Imaging Two Geomagnetic Storms in Energetic Neutral Atoms

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Abstract. The IMAGE mission is the first of its kind. It is designed to comprehensively image a variety of emissions from the Earth's magnetosphere with sufficient time resolution to follow the dynamics associated with the development of magnetospheric storms. This paper describes initial observations of two qualitatively different geomagnetic storms by the IMAGE High Energy Neutral Atom imager (HENA). HENA images formed at energies between 10 and 60 keV/nucleon reveal the distribution and the evolution of energetic ion distributions as they are injected into the ring current during geomagnetic storms, drift about the Earth on both open and closed drift paths, and decay through charge exchange to pre-storm levels. Substorm ion injections are also imaged, as are regions of low altitude, high latitude ion precipitation into the upper atmosphere. Two events are discussed: one a major magnetic storm (the "Bastille Day" storm of July 15 and 16, 2000, Dst = –300nT), and the other, a minor storm (June 10, 2000, Dst = -55nT). The larger storm is characterized by ion injection deep into the magnetosphere (L~3 R_E), while the images from the minor storm are consistent with injection to L~7 R_E.

Introduction

The IMAGE Mission [Burch, 2000] was designed to explore several magnetospheric plasma regions never before routinely imaged. These regions include the cusp, magnetopause, and plasmapause (using radio propagation techniques); the plasmasphere (using resonant scattered He^+ 30.4 nm emission); the proton aurora (using Doppler shifted Lyman alpha emission); and the hot plasma populations (by imaging their emission in energetic neutral atoms).

The HENA instrument [Mitchell et al., 2000] is designed for this last objective, using atoms above about 10 keV/nucleon. Energetic neutral atoms (ENAs) are created through charge exchange interactions between the singly charged ions in hot magnetospheric plasmas and cold, neutral exospheric atoms (the hydrogen geocorona, which drops exponentially with height at high altitudes, and the atomic oxygen exobase at low altitudes). The ENAs freely escape their source region since they are no longer magnetically trapped. Since its launch on March 25, 2000, the IMAGE spacecraft has been in full operation through the course of several magnetic storms. HENA has continuously imaged the ring current at two minute time resolution in the 10 to 200 keV range throughout each of these storms, with the exception of orbital positions within the radiation belts where the instrument is set to a "safe" high voltage level and does not return science data.

Charge exchange neutrals in the 30 to 200 keV energy range have previously been detected by instruments on several Earth orbiting spacecraft, most of which were not specifically designed for ENA imaging: IMP-8 and ISEE-1 [Roelof et al., 1985, Roelof 1987]; the Swedish microsatellite Astrid [C:son Brandt et al., 1999]; the ISTP Geotail spacecraft, using the EPIC instrument [Lui et al., 1996], and most recently in the images returned by the CEPPAD detector on the ISTP Polar spacecraft [Henderson et al., 1997].

Imaging Technique

The HENA instrument has a geometric factor of approximately 1.0 cm^2sr, and a proton efficiency ~20% at 50 keV. Each pixel within a 120° swath of the sky is viewed as the scene is scanned during each spacecraft spin (spin period 2 minutes, spin axis to the orbit plane). Based on its trajectory, velocity, and species, counts in the appropriate pixel in the stored sky-map image are incremented. The HENA collimator serves to suppress charged particle entry by biasing adjacent collimating plates at ± 1.8 kV. The charged particle rejection reduces the ion flux by approximately 10^{-4} for ions <140 keV/q.

The HENA sensor images the ring current by recording the arrival direction and velocity of ENAs radiated from the optically thin emission regions, typically dominated by the ring current-exosphere interaction. Because the exosphere is relatively unchanging over time in shape and density, images of ENA produced by the interaction of the ring current energetic ion distribution with the exospheric hydrogen may be inverted through a variety of approaches to retrieve the original ring current ion distribution [e.g., Perez et al., 2000a, 2000b; Roelof and Skinner, 2000].

Magnetospheric Storm Observations

Since IMAGE launch, there have been several large geomagnetic storms. The first of these occurred on July 15 and 16, 2000, and has since been referred to as the "Bastille Day storm". Figure 1 compares one image measured in 39 to 60 keV hydrogen atoms during that event in three different formats. In the first image, as in each true image shown in this paper, the Earth's limb and terminator, as well as dipole field lines for L=4 and L=8 at noon, dusk, midnight and dawn are overlaid. The noon meridional field lines are labeled with an "S" for sunward, the tailward with an "A" for anti-sunward. Fig 1a presents the image, taken over the north pole, in unsmoothed pixels, converted to ENA flux. Figure 1b shows the same data, but in an array containing the actual counts in each pixel (accumulated over two minutes) of the image in Fig 1a. Figure 1c presents the same image again, but smoothed to reduce the statistical "speckling" that distracts the eye in Fig. 1a. Figure 1 is provided so that the reader may estimate the effects of the smoothing applied to the images in the remainder of the paper. Since the inherent angular resolution is larger than the pixels

