Observations of Neutral Atoms from the Solar Wind

Michael R. Collier[1], Thomas E. Moore[1], Keith W. Ogilvie[1],
Dennis Chornay[1,2], John Keller[1], S. Boardsen[1], James Burch[3],
B. El Marji[1,2], M.-C. Fok[1], S.A. Fuselier[4], A.G. Ghielmetti[4], B.L. Giles[1],
D.C. Hamilton[2], B. Peko[5], J.M. Quinn[6], T. Stephen[5], G.R. Wilson[7] and P. Wurz[8]

1. NASA/Goddard Space Flight Center, Greenbelt, Maryland
2. University of Maryland, College Park
3. Southwest Research Institute, San Antonio, Texas
4. Lockheed Martin Advanced Technology Center, Palo Alto, California
5. Denver University, Colorado
6. University of New Hampshire, Durham
7. Mission Research Corporation, Nashua, New Hampshire
8. University of Bern, Switzerland

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Abstract. We report observations of neutral atoms from the solar wind in the Earth's vicinity with the Low Energy Neutral Atom (LENA) imager on the IMAGE spacecraft. This instrument, unlike most other neutral atom imagers, was specifically designed to be capable of looking at and in the direction of the Sun. Observed enhancements in the hydrogen count rate in about the solar direction are correlated with neither solar ultraviolet emission nor suprathermal particles and are therefore deduced to be due to neutral particles from the solar wind. Based on the presence of sputtered oxygen observed in the tof spectra, the energy of these neutral particles exceeds ~1 keV, consistent with solar wind-like energies. In addition, the sputtered oxygen abundance tracks the solar wind speed, even when IMAGE resides deep inside the magnetosphere. These results show that low energy neutral atom imaging provides the capability to directly monitor the solar wind and/or magnetosheath from inside the magnetosphere.

1. Introduction

On March 25, 2000, the Low Energy Neutral Atom (LENA) imager, one of six science experiments on the IMAGE observatory, became the first instrument launched on a spacecraft to study the low energy, a few tens to a few thousands of electron volts, component of space plasmas [*Moore et al.,* 2000]. This marks a major advance in space plasma physics because much, if not most, of the plasma in the heliosphere is in the LENA energy range. Like more energetic neutral atom imaging instruments, LENA has the ability not only to detect neutral atoms, but also to determine their direction in two angles as well as their mass and energy [*Hsieh et al.,* 1992]. Because LENA was specifically designed to peer directly at the sun and responds to neutrals of energies of the order of 1 keV, the instrument will observe that fraction of the solar wind flow that represents neutral hydrogen. This component has been long-recognized as of potentially great importance for understanding solar, interplanetary and magnetospheric physics [*Akasofu,* 1964].

Charge exchange between solar wind protons and neutral particles is primarily resposible for the formation of the neutral solar wind, although there is a neutral component of the solar wind due to its equilibrium charge state distribution [*Arnaud and Rothenflug,* 1985] and due to recombination of solar wind ions with solar wind electrons [*Gruntman,* 1994]. The neutrals on which the solar wind protons charge exchange may originate from dust grains [*Schwadron et al.,* 2000; *Holzer,* 1977] or be interstellar neutral atoms or part of the Earth's geocorona. To highlight the potential importance of charge exchange with the Earth's exosphere, note that the geocoronal density at the magnetopause is comparable to the solar wind density [*Wallace,* 1970]. Also note that because charge exchange with the geocorona will occur preferentially near the Earth, the neutral solar wind characteristics may be heavily influenced by magnetospheric structures such as the magnetosphere and cusp producing, for example, angularly wider profiles and signals coming from directions offset from what might be expected from pure solar wind that had charge exchanged upstream of the Earth's bowshock.

2. Observations from the June 8, 2000 Event

After reaching science operations level on May 5, 2000, LENA had its first opportunity about a month later to observe a coronal mass ejection (CME) and its effect on the terrestrial environment [see companion papers in this issue by Moore *et al.* and Fuselier *et al.*]. On June 6, 2000, an intense solar flare was observed on the sun followed by a full-halo CME. The shock driven by this CME was observed on June 8, 2000 at the L1 point, 235 R_E upstream from the Earth, by the ACE spacecraft at about 08:42 UT and by the Wind spacecraft, 41 R_E upstream, at about 09:05 UT. A few minutes later, this disturbance passed the Earth where it and its effects were observed by the IMAGE spacecraft.

