Observations of Neutral Atoms from the Solar Wind

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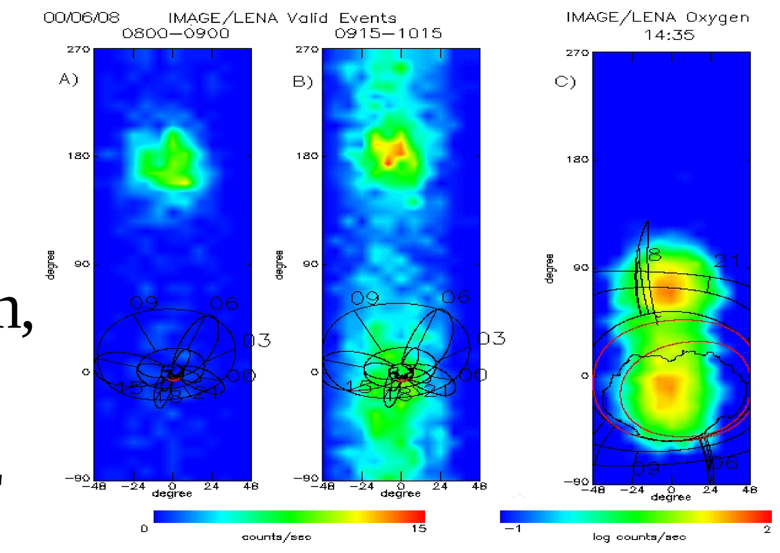

1. Introduction

The Low Energy Neutral Atom (LENA) imager (shown in the picture to the left of the title and author banner) is one of six science experiments that were launched on the IMAGE observatory on March 25, 2000 (see Fig. 1 below of IMAGE launch from Vandenberg AFB). This instrument was designed to accomplish remote sensing of the neutral component of space plasmas at energies from a few tens to a few thousands of electron volts (sample images for June 8, 2000 are shown in the picture to the right of the title and author baner). Neutral particles in this energy range, which encompasses most of the plasma in the heliosphere and result when energetic particles charge exchange with the Earth's hydrogen geocorona, have not previously been systematically observed. Similar to instruments which image more energetic neutral atoms, LENA has the ability to not only detect the neutral atoms, but also determine their mass, energy and direction (polar and azimuthal angles). LENA was designed to observe the Sun directly and responds to neutrals of energies of the order of 1 keV. Consequently, the instrument is capable of observing the fraction of the solar wind flow that is neutral hydrogen, which has been long-recognized as of potentially great importance for understanding solar, interplanetary and magnetospheric physics.

Figure 1.

Charge exchange between solar wind protons and neutral atoms can be primarily responsible for the formation of a neutral solar wind (see Fig. 2), although there is also a neutral component due to recombination of solar wind ions with solar wind electrons. These charge-exchanging neutrals may be interstellar neutral atoms, they may originate from dust grains or they may be part of the Earth's geocorona. The potential importance of charge exchange on the exospheric neutrals may be motivated by the realization that the neutral density at the nominal magnetopause is in fact comparable to the average solar wind density, so that the neutral density at this radial distance is not small. Since charge exchange in the geocorona will occur preferentially near the Earth, the neutral solar wind characteristics may be heavily influenced by magnetospheric structures.

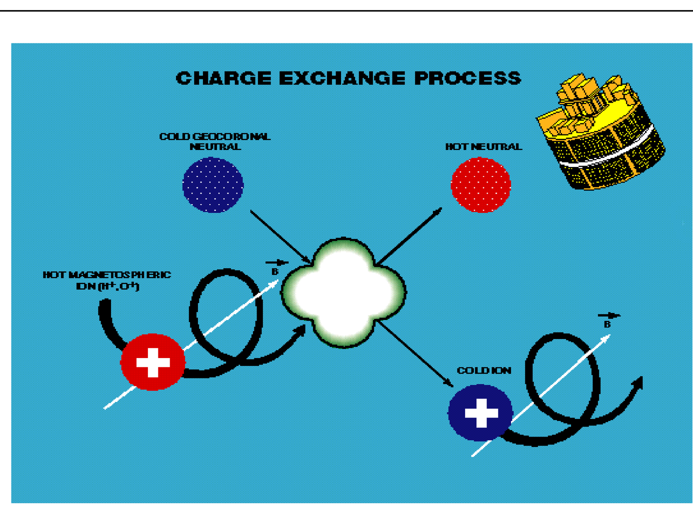

Figure 2.

