Observation and Interpretation of Energetic Neutral Hydrogen Atoms from the December 5, 2006 Solar Flare

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***Abstract*. We discuss STEREO observations of energetic neutral hydrogen atoms (ENAs) from the solar flare/coronal mass ejection event on 5 December 2006. Prior to the main solar energetic particle event, a burst of 1.6 to 15 MeV ENAs from the Sun was observed, apparently produced by either flare or shock-accelerated protons. RHESSI measurements of the 2.2-MeV γ-ray line provide an estimate of interacting flare-accelerated protons, leading to an improved estimate of ENA production by the flare. CME-driven shock acceleration is also considered. Taking into account ENA losses, we find that the observed ENAs must have been produced in the high corona at heliocentric distances $\geq$2 solar radii.**

***Keywords*: energetic neutral atoms, solar energetic particles, flares, CMEs**

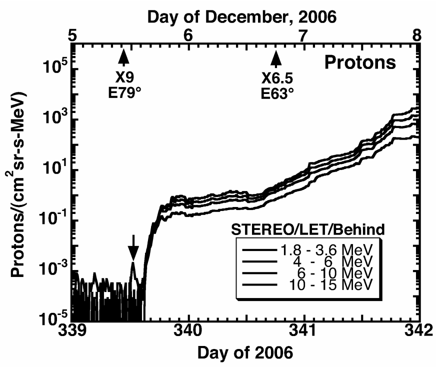

Fig. 1. Time history of low-energy protons measured by LET-B during 5 to 7 December 2006. The onset of two X-class flares is indicated. Note the particle burst preceding the main SEP event (arrow).

I. INTRODUCTION

When NASAs STEREO mission was launched in October 2006, the Sun was apparently well into solar minimum conditions. As a result, it was a surprise when active region 10930 unleashed 4 X-class flares in December 2006, each associated with a solar energetic particle (SEP) event. Although the STEREO spacecraft were still close to Earth, the Low Energy Telescopes (LETs) and High Energy Telescopes (HETs) were already operational. Time profiles for the first SEP event on December 5 are shown in Figure 1. Since this E79 event was not directly connected to Earth along the interplanetary magnetic field (IMF), energetic ions began arriving $\sim$4 hours after the X-ray flare. Also seen between 1130 and 1300 UT is a small, low-energy precursor. Surprisingly, $> 70\%$ of the particles in this burst arrived from within $\pm 10°$ longitude of the Sun, having traveled directly across the IMF. Mewaldt et al. [1] concluded that the precursor was composed of energetic neutral hydrogen atoms (ENAs) made from protons accelerated by the flare and/or CME-driven shock. In LET ENAs are stripped of their electron upon striking the front Kapton window. Solar ENAs therefore preserve their original direction until detection.

In this paper we review the ENA observations, discuss ENA production on the Sun, use RHESSI data for an improved estimate of ENA production by flare-accelerated protons, and compare ENA yields from flare and shock-accelerated particles.

II. STEREO AND RHESSI OBSERVATIONS

The LETs and HETs on STEREO together measure the nuclear charge (Z) and kinetic energy of $1 \leq Z \leq 28$ ions from $\sim$2 to $\sim$100 MeV/nuc. LET is composed of a double-ended array of 14 position-sensitive silicon solid-state detectors (SSDs), including ten $\sim$25 micron thick SSDs arranged in two fan-shaped arrays centered on a four-detector double-ended stack [2]. Particle arrival directions are measured over $130° \times 29°$ fans in the front and back directions with $\sim \pm 6°$ uncertainty in the ecliptic plane. The HET sensor consists of a stack of ten circular SSDs (each 1-mm thick) with a cone-shaped field of view with 55° full angle [3].

Protons in the December 5 precursor exhibited velocity-dispersion with higher-energy particles arriving first. Mewaldt et al. [1] used LET Z = 1 particles arriving from within 10° of the solar longitude to derive the ENA emission profile, using the measured kinetic energy (E) to determine particle velocity, v = $(2E/m)^{1/2}$ and the emission time (with m the proton mass). The similarity of the ENA and X-ray profiles in Figure 2 confirms that the ENAs originated in this solar event.

