A telescopic and microscopic view of a magnetospheric substorm on 31 March 2001

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[1] On March 31, 2001 at ~0635 UT when the CLUSTER constellation was near local midnight and at ~4 R_E geocentric distance, sensors observed an energetic electron injection event associated with a strong (AE ~ 1200 nT) magnetospheric substorm. Geostationary spacecraft 1991-080 located at ~20 LT also saw an abrupt electron injection event at ~0630 UT and FAST spacecraft instruments (~19 LT) detected a powerful set of magnetic field, electric field, and energetic plasma signatures at ~0637 UT. The energetic neutral atom imaging experiments onboard the IMAGE spacecraft detected an injection of substorm-produced ions in the pre-midnight sector commencing at ~0630 UT. Electron injection signatures at the four separate CLUSTER locations allow us to infer the location, speed, and direction of the substorm injection boundary. Hence, the CLUSTER (and IMAGE) telescope-microscope combination is a long-sought realization of a major magnetospheric research objective and shows the power of localized multi-point measurements from CLUSTER. *INDEX TERMS:* 2788 Magnetospheric Physics: Storms and substorms; 2720 Magnetospheric Physics: Energetic particles, trapped; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics. **Citation:** Baker D. N., R. E. Ergun, J. L. Burch, J.-M. Jahn, P. W. Daly, R. Friedel, G. D. Reeves, T. A. Fritz, and D. G. Mitchell, A telescopic and microscopic view of a magnetospheric substorm on 31 March 2001, *Geophys. Res. Lett.*, *29*(18), 1862, doi:10.1029/2001GL014491, 2002.

1. Introduction

[2] The Sun was very active during late-March and early-April of 2001: Numerous solar flares and coronal mass ejections (CMEs) were recorded by sensors onboard the Solar and Heliospheric Observatory (SOHO) spacecraft. Notably, a powerful solar eruption was observed at ~1000 UT on March 29, 2001 by the EIT experiment of SOHO, followed during the next several hours by the release of a large 'halo' CME event seen by the LASCO coronagraph experiment [N. J. Fox and the SOHO Consortium, private communication, 2001]. The halo CME apparently was directed toward the Earth and moved outward at high speed: Such an ejection could be expected to be very geoeffective. Early on March 31, 2001 a strong interplanetary shock wave struck the Earth, initiating one of the largest geomagnetic storms of this solar cycle (minimum Dst ~−360 nT at ~0900 UT on March 31). Direct observations near geostationary orbit [M. Thomsen, private comm.] showed that the magnetopause, and very probably even the Earth's bow shock, were pushed inside the geostationary orbit (=6.6 R_E geocentric distance). Such an extreme magnetospheric global "compression" is very rare [e.g., *Shue et al.*, 1998].

2. CLUSTER Observations

[3] CLUSTER consists of four identically-instrumented spacecraft flying in a (generally) tetrahedral configuration. The spacecraft move in a highly elliptical (and highly inclined) orbit with a perigee of ~4 R_E geocentric distance and an apogee of ~19 R_E [*Escoubet et al.*, 1997]. During the period of interest in late March 2001, the CLUSTER perigee was near the magnetic equatorial plane in the slightly pre-midnight local time sector. A detail of the CLUSTER orbit from 0400 to 1000 UT on March 31 is shown projected onto the $(X\text{-}Y)_{GSE}$ plane as the small inset in Figure 1a. The four separate CLUSTER spacecraft positions are shown by the different plotting symbols and are designated by C1 through C4. The tetrahedral relationship is exaggerated by a factor of ten (i.e., separations × 10) for plotting clarity. The CLUSTER constellation was below the Z = 0 plane and in the pre-midnight sector at 0635 UT. This time was a significant one based on various available data including those from the Research with Adaptive Particle Imaging Detectors (RAPID) experiment on CLUSTER which measures energetic electrons (20–400 keV) and energetic ions (30 keV–1.5 MeV) [*Wilken et al.*, 1997].

