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SOME CHARACTERISTICS OF ENERGETIC NEUTRAL ATOM STORM ON OCTOBER 3, 2001

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ABSTRACT

We have studied energetic neutral atom (ENA) disturbances during the magnetic storm main phase that occurred on October 3, 2001, using the ENA data from the HENA instrument onboard the IMAGE spacecraft. We find that the main phase is characterized by five ENA enhancement events that occurred quasi-periodically. The repetitive ENA enhancements are most significant in the highest energy (138–222 keV) oxygen channel and become less significant for hydrogen and in lower energies. Also they are separated by ~1.2 to ~1.7 hrs, which is well below an average period usually seen for other repetitive injection events.

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1. INTRODUCTION

Magnetic storms are characterized by various types of disturbances in the magnetosphere and ionosphere. They include auroral intensification, occurrence of consecutive substorms, large scale stretching of the inner magnetospheric magnetic field, energetic particle generation that can contribute to the ring current, etc. Local measurements by spacecraft and on the ground have long been used to interpret the storm-time disturbances.

The global aspect of the storm-time disturbances can be studied using energetic neutral atom (ENA) images. ENAs are generated by charge-exchange interactions between energetic trapped ions within the inner magnetosphere close to the Earth and cold ambient neutral atoms in the geo-corona. These ENAs travel freely without being affected by electromagnetic fields in the magnetosphere, and thus one can use them 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 & Henderson 2001, Brandt et al. 2002b, 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, Nose 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).

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In the present study, we use the ENA data from the HENA instrument onboard the IMAGE satellite to study particle generation features during a magnetic storm. 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 ~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, it is tens of degrees for oxygen (Mitchell et al. 2003).

One of the most intriguing features during some storms is continuous production of energetic particles in a quasi-periodic manner. Some of them are often referred to as sawtooth injection oscillations (e.g., Lee et al. 2004), the period of which is usually found to be ~2-4 hrs. Most of previous studies primarily used locally measured charged particles to interpret storm-time energetic particle production events. Those local measurements did not distinguish between different ion species, however. In the present work, we report a storm- time for which the IMAGE spacecraft look-direction is ideal so that five consecutive enhancements of the ENA flux are well covered by the spacecraft's observation. Our work based on the ENA data not only provides a global aspect of the energetic particle generation but also distinguishes between hydrogen and oxygen.

2. ENA OBSERVATIONS AND ANALYSIS

The storm event we examine here occurred on October 3, 2001. The Sym-H index data is shown in Figure 1a. The Sym-H index started to decrease at ~07 UT on Oct 3, and reached the minimum value, about −186 nT, at ~14.4 UT on Oct 3. The interval represents the main phase of this storm, which was then followed by the recovery phase.

Since our main goal of the present work is to study ring current particle flux variations using the ENA data from the HENA instrument onboard the IMAGE spacecraft, we have first checked the spacecraft locations and look-direction during the main phase of this storm. Figure 2 shows the satellite trajectories for an interval on Oct 3, and indicates that the spacecraft position and look-direction was very good during the main phase of this storm. Figure 1b shows the Sym-H index for an expanded interval that covers the storm main phase.

We have examined the ENA data quantitatively 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 $4\pi\rho^2\phi$, where ρ is the geocentric distance of the satellite and ϕ 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.

Figure 1c shows the computed total ENA emission rate. The results are distinguished between hydrogen and oxygen, and between energies. The low energy (27–50 keV) hydrogen shows an

