Energetic neutral atom response to solar wind dynamic pressure enhancements

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We have investigated the response of the ring current to solar wind dynamic pressure (P_{dyn}) enhancement impacts on the magnetosphere by using energetic neutral atom (ENA) images obtained by the High-Energy Neutral Atom (HENA) imager on board the IMAGE spacecraft. In this work we present several events by distinguishing between pressure events where only the pure compression effects exist (without substorm effects) and those where the substorm is triggered by the P_{dyn} enhancement, and we find notable differences between these two types of events. First, for the pure compression events, we present four events where the P_{dyn} increases by ~100% to ~450% under northward interplanetary magnetic field (IMF) conditions. The P_{dyn} enhancement results in weak-to-modest ENA emission increases in both the hydrogen and oxygen channels: The total ENA rate increases by ~25% to ~40% relative to averages over the 1-hour period prior to the P_{dyn} enhancement impact. This ENA enhancement is due to ions adiabatically energized by the compression. The increased ENA emission rate drops as P_{dyn} decreases, implying that the ENA responses are directly caused by the adiabatic compression and decompression process. Also, the pure compression events lead to overall global, quasi-simultaneous increases of ENA in contrast to pure substorm-induced ENA enhancements that are initially localized in the nightside region followed by the drift effect. Next we present two events where the P_{dyn} enhancement was ~100% and >300%, respectively, under strongly southward IMF conditions, IMF B_z ≤ −10 nT, and a substorm was triggered. For both events the hydrogen and oxygen ENA emission increase is far more significant than that for the pure compression events, more than 100% even when the low-altitude contribution was excluded. This is primarily owing to energetic ions generated by the triggered substorm, although the compression effect itself occurs as well. Also, the ENA enhancement appears to be not as global in magnetic local time (MLT) as for the pure compression events, because of the predominant substorm effect that starts near midnight and spreads in MLT.


1. Introduction

Abrupt enhancements of the solar wind dynamic pressure (P_{dyn}) when impacting the magnetosphere lead to disturbances of the magnetosphere-ionosphere system in various ways. These include ground magnetic disturbances [e.g., Russell et al., 1994, and references therein], a geosynchronous magnetic field response [e.g., Wing et al., 2002; Lee and Lyons, 2004, and references therein], a geosynchronous energetic particle disturbance [e.g., Lee et al., 2005], a response throughout the magnetotail [e.g., Nakai et al., 1991; Kawano et al., 1992; Fairfield and Jones, 1996; Collier et al., 1998; Ostapenko and Maltsvev, 1998; Kim et al., 2004], an auroral disturbance [e.g., Lyons et al., 2000, 2005; Zesta et al., 2000; Chua et al., 2001; Boudouridis et al., 2003], and a polar cap convection change [e.g., Lukianova, 2003; Boudouridis et al., 2003]. Some of the typical compression effects are worthwhile to mention more specifically here as they are used in the present paper. First, an obvious effect by an enhanced P_{dyn} when impacting the magnetosphere is an increase of the ground geomagnetic H component at low latitudes due to enhanced magnetopause current density [e.g., Russell et al., 1994, and references therein]. Also, the magnetospheric magnetic field should be compressed, and geosynchronous spacecraft observations can easily confirm the magnetic compression effect [e.g., Wing et al., 2002; Lee and Lyons, 2004, and references therein]. Auroral brightening takes place in regions other than near-midnight where substorm
onset brightening usually occurs, and it sometimes appears to be relatively global, covering both the dayside and nightside [e.g., Lyons et al., 2005; Chua et al., 2001]. Another compression feature is that the charged particles trapped within the magnetosphere are accelerated adiabatically. Local measurements of energetic charged particles, for example, at geosynchronous orbit, often reveal particle flux increases as a result of the compression [e.g., Li et al., 2003]. However, they sometimes show flux decreases or little change as well. Lee et al. [2005] suggested the spatial profiles of the background adiabatic particle distributions determine whether or not locally measured fluxes show an increase.

[4] Another important effect related to the $P_{\text{dyn}}$ enhancement is substorm triggering under certain conditions. The $P_{\text{dyn}}$ trigger has been discussed by many researchers [e.g., Heppner, 1955; Schieldge and Siscoe, 1970; Kawatsuki et al., 1971; Burch, 1972; Kokubun et al., 1977; Zhou and Tsurutani, 2001; Liou et al., 2003; Lyons et al., 2005; Lee et al., 2005]. Using the Polar UV image data, Zhou and Tsurutani [2001] tested substorm triggering possibility by $P_{\text{dyn}}$ enhancement events associated with an interplanetary shock and reported that substorm triggering was observed for $\sim$44% of the studied events, for which the IMF $B_z$ was “strongly southward” for $>1.5$ hours. However it should be noted that most of their events actually correspond to weakly southward IMF conditions ($B_z \sim 0$ to $-4$ nT) prior to the shock. In addition, Liou et al. [2003] pointed out that what Zhou and Tsurutani [2001] meant by substorm triggering was not necessarily the substorm onset auroral breakup. By considering whether or not there was a substorm auroral breakup for a larger number of events, Liou et al. [2003] concluded that the probability of substorm triggering by a shock compression was very low for their studied events. However, Lyons et al. [2005] and Lee et al. [2005] suggested that substorm triggering by a $P_{\text{dyn}}$ enhancement is possible if the accompanied IMF is strongly southward whereas for northward and weakly southward IMF conditions, $P_{\text{dyn}}$ enhancements result in only typical compressive disturbances without a substorm onset. In fact, Lyons et al. [2005] and Lee et al. [2005] reported several examples of substorm triggering by a $P_{\text{dyn}}$ enhancement following $\sim$1-hour period of IMF $B_z \sim -8$ nT. However, for most of the events studied by Liou et al. [2003], the accompanied IMF was not strongly southward, having led to low probability of triggering. Although there has yet to be a realistic determination of the precise magnitude and length of the $P_{\text{dyn}}$ enhancement required for triggering a substorm as a function of the preceding IMF $B_z$ and $P_{\text{dyn}}$, it seems clear that prolonged and/or strong southward IMF is generally a favorable condition for a $P_{\text{dyn}}$ enhancement to trigger a substorm.