Figure 3 of the companion paper in this issue by Moore *et al.* (Low Energy Neutral Atoms in the Magnetosphere) shows a LENA spectrogram of the hydrogen, oxygen and combined count rate as a function of time on June 8, 2000, the day the CME-driven shock passed the Earth. The bright streak that starts out near 90° and drifts towards 180° is a signal initially thought to represent a response to the EUV photon flux from the Sun. This is roughly consistent with its motion relative to the IMAGE/LENA imager view of the Earth (nadir viewing direction, the direction of the Earth, is 0° on the vertical axis) as IMAGE begins to descend from a northern hemisphere dayside apogee toward perigee in the southern hemisphere. However, when this signal increased significantly at the arrival of a shock in the solar wind associated with a CME, it was concluded that at least part of this signal must represent neutral atoms from the solar wind. Subsequent analysis based on in-flight and calibration data show LENA to have a negligible response to UV.

Given that UV is not the cause of the observed enhancement from the solar direction, one must examine the possibility that this increase is due to suprathermal ions penetrating the collimator. At the time of the June 8, 2000 event LENA was fully operational with about 8.8 kV across the collimator. At this voltage level, the collimator filters out all particles with energies up to 55 keV/e while above about 83 keV/e most ions traverse the collimator and arrive inside the instrument. Because energetic ion spectra at these energies in most space plasma environments are rapidly decreasing power laws [*Collier et al.*, 1993], the primary contributor to the energetic ion flux entering LENA in-flight is likely close to the 55 keV/e lower limit on entering ion energy.

Figure 1 shows on the left hand y-axis with the solid lines and circles the time profile of the LENA background-adjusted Sun direction counts per spin. The profile peaks shortly after shock passage and slowly drops for about an hour thereafter. The ACE/EPAM ion flux data between 47 and 65 keV which includes the 55 keV low energy limit on LENA ion admittance on this day show practically a step function increase at the time of the shock. If LENA were responding to energetic ions, we would expect the time profile for the two rates to be similar. Thus, we can conclude that LENA is not responding to suprathermal particles at this time.

As further evidence that LENA is not responding to suprathermal particles, Fig. 1 also shows the solar wind ram pressure observed by the Wind spacecraft with dashed lines on the right hand y-axis and the times when the Boardsen *et al.* [2000] high latitude magnetopause model predicts that IMAGE is inside the magnetosphere indicated with the black bars on the top x-axis. Wind at this time was about 41 R_E upstream and about 27 R_E off the Sun-Earth line, well within the $\sim$40 R_E scale length inferred by Collier *et al.* [1998] for IMF correlations so that it is likely that Wind was serving as a reliable interplanetary monitor. Although the Boardsen *et al.* model predicts IMAGE moved across the magnetopause eight times in this three hour period, there are no sudden jumps in the LENA count rate associated with these crossings similar to what is frequently observed in ion data at energies around 80 keV. Furthermore, when IMAGE is inside the magnetosphere, we would not expect the energetic particles to arrive from the same direction as the sun pulse.

By eliminating light and charged particles as possible sources, we conclude LENA is observing neutrals at this time, and we strongly suspect that the sun pulse in general is primarily if not entirely due to neutral particles. However, we have not yet addressed the issue of whether or not the neutral atom energy is consistent with solar wind-like energies of the order of keV. Figure 2 shows LENA calibration data from the Denver University neutral beam facility. The upper panel shows a time-of-flight spectrum resulting from incident 30 eV atomic hydrogen. A well-defined hydrogen peak sits at low times-of-flight with no evidence of an oxygen peak. This is true below a transition that appears to fall somewhere between 300 eV and 1000 eV. Above this transition, as shown in the lower panel of Fig. 2 for 1000 eV atomic hydrogen, a siginificant oxygen peak appears probably due to high energy hydrogen sputtering lower energy oxygen or water off the conversion surface.