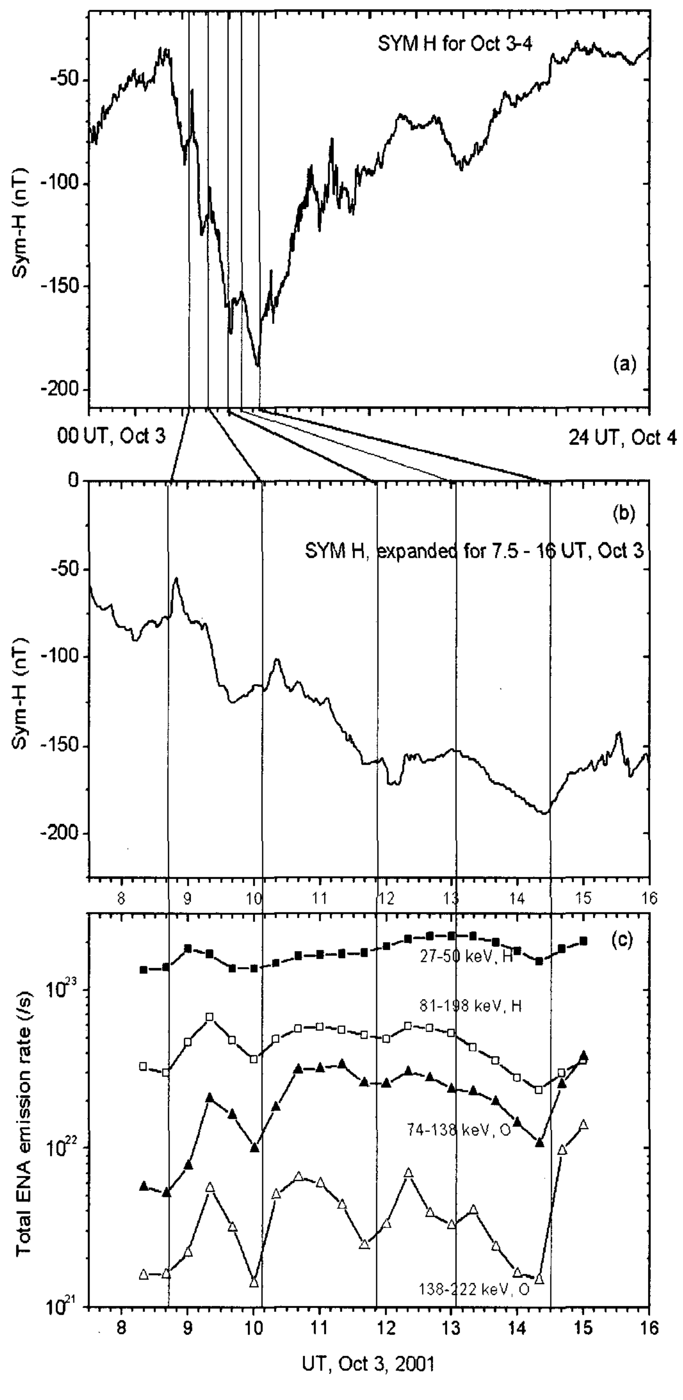

Figure 1. (a) Sym-H for Oct 3-4, 2001 (b) Sym-H expanded for 7.5-16 UT Oct 3, 2001 (c) Total ENA emission rate.

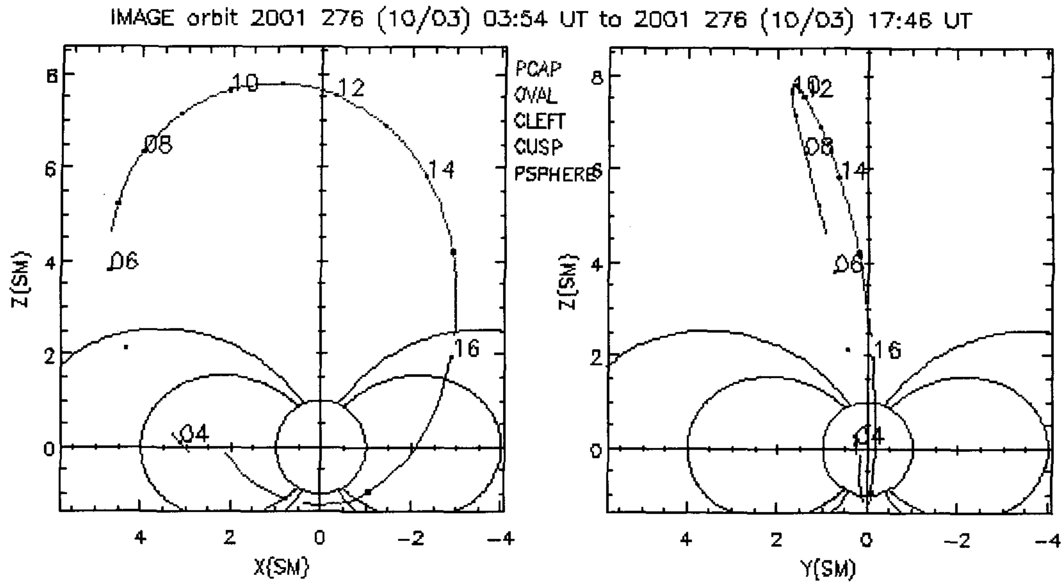

Figure 2. The IMAGE spacecraft orbit for an interval on Oct 3, 2001.