[5] When a $P_{\text{dyn}}$ enhancement triggers a substorm, the direct compression effect still exists. The substorm effect is dominant in the premidnight sector and the direct compressional effect is seen elsewhere. Lyons et al. [2005] and Lee et al. [2005] referred to this as a two-mode type response. For example, the magnetopause current enhancement leads to increases in the dayside ground $H$, whereas quasi-simultaneously the ground $H$ component shows larger increases on the nightside owing to the wedge current formation of the triggered substorm [Lyons et al., 2005; Lee et al., 2005]. Also, auroral brightening consists of substorm breakup near the Harang reversal region and additional brightening elsewhere, which is the direct results of compression [Lyons et al., 2005]. The geosynchronous measurements of energetic charged particles by Los Alamos National Laboratory (LANL) spacecraft show particle flux enhancements due to substorm injections as well as compressive flux changes [Lee et al., 2005].

[6] In this paper we are interested in examining global responses of energetic particles to a $P_{\text{dyn}}$ enhancement. Previous information on such global responses has only been obtained from studies using local measurements. The energetic neutral atom (ENA) images, which we use in the present paper, are a useful tool for studying the global aspect. ENAs are produced by charge-exchange interactions between energetic trapped ions and cold ambient neutral atoms in the geocorona. These ENAs travel freely without being affected by electromagnetic fields in the magnetosphere, and they can be used to remotely measure the magnetospheric ions. This powerful tool for space plasma diagnostics has been used substantially for ring current study [e.g., Roelof, 1987; Henderson et al., 1997; Brandt et al., 2002a; Ohtani et al., 2006], for substorm or storm-substorm relation research [e.g., Jorgensen et al., 2000; Reeves and Henderson, 2001; Brandt et al., 2002b, 2002c; Reeves et al., 2004; Ohtani et al., 2005; Pollock et al., 2003], for oxygen studies [e.g., Lui et al., 2005; Mitchell et al., 2003; Nosé et al., 2005], and for other issues [e.g., Perez et al., 2004; Vallat et al., 2004]. Several spacecraft have made ENA observations, such as ISEE 1 [Roelof, 1987], Astrid [Barabash, 1995; Brandt et al., 1999], Geotail [Lui et al., 1996], POLAR [Henderson et al., 1997], Cassini [Mitchell et al., 1998] and IMAGE [Mitchell et al., 2000].

[7] This paper is a first report on the global responses of the ENA to abrupt $P_{\text{dyn}}$ enhancements using the ENA data from the High-Energy Neutral Atom (HENA) instrument onboard the IMAGE spacecraft. While previous studies examined local measurements to understand differing characteristics of the energetic particle responses, here we examine both in situ satellite measurements and global ENA images in order to better understand the magnetospheric responses to the $P_{\text{dyn}}$ enhancements. In section 2 we describe the general characteristics of the studied $P_{\text{dyn}}$ enhancement events and the relevant data used in this paper. In sections 3 and 4 we present the ENA responses for events with and without substorm triggering, respectively. Discussion and conclusions are given in section 5.

2. Event Selection and Data

[8] The present work is a case study where we examine the global response of the ENA for six $P_{\text{dyn}}$ enhancement events. The $P_{\text{dyn}}$ increase for all events is abrupt and clearly noticeable. Specifically, the relative enhancement of $P_{\text{dyn}}$ is $\gtrsim 100\%$. Also the $P_{\text{dyn}}$ enhancement impact for all events is well separated or clearly distinguished from any earlier substorm occurrence. Most importantly, the IMAGE spacecraft at the time of a $P_{\text{dyn}}$ event has to be at a proper position that is not too close to the Earth, preferably near apogee, and with a good look direction. This is a critical requirement for a reliable study on ENA responses to $P_{\text{dyn}}$ enhancements, and all of our six events meet this requirement to a
reasonable degree. Also, all but one of our events are relatively free from the solar contamination problem that often limits the selection of suitable events. Four \( P_{\text{dyn}} \) events are under a northward or weakly southward IMF condition for which the magnetospheric response involves no substorm triggering, and two \( P_{\text{dyn}} \) events are under a strongly southward IMF condition where a substorm is triggered by the \( P_{\text{dyn}} \) enhancement impact. Lyons et al. [2005] suggested that there is a possible interplay effect between simultaneous changes of IMF and \( P_{\text{dyn}} \) particularly when the accompanied IMF Bz is strongly southward. In fact, it is quite often the case that both IMF and \( P_{\text{dyn}} \) change together. The latter two events under strongly southward IMF conditions were selected as they meet the condition to a reasonable degree of not having a significant IMF change, in particular in IMF Bz, around the time of the \( P_{\text{dyn}} \) enhancement to avoid the possible interplay effect (we did not require this condition when the IMF is northward).