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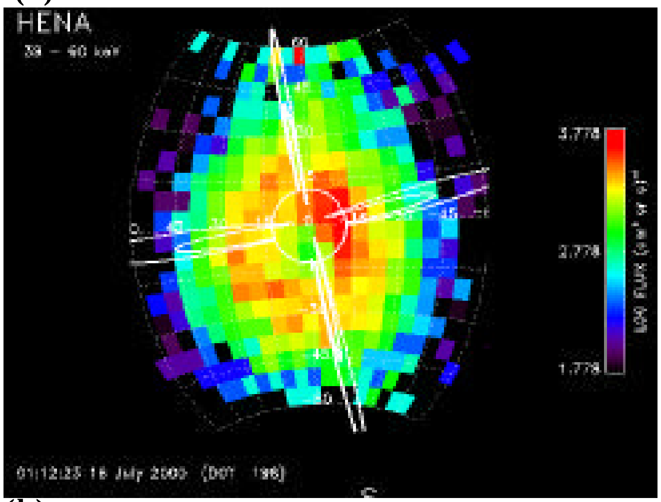
into which counts are accumulated, the smoothing does not eliminate or mask statistically meaningful structure.

(a)



(b)

1	0	0	1	0	0	1	5	1	11	1	1	3	2	2	0	0	0	0	0
0	0	0	1	0	4	1	5	1	1	3	4	0	1	2	0	1	0	0	0
0	0	0	0	0	2	3	0	4	7	6	2	5	5	1	1	0	1	0	1
0	0	0	2	0	4	4	5	3	9	13	9	8	4	2	1	5	1	0	1
1	0	1	0	3	7	7	10	16	14	17	13	11	7	6	6	1	0	1	0
0	0	1	3	2	11	21	18	26	20	24	17	12	6	4	4	0	1	1	0
1	2	1	5	12	20	28	36	42	26	33	35	25	23	13	8	1	1	2	0
2	1	6	12	19	24	34	56	45	44	63	53	26	25	22	15	3	0	1	1
1	2	2	12	27	44	47	52	45	63	81	92	51	34	21	9	11	1	3	2
0	5	11	14	29	47	57	55	51	69	90	128	77	46	23	14	6	5	2	0
1	3	6	24	36	54	50	45	40	29	72	136	59	41	38	23	5	8	1	0
0	1	9	22	40	64	44	45	36	20	33	86	64	46	39	13	6	3	1	0
0	4	11	20	24	46	47	35	31	27	32	62	50	45	26	19	4	4	1	0
3	2	9	10	17	48	45	55	43	37	35	43	33	36	25	17	5	2	5	0
1	2	8	10	15	21	27	30	31	34	33	29	31	25	13	7	4	0	1	0
1	0	3	7	11	13	13	26	31	22	27	25	23	21	12	7	4	3	0	0
1	1	2	0	6	4	14	13	15	13	22	10	9	11	7	2	2	0	1	0
0	1	1	1	1	6	8	5	7	4	5	4	7	2	2	2	3	0	0	1
0	0	1	1	2	1	2	1	2	1	4	4	3	2	1	4	0	0	0	0
0	0	0	0	0	0	0	1	1	1	0	0	0	1	2	0	1	1	0	0

(c)

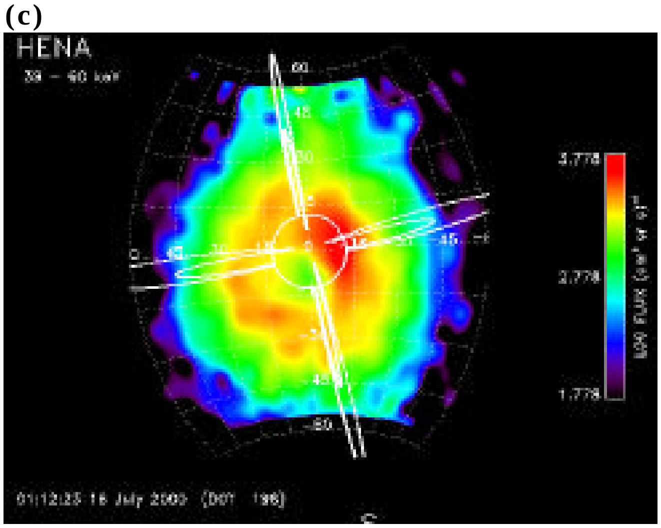


Figure 1. HENA ENA ring current emission 0112UT July 16, 2000. (a) Image from above the Earth's north pole. This vantage point provides a fairly undistorted view of the local time distribution of ENA emission. (High pixel fluxes along the top edge result from an instrument artifact.) (b) Same data as (a), in array of pixel values. (c) Same as (a), but pixels are smoothed.