obvious ENA emission increase starting at ~0842 UT, a rather gradual, slow weak increase after ~1000 UT, and another modest increase at ~1430 UT. The high energy (81–198 keV) hydrogen and the low energy (74–138 keV) oxygen indicate more significant ENA variations: They both show ENA increases at ~0842, 1009, 1151, and 1430 UT. The high energy (138-222 keV) oxygen indicates the most dramatic and obvious ENA increases at ~0842, 1009, 1151, 1303, and 1430 UT. They are separated by ~1.4 hrs on average, which is substantially shorter than what is usually found for other storm-time continuous particle injections.

3. DISCUSSION

We have found two main results in the present work. First, the ENA enhancement is higher for oxygen than for hydrogen, and more significant in higher energy channels. It seems to indicate that the ENA enhancement is stronger for particles with a longer gyroperiod and a larger gyroradius. The ENA enhancement can in general be understood as a combination of spatial effect of neutral particles and ion acceleration effect. The spatial effect means that the neutral density increases rapidly toward the Earth and this can affect the charge exchange rate to produce more ENA emission than what is expected from a pure acceleration effect. We suspect that the differing ENA production rate between species and energies is more likely due to the ion acceleration effect that may be different between different species and energies. For example, it has been noted (e.g., Nose et al. 2005) that oxygen ions can suffer from non-adiabatic acceleration as their gryoperiod is much longer than that for protons. This may account for the larger enhancement of oxygen seen in Figure 1, but a solid conclusion requires a more detailed numerical calculation.