[9] The IMAGE satellite, launched in March 2000 [Burch, 2000], is the first satellite equipped with instruments that can globally image ENA with high resolution. The HENA instrument is one of the neutral atom imaging instruments on the satellite, and detects charge exchange neutrals of high energies, 10 keV to \( \sim 200 \) keV, with 2 min time resolution [Mitchell et al., 2000]. HENA can also image the ENA emissions separately in hydrogen and oxygen, but only after August 2001; before then, the instrument could measure the oxygen ENA flux only with the lowest-energy (<10 keV/nucleon) hydrogen channel and only for disturbed periods [Mitchell et al., 2003]. Also, while the effective angular resolution of the instrument is several degrees for hydrogen (~8 degrees or better above the energy of \( \sim 50 \) keV/nucleon), it is tens of degrees for oxygen [Mitchell et al., 2003].

[10] In addition to the IMAGE HENA ENA data, we use geosynchronous magnetic and charged-particle flux data, ground geomagnetic H-component data, and auroral images in order to check for the compression effect and to determine whether or not a substorm occurred.

3. Pure Compression Effect With No Substorm Triggering

[11] In this section we present events that are associated with a \( P_{\text{dyn}} \) enhancement under a northward or weakly southward IMF condition. For these events, there was no substorm triggered by the \( P_{\text{dyn}} \) enhancement impact, which therefore allows us to study the pure compression effect.

3.1. The 18 August 2001 Event

[12] For this event the dynamic pressure increased by \( \sim 450\% \), while the IMF Bz remained northward, as shown in Figure 1a. The ACE solar wind and IMF data in Figure 1a are presented as time shifted by 50 min. This transit time was determined by looking at the low-latitude H increases, and the geosynchronous magnetic field and energetic charged-particle flux responses, which are presented in Figures 1b–1d. From the ground H data and the geosynchronous measurements, it is seen that the \( P_{\text{dyn}} \) enhancement impacts occurred in a two-step manner, namely, a first pressure increase impacted the magnetosphere at \( \sim 0605 \) UT followed by a larger one \( \sim 10 \) min later, although this feature is not seen in the ACE measurements. The data indicate that the later larger pressure increase impacted the magnetosphere \( \sim 50 \) min after ACE observed it, which we therefore have used to time shift the solar wind data. Time
shifting of the solar wind data can in general be done by several methods: For example, we find that the Weimer mapping [Weimer et al., 2003] gives a time shift of ~50 min for this pressure increase event, whereas the transit time based on the ACE X-position and the observed solar wind speed from ACE is ~45 min for this event. At times the existing time-shifting methods are not precise. For the purpose of the present work, we observe the effects of the pressure impacts in the magnetospheric data, so that it is sufficient to time shift the solar wind data on the basis of the impact time seen in this data. We have done this for all the events in this paper, except for the last event for which we used Geotail data without a time shift because of its relatively near-Earth location.

[13] In Figure 1b we present the ground H data from two representative low-latitude stations (ABG and LRM) on the dayside. The data clearly show an H increase, which is due to the enhancement in magnetopause current intensity by the P_{dyn} impact. Similar H increases were confirmed at other MLT stations (data not shown), implying a global H increase. At around the P_{dyn} impact time, GOES 8 was at postmidnight, and GOES 10 was at premidnight, and both

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**Figure 2.** The energetic neutral atom (ENA) flux images from the IMAGE High-Energy Neutral Atom (HENA) instrument for <10 keV hydrogen, 27–60 keV hydrogen, and 60–198 keV hydrogen for four selected time intervals before and after the P_{dyn} impact at ~0605 UT, 18 August 2001.
spacecraft measurements reveal increases of the magnetic field magnitude $B$. The $B_x$ and $B_z$ (data not shown) also increased in a similar manner. These are simple compressive field responses without a substorm dipolarization. The geosynchronous energetic particle data from LANL spacecraft also indicated a global response. We present the energetic proton flux data at energies 50–400 keV from two LANL spacecraft on the dayside in Figures 1c and 1d, which reveal simple flux increases verifying the $P_{\text{dyn}}$ impact (It should be noted that the 50–75 keV proton channel is often affected by background contamination). Another LANL spacecraft 1991-080 situated at ~19 MLT (data not shown) shows similar flux increases. No evidence for a substorm injection is seen from any of the LANL particle measurements. The global auroral images from the Wideband Imaging Camera (WIC) on the IMAGE spacecraft (data not shown) also show only the compressive auroral enhancement and no evidence for the nightside Harang region brightening that identifies substorm triggering.

Figure 3. (a) Total ENA emission rate (see text about the computation details) for the $P_{\text{dyn}}$ event on 18 August 2001. (b) Total emission rate normalized to averages over 1 hour prior to the $P_{\text{dyn}}$ impact at 0605 UT.

hydrogen, and 60–198 keV hydrogen (Note that different color scales are used). They are presented in an azimuthal equidistant projection with a $120^\circ \times 120^\circ$ field of view (see more explanation in the work of Brandt et al. [2002c], for example). The circle at the center represents the limb of the Earth and dipole field lines are drawn for $L = 4$ and 8 at 00, 06, 12, and 18 MLT for reference. The images show that the ENA flux enhancement is weak-to-modest. More importantly, the enhancement is overall global and quasi-simultaneous in MLT, and does not reveal any evidence for

