12-15-1997

Global energetic neutral atom (ENA) measurements and their association with the Dst index

A. M. Jorgensen

Harlan E. Spence
Boston University, harlan.spence@unh.edu

M. G. Henderson

G. D. Reeves

M. Sugiura

See next page for additional authors

GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 24, PAGES 3173-3176, DECEMBER 15, 1997

Global Energetic Neutral Atom (ENA) measurements and their association with the *Dst* index

A. M. Jorgensen, H. E. Spence

Center for Space Physics, Boston University, MA, USA

M. G. Henderson, G. D. Reeves

Los Alamos National Laboratory, Los Alamos, NM, USA

M. Sugiura

Research Institute of Science and Technology, Tokai University, Tokyo, Japan

T. Kamei

Data Analysis Center for Geomagnetism and Space Magnetism, Kyoto University, Kyoto, Japan

Abstract.
We present a new global magnetospheric index that measures the intensity of the Earth's ring current through energetic neutral atoms (ENAs). We have named it the Global Energetic Neutral Index (*GENI*), and it is derived from ENA measurements obtained by the Imaging Proton Spectrometer (IPS), part of the Comprehensive Energetic Particle and Pitch Angle Distribution (CEPPAD) experiment on the POLAR satellite. *GENI* provides a simple orbit-independent global sum of ENAs measured with IPS. Actual ENA measurements for the same magnetospheric state look different when seen from different points in the POLAR orbit. In addition, the instrument is sensitive to weak ion populations in the polar cap, as well as cosmic rays. We have devised a method for removing the effects of cosmic rays and weak ion fluxes, in order to produce an image of "pure" ENA counts. We then devised a method of normalizing the ENA measurements to remove the orbital bias effect. The normalized data were then used to produce the *GENI*. We show, both experimentally and theoretically the approximate proportionality between the *GENI* and the *Dst* index. In addition we discuss possible implications of this relation. Owing to the high sensitivity of IPS to ENAs, we can use these data to explore the ENA/*Dst* relationship not only during all phases of moderate geomagnetic storms, but also during quiescent ring current periods.

Introduction

Energetic Neutral Atom (ENA) measurements have been reported since the 1970's. Hovestadt and Scholer [1976] first suggested that highly anisotropic energetic hydrogen measurements were observations of energetic neutrals generated by the charge exchange of ring current particles with the tenuous hydrogen geocorona. The first association of ENA flux with ring current activity was made by Roelof et al. [1985]. They analyzed ENA measurements from IMP 7/8 and ISEE 1, and demonstrated, using hourly averages, a rough correspondence between ENA count rate and the rate of ring current recovery as measured by the *Dst* index.

Recently, Lui et al [1996] have reported on the first direct composition measurements of ENAs. They reported data from a single GEOTAIL pass around the day side of the earth, in which the ring current ENA flux was observed continuously for about 12 hours. Results from the Swedish ASTRID/PIPPI ENA imager were reported by Barabash et al. [1997], and C:son Brandt et al. [1997].

We demonstrate further the value of ENA measurements using data from the Imaging Proton Spectrometer (IPS), part of the Comprehensive Energetic Particle and Pitch Angle Distribution (CEPPAD) experiment [Blake et al., 1995] on the POLAR satellite. The first ENA images from IPS have previously been reported by Henderson et al. [1997]. In apparent contrast to previous reports, our observations suggest a relationship between ENA production and the *Dst* index, rather than the time derivative of the *Dst* index, although we suggest that this difference is not a contradiction, but rather reflects two different complimentary approaches to the same problem.

Data set and analysis

Although designed primarily to measure energetic ions, the IPS has the ability to detect ENAs. ENAs are identified as a weak signal of highly directional particles coming from the general direction of the earth (see for example figure 2a in Henderson et al. [1997]) In this paper we use data from the integral energy channel, which samples the complete unit sphere in 256 "pix-

Paper number 97GL03095.
0094-8534/97/97GL-03095$05.00

els": 9 look directions from parallel to anti-parallel to the spacecraft spin axis and 32 sampling intervals (sectors) in each spacecraft spin (except for the spin-aligned look directions, which sample 16 times per spin). This channel integrates over the full energy range of the IPS (15 keV-1500 keV) every 6 second spin. This covers the full range of energies responsible for the bulk of the ring current and plasma pressure in the inner magnetosphere.