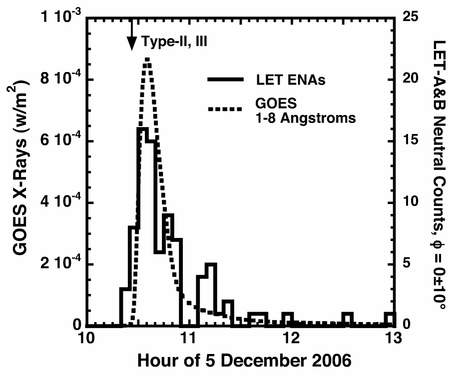

Fig. 2. The derived emission profile of the 1.6 15 MeV ENA burst (in counts per 5 minutes) is compared with the 1-minute GOES X-ray profile and the onset of STEREO type-II and type-III radio bursts (adapted from [1]).

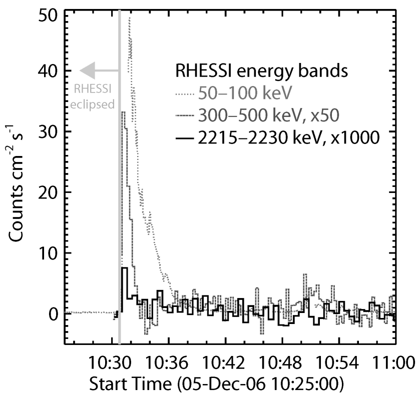

Fig. 3. ENA spectrum from the 5 December 2006 solar event, based on particles arriving from within $\pm 10°$ of the Sun and derived solar emission times from 1015 to 1145 UT (from [1]). The $>$5 MeV points may include some neutron-decay protons (see text). ENAs with $<$1.8 MeV are not included due to detection uncertainties.

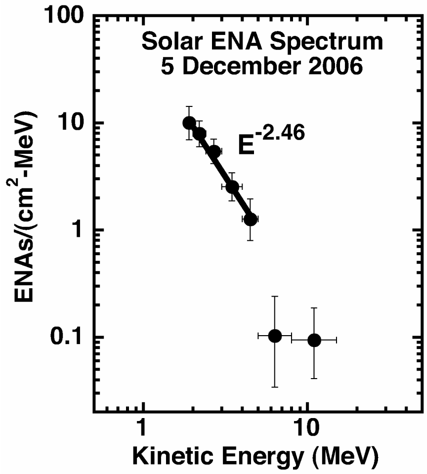

Fig. 4. RHESSI light-curves for the December 5, 2006 flare in three energy bands, scaled for clarity. The 50 to 100 keV light-curve (dotted) and the 300 to 500 keV light-curve (dashed, background-subtracted) are primarily electron bremsstrahlung continuum emission, while the 2215 to 2230 keV light-curve (solid, background-subtracted) is dominated by the 2.223 MeV neutron-capture line. The vertical gray bar signifies when RHESSI came out of eclipse, showing that RHESSI likely missed part of the emission. The 50 to 100 keV light-curve has data removed when the instrument had high deadtime, most notably soon after exiting eclipse.

The ENA energy spectrum is shown in Figure 3. The 5 to 15 MeV emission also appears to be due to ENAs, but could also include some neutron-decay protons. Assuming isotropic emission, Mewaldt et al. [1] estimated that 1.8×10^{28} ENAs with 1.8 to 5 MeV escaped from the upper hemisphere of the Sun.

RHESSI also observed the December 5 flare (see Figure 3), including high-energy X-rays and γ-rays, although it likely missed the initial part of the emission due to being in eclipse (note that soft X-ray emission in Figure 2 began at $\sim$1019 UT and peaked at $\sim$1035). The RHESSI observations start at $\sim$1031 UT and the X and γ emission is no longer significant after more than a few minutes. Although this high-energy emission is largely bremsstrahlung continuum produced by flare-accelerated electrons, a 2.223 MeV neutron-capture line is also produced as a result of flare-accelerated ions with energies $>\sim$20 MeV/nuc interacting with the lower chromosphere and producing neutrons that are captured at even greater depths (e.g., [4]). The neutron-capture line is so narrow it is not spectrally resolved by RHESSIs germanium detectors ($\sim$10 keV FWHM at this energy) and can be seen even at relatively low fluxes. For more on RHESSI see Lin et al. [5].