Figure 4. (a–d) The IMF $B_z$, dynamic pressure $P_{\text{dyn}}$ data from ACE, presented as time shifted by 1 hour, geosynchronous magnetic field data from GOES 8 and 10, and geosynchronous energetic charged-particle flux data from LANL for an interval on 30 September 2002.
Figure 5. The ENA flux images from the IMAGE HENA instrument for 27–60 keV hydrogen, 60–
198 keV hydrogen, and 74–222 keV oxygen for selected time intervals before and after the \( P_{\text{dyn}} \) impact
on 30 September 2002.
substorm-injected particles on the nightside; for substorm events, an ENA emission enhancement first occurs at midnight and then spreads toward the duskside all the way around to noon reflecting the ion drift effect, which is faster and clearer for higher energies than for lower energies [e.g., Pollock et al., 2003; Mitchell et al., 2001]. The lack of evidence for a substorm in the ENA response is consistent with the other observations discussed above.

[15] The ENA response can be quantitatively examined by computing the total ENA emission rate from the ring current. This can be done by integrating the measured ENA flux through a virtual spherical surface encompassing the Earth. Here we adopt a simple model where the ENAs are assumed to be emitted isotropically from the ring current, as used in the study by Lui et al. [2005]. The total ENA emission rate is given by $4\pi r^2 \Psi$, where $r$ is the geocentric distance of the satellite and $\Psi$ is the integral of differential ENA flux normal to the sphere over all pixels at the spacecraft location. This isotropic emission model is a simple approximation that does not take into account the anisotropy associated with a strong interaction with the upper atmosphere producing a complicated dependence on viewing geometry. It does not include the ENAs that go into the surface of the Earth, but only includes those that escape into space. However, this method is useful in the aspect that the ENA flux measured by spacecraft is generally dependent on the satellite radial position [Ohtani et al., 2005], and this method takes into account the radial position effect by integrating the measured flux over a sphere.

[16] Figure 3a shows the computed total ENA emission rate for a time interval before and after the pressure impact at 0605 UT. For all energies, the ENA emission rate increased after the pressure impact preceded by a slow decrease. The ENA emission rate increase appears to be gradual because of the smaller $P$ increase at 0605 followed in 10 min by the larger increase, and the 10 min averaging of the ENA observations. Figure 3b shows the total emission rate normalized to averages over 1 hour prior to the pressure impact for each species and channel. The relative change is largest for $<10$ keV hydrogen, but less than 30%.

3.2. The 30 September 2002 Event

[17] For this event, $P_{\text{dyn}}$ increased by $\sim100\%$ under northward IMF $B_z$ as shown in Figure 4a, where a time shift of 1 hour was applied to the ACE data. The geosynchronous responses to this pressure enhancement impact can be seen in the other panels of Figure 4, which occurred at $\sim1930$ UT. Figure 4b shows the geosynchronous magnetic field magnitude, and the abrupt increases on the dayside in response to the $P_{\text{dyn}}$ enhancement impact at $\sim1930$ UT are clear. In Figures 4c and 4d are shown the geosynchronous charged-particle flux data from LANL spacecraft near midnight and on the morningside. The charged-particle responses are weak-to-modest flux increases without any evidence of substorm injection.

[18] Around the pressure impact time, IMAGE was located at $r \sim 7.9$ Rs, and MLAT of $\sim53.3^\circ$. The HENA ENA images as shown in Figure 5 exhibit weak-to-modest increases of the ENA emission. Although the instrument look direction was slightly tilted, the images indicate no evidence of substorm occurrence and the compression-induced ENA enhancement is clearly seen on the dayside. In order to see the ENA responses quantitatively for this event, we have done similar calculations of the total ENA emission rate as for the previous event. The results are shown in Figure 6 in the same format as Figure 3. The relative increase of the total ENA emission rate is largest for oxygen, but is only $\sim25\%$ at the peak. Here we presented the oxygen ENA for the energy range 74–222 keV, as the HENA instrument was capable of producing ENA images for both hydrogen and oxygen separately after August 2001.

3.3. The 13 August 2000 Event

[19] This event is characterized by three successive $P_{\text{dyn}}$ enhancements that are separated by $\sim40$ min to 1 hour under the northward IMF condition. The time-shifted solar wind data, the low-latitude ground $H$ data, and the geosynchronous data are presented in Figure 7. We have identified three major pressure events impacting the Earth at $\sim0205$ UT, 0305 UT, and 0345 UT, respectively. The enhancement at 0305 UT is the largest, $\sim300\%$. The low-latitude $H$ increases on the dayside and the geosynchronous magnetic compressions are clear for all three events as shown in Figure 7b (only the total geosynchronous magnetic field is shown). The geosynchronous particle fluxes at dayside MLTs reveal increases due to the adiabatic compression effect, and do not show dispersion signatures that would be expected from a nightside substorm injection.
No substorm evidence is thus seen from the geosynchronous observations. There are also other pressure enhancements as seen in the ACE observations that have clear responses on the ground and at geosynchronous orbit.