Figure 3 shows a time-of-flight spectrum taken over the time period of the enhancement on June 8, 2000. In addition to the hydrogen and oxygen peaks, there is a third ringing peak which appears in the in-flight data but not in the calibration data probably because we are running in-flight at a higher start microchannel plate bias level producing an enhanced gain. However, it is interesting to note that this peak sits about where we would expect the peak for H^{2-}. Note that there is a pronounced oxygen peak in the time-of-flight spectrum so, banning the possibility that there are large neutral oxygen fluxes in the solar wind, this suggests the neutral hydrogen has energy ~1 keV

This also suggests that the ratio of hydrogen to oxygen in the LENA time-of-flight spectrum may be used to monitor solar wind speed from inside the magnetosphere. The left hand y-axis and solid line in Figure 4 shows the solar wind speed with time as observed by the SWE instrument on Wind. The right hand y-axis and solid circles indicate the background-adjusted sun sector hydrogen to oxygen ratio from hour long tof spectra averages. Prior to the shock passage, the ratio is typically below 0.30 while after the shock passage the ratio is above 0.40 indicating that LENA has observed the solar wind speed increase from inside the magnetosphere.

3. Discussion

Having argued that LENA has observed neutral particles from the solar wind, we should estimate the neutral flux during the enhancement period and compare to expectations. Based on Fig. 1, the count rate during the enhancement is about 15 counts per spin. Each spin sector is observed for about 2.7 seconds so that this is a count rate of 5.6 s^{-1}. At solar wind-type energies, LENA's neutral hydrogen efficiency is about 6.4×10^{-5}. With LENA's 1 cm^2 aperture, this implies a flux of about 8.8×10^4 $cm^{-2}s^{-1}$. At this time, the solar wind flux was $\sim 10^9$ $cm^{-2}s^{-1}$ (12 cm^{-3} density and 800 km/s speed) yielding a flux ratio of neutrals to solar wind of about 10^{-4}.

This value is comparable to the expected neutral solar wind component at 1 AU [*Gruntman,* 1994; *Holzer,* 1977]. However, the LENA observations include the potentially significant contribution due to charge exchange with the geocorona which should raise the ratio. On the other hand, given the IMAGE orbit on this day, LENA is probably observing the neutral solar wind that charge exchanges before the bowshock on the edge of its field of view which should lower the ratio. In any case, in an order-of-magnitude sense the observed LENA count rate is about what would be expected for the neutral solar wind.

To illustrate the potential importance of charge exchange with the Earth's geocorona, we will do a simple calculation to estimate the expected fraction of the signal resulting from this effect. Using the geocoronal density N(R) determined by Wallace *et al.* [1970] as

$$\mathrm{N(R)} = 10 \cdot \left(\frac{11}{\mathrm{R}}\right)^{3} \mathrm{cm}^{-3}, \tag{1}$$

where R is the distance from the Earth in Earth radii (the hydrogen atom distribution is a smoothly varying function of the distance from the center of the planet) we can calculate the neutral atom flux due to charge exchange with the geocorona $\mathrm{F_{geo}}$ as [*Roelof,* 1997; *Roelof and Skinner,* 2000]

$$\mathrm{F_{geo}} = \int_{\mathrm{r_{mp}}}^{\infty} \mathrm{N(R)}\, \sigma\, \mathrm{n_{sw} v_{sw}}\, \mathrm{dR}, \tag{2}$$

The solar wind neutrals are expected to emerge from the charge exchange collision with their initial velocity, $\mathrm{v_{sw}}$, and the solar wind density, $\mathrm{n_{sw}}$, not significantly depleted so that the fraction of the solar wind density we expect to be neutral due to its interaction with the Earth's geocorona is simply

$$\frac{\mathrm{n_{geo}}}{\mathrm{n_{sw}}} = \int_{\mathrm{r_{mp}}}^{\infty} \mathrm{N(R)}\, \sigma\, \mathrm{dR}, \tag{3}$$

Using equation (1) for the neutral density and taking $\sigma = 2\text{x}10^{-15}$ cm^2, we get

$$\frac{n_{geo}}{n_{sw}} = 10\,\text{cm}^{-3} \cdot 11^3 \cdot 2\text{x}10^{-15}\,\text{cm}^2 \cdot 6371\text{x}10^5\,\text{cm} \cdot \int_{r_{mp}}^{\infty} \frac{dR}{R^3}$$
$$= \frac{8.5\text{x}10^{-3}}{r_{mp}^2}, \qquad (4)$$

where r_{mp} is measured in Earth radii.