[4] Figure 1 shows selected data from the CLUSTER/RAPID investigation. The upper panel (Figure 1a) shows electron differential fluxes in the energy range 39–51 keV for the period 0615 UT to 0800 UT on March 31. Corresponding data from each of the equivalent energy channels on the four CLUSTER spacecraft (S/C) are plotted together using different line formats. At first glance, the flux profiles look rather similar for all four S/C: At the beginning of the interval the measured fluxes were low (near background) and then there was a very rapid rise in fluxes (by 2–3 orders of magnitude) at about 0630 UT. This was followed by a broad, slowly−decaying flux event during at least the subsequent hour. Were an event of such a general character seen at geostationary

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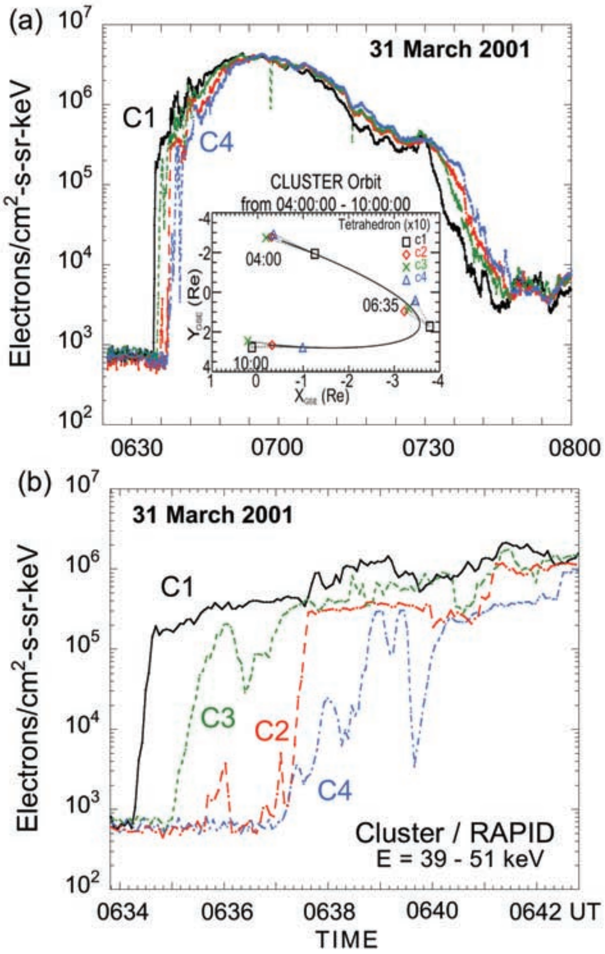

Figure 1. Selected energetic electron flux profiles from four CLUSTER S/C on March 31, 2001: (a) 39–51 keV data from 0615 to 0800 UT; and (b) A detail of data from 0634 to 0643 UT. The small inset in (a) shows CLUSTER orbital locations on March 31, 2001.

Earth orbit (GEO), it would likely be classed as a "dispersionless" substorm injection event [e.g., *Baker et al.*, 1978 and references therein]. However, as made clear by the inset, the CLUSTER constellation was well inside geostationary orbit (r $\sim$ 4 R_E) and in a region where only stable radiation belt fluxes normally are seen.

[5] More careful examination of the RAPID data shows that the four CLUSTER spacecraft, despite being at most a few hundred km apart, actually experienced very different flux onset timing and profile shapes. Figure 1b shows an expanded portion of the 39–51 keV flux profiles for the interval from 0634 to 0643 UT. As is evident, the abrupt flux enhancements which in broad overview had appeared quite similar for the four S/C actually were strikingly different in detail. CLUSTER S/C 1 (C1) showed the enhancement first (at 0634:20 UT), followed by C3 (at 0635:10 UT). There then were more complex onsets for C2 and, finally, C4. Overall, the flux enhancements at the four S/C, which eventually reached nearly identically the same peak flux level, rose at times that easily differed by 2–3 minutes. Such differences in onset time were seen, we again note, for spacecraft that were separated by tens to hundreds of km.

3. Solar Wind and Concurrent Magnetospheric Conditions

[6] The Advanced Composition Explorer (ACE) mission made solar wind plasma and interplanetary magnetic field observations from a vantage point $\sim$240 R_E upstream of the Earth in its L1 orbit. Figure 2a here shows the solar wind speed (V_{SW}) measured by ACE during the interval 0000–0800 UT on March 31. The data show two abrupt enhancements in V_{SW}, one at $\sim$0030 UT in which V_{SW} jumped from $\sim$420 km/s to >600 km/s and a second jump at $\sim$0200 UT in which V_{SW} went up to $\gtrsim$700 km/s. Interplanetary magnetic field (IMF) measurements from ACE (only the B_z component is plotted here) are shown in Figure 2b. The passage of the interplanetary shock is clear from the large, rapid increase and direction changes in B_z at $\sim$0030 UT. Perhaps most striking, however, were the large field magnitudes: Initially after the shock passage B_z was very strongly positive ($B_z > +40$ nT) and later B_z was even more strongly negative ($B_z \lesssim -50$ nT). Such high solar wind speeds and strongly southward IMF would clearly be expected to drive geomagnetic activity.