Figure 2 shows images in ENA for hydrogen energies between 50 and 60 keV based on TOF measurement of the ENA. While this TOF range also corresponds to helium at 200 to 240 keV and oxygen at 800 to 960 keV, at such energies the flux of helium and oxygen should be significantly lower than that of hydrogen at 50 to 60 keV. The series of images is taken by the IMAGE spacecraft through one complete orbit. The solar wind shock reached the Earth's magnetopause at about 1430 UT on July 15. The first image is from an hour later, and shows emission from the northern hemisphere where field lines presumably containing freshly injected particles from the duskward hemisphere have reached low altitudes (where the ambient neutral density is high so that the probability for charge exchange is markedly elevated).

Substorm activity near 1600 UT produces an enhancement in the ENA flux in the 1555 UT image. The 1955 UT image, following the storm onset, shows greatly elevated ENA emission not only from the north as before, but also from the south.

Note that at these energies, scattering in the instrument limits the angular resolution to about 10° full-width-half-maximum (FWHM) in instrument elevation angle (roughly horizontal in the 1955 UT image), and about 6° in instrument azimuth. Because the low altitude emission is so much brighter than the high altitude emission [Roelof, 1997], the scattered wings of the low altitude pixels at this time dominate and mask the high altitude emission out to about 3 R_E. Shortly after this image was accumulated, IMAGE entered the outer radiation belts, where the HENA high voltages are routinely turned down as a safety precaution.

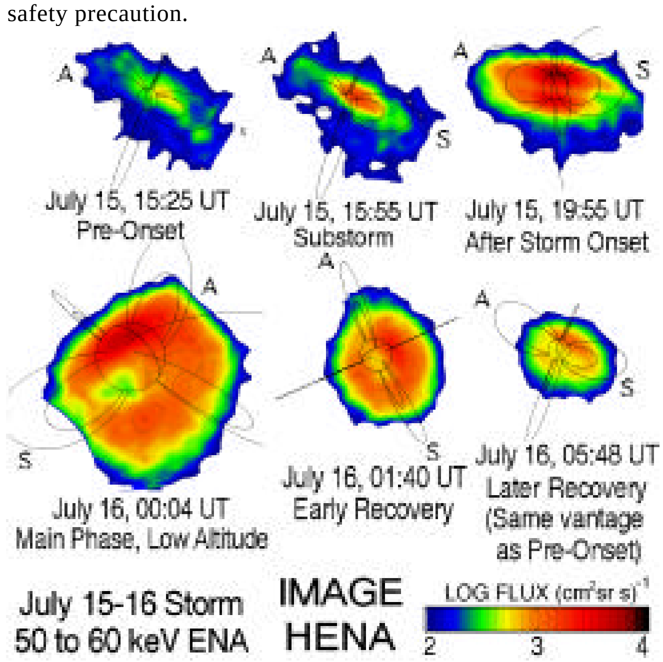


Figure 2. Images from the July 15, 16 2000 storm. This 14 hour sequence covers an entire orbit, so the distance from Earth and viewing perspective varies greatly. In each instance, the brightest emission stems from low altitude mirroring ions that charge exchange in the dense low altitude exosphere.

The image at 0004 UT on July 16 is the first after high voltage ramp-up as IMAGE leaves the radiation belts again on its outbound leg. From this vantage point, the Earth is fairly close and the emission more than fills the HENA field of view (FOV). Thus, the sharp cutoffs in emission toward noon and midnight simply represent the limits of the 120° HENA FOV. At this stage, the storm is in the main phase, Dst = –295 nT. The recovery begins almost immediately, so the final images show the emission as the Earth recedes and the storm recovers. Of note in the storm recovery images are two characteristics: 1) the emission shows little structure in local time, and 2) the emission is peaked inside L = 4, and falls steeply at larger L values. This is in contrast to the more modest event we now discuss.

Partial Ring Current Observations

Figure 3 shows several images of the ring current taken as the spacecraft flew over the north pole on June 10, 2000 during a moderate storm period when Dst never went below –60 nT. These images are from the HENA TOF channel that corresponds to 16 to 27 keV hydrogen atoms. Although energetic oxygen may also contribute to this image, hydrogen is thought to dominate. It is immediately apparent that the peak emissions, which appear to have been broadly injected on the night side, drift clockwise around the Earth by about 90° over the span of about 1.5 hours. This corresponds to a complete drift about the Earth in about 6 hours.