At standard magnetopause distances of 10 R_E, this results in a fraction of about 10^{-4}, comparable to the expected neutral solar wind component at 1 AU [*Gruntman,* 1994; *Holzer,* 1977] so that this effect under normal circumstances will tend to double the neutral solar wind flux.

9. Conclusions

We have reported observations of a count rate increase observed by LENA on June 8, 2000 when a shock driven by a CME associated with a solar flare on June 6, 2000 arrived at the Earth. By establishing that the signal coming from the general direction of the sun is neither due to UV photons nor due to suprathermal particles, we have concluded that the enhancement and likely the pre- and post-event signal are due to neutral solar wind. We have shown based on a comparison between LENA time-of-flight spectra from calibration and from this event that the observed neutral hydrogen energies are ~1 keV, energies characteristic of the solar wind. In addition, we observed in the solar wind neutral particles the large solar wind velocity jump associated with the shock passage. We estimate the observed neutral solar wind flux based on LENA efficiencies from calibration data and arrive at a solar wind neutral flux to solar wind ion flux ratio of about 10^{-4}, consistent with expected neutral solar wind fluxes at 1 AU. However, we point out that much of this signal may be due to solar wind charge exchange with the geocorona near the magnetopause. These results show that low energy neutral atom imaging provides the capability to directly monitor the solar wind and/or magnetosheath from inside the magnetosphere.

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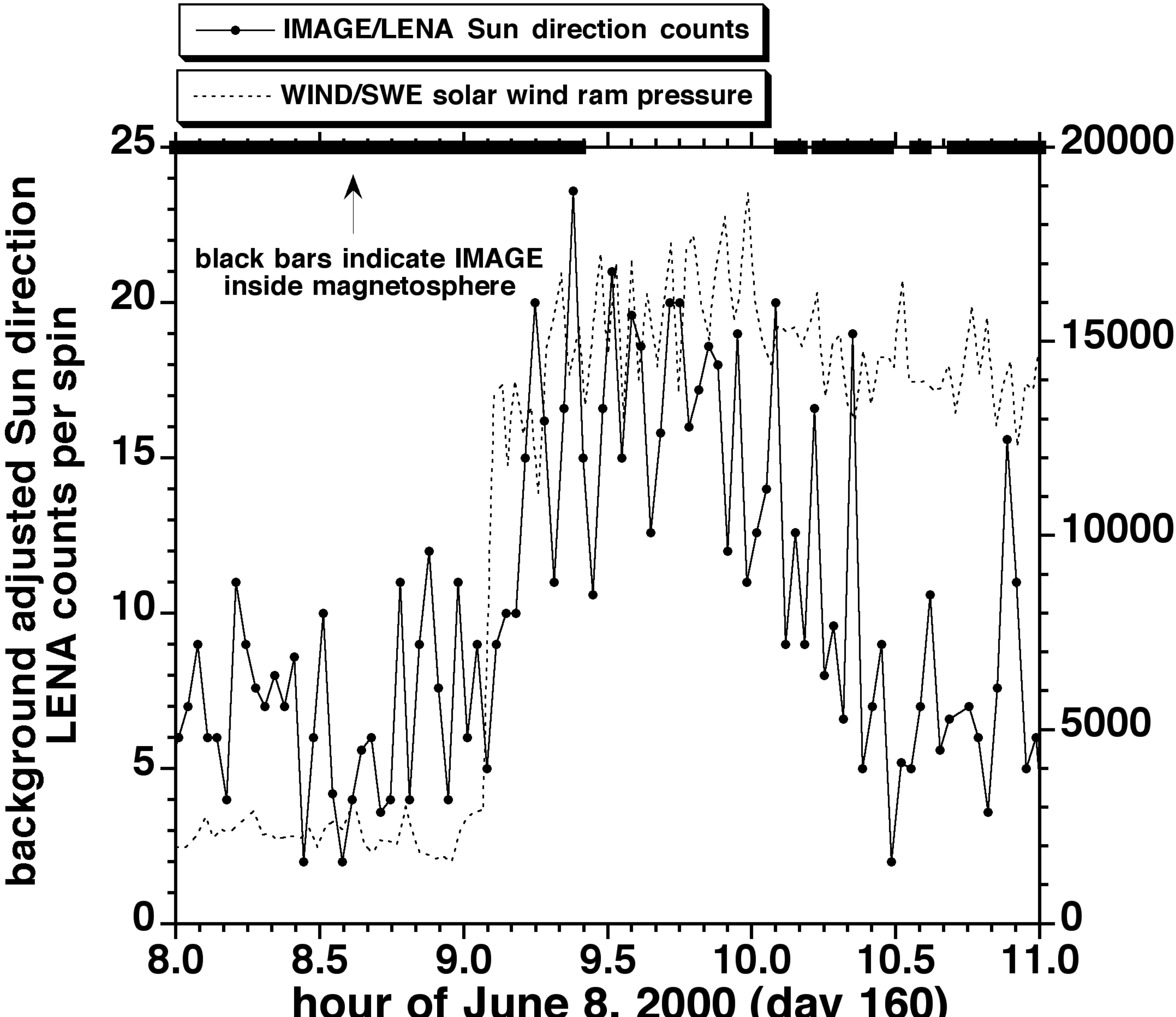
Figure Captions