[7] Figure 2c shows supporting evidence that, indeed, there was strong substorm activity resulting from the solar wind drivers observed by ACE. The panel shows 50–315 keV electron flux values measured by instruments onboard LANL spacecraft 1991–080 at geostationary orbit. The data interval shown is 0500 UT to 0900 UT. A gradual, steady decline in fluxes occurred in all energy channels from 0500 UT until $\sim$0630 UT (as is characteristic of the substorm growth phase at geostationary orbit). There then was an abrupt flux increase at $\sim$0630 UT in all energy channels as is characteristic of substorm injection events during the substorm expansion phase onset [e.g., *Baker et al.*, 1978].

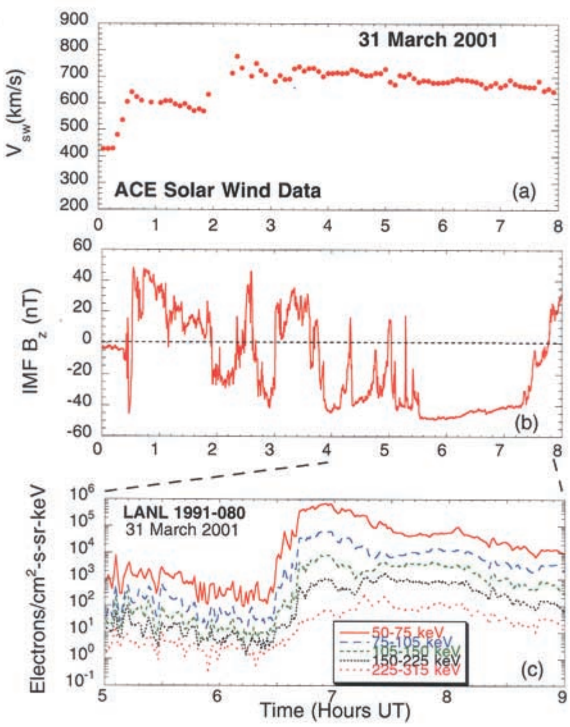

Figure 2. (a) ACE solar wind speed; (b) ACE IMF Bz data; and (c) LANL electron data on March 31, 2001.

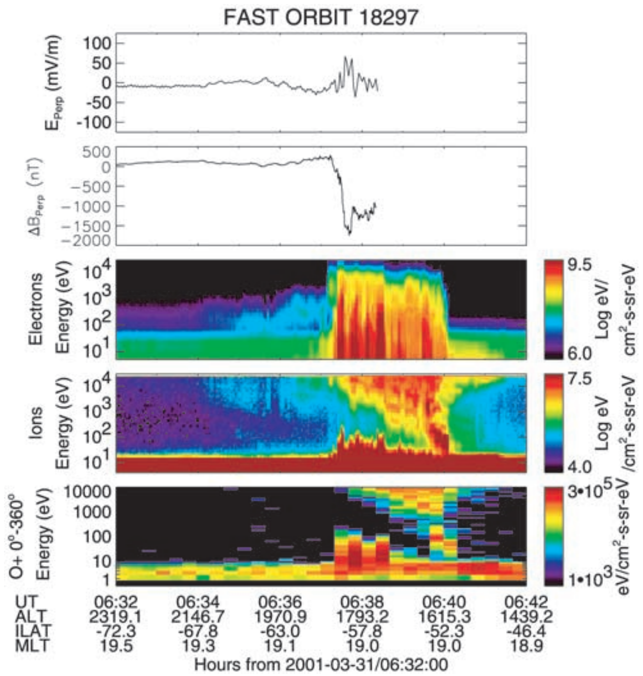

Figure 3. FAST data for the period 0632 to 0642 UT on March 31, 2001.

Shifting the ACE solar wind measurements forward in time by the requisite 30–45 min (to account for solar wind transit time) shows that the LANL substorm injection event was very plausibly associated with an extended interval of southward IMF which would have loaded energy into the magnetosphere during the substorm growth phase. Auroral electrojet indices from the World Data Center (in Kyoto, Japan) showed a major enhancement at $\sim$0630 UT with AE reaching $\sim$1200 nT (data not shown).