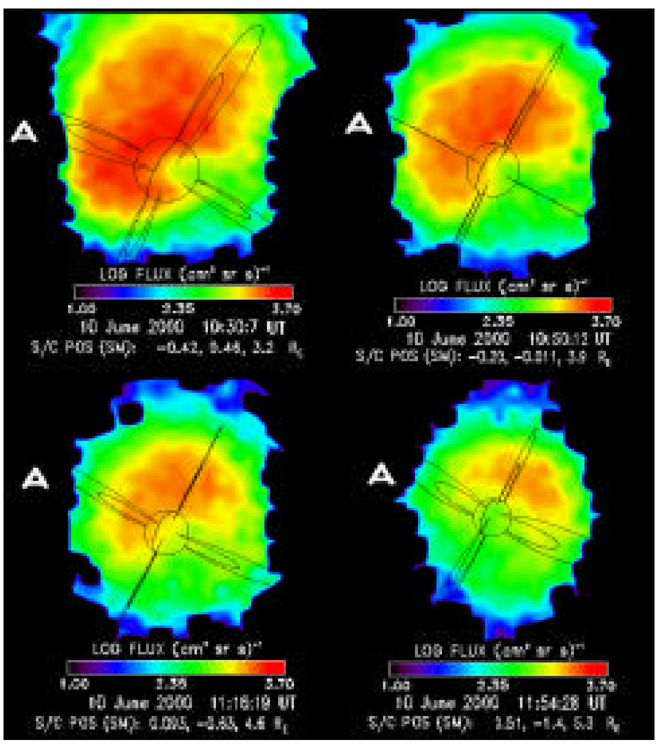


Figure 3. Sequence of images from June 10, 2000 storm of ENA emission at 16 to 27 keV (assuming hydrogen). Although the spacecraft moves within its orbit over the 1.5 hours covered by this sequence, the viewing perspective changes little enough that the gradient/curvature drift of the parent ion population can be followed. Over this period, the pattern rotates clockwise about the Earth by ~ 90°. The rectangular scallops along the edges of some images are smoothing artifacts equal in linear dimension to 2 adjacent pixels (roughly the size of two pixels at this energy). Peak pixels contain about 100 counts.

Using the drift frequencies calculated by Shultz and Lanzerotti [1974], this rotation rate would be expected for 20 keV protons at L ~ 7. Similarly, we would predict the drift time for an L = 7 injection of 40 keV protons to be about 3 hours, or 90° in 45 minutes. This is in fact what is observed in the 39 to 50 keV images for this event (Figure 4). Thus the HENA data for this injection of ions on the nightside on June 10, 2000 are consistent with protons being injected at L ~ 7, then drifting under gradient and curvature drift around to the dayside.

In contrast to the Bastille Day storm (Figs 1, 2), the bulk of the ENA emission in this relatively weak event lies much farther from the Earth. Although the color bars are different for the two events, the flux at 3 to 4 R_E is much higher for the Bastille Day storm, while the flux at 6 to 8 R_E is higher for the June 10 storm. However, in the June 10 storm, the particles are not stably trapped at those distances and these energies, so they eventually drift out of the magnetosphere in the dawn/noon quadrant.

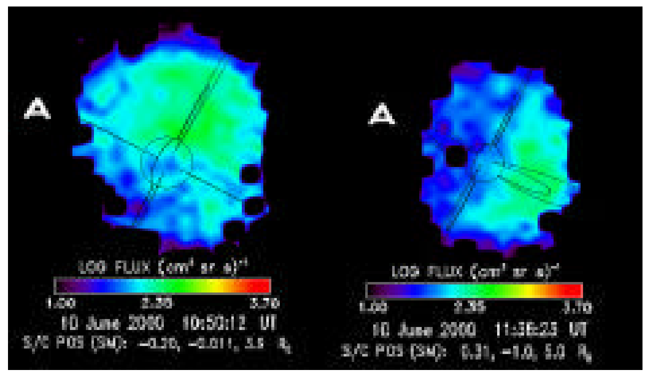


Figure 4. Two images from June 10, 2000 storm of ENA emission at 39 to 50 keV, assuming hydrogen atoms dominate. Over the 45 minute period between these images, the pattern rotates clockwise about the Earth by about 90°.

Conclusions

ENA images of the Earth's inner magnteosphere present both challenges and opportunities for understanding storms and substorms. Even without mathematical inversion of the images to retrieve the parent ion distributions, the initial images reveal the global topology of the ring current, thus yielding insights not possible before the availability of ENA imaging. It is clear that the contribution to the ring current in the small, June 10 storm and associated substorms was much further from Earth, and much more dependent on open drift path dynamics, than in the larger storm on July 16 where the ions contributing to Dst drifted primarily on closed paths.

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