RHESSI data can be used to estimate the number of flare-accelerated protons interacting in the solar atmosphere. The neutron-capture line fluence determined from a spectral fit is $(3.2 \pm 0.9) \times 10^{-2}$ photons/cm^2, although this fluence has been attenuated by a level of Compton scattering in the solar atmosphere that depends on the heliocentric angle of the γ-ray source [6]. From RHESSI hard X-ray imaging, the source at energies of 70 to 150 keV has a heliocentric angle of 79.5° (S. Krucker, private communication). Assuming that the neutron-capture line emission comes from approximately the same location (the 2.2 MeV line is not strong enough in this flare to image directly), then the line flux is attenuated by 67% before observation. Correcting for this attenuation and then using neutron-capture line yields predicted by simulations (R. Murphy, private communication), the observed fluence corresponds to 1.3×10^{31} interacting protons $\leq$30 MeV, assuming a proton spectral index of -3.5. If RHESSI missed part of the neutron-capture line emission, the total number of interacting protons would be larger.

Inspired by earlier 1-AU observations of solar flare neutrons [7] and neutron-decay protons [8,9] during large solar flare events, the LET and HET data were examined for evidence of neutron-decay protons, which should have a broad range of pitch angles [8,10]. The HETs observed a 2σ excess of 13-40 MeV protons during the ENA burst [1], consistent with a neutron-decay proton spectrum with $\sim$ 10% of the intensity observed in the E75° event of 3 June 1982 [8]. An independent upper limit on the number of interacting protons was obtained [1] by assuming the 2-σ excess of 13-40 MeV protons was due to neutron-decay protons. Scaling an analysis of the 3 June 1982 event [11], Mewaldt et al. [1] estimated 3.1×10^{32} interacting protons with > 30 MeV, $\sim$24 times the RHESSI lower limit. For an $E^{-3.5}$ proton spectrum [12],[13],[4] the number of interacting protons with 1.8 to 5 MeV range from $> 1.3 \times 10^{33}$ (based on RHESSI) to $< 3.3 \times 10^{34}$ [1]. The RHESSI limit is the better of these estimates because it is based on γ-ray data from the same solar event and uses up-to date cross sections and models.

III. ENA Production and Loss

The timing of the ENA emission (Figure 2) suggests ENA production by flare-accelerated protons. ENAs are usually attributed to charge-exchangebetween energetic ions and neutral H and He. However, at coronal temperatures (1-2 MK) or in the flare site (3-30 MK [14]), there should not be significant neutral H or He. ENAs are also produced by radiative recombination with ambient electrons $(H^+ + e \rightarrow H + \gamma)$ with a cross section given by σ_{rr} = 1.28 x 10^{-25} $E^{-2.0}$ cm^2 (based on [15], with E in MeV). In addition, Mewaldt et al. [1] suggested that charge exchange with heavy coronal ions that retain some electrons are important (e.g., $H^+ + O^{6+} \rightarrow H + O^{7+}$). Based on their first-order theoretical estimates, heavy-ion charge-exchange processes (summed over species) could contribute $\sim$150 times more than radiative recombination.

Following Mewaldt et al. [1], we assume that all $<$ 10 MeV protons slow and stop in the solar atmosphere. Using the RHESSI limit on 1.8-5 MeV protons and the cross sections described above we find that $> 4 \times 10^{31}$ ENAs are produced with 1.8-5 MeV. This is $>$1000 times more than needed to explain the LET observations (assuming isotropic emission and all upward-moving ENAs escape the Sun). However, once produced, ENAs are ionized by electron and proton impact ionization and by UV. At MeV energies the electron and proton ionization cross sections are equal and can be represented as $\sigma_i = 2.3 \times 10^{-17} E^{-0.895} cm^2$, with E the ENA energy in MeV [16]. The attenuation factor is then F(R) = $\exp(-\sigma_i N_R)$ where N_R (in cm^{-2}) is the overlying column density of protons and electrons integrated from heliocentric distance R (at E79) to the STEREOs, using nominal coronal densities [17].