From the full resolution 6 second data, 20 minute averages are produced at 10 minute intervals. In regions where there are no (or only very few) energetic ions, the signal observed by the IPS has two components: the ENA flux from the magnetosphere; and an isotropic cosmic ray/weak ion background. The IPS is also sensitive to light, and consequently some pixels are contaminated by earthlight or sunlight. The first step in the reduction is to identify these pixels, and exclude them from our analysis. The next step in the reduction is to subtract out the background due to cosmic rays and weak fluxes of energetic ions. A very simple method which has proved adequate in most cases is to assume that the background is isotropic. This is a very good assumption for cosmic rays, and even works well for subtracting out occasional weak Polar Energetic Particle (PEP) [Spence, et al., 1997a] signatures. Then the background can be computed as the average count rate in the pixels that look away from the Solar Magnetospheric (SM) equatorial (XY) plane. When POLAR is at large distances from the earth, presumably all ENAs are emitted relatively near to the XY SM plane, and therefore pixels that look away from the XY SM plane observe only the background. This computed background is then subtracted from each of the pixels looking towards the XY SM plane. The result of these computations leaves us with a data set of "pure" ENA counts measured by the pixels looking towards the XY SM plane. Since a typical ENA count rate in a pixel is 2-10 cts/sec (during storms) or greater, and a typical background count rate is 0.8 cts/sec, the 20 minute data set has typical counting uncertainties of 2-10%.

Next we introduce the measure that we call the Global Energetic Neutral Index (*GENI*). *GENI* is the total ENA count rate (summed over all pixels looking onto the XY SM plane) that would have been measured by the IPS instrument if it were situated at a standard reference point at 9 Re along the northern magnetic pole. In general the measured ENA count rate will depend on the relative location of the ENA source region (the ring current) and the satellite. The standard location is therefore introduced in an attempt to create a measure free of orbit biases. But in order to calculate *GENI*, we must have some method for transforming count rates from an arbitrary location in the magnetosphere to count rates at the standard location. To do so, we assume that ENAs measured in each pixel are emitted isotropically from a point source located at the projection of the center of the pixel's look direction on the XY SM plane. The count rate from that point source can be calculated at any point, by multiplying it with the ratio of distances squared between the point source, and the standard location, and the point source and the actual location of the satellite. Figure 1 illustrates this process graphically, and mathematically it is expressed as

$$GENI = \sum_i n_i \left(\frac{|\vec{r}_{sat} - \vec{r}_{prj,i}|}{|\vec{r}_{std} - \vec{r}_{prj,i}|} \right)^2 , \qquad (1)$$

where the sum is over all pixels that look onto the XY-SM plane, n_i is the ENA count rate in each pixel, $\vec{r}_{sat}$ is the location of the satellite, $\vec{r}_{prj}$ is the location of each point source, and $\vec{r}_{std}$ is the location of the standard point.

Because most of the ENAs are emitted from the ring current region, we should expect some sort of direct relationship between *GENI* and *Dst*. Indeed we find that the *GENI* tracks the provisional *Dst* index produced by the World Data Center C2 in Kyoto, remarkably well, as shown in Figure 2. The fact that the absolute magnitudes of the *GENI* and *Dst* index are nearly identical is purely a coincidence. It is important to note in figure 2 that *GENI* tracks *Dst* not only during the recovery phase of moderate storms (January 10 and onwards) but also during storm main phase (February 9) and during prolonged quiet periods (Early February).