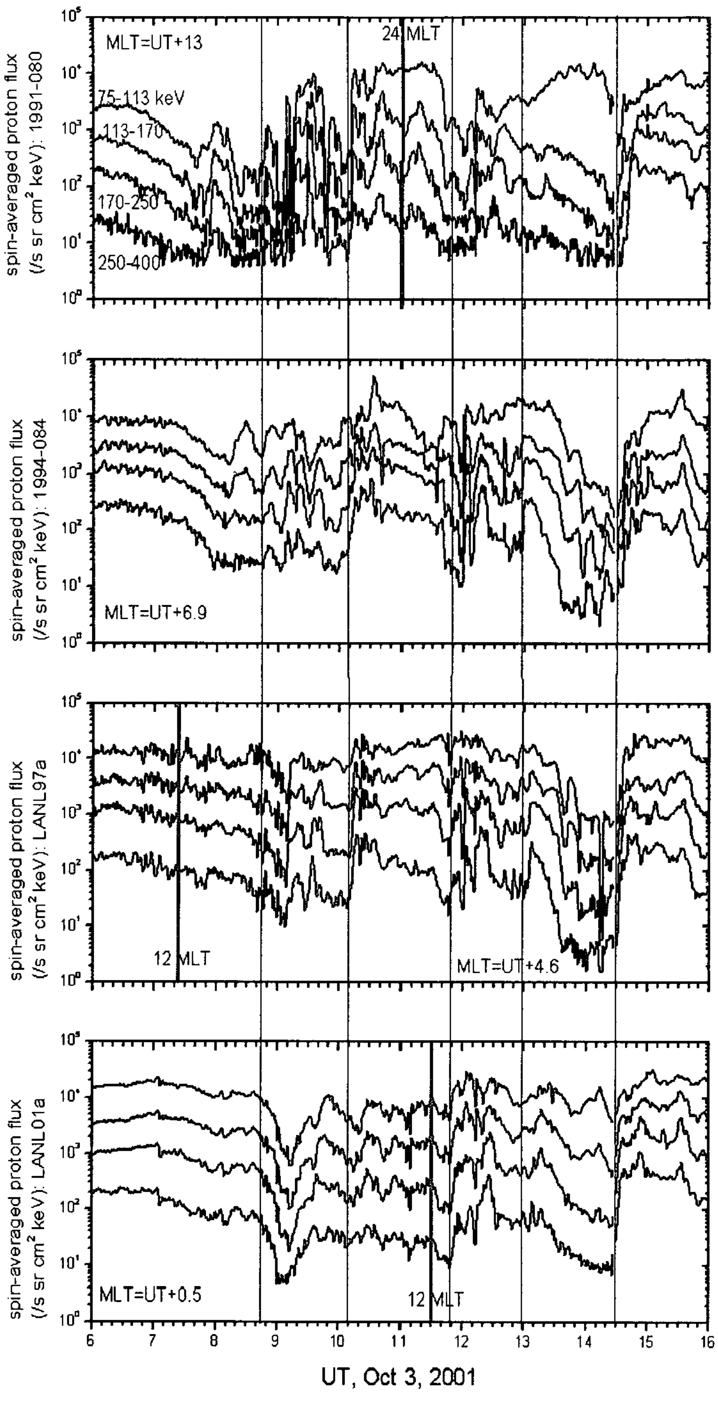

Figure 3. Energetic proton flux from the LANL spacecraft for Oct 3, 2001.

Second, the quasi-periodic ENA enhancements in the present storm-time are separated by $\sim$1.2 to $\sim$1.7 hrs. The repetitive nature seen in the ENA data is also seen in the local proton flux measurements as shown in Figure 3. Figure 3 shows the proton flux data from the LANL geosynchronous spacecraft in four energy channels between 75 and 400 keV. The proton flux variations in Figure 3 look rather complicated, but a close examination indicates a good temporal agreement between the major proton flux enhancements and the ENA flux enhancements found above (note that the temporal agreement should not be expected to be perfect since the available LANL proton flux is usually given 1-min time resolution whereas the ENA data from the HENA instrument is obtained at 2-min time resolution and one usually has to take an average over several spin periods; spin period=2min). In general, repetitive particle injections are seen during some of major storm-times (Lee et al. 2004), and similar, though not equivalent, phenomena are almost always seen during corotating high-speed solar wind streams (Lee et al. 2006). The average period of such conventional repetitive injections is normally 2–4 hrs, which thus implies that the period of our event is well-below the conventional periodicity.

What determined the shorter periodicity in our event is an interesting question that warrants a further examination. One possibility is that the quasi-periodic injections and ENA enhancements are due to quasi-periodic variations of solar wind dynamic pressure and/or the interplanetary magnetic field. Our preliminary analysis seems to support this possibility to some extent (data not shown), but it requires a rigorous investigation for a solid conclusion.

Comparing the observed ENA data with local in situ measurements of ions would be useful (Vallat et al. 2004), but it requires availability of a spacecraft at an ideal location that measures and distinguishes ion species. For the present event, the local measurement only at geosynchronous orbit is available as shown in Figure 3. It should however be noted that the ENA images (not shown) indicate the observed ENA came primarily from the region inside the geosynchronous orbit, which makes it impractical to quantitatively compare between the ENA observation and the LANL proton observation.

The ENA emission rate is sometimes affected by emissions at low altitude where more neutral particles are present and the charge exchange is dominated by nearly-mirroring/precipitating ions rather than near-equatorial ring current ions. It is currently a challenging task to separate the low altitude contribution from the total ENA emission. In fact, the ENA flux enhancement is generally not directly proportional to ion flux enhancement due to several reasons (Ohtani et al. 2005, 2006). Alternatively, the observed ENA flux can be inverted into parent ions (Brandt et al. 2002a,b), although it is technically quite difficult. It would be certainly be worthwhile to examine the inverted ions.

Jorgensen et al. (2000) reported that ENA enhancements are a new robust substorm indicator. Whether or not all of the ENA enhancement events found during the present storm-time are classic substorms should be answered in future. It would require to carefully examine auroral data, ground magnetic field data at mid to high latitudes, as well as geosynchronous magnetic and particle data in detail. This will be reported in a separate publication in future.

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