has a $B_z$ northward turning. There is an obvious difference in the interplanetary conditions between Figures 1 and 2 in that the dynamic pressure increase in this case is only caused by the increase in the solar wind density. The solar wind velocity has no obvious change during the process of the dynamic pressure increase.

[13] The images in Figure 4 show the auroral ovals before and after the increase in the solar wind dynamic pressure. The format is the same as that for Figure 2, except that the auroral images are selected in a shorter interval of 3 min. There is no obvious intensification of the dayside aurora during the process of the solar wind dynamic pressure increase, and only the pre-midnight sector of the auroral oval is intensified by the $B_z$ northward turning.

[14] As a summary of the above discussion, Table 2 lists the similar events with no dayside auroral intensifications by the increases in the solar wind dynamic pressure from 1997 through 1999. The format is the same as that for Table 1.

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**Figure 2.** Global auroral images from Polar UVI for the solar wind dynamic pressure increase with onset at 03:59 UT on 5 July 1998. Because of the limits of the image data, we select one auroral image every 6 min. A magnetic coordinate system is used. The geomagnetic north is at the center of each image, and the given magnetic latitudes increase by a step of 10° from the outer magnetic latitude 50° to the center. Noon is at the top and dawn is on the right. The linear color scale indicates the photon flux (photons cm$^{-2}$ s$^{-1}$) collected in the instrumentation aperture due to optical emission within a single pixel at the emission region.

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**Table 1.** The Interplanetary Conditions for the Events of the Dayside Auroral Intensifications by the Increases in the Solar Wind Dynamic Pressure From 1997 to 1999

<table>
<thead>
<tr>
<th>Date</th>
<th>$P_{\text{dyn}}$ (nPa)</th>
<th>$B_x$ (nT)</th>
<th>$B_y$ (nT)</th>
<th>$B_z$ (nT)</th>
<th>$D_p$ (n/cc)</th>
<th>$V'_\parallel$ (km/s)</th>
<th>$B_l$ (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 Feb 1997</td>
<td>1321</td>
<td>1324</td>
<td>2</td>
<td>6</td>
<td>$-3$</td>
<td>$-3$</td>
<td>0</td>
</tr>
<tr>
<td>22 Nov 1997</td>
<td>0950</td>
<td>0952</td>
<td>3</td>
<td>10</td>
<td>$-1$</td>
<td>$-1$</td>
<td>$-1$</td>
</tr>
<tr>
<td>3 May 1998</td>
<td>1743</td>
<td>1753</td>
<td>1</td>
<td>7</td>
<td>$-2$</td>
<td>$-1$</td>
<td>$-3$</td>
</tr>
<tr>
<td>29 May 1998</td>
<td>1536</td>
<td>1539</td>
<td>5</td>
<td>12</td>
<td>$-4$</td>
<td>$-5$</td>
<td>$-4$</td>
</tr>
<tr>
<td>5 Jul 1998</td>
<td>0359</td>
<td>0400</td>
<td>2</td>
<td>5</td>
<td>$-7$</td>
<td>$-7$</td>
<td>$-12$</td>
</tr>
<tr>
<td>26 Aug 1998</td>
<td>0650</td>
<td>0653</td>
<td>2</td>
<td>16</td>
<td>$-1$</td>
<td>$-1$</td>
<td>$-5$</td>
</tr>
<tr>
<td>24 Sep 1998</td>
<td>2345</td>
<td>2348</td>
<td>4</td>
<td>10</td>
<td>$-7$</td>
<td>$-7$</td>
<td>$-11$</td>
</tr>
<tr>
<td>2 Oct 1998</td>
<td>0724</td>
<td>0728</td>
<td>2</td>
<td>9</td>
<td>$-7$</td>
<td>$-6$</td>
<td>$-10$</td>
</tr>
</tbody>
</table>

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Table 2 gives the IMF and plasma parameters for each event before and after the solar wind dynamic pressure increases.