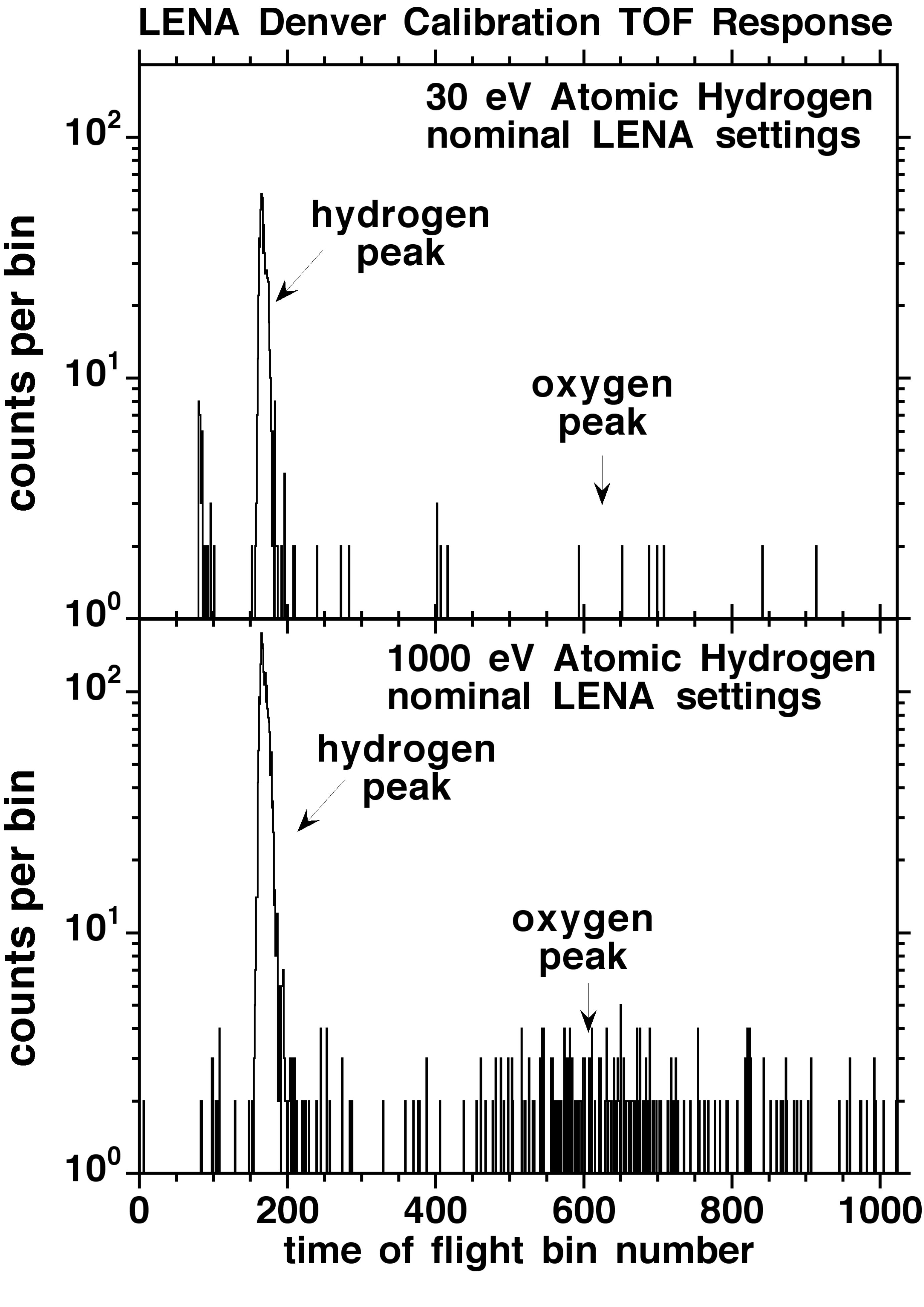
Figure 1. A comparison between the LENA sun sector count rate data and the solar wind ram pressure on June 8, 2000. This figure also shows with black bars along the upper x-axis when the IMAGE spacecraft based on the high-latitude magnetopause model of Boardsen *et al.* [2000] is inside the magnetosphere. The model predicts that during the June 8, 2000 event IMAGE moved back and forth across the magnetopause many times. This implies that if IMAGE were responding to energetic particles during this time, there would be changes in the signal corresponding to the boundary crossings. Because no such changes are observed and the distribution is less isotropic than would be expected from energetic particles, it is concluded that LENA is not responding to suprathermal ions during this time period. Both the solar wind ram pressure and the Boardsen *et al.* model results are derived from Wind spacecraft data.