2. LENA Operation

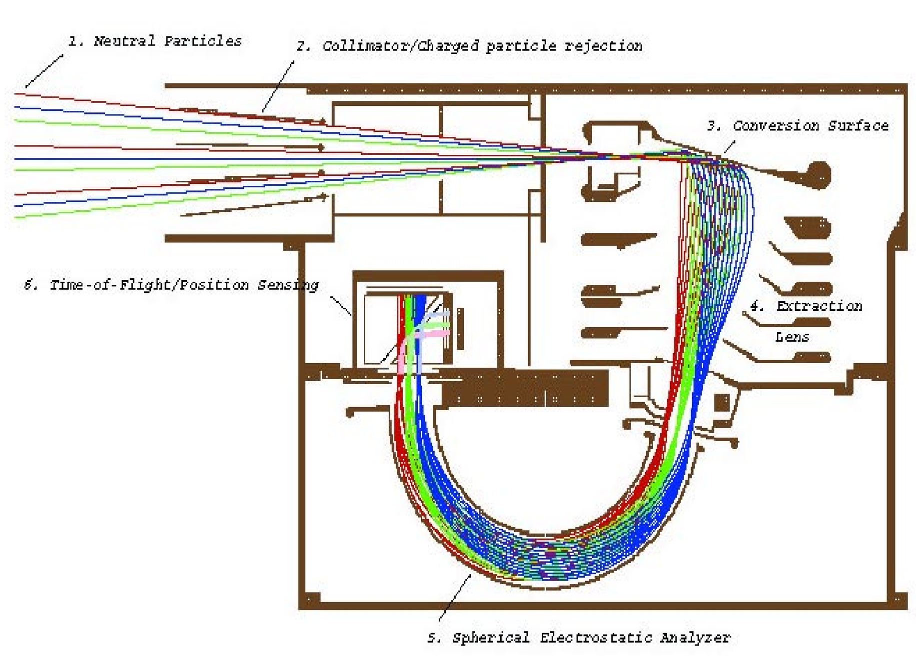

Figure 3.

Fig. 3 shows a cross section of the LENA instrument showing particle paths through the sensor. Neutral particles (1) enter the instrument through a collimator (2 and Fig. 4) which filters charged particles. LENA converts neutrals to negative ions through a near specular glancing reflection from a tungsten surface (3). Negative ions from the surface are then collected by the extraction lens (4 and Fig. 5) which focuses all negative ions with the same energy to a fixed location. In the extraction lens, the ions are accelerated by as much as 20 kV prior to entering the electrostatic analyzer (5). Finally, the ions pass into a time-of-flight/position sensing section (6 and Fig. 6) where ion mass, energy and angle are determined.

LENA data are available to the general public at the same time they are available to the LENA team at http://goewin.gsfc.nasa.gov/ LENA/.

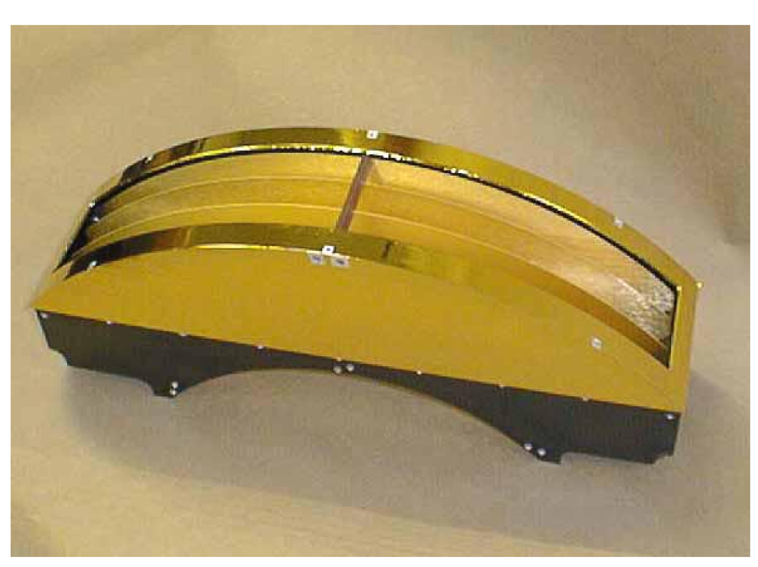

Figure 4.

Figure 5.

Figure 6.

3. Sun Pulse Observations

Many clear and consistent features appeared in the LENA data immediately upon reaching science level operations. Fig. 7 shows some of these features on May 24, 2000, shortly after LENA reached science level, in the form of a spectrogram which plots the time of day along the x-axis and the LENA spin angle along the y-axis. The color indicates the total event rate, irrespective of the time-of-flight. As mentioned in the previous section, LENA images in two angles, although only one is plotted in the spectrogram format.