Discussion

There are several assumptions that we have made in producing the *GENI*. First, we assume that all ENA production takes place in the XY SM plane at a point which is the center of the projection of the corresponding pixel in IPS. This is obviously not true, since ENAs are produced wherever there are both neutrals and energetic ions - a region that extends quite far out of the XY plane. However when POLAR is at a sufficiently high altitude (for example Z-SM > 3 Re) this is probably a reasonable zeroth-order assumption. The other assumption we make is that from every point where ENAs are produced, they are emitted isotropically. This is obviously not true either, since the charge-exchange process that produces ENAs preserves pitch-angle information, and thus the ENA flux observed along a line of sight from a given location depends not only on the production rate at that location, but also on the angular anisotropy at that location (a combination of the pitch-angle distribution and orientation of the field line). The reason that the assumption of isotropy is probably more reasonable than stated above is that each pixel of IPS is integrating over a large volume of space with a great variety of anisotropies, and field orientations in most cases, and therefore tends to diminish the importance of any local anisotropies.

The association between ENAs and the *Dst* index has previously been discussed theoretically by Roelof et al. [1985]. They derived a relationship between the recovery rate of the ring current as measured by *dDst/dt*, and the total ENA production in the magnetosphere. Using this relation they concluded that charge exchange

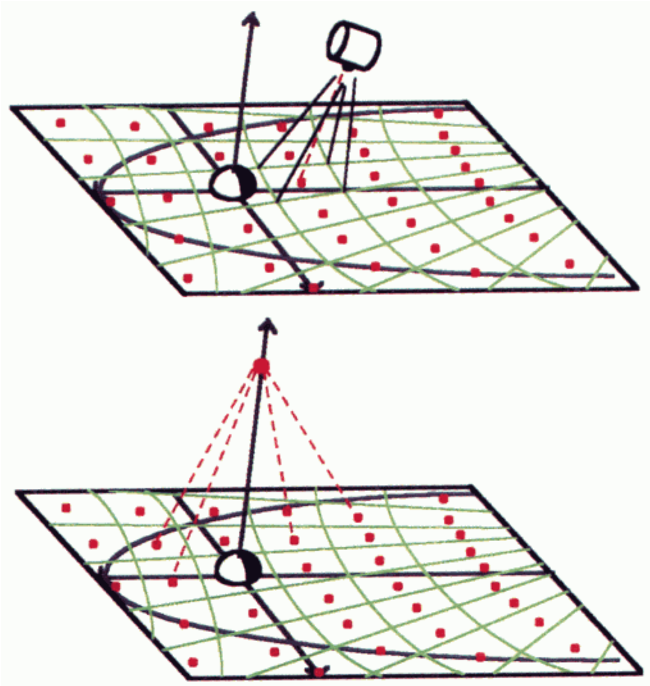

Figure 1. GENI is calculated by re-normalizing the ENA counts to some standard location. This is done by first projecting the pixel count rates to the equator, and then recalculating the expected count rate at the standard position, from the projected points

dominates the ring current recovery. They only applied their relation to the storm recovery phase at times when the charge exchange process is thought to dominate the ring current loss and thus the recovery rate of *Dst* ($dDst/dt$). With POLAR we observe an approximate proportionality between ENA production and the *Dst* index even during periods when the ring current is growing (i.e. storm main phase). Such periods were not considered directly by Roelof et al. [1985] so we explore along parallel arguments why ENAs should track *Dst* at all times.

The Dessler-Parker-Sckopke relation can be rewritten

$$\frac{\Delta B}{B_0} = \frac{< E > N}{E_B}, \qquad (2)$$

where N is the total number of energetic ions in the ring current, $< E >$ is their average energy, B_0 is the surface magnetic field strength at the equator, ΔB is the magnetic field deviation at the center of the Earth, and E_B is the total energy of the magnetic field outside the Earth. The total ENA production rate can be written as follows:

$$N_{ENA} = \int d^3r \int dE \int d\Omega j_{ion}(\vec{r}, E, \Omega, t)\sigma(E)n_H(\vec{r}), \qquad (3)$$

which by use of the mean value theorem can be reduced to

$$N_{ENA} = \sigma(E_0)n_H(\vec{r_0})N, \qquad (4)$$

where E_0 and $\vec{r_0}$ are a "characteristic" energy and radius vector for the ring current respectively. Assuming that ΔB is a good approximation for *Dst*, we can eliminate N from (4) and (2) to obtain

$$N_{ENA} = \frac{E_B}{B_0}\left[\frac{\sigma(E_0)n_H(\vec{r_0})}{< E >}\right] Dst \qquad (5)$$