Figure 2. The two panels in this figure show a comparison of the time-of-flight spectra from the Denver University calibration resulting from incident atomic hydrogen. The top panel shows a time-of-flight spectrum resulting from 30 eV atomic hydrogen. Note the absence of a sputtered oxygen peak. The lower panel shows a time-of-flight spectrum resulting from 1 keV atomic hydrogen. At these higher, solar wind-type energies, a sputtered oxygen peak is apparent in the time-of-flight data.

Figure 3. This figure shows a LENA time-of-flight spectrum taken during the June 8, 2000 event from about 0900-1100 UT. The spectrum only includes events coming from the general direction of the sun. The pronounced oxygen peak in the spectrum indicates that the neutral hydrogen energies are $\sim$1 keV, consistent with expected neutral solar wind energies.

Figure 4. The jump in solar wind speed observed by Wind during the shock passage on June 8, 2000, indicated by the solid line and left hand y-axis, is reflected in the ratio of atomic hydrogen to sputtered oxygen signal observed by LENA coming from the direction of the sun, indicated by the solid circles and right hand y-axis. Because IMAGE is inside the magnetosphere during most of the time period covered by Fig. 4, these results indicate the low energy neutral atom imagers can directly monitor interplanetary conditions from inside the magnetosphere.


IMAGE/LENA Sun direction counts
WIND/SWE solar wind ram pressure
black bars indicate IMAGE inside magnetosphere
background adjusted Sun direction LENA counts per spin
solar wind ram press (pPa)
hour of June 8, 2000 (day 160)
0
5
10
15
20
25
5000
10000
15000
20000
8.0
8.5
9.0
9.5
10.0
10.5
11.0
figure 1