[8] A somewhat surprising point is that S/C 1991-080 was located at $\sim$20 LT at the time ($\sim$0630 UT) of the relatively dispersionless electron injection shown in Figure 2c. It is relatively rare to see dispersionless electron injection events as far in the pre-midnight sector as 20 LT [*Baker et al.*, 1978; *Friedel et al.*, 1996]. It is much more common to see such dispersionless electron injections near local midnight or in the post-midnight sector. Fortunately, the Fast Auroral Snapshot (FAST) spacecraft was operating in the local dusk sector ($\sim$19 LT) in the southern hemisphere at $\sim$1800 km altitude (and invariant latitude $\sim -60°$): These data provide further evidence to support a far−premidnight substorm onset.

[9] Figure 3 shows selected data from the FAST satellite [*Carlson et al.*, 1998] for the period 0632 UT to 0642 UT. The panels include: (a) The electric field perpendicular to ambient B and nearly along the velocity of the spacecraft ($\mathbf{V}_{sc}$- mostly Northward); (b) The perturbation magnetic field (ΔB) in the $\mathbf{V}_{sc} \times \mathbf{B}$ direction (mostly Eastward); (c) The electron differential energy flux in an energy-time (E-t) spectrogram from $\sim$5 eV to $\sim$30 keV; (d) The ion E-t spectrogram in the same energy range; and (e) The E-t spectrogram of O^+ ions from $\sim$1 eV to 10 keV. The FAST data (especially panels (c) and (d)) suggest that the spacecraft was in a relatively quiescent (and benign) plasma sheet environment from $\sim$0634 UT to $\sim$0637 UT. Abruptly at 0637 UT, FAST was immersed in an intense population of downflowing electrons and upflowing ions. From careful analysis and comparison of the total ion sensor (panel (d)) and the composition sensor (panel (e)) response, it is concluded that the upflowing ions detected by FAST from 0637 until at least 0640 UT were almost entirely comprised of O^+ ions. Note that the ions were of such high energy that they were mostly offscale.

[10] The strong perturbation in the East-West component of the magnetic field (Figure 3b) was one of the largest ever recorded by FAST [R. J. Strangeway, private communication, 2001] and indicates a powerful upward current with current densities reaching $\sim$40 A/m^2. The moderate electric field ($\sim$60 mV/m) suggests high ionospheric conductivity. The electric field, however, remained positive for tens of seconds (auroral electric field structures are often less than 1 s) and thus carries several kilovolts of potential across the current sheet. This set of observations is atypical of the Region 1 current system and suggests that at 0637 UT FAST may have encountered the upward substorm current wedge.

4. Global Neutral Atom Imaging

[11] The IMAGE spacecraft has onboard several ultraviolet (UV) and energetic neutral atom (ENA) imaging systems [*Burch et al.*, 2001]. Unfortunately, the UV systems were turned off during an interval of time that included March 31, but the medium-energy (MENA) and high-energy (HENA) sensor systems were operative throughout March 31. As described by *Burch et al.* [2001], the MENA sensors cover the energy range 1–30 keV and the HENA sensors cover 16–500 keV ENA energies. The ENA signatures are produced by charge-exchange reactions between energetic magnetospheric ions and hydrogen atoms in Earth's (charge-neutral) exosphere. The ENAs are able to move freely across magnetic field lines on direct paths from their points of

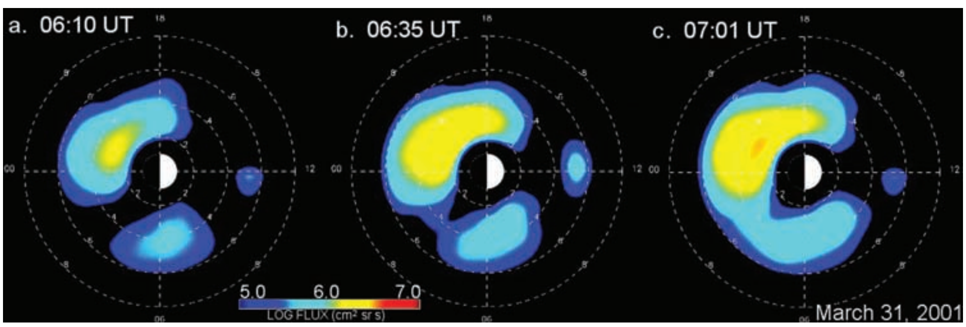

Figure 4. IMAGE 100–160 keV oxygen ENA images for selected times as shown on March 31, 2001.