Since our measurements indicate that $Dst = KN_{ENA}$, where K is a constant, the bracketed term in (5) must be constant. This most likely implies that

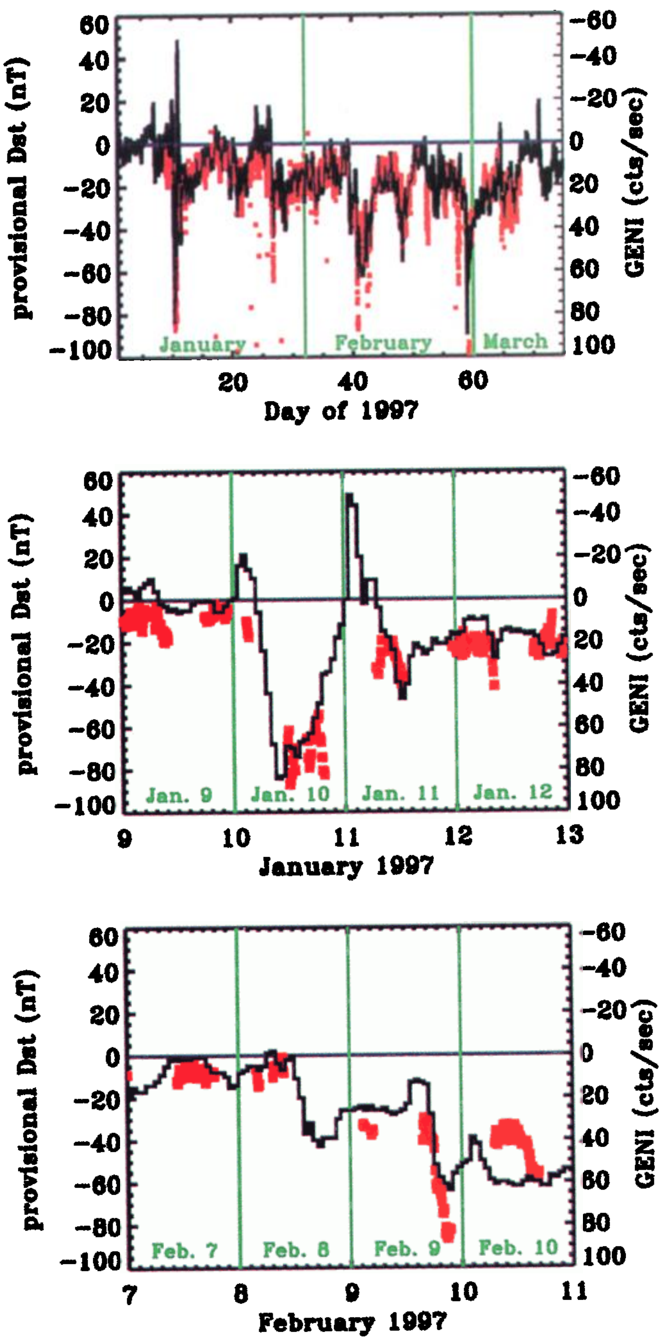

Figure 2. Dst and ENA as a function of time for the first 2.5 months of 1997, as well as closer looks at the January 10, 1997 storm and the February 8-9, 1997 storm.

E_0, $< E >$ and $\vec{r}_0$ are constant and independent of *Dst* for the storms we have observed, since both σ and n_H are rapidly varying functions of their parameters.

By careful inspection of ENA and *Dst* data values, we find that occasionally there is a tendency for measured ENA values to overshoot during main phase (i.e. too much ENA is produced to maintain a proportionality with *Dst*), and occasionally there is a tendency for ENA values to undershoot during recovery phase. This would be consistent with the inward motion of the ring current during storm main phase. As of yet these measurements are inconclusive, but they do yield the possibility of independently measuring the motion and energization of the ring current from *GENI* measurements on a scale smaller than the pixel size. In addition, the energy of the ring current ions can be measured through ENAs, fixing two of the three unknown variables, thus allowing us to determine the variation of $\vec{r}_0$ from small variations in the scaling factor between *Dst* and N_{ENA}