4. Discussion and Conclusions

[15] Previous investigations are mainly focused on the effects of the solar wind density and the dynamic pressure resulting from it and focus less on the effect of the solar wind velocity. For example, Kennel et al. [1985] and Tsurutani et al. [2001] have inferred theoretically that it is the solar wind density increase that typically plays the key role in the solar wind dynamic pressure increase from the relationship between the solar wind density and magnetic field compression and the shock magnetosonic Mach number. The solar wind density clearly enhances the intensity of the auroral electrojets but its efficiency is different depending on the IMF polarity [Shue and Kamide, 1998, 2001]. To examine how the solar wind density and velocity individually affect the auroral brightness, Shue et al. [2002] statistically considered the solar wind density and velocity separately rather than the combined dynamic pressure. However, in their work they averaged their high-resolution images to hourly ones, which may wash out some small-scale phenomena, for example, the sudden auroral brightness near noon due to an interplanetary shock and may not show good relationships on the dayside.

Table 2. The Interplanetary Conditions for the Events With No Dayside Auroral Intensifications for the Increases in the Solar Wind Dynamic Pressure From 1997 to 1999

<table>
<thead>
<tr>
<th>Date</th>
<th>$t_0$ (UT)</th>
<th>$t_1$ (UT)</th>
<th>$P_0$</th>
<th>$P_1$</th>
<th>$B_x$</th>
<th>$B_y$</th>
<th>$B_z$</th>
<th>$D_p$ (n/cc)</th>
<th>$\mid V_{\parallel}$ (km/s)</th>
<th>$\mid B_l$ (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Mar 1998</td>
<td>0844</td>
<td>0848</td>
<td>3.5</td>
<td>7.5</td>
<td>−3</td>
<td>−2</td>
<td>−3</td>
<td>11</td>
<td>11 8 10</td>
<td>6 3 15 30 350 350 11 10</td>
</tr>
<tr>
<td>20 Aug 1998</td>
<td>0548</td>
<td>0551</td>
<td>3.6</td>
<td>5.0</td>
<td>3</td>
<td>4</td>
<td>7</td>
<td>−9 −7 7 3</td>
<td>12 28 330 340 9 8</td>
<td></td>
</tr>
<tr>
<td>11 Feb 1999</td>
<td>2132</td>
<td>2133</td>
<td>3.11</td>
<td>−6</td>
<td>−9</td>
<td>−8</td>
<td>−9</td>
<td>2 3 7 18</td>
<td>24 22 18 −3 8 28 430 430 24 21</td>
<td></td>
</tr>
<tr>
<td>7 Sep 1999</td>
<td>0655</td>
<td>0703</td>
<td>5.9</td>
<td>7.4</td>
<td>6</td>
<td>−8</td>
<td>−4</td>
<td>−1 4 −1 −4</td>
<td>15 29 380 400 11 6</td>
<td></td>
</tr>
<tr>
<td>23 Sep 1999</td>
<td>0210</td>
<td>0219</td>
<td>7.14</td>
<td>16</td>
<td>15</td>
<td>13</td>
<td>14</td>
<td>−4 −7 −9 −6</td>
<td>10 21 570 570 17 16</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. The interplanetary condition for a period of 08:00–10:00 UT on 5 March 1998. The format is the same as that for Figure 1.
Case by case, we have shown two types of events from 1997 through 1999 in which the dayside auroras are or are not intensified by the solar wind dynamic pressure increases. Table 1 selects eight events for the dayside auroral intensification following the solar wind dynamic pressure increases, while Table 2 lists five events with no obvious intensification of the dayside auroras with similar changes in the solar wind dynamic pressure as in the events in Table 1. As mentioned above, the dynamic pressure increases for the events in Table 1 come from both the density and the solar wind velocity, while for the events in Table 2, the pressure variations are mainly from the contribution of density. Even in the events of 11 February 1999 and 23 September 1999, the large dynamic pressure increases \((P_1 - P_0 > 5 \text{ nT})\) did not generate obvious dayside aurora intensifications. This possibly hints that the dayside aurora intensification requires contributions of both density and solar wind velocity increases. The dynamic pressure increase caused only by the density (without the velocity contribution) could not be able to create the obvious dayside aurora intensification. This result has not been presented by Shue et al. [2002] or other works. Since the number of the studied cases is limited, more events or further studies need to be made to test the generality of this result.