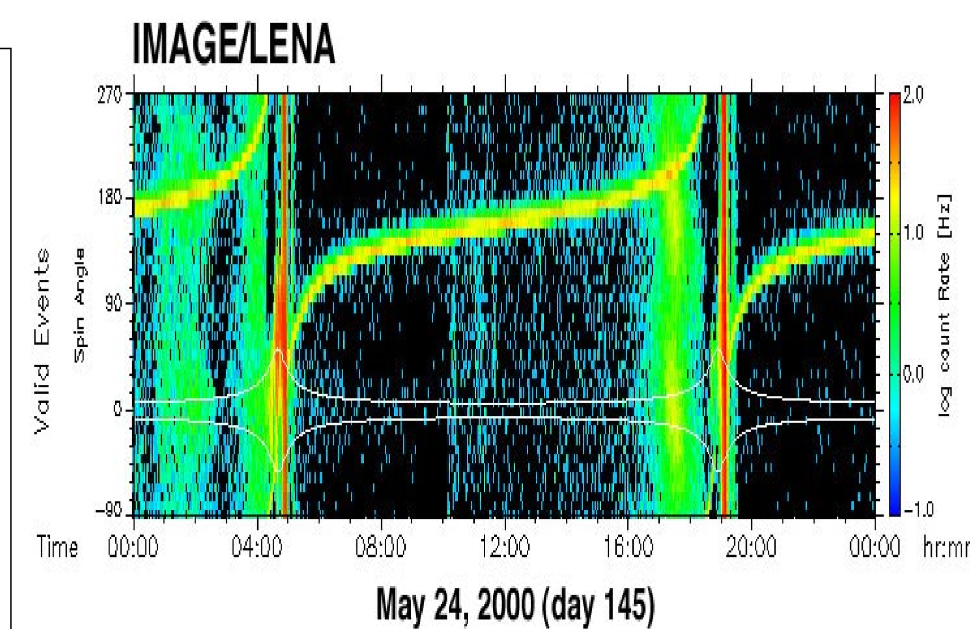

Figure 7.

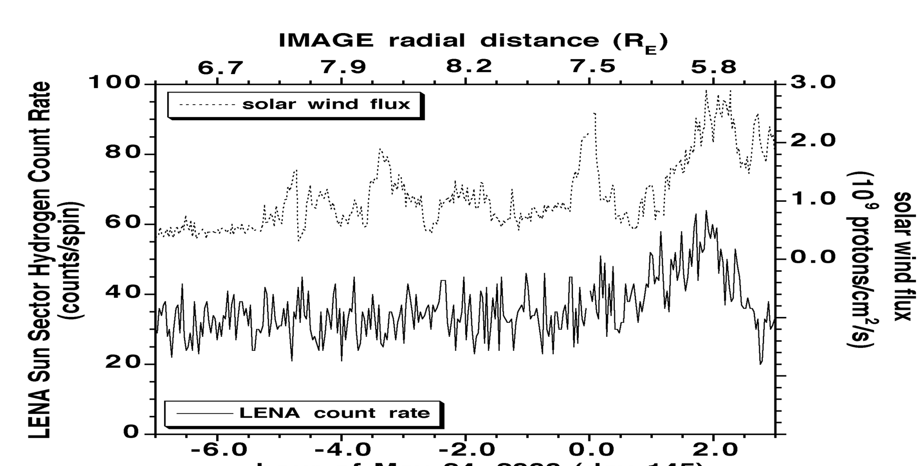

Figure 8.

One notable feature is the bright yellow/orange streak which begins near 180 degrees and drifts through all angles. This "Sun pulse" appears at the spin angle closest to the Sun. On this particular day, the Sun was within LENA's +/-45 degree field-of-view so that the Sun pulse is actually in the direction of the Sun. Note that when IMAGE moves behind the Earth, the angular range of which is indicated by the white lines, the Sun pulse is occulted. It was apparent early in the mission that not only did the signal from the Earth respond to solar wind pressure variations, but that the intensity of the Sun pulse did, as well.

Fig. 8 shows an example of an increase in the Sun sector LENA count rate resulting from an increase in solar wind flux. The solar wind number flux, measured by WIND about 45 R_E upstream and about 6 R_E off the Sun-Earth line is indicated by the upper, dashed-line trace and the right hand y-axis. The LENA Sun sector hydrogen counts per spin is plotted with the lower solid trace and the left hand y-axis. There are a number of short-lived enhancements in the solar wind flux which are not obviously associated with enhancements in the LENA rate, perhaps due to its hirsute profile. However, the largest enhancement in solar wind flux, which is observed at about 0200 UT, accompanies a concrescent enhancement in the LENA Sun sector hydrogen rate. Ultraviolet data from SOHO show that there was no enhancement at this time so that the increase in the LENA count rate cannot be due to any sensitivity to light.