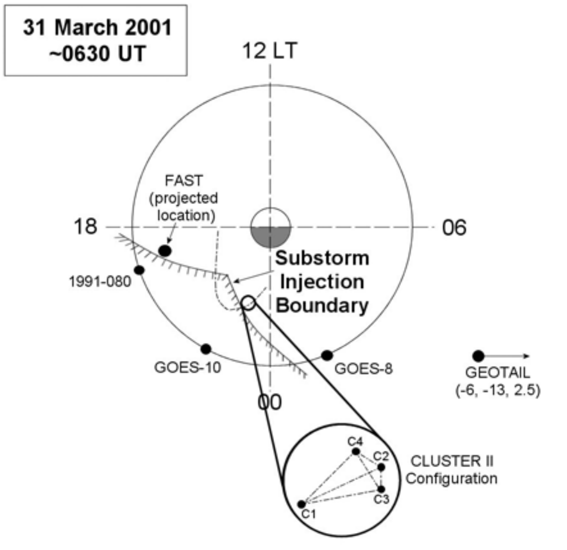

Figure 5. A schematic summary of the substorm onset events at ∼0635 UT on March 31, 2001.

origin. This allows construction of images of the parent ion source population. We have examined images from both ENA systems on March 31 and in the range of overlap (∼16–30 keV) the two imagers agree quite well. Here in Figures 4a–c we show selected HENA images. In this case the atoms were oxygen in the energy range 100–160 keV. Onset times shown are: (a) ∼0610 UT; (b) ∼0635 UT; and (c) ∼0701 UT.

[12] The ENA images in Figure 4 show data in the substorm growth phase (a) and in the expansion phase (b and c). The Earth is shown in the center of each frame with local noon to the right. A constrained linear inversion technique [P. Brandt, private communication, 2002] is used on the HENA data. Equatorial radial distances from 2 to 8 R_E are shown by the dashed concentric circles. From the inversion it is difficult to determine the precise radial distribution of ions. However, the sequence of images show that the ENA fluxes were relatively low prior to ∼0630 UT, and became greatly enhanced after ∼0630 UT. The largest ENA enhancements were initially detected well toward the dusk sector (i.e., pre-midnight).

5. Interpretation and Conclusions

[13] From the results presented here, we conclude that a substorm injection boundary [see *Baker et al.*, 1996 and references therein] was probably pushed very close to the Earth during the extreme conditions that obtained on March 31. We also conclude that the substorm "current wedge" region was shifted far toward the premidnight sector in this exceptional case. The geometry for this event is portrayed in Figure 5.

[14] It is evident that S/C 1991-080 and FAST, despite being in the post-dusk sector, were enveloped by particle populations and magnetic field reconfigurations suggesting powerful substorm boundary effects. Although not shown here, data from GOES-10 at ∼22 LT showed a magnetic field dipolarization at ∼0630 UT, consistent with GOES-10 being within the substorm current wedge region [H. Singer, private comm., 2001]. As shown here, the CLUSTER constellation, especially C1 and C3, saw the substorm energetic electron injection boundary pass over them at 0634:20 and 0635:10 UT, respectively. The boundary then apparently just barely reached C2 at 0635:40 UT (see Figure 1b) and then receded slightly. Not until 0637:20 was C2 fully enveloped by the boundary passage and C4 was gradually engulfed by the injection boundary in an extended interval from 0637:20 until after 0639 UT.

[15] The CLUSTER S/C were arrayed essentially as portrayed in the small inset in Figure 5: C1 was furthest from local midnight and also was closest to Z = 0 at 0635 UT. The constellation of S/C was moving slowly (<1 km/s) in the X-direction at 0635 UT, but was moving faster in Y and Z (V_y = +2.5 km/s and V_z = +4.0 km/s) at that time. From the times of the electron injection boundary crossings derived from Figure 1b and given the known relative S/C separations, we calculate that the injection boundary had velocity components (V_x, V_y, V_z) = (8, −24, −10) km/s at ∼0635 UT. This had slowed to (1, −10, −8) km/s by ∼0636 UT. Thus when observed by CLUSTER, the boundary was nearly stationary (or was undulating) after 0637 UT. The motions that were occurring near the CLUSTER locations from 0634 to 0636 were predominantly in the −Y and −Z directions. Hence, the injection boundary was spreading in azimuth and also was spreading (dipolarizing?) in the north−south sense. We look forward to analyzing all CLUSTER plasma and field data to refine our understanding of this case.

[16] **Acknowledgments.** This work was supported by grants from NASA. We thank ACE, CLUSTER, FAST, GOES, IMAGE, and SOHO teams for data and many useful discussions. We thank P. Brandt for HENA data plots.

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