There are two main mechanisms responsible for the dayside aurora intensification, and they might take place at the same time that the magnetosphere is compressed. First, the adiabatic compression of the magnetosphere can produce the enhancement of the dayside aurora [Tsurutani et al., 2001; Zhou et al., 2003]. Preexisting plasma on outer zone magnetospheric field lines becomes betatron accelerated and energized from the absorption of solar wind dynamic energy. By conservation of the first adiabatic invariant, the increase in the particle perpendicular kinetic energy leads to the loss cone instability and finally makes the dayside aurora brighten [Zhou and Tsurutani, 1999; Tsurutani et al., 2001].

When the solar wind dynamic pressure increase compresses the magnetosphere, the electrons will interact with the electrostatic electron cyclotron harmonic (ECH)
and whistler mode waves through the process of pitch angle diffusion and finally precipitate into the atmosphere, intensifying the dayside aurora [e.g., Perona, 1972; Saito et al., 1974; Horne et al., 2003; Su et al., 2009, 2010]. The other major mechanism suggests that the compression of the magnetosphere may lead to intensification of field-aligned currents [Araki, 1994; Lysak et al., 1995], which can cause the intensification of the dayside aurora [Tsurutani et al., 2001; Zhou et al., 2003]. The field-aligned currents can be generated by some magnetopause processes under shock conditions, such as magnetic shearing, magnetopause perturbation, magnetic reconnection and/or Alfvén wave generation [Zhou et al., 2003; Lu et al., 2003].

[20] Recently, there are many efforts which attempt to find the role of the solar wind velocity on the magnetospheric activity. Brautigam et al. [1991] use $B_z$ and solar wind velocity instead of $K_p$ to report the auroral ion and electron precipitation and auroral fluxes, and their study shows that an increase in solar wind velocity is most efficient in increasing auroral fluxes as well as magnetospheric activity during northward $B_z$. Meurant et al. [2004, Table 2] find that the solar wind dynamic pressure increase acts as a switch triggering the auroral activity induced by the shock. From their statistical study, the solar wind velocity appears well correlated with the auroral power, in contrast to the solar wind density and the magnitude of the dynamic pressure, which appear to play a minor role. Meurant et al. [2004] pointed out that the solar wind velocity and IMF magnitude seem to be the two most significant quantities to describe the shock-induced activity. For strong solar wind dynamic pressure pulses, the solar wind velocity, especially its variation, is the solar wind property that causes a stronger response of the magnetosphere in terms of flux closure [Hubert et al., 2009]. Our statistical results show that the increase in solar wind velocity seems critical to whether the solar wind dynamic pressure increase can cause the dayside aurora intensification, and these results provide further support that the solar wind velocity, especially its variation, plays an important role in the solar wind–magnetosphere coupling and magnetospheric activity. When the solar wind dynamic pressure increase is accompanied by the solar wind velocity increase, as well as the adiabatic compression, the perpendicular kinetic energy of the preexisting particle on outer zone magnetospheric field lines will increase rapidly following the solar wind velocity increase, since the origin of the solar wind velocity’s control on the particle-precipitated power is the $B \times V$ solar wind electric field [Liou et al., 1998; Meurant et al., 2004]. An increase in the particle perpendicular kinetic energy that leads to loss cone instabilities will increase the particles’ chances to scatter into the loss cone, and then the particles collide with upper ionosphere atoms and molecules and lose most of their energy by electron excitation. Consequently, the dayside aurora is intensified [Tsurutani et al., 2001]. In the next step, we will quantitatively study the relationship between the increase in solar wind velocity and the auroral intensity and its boundaries and further validate the role of solar wind velocity on dayside aurora enhancement.

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