4. The June 8, 2000 Event

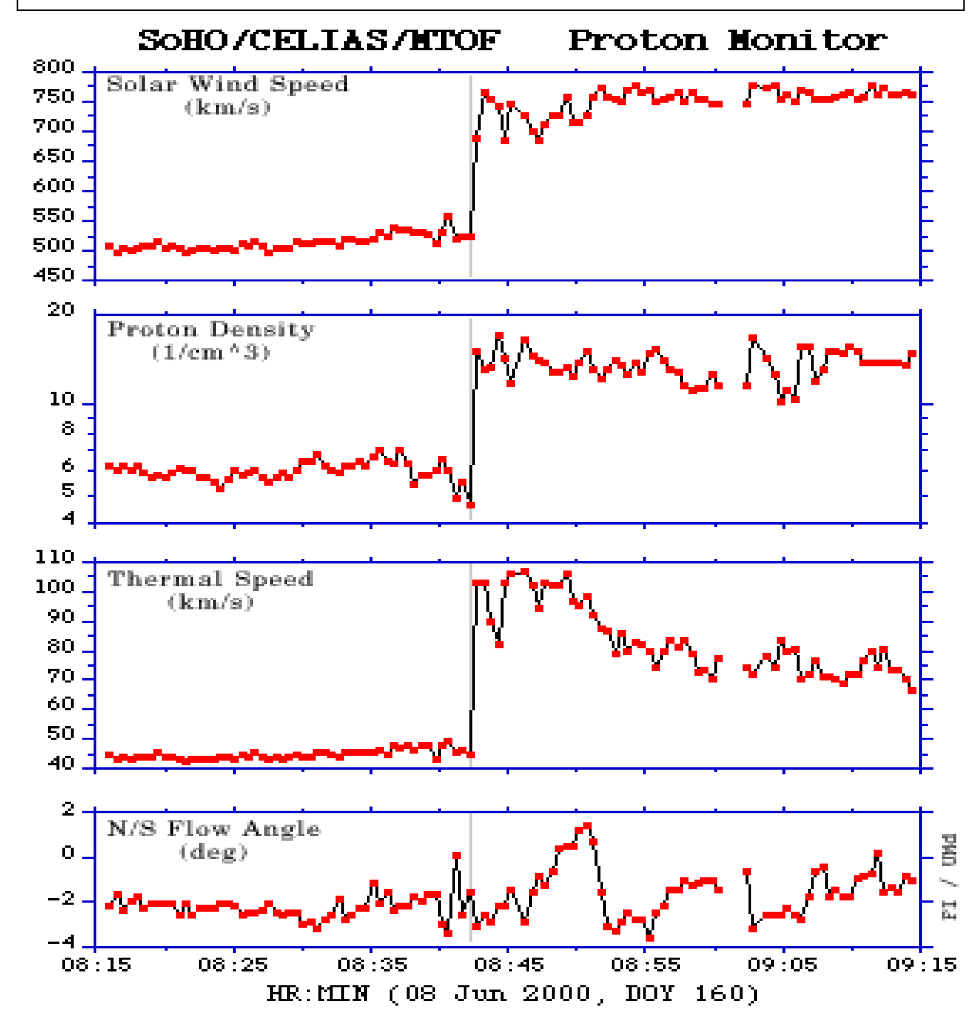

Figure 9.

About one month after beginning science operations on May 5, 2000, LENA had an opportunity to observe a coronal mass ejection (CME) and its effect on the terrestrial environment. On June 6, 2000, an intense solar flare was observed and was followed by a full-halo CME propagating toward the Earth. The shock wave driven by this CME was observed by the Advanced Composition Explorer (ACE) and the Solar and Heliospheric Observatory (SOHO) spacecraft at about 0842 UT on June 8, 2000 at the L1 point, 235 R_E upstream from the Earth (see Fig. 9), and by the WIND spacecraft, 41 R_E upstream, at about 0905 UT. At 0911 UT this disturbance passed the Earth where it and its effects were observed by the IMAGE spacecraft. Fig. 10 shows a cartoon of the IMAGE geometry along with LENA's field-of-view during this event.

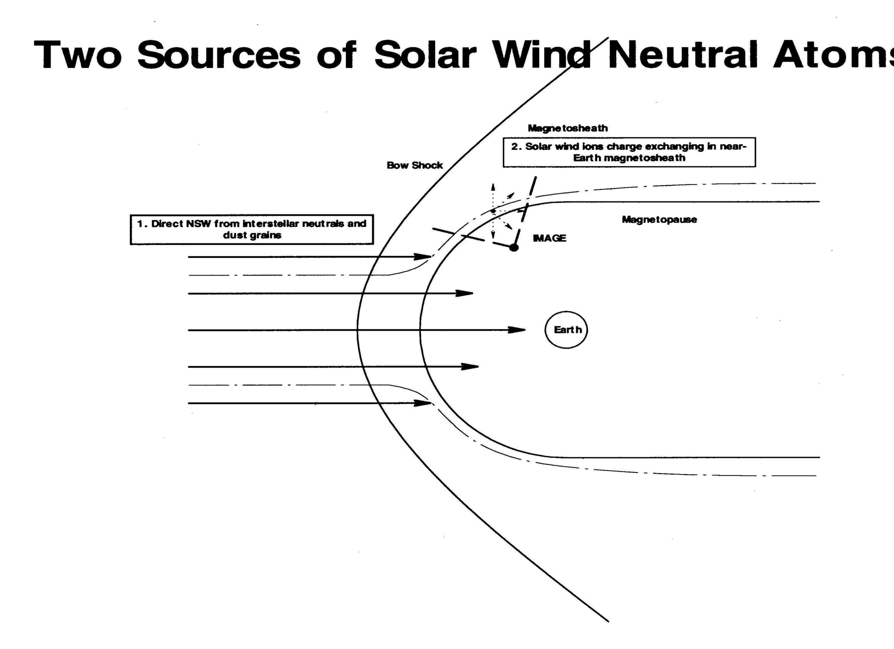

Figure 10.