In the standard picture of a solar flare (Figure 5) magnetic reconnection suddenly releases a great deal of energy in the corona and energetic particles are accelerated by one or more processes [19]. Aschwanden [19] estimated from X-ray studies that the height of the reconnection region varies from $\sim$5,000 to $\sim$50,000 km, with an extreme maximum of $\sim$200,000 km (heliocentric radius of $\sim$1.3 $R_\odot$). The reconnection process produces upward and downward proton and electrons beams. Downward-directed electrons produce bremstrahlung radiation from the chromoshperic footpoints of the flare as observed by RHESSI (Figure 4), while nuclear reactions of downward-directed protons produce nuclear γ-rays as well as neutrons which get captured to produce the 2.2 MeV n-capture line (Figure 4). In addition, the footpoints will be copious ENA production sites because of neutral H and He in the chromosphere. However, as shown in Figure 6, very few ENAS produced in the chromosphere will escape the Sun.

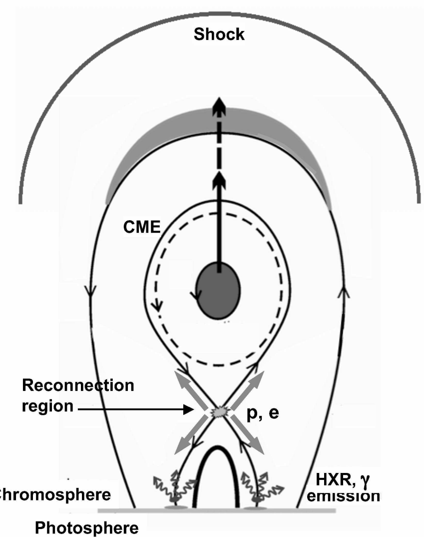

Fig. 5. Schematic of a solar flare, including the reconnection region where energy is released and particles accelerated, the chromospheric foot-points where x-rays and γ-rays are produced, a CME and CME-driven shock. ENAs are produced wherever there are accelerated particles, with a yield proportional to the energetic-particle and ambient densities (adapted from a RHESSI Science Nugget [18]).

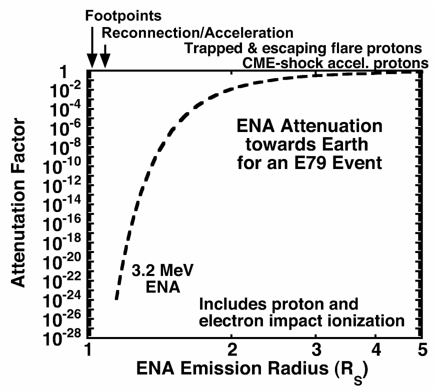

Fig. 6. The attenuation factor for 3.2 MeV ENAs produced at a given heliospheric radius (for an E79 flare with ENAs directed towards Earth). ENA production locations are indicated on top.

The acceleration region also produces ENAs, but for typical coronal densities, the attenuation factor for 3-MeV ENAs produced at 1.15 to 1.3 $R_\odot$ (the maximum from [19]) ranges from 10^{-24} to 10^{-13}. It appears that neither the acceleration site or flare footpoints would be observable from Earth for east-limb flares.

Accelerated protons and electrons also move upward in the corona and some fraction often escape into interplanetary space. In order to explain our estimated ENA yield of 1.8 x 10^{28} with the ENA production estimate from RHESSI requires an attenuation factor of <1000 even if 50% of the accelerated protons (optimistically) move upward. For typical coronal densities this implies that the ENA production takes place at a heliocentric radius of >∼ 2 $R_\odot$ (Figure 6). However, enough ENAs may escape if some fraction of the flare-accelerated protons escape into the corona and interplanetary space.