LENA Denver Calibration TOF Response
30 eV Atomic Hydrogen
nominal LENA settings
hydrogen peak
oxygen peak
1000 eV Atomic Hydrogen
nominal LENA settings
hydrogen peak
oxygen peak
counts per bin
10^0
10^1
10^2
0
200
400
600
800
1000
time of flight bin number

figure 2

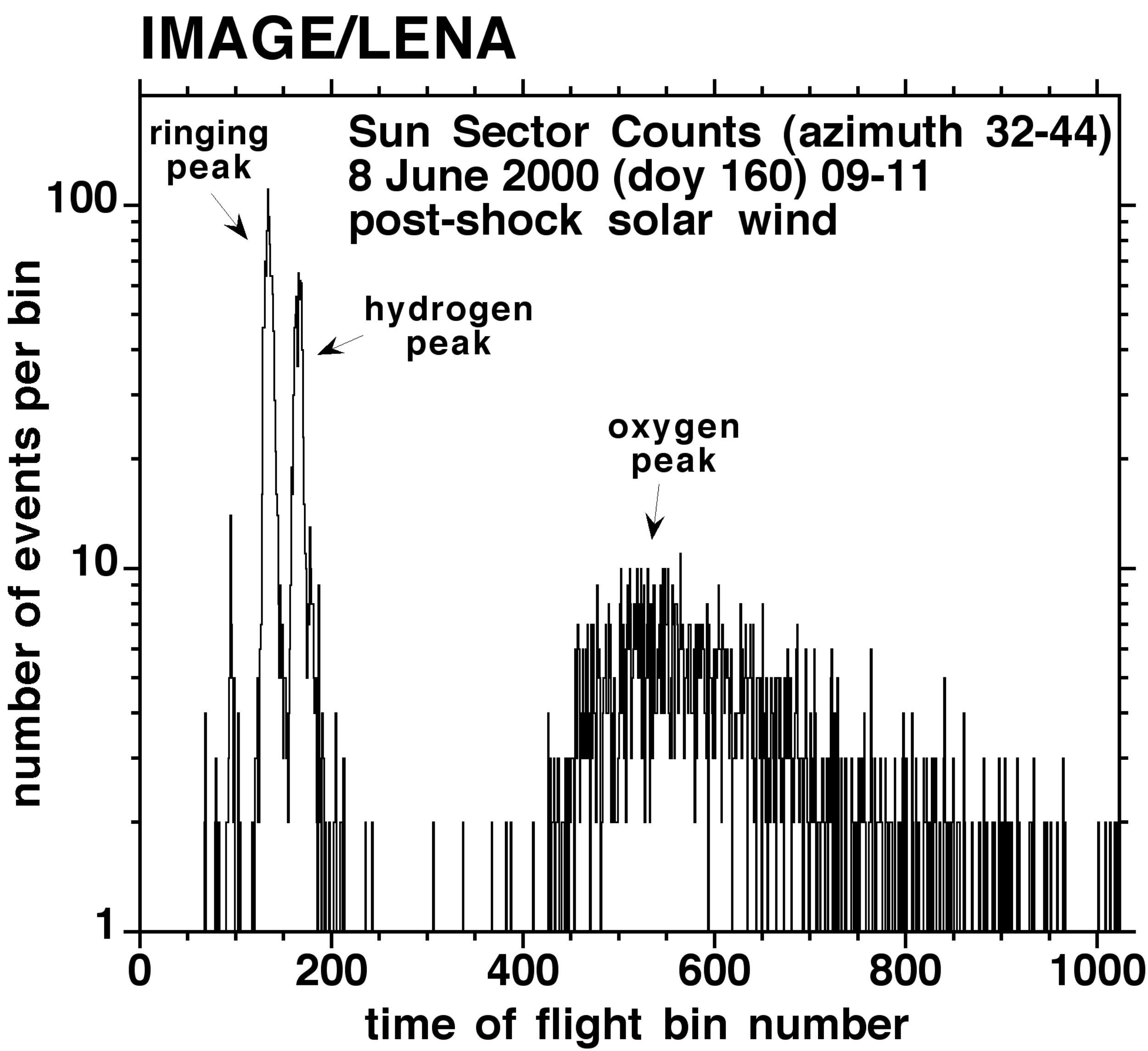
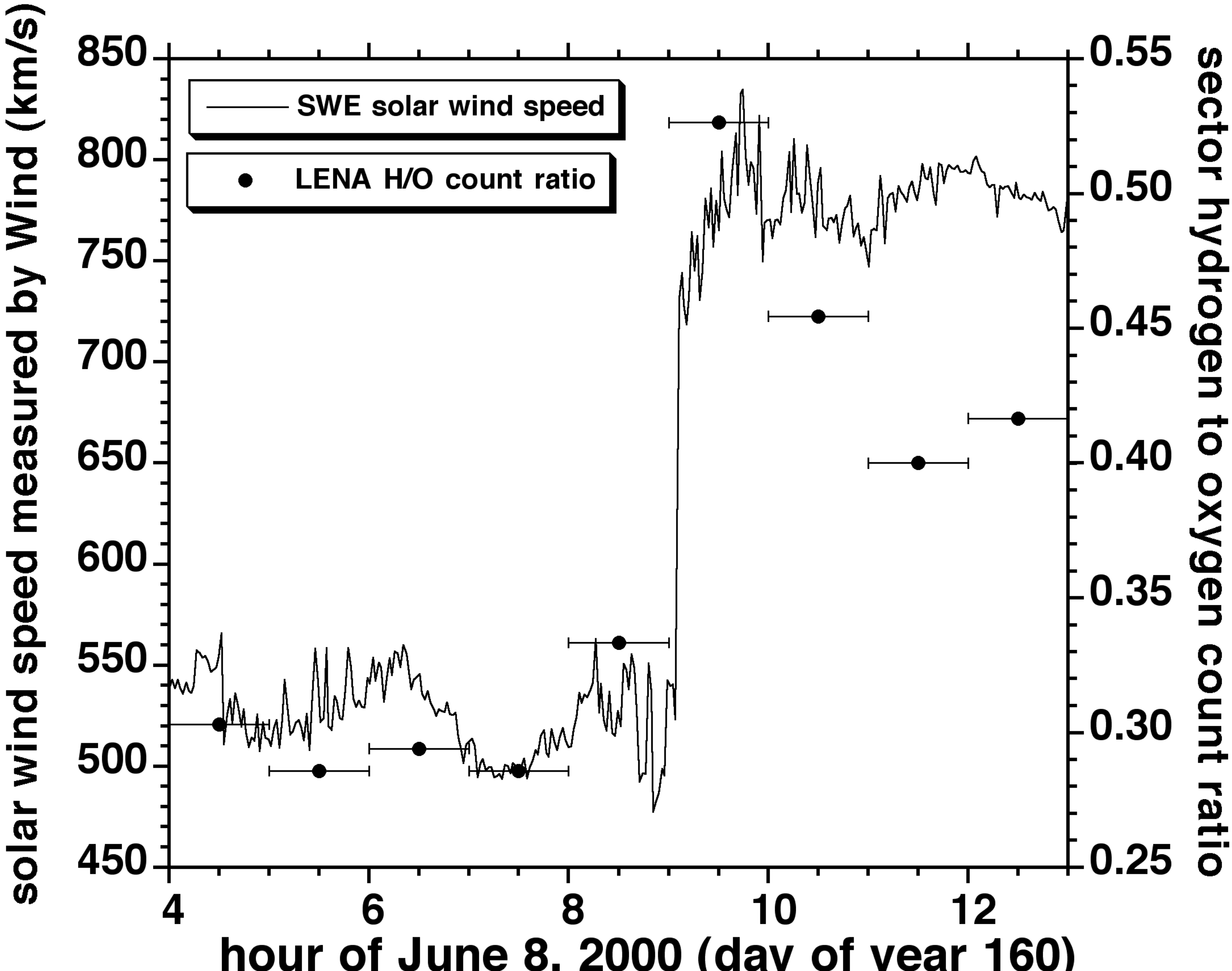

IMAGE/LENA
Sun Sector Counts (azimuth 32-44)
8 June 2000 (doy 160) 09-11
post-shock solar wind
ringing peak
hydrogen peak
oxygen peak
100
10
1
0
200
400
600
800
1000
number of events per bin
time of flight bin number

figure 3



SWE solar wind speed
LENA H/O count ratio
solar wind speed measured by Wind (km/s)
background-adjusted sun sector hydrogen to oxygen count ratio
hour of June 8, 2000 (day of year 160)
850
800
750
700
650
600
550
500
450
0.55
0.50
0.45
0.40
0.35
0.30
0.25
4
6
8
10
12

figure 4