[20] Between the first pressure impact and the third one, the IMAGE spacecraft was located at \( r \sim 8.0 \) to \( 8.1 R_E \), and \( \text{MLAT} \sim 61.5^\circ \) to \( 57.2^\circ \). Figure 8 shows the ENA images for selected times before and after the three \( P_{\text{dyn}} \) enhancements. The ENA enhancement is weakest for the first \( P_{\text{dyn}} \) event, which is the smallest pressure increase, and more noticeable for the other two \( P_{\text{dyn}} \) events. An animation for these three events is available in the auxiliary material. As for the previous events, the total ENA emission rates are shown in Figure 9. It is clearly seen from Figure 9 that the ENA changes are consistent with the multiple \( P_{\text{dyn}} \) changes, implying generation and decay of the enhanced ENA emissions directly by the adiabatic compression-decompression process. The relative increase of the total ENA emission rate is largest for <10 keV hydrogen, reaching \( \sim 40\% \) at the peak, owing to the \( P_{\text{dyn}} \) enhancement event at 0305 UT. We remark that the <10 keV hydrogen channel may contain some substantial amount of oxygen since this event occurred during the recovery phase of an intense storm with \( \text{Dst}_{\text{min}} \sim -240 \text{ nT} \) that started on 12 August.

### 3.4. The 29 September 2001 Event

[21] Figure 10 shows two events separated by \( \sim 44 \) min. We present these two events to demonstrate the difference in the ENA response between the pure compression effect as in the above examples and the pure substorm effect without being associated with a \( P_{\text{dyn}} \) trigger. The first event is a substorm starting at \( \sim 0854 \) UT. Prior to 0854 UT, the IMF \( B_z \) as observed by ACE was primarily northward or near zero for \( \sim 40 \) min which was preceded by a \( \sim 3 \)-hour interval of weakly southward IMF \( B_z \). There was no significant \( P_{\text{dyn}} \) increase in the solar wind observations by ACE or by WIND and Geotail (data not shown) for this substorm onset. The low-latitude \( H \) data at selected stations are shown in Figure 10b. At and near 0854 UT, the low-latitude \( H \) at dayside stations (BNG, ABG) is nearly constant, which confirms that there was no \( P_{\text{dyn}} \) increase impact, whereas the nightside station (HON) shows a gradual increase in \( H \), which reflects the substorm wedge current formation. There was also not a compressional signature in the LANL particle data away from the substorm onset region. The geosynchronous magnetic field substorm dipolarization is seen in Figure 10b, and the geosynchronous substorm particle injection is clear in Figures 10c and 10d. The IMAGE WIC auroral images (data not shown) exhibit substorm auroral breakup clearly.

[22] The \( P_{\text{dyn}} \) increase from <2 nPa to \( \sim 5-6 \) nPa abruptly impacted the magnetosphere at \( \sim 0938 \) UT when the preceding substorm was in the late recovery phase. This \( P_{\text{dyn}} \) increase occurred while the IMF \( B_z \) was northward. The \( P_{\text{dyn}} \) impact effect is clearly seen as the global \( H \) increases at low-latitude stations (on both dayside and nightside) as shown in Figures 10b. It is also seen as additional increases in the geosynchronous particle flux as shown in Figures 10c and 10d. It is less clear in the GOES 10 magnetic field data near midnight, but GOES 8 at dawn saw some increase of the geosynchronous magnetic field (data not shown). The IMAGE WIC auroral images (data not shown) reveal sudden global intensification by the \( P_{\text{dyn}} \) impact while the preceding substorm-caused auroral activity was in the decaying stage.

[23] Around the \( P_{\text{dyn}} \) impact time, IMAGE was located at \( r \sim 6.9 R_E \), and MLAT \sim 79°. Figure 11 shows the ENA flux images for 27–60 keV hydrogen, 60–198 keV hydrogen, and 74–222 keV oxygen for three selected time intervals, that is, before the substorm onset, right after the
substorm onset, and right after the $P_{\text{dyn}}$ enhancement impact, respectively. The ENA increases are seen primarily on the nightside after the substorm onset. This is particularly clear for high-energy hydrogen and oxygen. The drift effect toward the duskside was also confirmed (images not shown). After the $P_{\text{dyn}}$ enhancement impact, the ENA increased globally both on the dayside and on the nightside. The difference in ENA response between the earlier substorm effect and the later $P_{\text{dyn}}$ enhancement effect is more clearly seen in Figures 12 and 13.

[24] The results of total ENA emission rate computations as done for the earlier events are shown in Figure 12. The

Figure 8. The ENA flux images from the IMAGE HENA instrument for $<10 \text{ keV}$ hydrogen, $27-60 \text{ keV}$ hydrogen, and $60-198 \text{ keV}$ hydrogen for six selected time intervals before and after three $P_{\text{dyn}}$ impacts on 13 August 2000.
ENA increases are clear for both the substorm and the $P_{\text{dyn}}$ enhancement event. It is also clear in Figure 12a that it was in the declining phase of the ENA level (the substorm recovery phase) when the pressure effect took place which led to a further rise of the ENA emission rate. Figures 12b and 12c show the relative increases of the total ENA emission rate as normalized to averages over 1 hour prior to the substorm onset time and those as normalized to averages over 30 min prior to the $P_{\text{dyn}}$ enhancement impact time, respectively. First, Figure 12b indicates that the relative increases due to the substorm effect reached up to $\sim 70\%$ for oxygen and $\sim 25\%$ for high-energy hydrogen compared to 1-hour averages prior to the substorm onset time. It is very weak for lower-energy hydrogen. This difference is expected during substorms owing to the nonadiabatic behavior of $O^+$ ions [Fok et al., 2006; Jones et al., 2006; Delcourt et al., 1990]. After the peaks, the relative ENA emission rate decreased, implying that the substorm was in the recovery phase and that ions were lost owing to charge exchange. Then the $P_{\text{dyn}}$ enhancement impacted at 0938 UT and raised the relative increase of the ENA emission rate up to $\sim 136\%, \sim 44\%, \sim 31\%$, for oxygen, high-energy hydrogen, and low-energy hydrogen, respectively, as shown in Figure 12b. When compared to the 30-min averages prior to the $P_{\text{dyn}}$ enhancement impact time, Figure 12c indicates that the pressure impact raised the ENA emission up to $\sim 50\%$ for oxygen and $\sim 20\%$ for hydrogen. The higher relative increase of oxygen compared to that of hydrogen was also found for the event on 30 September 2002 above (Figure 6), and it would be worthwhile to check whether or not this is a general feature from a statistical viewpoint.

