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

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Abstract: We discuss observations of energetic neutral hydrogen atoms (ENAs) from a solar flare/coronal mass ejection event reported by Mewaldt et al. (2009). The observations were made during the 5 December 2006 X9 solar flare, located at E79, by the Low Energy Telescopes (LETs) on STEREO A and B. Prior to the arrival of the main solar energetic particle (SEP) event at Earth, both LETs observed a sudden burst of 1.6 to 15 MeV particles arriving from the Sun. The derived solar emission profile, arrival directions, and energy spectrum all show that the <5 MeV particles were due to energetic neutral hydrogen atoms produced by either flare or shock-accelerated protons. RHESSI measurements of the 2.2-MeV γ-ray line provide an estimate of the number of interacting flare-accelerated protons in this event, which leads to an improved estimate of ENA production by flare-accelerated protons. CME-driven shock acceleration is also considered. Taking into account ENA losses, we conclude that the observed ENAs must have been produced in the high corona at heliocentric distances $\geq$2 solar radii.

I. Introduction

When NASA's STEREO mission was launched in October 2006 it appeared that the Sun was well into solar minimum conditions. As a result, the solar community was caught by surprise when active region xxxx emerged over the east limb in early December, 2006 and suddenly unleashed a series of 4 X-class flares, each associated with a solar energetic particle (SEP) event. At the time the two STEREO spacecraft were still located close to Earth. Fortunately, the Low Energy Telescopes (LETs) and High Energy Telescopes (HETs) were already operational and measured time profiles from LET for the first event on December 5 are shown in Figure 1. Since this event originated at E79 there was no direct connection to Earth along the interplanetary magnetic field and the most energetic particles began arriving just after 1400 UT, ~4 hours after the X-ray flare. However, also seen in Figure 1 is a small, low-energy precursor, arriving between 1130 and 1300 UT. Surprisingly, >70% of the particles during this burst (apparently all protons with 1.6 to 15 MeV) were found to arrive from within ±10° longitude of the Sun, having apparently traveled from the Sun directly across the interplanetary magnetic field (oriented at 36° to 67° to the Earth-Sun line during this interval). After considering alternatives such as neutron-decay protons, Mewaldt et al. [1] concluded from several lines of evidence that the precursor was composed of energetic neutral hydrogen atoms (ENAs) made in the December 5 eruption from protons accelerated by the flare and/or CME-driven shock. In

LET the ENAs are stripped of their electron upon striking the thin front Kapton window. Solar ENAs therefore preserve their original direction until detection.

In this paper we review the December 5 observations, discuss ENA production processes on the Sun, make use of RHESSI data to provide an improved estimate of ENA production by flare-accelerated protons, and compare estimated and measured yields of ENAs from both flare and shock-accelerated particles.

II. STEREO AND RHESSI OBSERVATIONS

The SEP observations discussed here were made by the LETs and HETs on STEREO, which together measure the nuclear charge (Z) and kinetic energy of H, He and heavier ions up through Ni from ~2 to ~100 MeV/nuc. LET is composed of a double-ended array of 14 position-sensitive silicon solid-state detectors, including ten ~25 micron thick detectors arranged in two fan-shaped arrays centered on a four-detector double-ended stack [2]. Particle arrival directions are measured over 130° x 29° fans in the front and back directions with ~±6° uncertainty in the ecliptic plane. The HET sensor consists of a stack of ten circular silicon solid-state detectors (each 1-mm thick) with a single-ended cone-shaped field of view with 55° full angle [3].

The LET sensors are normally oriented such that the Sunward fan is parallel to the ecliptic and centered 45° west of the Sun along the nominal (Parker spiral) interplanetary magnetic field. However, during December 2006 the STEREO-B spacecraft was flying up-side down such that the LET-B Sunward fan and HET-B were centered 45° east of the Sun. As a result, the two LETs combined could measure particle arrival directions over 360° of the ecliptic plane.

Protons in the December 5 precursor exhibited velocity-dispersion with higher-energy particles arriving first. Mewaldt et al. [1] used LET measurements of 1.6 to 15 MeV, 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 the particle velocity, $v = (2E/m)^{1/2}$ and derive the emission time(with m the proton mass). The resulting emission profile is compared to the GOES X-ray profile in Figure 2. The remarkable similarity of the ENA and GOES X-ray profiles confirms that the ENAs originated in this solar event.

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

The December 5 flare was also observed by RHESSI (see Figure 3). RHESSI observed high-energy X-rays and γ-rays from the flare, although it likely missed the initial part of the emission due to being in eclipse (note that the soft X-ray emission in Figure 2 began at ~1019 UT and peaked at ~1035). The RHESSI observations start at ~1031 UT and the X and γ emission in Figure 3 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 >~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 that it is not spectrally resolved by *RHESSI*'s germanium detectors (~10 keV FWHM at this energy) and can be seen even at relatively low fluxes. For more information on RHESSI see Lin et al. [5].