Fig. 11 shows a LENA spectrogram of the combined hydrogen and oxygen count rate as a function of time on the day the CME-driven shock passed the Earth, June 8, 2000. The sun pulse, in time, near 180 degrees is a signal initially thought to represent a response to the EUV photon flux from the Sun. The angular range of the Earth is indicated by the dashed white lines, and the yellow brightening around 0950 UT is a neutral oxygen burst. However, when the sun pulse increased significantly at the arrival of a shock (at 0911 UT) in the solar wind associated with the CME, it was concluded that at least part of this signal must represent neutral atoms in the solar wind.

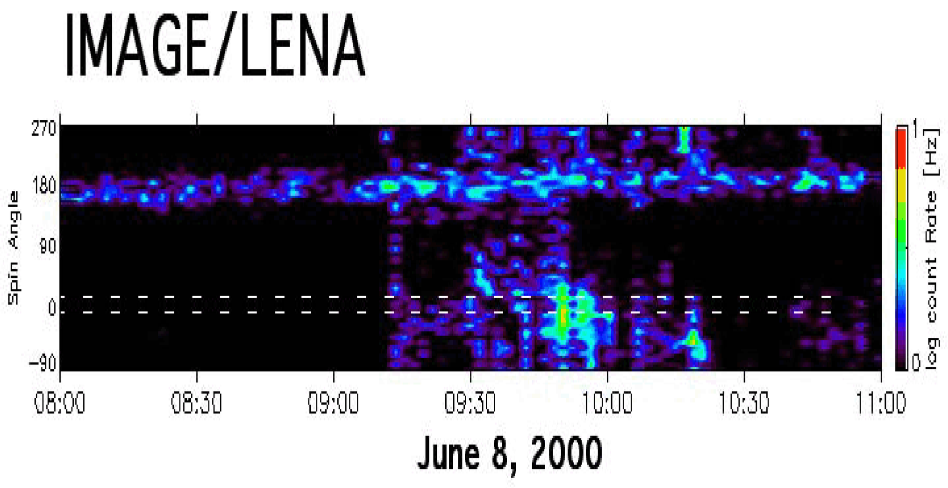

Figure 11.

The LENA UV response is a result of the ionization of particles inside the instrument by photons, as light does not penetrate to the microchannel plates (see Fig. 3). Thus, the instrument UV response scales with pressure at or near the conversion surface, and the response to UV based on calibration data scaled to the ambient pressures expected on orbit shows that LENA has a negligible UV response in orbit.

As additional evidence that LENA is not responding to UV, Fig. 12 shows the EUV data from SOHO on June 6-8, 2000. The upper solid line shows the photon flux between 0.1 and 50 nm and the lower dashed curve shows the photon flux between 24 and 34 nm. The activity on June 6 associated with the CME is apparent in the data with some subsequent activity on June 7 (which was not associated with a LENA count rate enhancement). During the event on June 8, indicated by the vertical line, there is no enhancement in the UV flux, indicating that the enhancement seen in the sun pulse by LENA is not due to an increase in solar EUV.

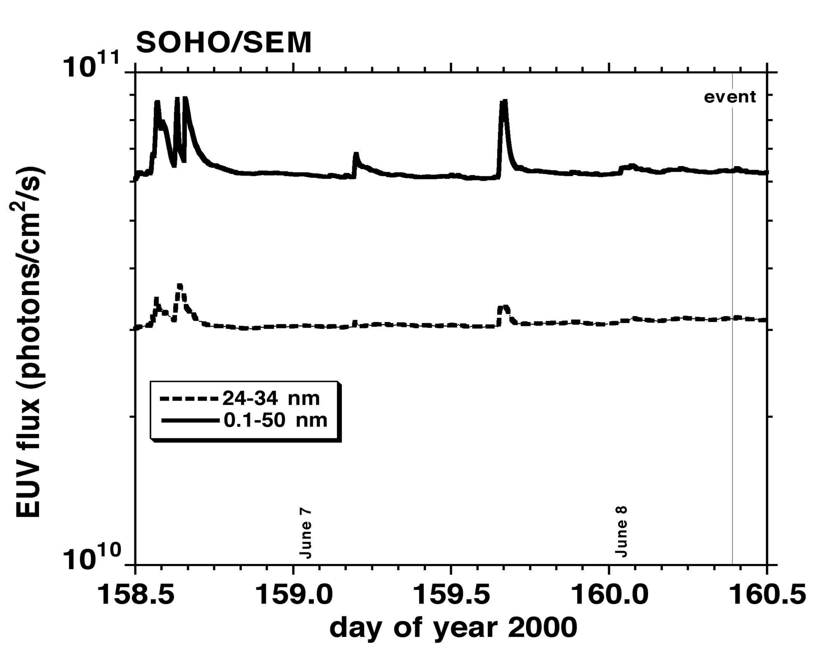

Figure 12.