Figure 9. (a) Total ENA emission rate (see text about the computation details) for the $P_{\text{dyn}}$ events on 13 August 2000. (b) Total emission rate normalized to averages over 1 hour prior to the $P_{\text{dyn}}$ impact at 0205 UT.

Figure 10. (a–d) The IMF $B_z$, dynamic pressure $P_{\text{dyn}}$ data from ACE, presented as time shifted by 33 min, geomagnetic H at low-latitude stations, geosynchronous magnetic field data from GOES 10, and geosynchronous energetic charged-particle flux data from LANL for an interval on 29 September 2001.
We find that it is useful to separate the contributions to the total ENA emission rate between dayside and nightside. This helps us to demonstrate the difference between the substorm effect and the later pressure effect. The separate contributions to the total ENA emission rate were estimated by integrating the ENA flux over a hemisphere that covers only the dayside or nightside. The computed dayside (Figure 13, thick line) and nightside (Figure 13, thin line) contributions are shown in Figures 13a–13c for low-energy hydrogen, high-energy hydrogen, and oxygen, respectively. For all species, the ENA increase is obvious on the nightside at the time of the substorm onset. The dayside increase is seen only for oxygen but is delayed compared to that on the nightside. This is likely generated by the azimuthally drifting charged particles after the injection. In contrast, at and after 0938 UT when the $P_{\text{dyn}}$ enhancement impacted the magnetosphere, the ENA increased notably both on the dayside and on the nightside.

Figure 11. The ENA flux images from the IMAGE HENA instrument for low-energy hydrogen, high-energy hydrogen, and oxygen for three selected time intervals for the event on 29 September 2001.
without a significant time difference, which is the global response of the ENA to the pressure hit.

4. Events With Both Compression and Triggered-Substorm Effects

[26] In this section we present two events where the $P_{\text{dyn}}$ increased under strongly southward IMF conditions and thus during major storms with $\text{Dst}_{\text{min}}$ less than $-100$ nT. Both events are characterized by the substorm occurrence triggered by the $P_{\text{dyn}}$ enhancement as well as by the typical compression effect.

4.1. The 11 August 2000 Event

[27] For this event, $P_{\text{dyn}}$ increased by $\sim 100\%$ under a strongly southward IMF condition as can be seen in Figure 14. The IMF Bz remained less than $-11$ nT before and after the pressure change. The geosynchronous response for this event was studied by Lee et al. [2005], and the auroral response by Lyons et al. [2005], suggesting that the $P_{\text{dyn}}$ enhancement impacted the magnetosphere at $\sim 0412$ UT. The $P_{\text{dyn}}$ enhancement triggered the substorm dipolarization on the nightside as shown in Figure 14c. Nearly simultaneous with the nightside dipolarization, the energetic particle flux at $\sim 17$ MLT increased with nearly no dispersion in energy as shown in Figure 14d. Also, nearly at the same time, as shown in Figure 14e, the energetic particle flux at $\sim 11$ MLT decreased rather sharply with no dispersion in

Figure 12. (a) Total ENA emission rate (see text about the computation details) for the $P_{\text{dyn}}$ events on 29 September 2001. (b) Total emission rate normalized to averages over 1 hour prior to the substorm onset time at 0854 UT. (c) Total emission rate normalized to averages over 30 min prior to the pressure impact time at 0938 UT.

Figure 13. (a–c) ENA emission rates computed separately for contributions from dayside (thick lines) and nightside (thin lines) for the events on 29 September 2001.
energy, which was followed by increases at ∼0420 UT and after. It should be noted that the earlier sharp dispersionless reduction of the flux at ∼11 MLT reflects the compression effect. It was suggested by Lee et al. [2005] that the change in the particle flux at a given energy channel due to a $P_{\text{dyn}}$ enhancement must in general be determined by a combination of adiabatic acceleration and the spatial (radial) profile of the source particle distribution at constant first and second adiabatic invariants. Therefore in general the compression effect on particle flux change for a given $P_{\text{dyn}}$ enhancement can be different for different particle species, different energy channels, and different MLT and radial regions depending on the radial profiles of the background adiabatic particle distribution. The dispersionless electron flux decrease in Figure 14e implies the possibility that the particle distribution function at the time of the $P_{\text{dyn}}$ enhancement at the location of the spacecraft decreased with increasing radial distance. The later dispersed increase at the prenoon sector reflects the energy-dependent drift of substorm-injected particles. Other LANL spacecraft data (not shown here, but see Figure 11 of Lee et al. [2005]) also indicate clearly the particle drift effect that is consistent with the substorm injection feature. Therefore effects of both nightside triggered-substorm and dayside compression exist in the geosynchronous responses. Lyons et al. [2005] also reported that for this same event the IMAGE WIC auroral data exhibited both dayside brightening and nightside Harang region brightening, indicating the compressive effect and the substorm occurrence, respectively. Note that the magnetic field elevation angle and the particle flux (as seen by 1989-046) gradually reduced prior to the substorm onset (or the pressure impact time), which reflects the magnetic field line stretching under the strongly southward IMF condition. This was not seen for the pure compression events above, which occurred under northward IMF conditions.