We now consider CME-shock-accelerated particles. The type-II burst (Figure 2) signals formation of a coronal shock, while the coincident type-III burst is due to electrons escaping the corona. Unfortunately, there are no CME observations because SOHO/LASCO was undergoing routine maintenance and the STEREO coronagraphs were not yet operational. However, assuming the CME was launched at ∼1020, a 2000 km/sec CME would be at ∼2.2 $R_\odot$ at ∼1027 UT when type-II emission occurred and would travel to ∼7 $R_\odot$ in ∼30 minutes. A realistic calculation of ENA emission requires a multi-dimensional model; here we compare the energy needed for ENA production with that of a fast CME.

At a given heliocentric radius R we can relate the number of ENAs produced to the number of accelerated particles in the same energy range with:

$$N_{ENA} = N_{SEP}\ v\ t\ N_T(R)\ \sigma\ F(R) \qquad (1)$$

Here N_{ENA} is the number of 1.8-5 MeV ENAs required to explain the observations (assuming isotropic emission), N_{SEP}(R) is the number of accelerated 1.8-5 MeV protons at radius R, v is the SEP velocity, t is the interaction time, N_T(R) is the number of targets per cm^3, σ is the species-weighted cross section for ENA production, and F(R) is the fraction of ENAs that escape the Sun toward Earth. To evaluate equation (1) we assume a strong shock with a density jump of 4, which produces accelerates protons with dJ/dE $\propto E^{-1}$. We assume accelerated particles spend equal time on both sides of the shock so that N_T is ∼2.5 times the normal coronal density. For simplicity we use ∼3-MeV protons and ENAs to represent the 1.8-5 MeV interval. In Figure 2 most ENA emission occurs ∼30 minutes, so t = 30 minutes.

Inverting (1) to solve for N_{SEP} as a function of R, we find that from ∼2 $R_\odot$ to ∼7 $R_\odot$ the production and attenuation terms tend to balance, giving an average for N_{SEP} of ∼2 x 10^{34}. We convert this to an energy requirement of $E_{SEP} \approx 3$ x 10^{29} ergs by multiplying by the energy content of ∼0.01 to 30 MeV protons (rather than just 1.8-5 MeV) where 30 MeV is typical of the maximum energy at which SEP power-law spectra steepen in large events [20],[21]. A study of the largest SEP events [22] found that the kinetic energy contained in SEPs was, on average, ∼ 10% of the CME kinetic energy, with the median kinetic energy of CMEs that produce large SEP events $\sim 1.8 \times 10^{32}$ egs (see also [23]). Assuming a kinetic energy of 1 x 10^{32} ergs for the 5 December 2006 CME, our estimate of $E_{SEP} \approx 3 \times 10^{29}$ ergs amounts to only 0.3% of the assumed CME kinetic energy, not unreasonable for this prime acceleration region close to the Sun. A somewhat slower CME is possible if the CME was launched before ∼1020 UT.

IV. Summary and Conclusions

RHESSI observations of the neutron-capture line lead to improved estimates of flare-accelerated protons and ENA production in the 5 December 2006 event. If flare-accelerated protons produce most ENAs they must be created at >2 Rs to escape the Sun in sufficient numbers. This suggests that escaping rather than trapped flare protons are more likely responsible. The observed ENA emission, if due to CME-shock accelerated protons, would require only a small fraction (∼0.3%) of the kinetic energy of typical CMEs responsible for large SEP events. Furthermore, the timing of the ENA emission is plausible for CME speeds of 1500-2000 km/s. More detailed modeling of flare and shock-related ENA production would help interpret these observations.

In the approaching solar maximum STEREO ENA and SEP observations from multiple points of view, aided by modeling and imaging missions such as RHESSI and STEREO, can provide a new window into SEP acceleration and transport by revealing when, where, and how the poorly known spectra of low-energy (<10 MeV) solar protons interact with solar matter.

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