UV radiation is not the cause of the observed enhancement in the sun pulse. However, it is possible that this increase is due to suprathermal ions penetrating the collimator. At the time of the June 8, 2000, event a potential of about 8.8 kV was across the collimator (significantly higher than the collimator setting during the May 24, 2000 event) to filter out all ions with energies up to about 50 keV/e, while above about 100 keV/e most ions can traverse the collimator and arrive inside the instrument. Because ion spectra at these energies in most space plasma environments follow rapidly decreasing power laws, the primary contributor to the energetic ion flux entering LENA is likely close to 50 keV/e.

Thus the enhanced sun pulse seen in LENA observations could be due to ions with energies at or above 50 keV/e. If this is the case, such ions would have been observed by the Electron, Proton, and Alpha Monitor (EPAM) aboard the ACE spacecraft. Figure 13 compares the LENA background-adjusted counts per spin (light trace, left hand y-axis) from the solar direction with the ACE/EPAM ion flux data (heavy trace, right hand y-axis, plotted logarithmically) for this event. The counting rate contained in the LENA data peaks shortly after the shock's passage and slowly decreases for about an hour thereafter. The ACE/EPAM flux data for ions with energies between 47 and 65 keV/e, which includes the 50 keV/e low energy limit for LENA ion admittance, show a step-function type increase at the time of the shock. If the LENA response were due to these energetic ions, we would expect the time profiles for the observations to be much more similar. This suggests that the enhanced sun pulse observed by LENA is not due to these suprathermal ions.

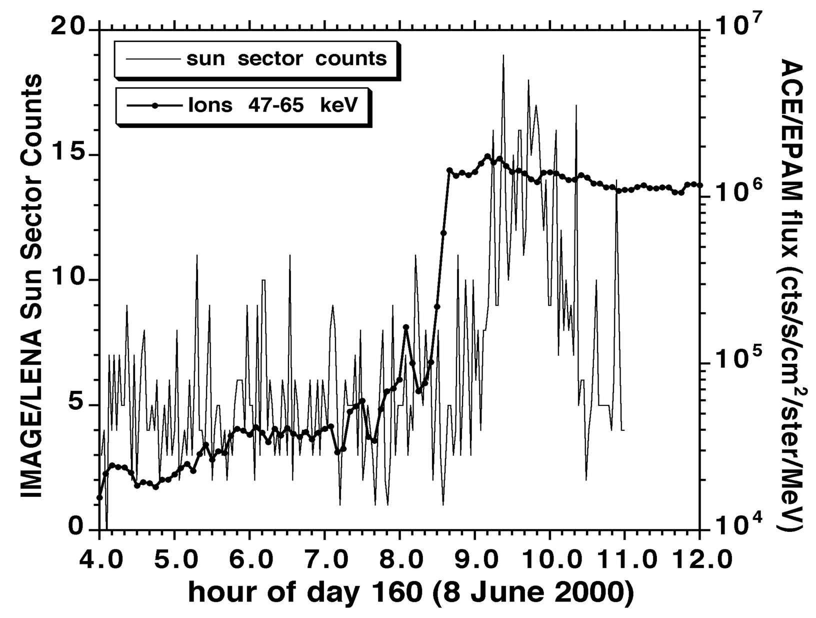

Figure 13.

We conclude LENA observed neutral particles from the solar direction during this event, indicating the Sun pulse was and in general is primarily due to neutral particles. We now address the issue of whether or not the neutral atom energies are consistent with solar wind-like energies of the order of 1-5 keV. Fig. 14 shows LENA calibration data taken at the University of Denver neutral beam facility. The upper panel shows a time-of-flight spectrum resulting from incident 30 eV atomic hydrogen. There is a well-defined hydrogen peak at low times-of-flight with no evidence of an oxygen peak. An oxygen peak appears when the energy of the incident neutral hydrogen exceeds a threshold between 300 eV and 1000 eV. Above this transition, as shown in the lower panel of Fig. 14 for 1000 eV atomic hydrogen, a significant oxygen peak is present, believed to be due to the sputtering of adsorbed oxygen or water from the conversion surface.

Fig. 15 shows a time-of-flight spectrum taken during the enhancement on June 8, 2000. The spectrum only includes events coming from the general direction of the Sun. Note the prominent oxygen peak. Since large neutral oxygen fluxes do not occur in the solar wind, this suggests the neutral hydrogen has energy above 300 eV, at which sputtering can occur. This is consistent with solar wind-type energies.