Figure 14. (a–e) The IMF Bz, dynamic pressure $P_{\text{dyn}}$ data from ACE, presented as time shifted by 70 min, geosynchronous magnetic field data from GOES 8 and 10, and geosynchronous energetic charged-particle flux data from LANL for an interval on 11 August 2000.
Figure 15. The ENA flux images from the IMAGE HENA instrument for low-energy hydrogen, high-energy hydrogen, and <160 keV oxygen as obtained from <10 keV/nucleon hydrogen channel for four selected time intervals for the event on 11 August 2000.
the nightside but soon spreads in MLT and owing to strong low-latitude emissions confined near the Earth for this event. [29] The large enhancement of the ENA at low-altitude where the precipitating/nearly mirroring ions can charge exchange with the much more dense oxygen can be seen in Figure 15. In fact, this is often the case for storm-time substorms like this event. The low-altitude emission therefore contributes to the total ENA emission rate to some extent. It is interesting to check the extent to which the low-altitude emission contributed to the large enhancement of the total ENA emission rate found above. Thus we have repeated the calculation of the total ENA emission rate by excluding the near-Earth region which we defined to be within 15° in both azimuth and elevation centered at Earth. The calculation approximately represents the ENA emission rate in the ring current region only and the results indicate that the relative increase of the total ENA emission rate as normalized to averages over 1 hour prior to the pressure impact reaches up to ~110% for 60–198 keV hydrogen and ~94% for <160 keV oxygen, which is still significantly higher than those for the earlier pure compression events. It is however much smaller, ~15%, for 27–60 keV hydrogen, implying that the ENA flux enhancement in the ring current region in this energy channel is weaker than that generated by the precipitating/nearly mirroring ions.

4.2. The 14 October 2000 Event
[30] For this $P_{\text{dyn}}$ enhancement event which impacted the magnetosphere at ~0952 UT, the accompanied IMF was strongly southward, $B_z \sim -10$ nT, as shown in Figure 17a. Note that the solar wind data from Geotail is shown without a time shift. The $P_{\text{dyn}}$ effect is easily confirmed by looking at the ground H response at low-latitude stations as shown in Figure 17b. Using the IMAGE WIC auroral images, Lyons et al. [2005] showed that both dayside compressive brightening and nightside substorm brightening occurred in response to this pressure impact. The geosynchronous proton flux responses are shown in Figures 17c and 17d, which indicate nightside and dayside flux increases that

![Figure 16](image1.png)

**Figure 16.** (a) Total ENA emission rate (see text about the computation details) for the $P_{\text{dyn}}$ events on 11 August 2000. (b) Total emission rate normalized to averages over 1 hour prior to the $P_{\text{dyn}}$ impact at 0412 UT.

![Figure 17](image2.png)

**Figure 17.** (a–d) The IMF $B_z$, dynamic pressure $P_{\text{dyn}}$ data from Geotail, presented without a time shift, ground magnetic field data at M’Bour (MBO) and Bangui (BNG), and geosynchronous energetic charged-particle flux data from LANL for an interval on 14 October 2000.
are quasi-dispersionless in energy and quasi-simultaneous between the two spacecraft separated by ∼6 hours in MLT. The electron flux response reveals clearly the substorm drift effect of the nightside injected particles and the GOES magnetic field data shows the substorm dipolarization (data shown in Figure 14 of Lee et al. [2005]). Also, note that the abrupt particle flux increases were preceded by gradual decreases of the flux due to the field line stretching, which is typically seen under the strongly southward IMF condition.

[31] Around the pressure impact time, IMAGE was located at \( r \sim 8.1 \) R\(_E\), and MLAT \( \sim 61.4^\circ \). The ENA images are shown in Figure 18 for selected times before and after the \( P_{\text{dyn}} \) impact. It is clearly seen that after the \( P_{\text{dyn}} \) impact the ENA emission increased notably for hydrogen in two energy ranges and oxygen on the nightside owing to the triggered substorm. There was significant contamination due to solar illumination on the dayside, because of which it is not plausible to estimate quantitatively the dayside ENA response for this event. However, assuming that the

Figure 18. The ENA flux images from the IMAGE HENA instrument for low-energy hydrogen, high-energy hydrogen, and <160 keV oxygen as obtained from <10 keV/nucleon hydrogen channel for three selected time intervals for the event on 14 October 2000.
ENA is emitted only from the nightside, we find that the total ENA emission rates relative to averages over 1 hour prior to the \( P_{\text{dyn}} \) impact increase by \( \sim 300\% \) for 60–198 keV hydrogen, \( \sim 220\% \) for \(<160 \text{ keV} \) oxygen, and \( \sim 100\% \) for 27–60 keV hydrogen. These numbers would of course be different if the entire region, both dayside and nightside, were included in the computations. Nevertheless, it is clear that the real values of the total ENA emission rate must be still significantly higher than those for the pure compression events unless the ENA emission is greatly reduced on the dayside by the same pressure impact, which we think is unlikely.