Our discussion of the direct relation between N_{ENA} and *Dst* actually does not contradict the results of Roelof et al [1985]. During storm recovery, the exponential decay of *Dst* with time means that $dDst/dt \propto Dst$. Thus we should expect *GENI* to be proportional to both *Dst* (our finding) and its derivative (during storm recovery only) [Roelof et al., 1985]. During main phase, when the ring current is being formed, only the general form of the equation from Roelof et al. (1985) can be used. Their equation 10 includes a ring current source term which can be neglected during recovery phase (conclusion of their paper) but not during main phase (solutions not considered in their paper). This source term must be sufficiently larger than the loss term (ENA production) to grow the ring current at a rate such that *Dst* tracks ENA production. So in principle equation 10 of Roelof et al. (1985) can be used to measure the ring current energy injection rate given the derivative of the *Dst* index and the ENA production rate.

We have shown that it is possible to reproduce the *Dst* index accurately from a particle based measurement, dominated by inner magnetosphere contributions. This allows for the possibility of settling the controversy of the relative contributions of the ring current and the magnetotail current to the *Dst* index. Initial analyses indicate that the tail contribution may not be significant.

Lastly, it should be noted that even given that the assumptions stated earlier are valid, *GENI* is not a perfect measure of the total ENA production rate. Rather, the *GENI* represents a family of indices, of which we have here explored only what may be called the $GENI_{9R_E}$. A more true measure of global ENA production would be $GENI_{\infty}$, which gives equal weight to all parts of the magnetosphere, rather than weighting higher the near earth regions as does $GENI_{9R_E}$.

Conclusion

We have created a Global Energetic Neutral Index (*GENI*), which reproduces with surprising accuracy the *Dst* index. We have shown that this index is an excellent proxy for the *Dst* index not only during storm recovery, but also during all levels of moderate geomagnetic activity. Smaller variations in the scaling factor between *Dst* and *GENI* may be used to explore details of the ring current evolution, such as the radial location of the ring current on a scale smaller than the instrument resolution. This study amply demonstrates the power of ENAs for probing quantitatively details of the global magnetosphere. For example, it appears that the *Dst* index is dominated by the ring current contribution, as opposed to other current systems.

Acknowledgments This work was supported by POLAR/CEPPAD MO&DA under NASA contract NAS5-97147. The authors wish to thank E. C. Roelof for useful comments.

References

Barabash, S., P. C. C:son Brandt, O. Norberg, R. Lundin, E. C. Roelof, C. J. Chase, B. H. Mauk, H. Koskinen. Energetic Neutral Atom Imaging by the ASTRID Microsatellite, Adv. Space Res., in press, 1997.

Blake, J. B., et al., CEPPAD experiment on POLAR, Space Sci. Rev., 71, 531, 1995.

C:son Brandt, P., S. Barabash, O. Norberg, R. Lundin, E. C. Roelof, C. J. Chase, B. H. Mauk, M. Thomsen. ENA Imaging From the Swedish Micro Satellite ASTRID During the Magnetic Storm of 8 February, 1995. Adv. Space Res., in press, 1997.

Henderson, M. G., G. D. Reeves, H. E. Spence, R. B. Sheldon, A. M. Jorgensen, J. B. Blake, J. F. Fennell. First Energetic Neutral Atom Images from Polar, submitted to GRL.

Hovestadt, D, and M Scholer. Radiation Belt-Produced Energetic Hydrogen in Interplanetary Space. JGR, v81, no28, October 1, 1976.

Lui, A. T. Y., D. J. Williams, E. C. Roelof, R. W. McEntire, and D. G. Mitchell, First Composition Measurements of Energetic Neutral Atoms, Geophys. Res. Lett., 23, 2641-2644, 1996.

Roelof, E. C., D. G. Mitchell, and D. J. Williams, Energetic Neutral Atoms (E 50 keV) from the Ring Current: IMP 7/8 and ISEE 1. JGR, v90, no11, pp10991-11008, November 1, 1985.

Spence, H. E., and J. B. Blake, First observations by the CEPPAD Imaging Proton Spectrometer aboard POLAR, Adv. Space Res., in press, 1997.

(received September 5, 1997;
accepted October 24, 1997.)