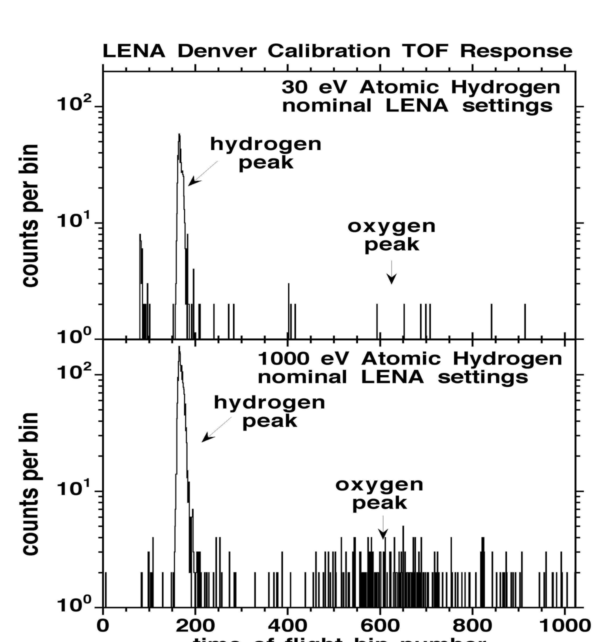

Figure 14.

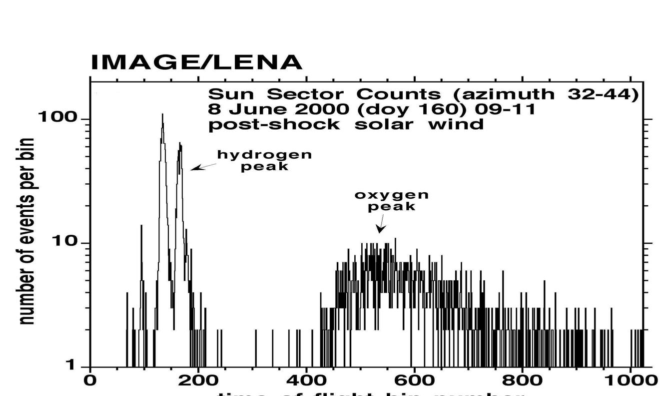

Figure 15.

5. Magnetosheath Sims.

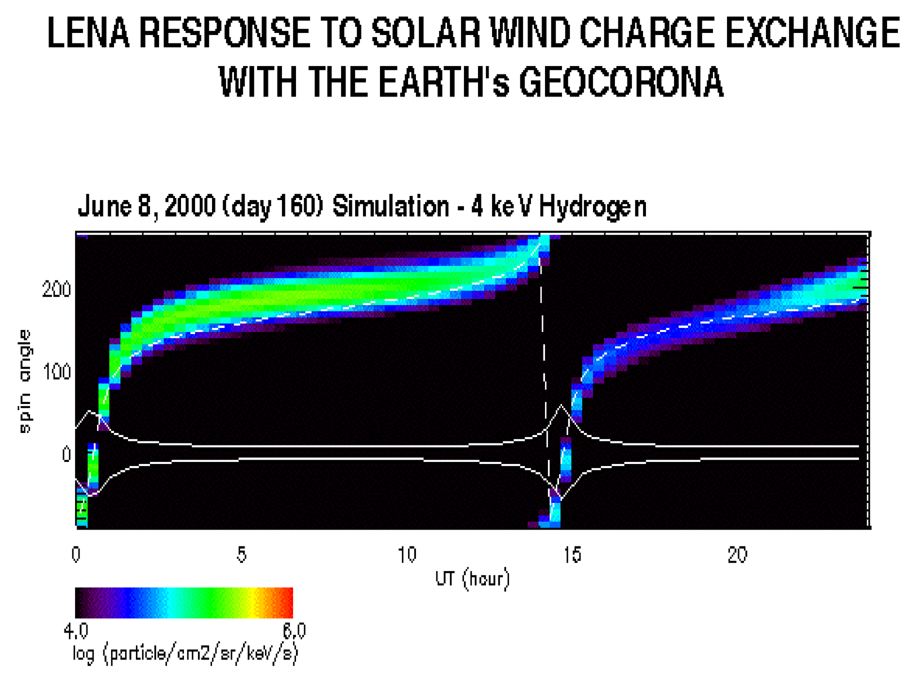

Figure 16.

When the Sun moved out of LENA's field-of-view, yet the Sun pulse was still visible, one possible explanation proposed was that LENA was observing solar wind charge exchange in the magnetosheath. Because the solar wind in the magnetosheath is deflected, hot, and has pronounced suprathermal tails, all factors that would contribute to observing charge exchange products far off the Sun-Earth line, this explanation seemed plausible.

To check this idea, we have performed simulations of LENA's response on June 8, 2000 to solar wind ions charge exchanging with the Earth's hydrogen geocorona in the magnetosheath. Fig. 16 is an example in spectrogram format for 4 keV hydrogen. Note that LENA's response integrates over all energies although the simulations indicate that the major contributor to the LENA response during this event is particles with energies around 4 keV. Note also that this simulation does not include any neutral component in the solar wind that does not result from charge exchange with the Earth's geocorona, i.e. the direct neutral solar wind. Finally, the simulation does not factor in the LENA instrument efficiencies.