5. Conclusions and Discussion

[32] In the present work we have distinguished between pure compression events (without substorm effects) and events where a substorm is triggered by the \( P_{\text{dyn}} \) enhancement. First, the pure compression events, all of which were for northward IMF conditions, result in weak-to-modest ENA emission enhancement: The total ENA emission rate relative to averages over 1 hour prior to the pressure impact increases by \( \sim 25\% \) to \( \sim 40\% \) in both hydrogen and oxygen channels for \( P_{\text{dyn}} \) enhancements of \( \sim 100\% \) to \( \sim 450\% \). This pure compression-induced ENA emission must be primarily due to adiabatically energized charged particles by the pressure compression. It should also be noted that the resultant ENA emission enhancement should be more than what is expected only from energization because the compression pushes the ions toward the Earth and the neutral atom density increases sharply [Ohtani et al., 2005; Brandt et al., 2002c]. This implies that the ENA emission enhancement is not proportional to the ion flux enhancement. Future work to compare the ENA and ion flux enhancements would help to clarify this issue. The enhanced ENA emission drops as the \( P_{\text{dyn}} \) decreases, implying that the ENA responses were directly caused by the adiabatic compression and decompression processes. It was also seen that the pure compression events lead to overall global, quasi-simultaneous in MLT, increases of ENA in contrast to pure substorm-induced ENA enhancements that are initially localized in the nightside region followed by the azimuthal drift effect.

[33] For the events where the \( P_{\text{dyn}} \) enhancement triggered a substorm, we have presented two events under strongly southward IMF conditions, both of which are during major storms with \( D_{\text{st}} \) less than \( -100 \text{ nT} \). Both events indicate significantly larger ENA emission than that for the pure compression events. For the 11 August 2000 event where the \( P_{\text{dyn}} \) enhancement is \( \sim 100\% \) under IMF Bz \( \sim -11 \text{ nT} \), the total ENA emission rate relative to averages over 1 hour prior to the pressure impact increased by \( \sim 170\% \) for 60–198 keV hydrogen and \( \sim 130\% \) for \( <160 \text{ keV} \) oxygen. They are still significant, \( \sim 110\% \) for 60–198 keV hydrogen and 94\% for \( <160 \text{ keV} \) oxygen, even when the near-Earth region where the low-altitude contribution is dominant is excluded from the estimation. For the 14 October 2000 event a quantitative estimation of the total ENA emission rate was limited owing to solar contamination, but the significant increase of the ENA emission was clear. The significant ENA emission for both events is of course mainly due to ions generated by the triggered substorm. Also, its appearance is not as global in MLT as for the pure compression events because of the predominant substorm effect that starts near midnight and spreads soon in MLT, but the global response to the compression exists as well.

[34] While we have found notable differences between the pure compression events and the \( P_{\text{dyn}} \)-triggered substorms, the present work is a case study based on six events. Our selection of six events consisted of four pure compression events during primarily northward IMF conditions and two \( P_{\text{dyn}} \)-triggered substorms during strongly southward IMF conditions. This selection gives sharp contrast between the two types of events; however there are many intermediate and more complex types of events. For example, we have in fact presented one additional event (the pure substorm event at 0854 UT on 29 September 2001) where the preceding IMF condition is neither simply northward nor strongly southward, where no obvious pressure trigger existed and where the ENA emission rate increase was intermediate. Clearly, a statistical analysis based on a larger number of events than included here is desired to check the generality of the present result. From a statistical viewpoint, it would be useful to determine whether or not ENA enhancement is generally larger when a substorm is triggered than when there is only the compression effect. It is also interesting to note the suggestion by Jorgensen et al. [2000] that the ENA emission is a new type of substorm signature.

[35] As discussed in section 2, our selection of events is limited by several conditions. One of the stringent conditions is the requirement of no significant IMF changes at the time of the \( P_{\text{dyn}} \) enhancement when the accompanied IMF is southward. This requirement was set because such a simultaneous IMF turning could interact with the \( P_{\text{dyn}} \) enhancement [Lyons et al., 2005], which can make it difficult to clarify the \( P_{\text{dyn}} \) effect alone. Quite often, both \( P_{\text{dyn}} \) and IMF in reality change together, and it would be interesting to examine the possible interplay effect using the ENA images along with other data.

[36] Extraction of the ion distribution from the observed ENA data is a challenging task in general, and there have been such attempts by some researchers [e.g., DeJamistre et al., 2004; Brandt et al., 2002c; Perez et al., 2001; Roelof and Skinner, 2000]. It would be interesting to examine the extracted ion distributions in response to the dynamic pressure impact and compare them with local measurements of ions in the inner magnetosphere. Also, use of both the LANL SOPA and MPA data would be interesting for comparison with the ions extracted from the IMAGE HENA ENA data. Furthermore, several researchers have suggested that the O\(^+\) ions during substorm expansion are energized more significantly than protons owing to their nonadiabatic behavior in response to the substorm dipolarization [e.g., Fok et al., 2006; Jones et al., 2006; Nosé et al., 2000; Delecourt et al., 1990]. The nonadiabatic behavior is expected because the oxygen gyroradius is comparable to the timescale of dipolarization. It would be interesting to check whether or not a similar nonadiabatic response of O\(^+\) ions can occur for the pure compression events where the solar wind dynamic pressure increases over a sufficiently short timescale to break down the first adiabatic invariant
and/or the second adiabatic invariant. This would, however, require a detailed numerical analysis based on a realistic magnetospheric model, and is beyond the scope of the present paper.

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References


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