The results shown in Fig. 16 are similar to what LENA observes on June 8, 2000, namely a wide Sun pulse around 180 degrees, the direction closest to the direction of the Sun and suggest that in fact LENA is responding primarily to solar wind charge exchange in the magnetosheath during this event.

6. Conclusions

LENA has observed a neutral particle component in the solar wind. These observations can be used to estimate the neutral flux during the enhancement period. As shown in Fig. 13, the count rate during the enhancement is about 15 counts per spin. Since each spin sector is observed for about 2.7 seconds, this reduces to a count rate of 5.6 per second. At solar wind energies, LENA's neutral hydrogen detection efficiency was measured to be about 6.4x10^{-5}. We regard this as being correct to within a factor of two, considering the different conditions in flight and the scatter of the data in the efficiency curves. LENA's entrance aperture has an area of one centimeter squared, which yields a flux of about 8.8x10^{4} cm^{-2} s^{-1}. At that time, the solar wind flux was about 10^{9} cm^{-2} s^{-1} (12 cm^{-3} density and 800 km/s speed) yielding a flux ratio of neutrals to solar wind protons of about 10^{-4}.

This value is comparable to the expected neutral solar wind component at 1 AU. However, given the IMAGE orbit on June 8, 2000, and the imager field-of-view, the signal has an apparent origin centered more than 45 degrees from the solar direction and so may originate largely from the magnetosheath interaction with geocoronal hydrogen. As mentioned earlier, a significantly stronger localized signal was observed prior to May 26, 2000 (see Fig. 17), before the solar direction passed beyond the nominal imager field of view.

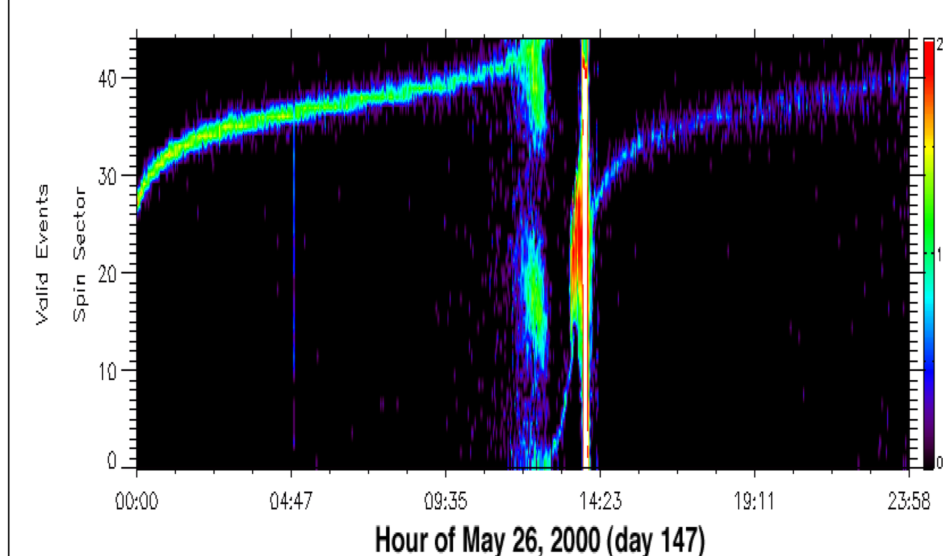

Figure 17.

Thus, we will also calculate the ratio of neutral flux to solar wind flux on May 24, 2000 when LENA was observing both the direct neutral solar wind and the effect of charge exchange with the Earth's geocorona. Referring back to Fig. 8, on this day the LENA enhancement is about 60 counts per spin or about 22 counts per second. Unlike the June 8, 2000 event, when the stop microchannel plate was operated at a higher level, the May 24, 2000 event occurred close enough to the start of science operations that the instrument stop microchannel plate bias level was conservatively lower. Consequently, the 1 keV atomic hydrogen efficiency was 1.5x10^{-5} during this event, and the neutral flux is about 1.4x10^{6} cm^{-2} s^{-1}. The solar wind flux during this enhancement was about 2.8x10^{9} cm^{2} s^{-1} which yields a flux ratio of neutrals to solar wind protons of about 5x10^{-4}. This likely implies a direct neutral solar wind to solar wind proton ratio in the low 10^{-4}s.

We have reported the detection of hydrogen atoms of energy >300 eV consistent with solar wind-type energies from the magnetosheath and interplanetary space. This work establishes two important facts:

(i) The LENA detection technique is now proven viable for the imaging of space plasma populations containing hydrogen atoms of solar wind energies.

(ii) there is a flux of neutral atoms, 10^{-3}-10^{-4} of the solar wind flux, in the magnetosphere.

This opens a new window for observation and a new topic for investigation in the role of low energy neutral atoms in space plasmas.