The RHESSI data can be used to estimate the number of flare-accelerated protons that interacted in the solar atmosphere. The neutron-capture line fluence determined from a spectral fit is $(3.2\pm0.9) \times 10^{-2}$ 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 70–150 keV has a heliocentric angle of 79.5° (Krucker, private communication). Assuming that the neutron-capture line emission comes from approximately the same location (the neutron-capture 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 above 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 observations of solar flare neutrons [7] and neutron-decay protons [8,9] at 1 AU during large solar flare events, the LET and HET data were also examined for evidence of neutron-decay protons, which should be observed over a broad range of pitch angles [8,10]. Although neither HET viewed the Sun, there was a 2σ excess of 13-40 MeV protons during the time interval of the ENA burst [1], which appear to be consistent with a neutron-decay proton spectrum with ~10% of the intensity observed by Evenson et al. [8] during the east-limb event of 3 June 1982. An independent upper limit on the number of interacting protons was obtained [1] by assuming that the 2-σ excess of 13-40 MeV protons was all due to neutron-decay protons. Scaling from Hua and Lingenfelter's [11] analysis of the 3 June 1982 event at E75°, Mewaldt et al. [1] estimated 3.1×10^{32} interacting protons with > 30 MeV, ~24 times the lower-limit based on RHESSI data. Assuming an $E^{-3.5}$ proton spectrum [12,13,4] leads to estimates of the number of interacting protons with 1.8 to 5 MeV that range from $>1.3 \times 10^{33}$ (based on RHESSI) to $<3.3 \times 10^{34}$ [1]. The RHESSI limit is undoubtedly the better of these two estimates because it is based on γ-ray data from the same solar event and makes use of up-to date cross sections and models.

III. ENA PRODUCTION AND LOSS

The timing of the ENA emission in Figure 2 suggests that the ENAs were produced by flare-accelerated particles. ENAs are usually attributed to processes in which energetic protons or heavier ions become neutral through charge exchange processes with H and He. However, at coronal temperatures (1-2 MK) or in the flare site (3 – 30 MK [14]), there are not expected to be neutral H or He on which to charge exchange ENAs can also be produced by radiative recombination with ambient electrons ($H^+ + e \rightarrow H + \gamma$) with a cross section given by $s_{rr} = 1.28 \times 10^{-25}$ $E^{-2.0}$ cm^2 (based on fitting theoretical cross sections [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., $H^+ + O^{6+}$

→ H + O^{+7}). Lacking measurements of this or related cross sections they made first order theoretical estimates suggesting that heavy-ion charge-exchange processes (summed over all coronal species) could contribute ~150 times more than radiative recombination.

Following Mewaldt et al. [1] we assume that all protons with <10 MeV slow down and stop in the solar atmosphere. Using the RHESSI limit on 1.8-5 MeV protons and the production cross sections described above we find that >4 x 10^{31} ENAs are produced with 1.8-5 MeV, which is a factor of >1000 more than needed to explain the LET observations if we assume isotropic emission and all upward-moving ENAs escape the Sun. However, once produced, ENAs will be 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 $\sigma_i = 2.3 \times 10^{-17} \times E^{-0.895}$ cm^2, with E the ENA energy in MeV [16] The attenuation factor is then given by $F(R) = \exp(-\sigma_i N_R)$ 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 (see cartoon in Figure 5) magnetic reconnection suddenly releases a great deal of energy in the corona and energetic particles are quickly accelerated by one or more processes [19]. Aschwanden [19] estimated from X-ray studies that the mean height of the reconnection region varies from ~5,000 to ~50,000 km, with an extreme maximum of ~200,000 km (corresponding to a heliocentric radius of ~1.3 Rs). The reconnection process produces upward and downward beams of protons and electrons (Figure 5). The electrons directed downward produce bremstrahlung radiation from the chromoshperic footpoints of the flare as observed by RHESSI (Figure 3), 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 3). In addition, these foot-points will be copious ENA production sites because there is neutral H and He in the chromosphere. However, as shown in Figure 6, very few ENAS produced in the chromosphere will ever escape the Sun.

The acceleration region will also produce ENAs, but assuming typical coronal densities, the attenuation factor for a typical 3-MeV ENA produced at 1.15 – 1.3 Rs (the maximum observed by Aschwanden [19]) ranges from 10^{-24} to 10^{-13}. It appears that neither the acceleration site or flare footpoints should be observable from Earth for east-limb flares.

Accelerated protons and electrons also move upward in the corona and some fraction 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 requires that the ENA production takes place at a heliocentric radius of >~2 Rs (see Figure 6). This might be satisfied if some fraction of the upward moving flare-accelerated protons escape into the corona and interplanetary space.

The agreement of the ENA and X-ray emission profiles suggests that flare-accelerated particles are responsible, but we should also consider CME-shock accelerated particles. The type-II burst in Figure 2 signals the formation of a coronal shock while the coincident type-III burst is due to electrons escaping the corona. Unfortunately, there are no CME observations of this event because SOHO/LASCO was undergoing routine maintenance and the STEREO coronagraphs had not yet been commissioned. However, assuming that the CME was launched when the x-ray emission began at ~1020, a 2000 km/sec CME would be at ~2.2 Rs at ~1027 UT when the type-II emission occurred and would travel to ~7 Rs in the next 30 minutes. To make a realistic calculation of the ENA emission from a CME-driven shock requires a dynamic, multi-dimensional model; here we compare the energy needed to produce the observed ENAs with that available from 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 the following equation:

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

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, 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 in Earth's direction. To evaluate this relation we assume a strong shock with a density jump of 4, which produces a proton spectrum with $dJ/dE \propto E^{-1}$. We assume that the accelerated particles spend equal time on both sides of the shock, in which case 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 of the ENA emission occurs within a 30-minute interval, so in this example t = 30 minutes.

If we invert this equation and solve for N_{SEP} as a function of R, we find that between ~2 Rs and ~7 Rs the production and attenuation terms tend to balance, giving an average number for N_{SEP} of ~2 x 10^{34}. We convert this to an energy requirement of $E_{SEP} \approx 3 \times 10^{29}$ ergs by multiplying by the energy content of ~0.03 to 30 MeV proton (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]. In a study of 23 of the largest SEP events of solar cycle 23 Mewaldt et al. [22] found that the kinetic energy contained in SEPs was, on average, ~10% of the CME kinetic energy, and that the median kinetic energy of CMEs that result in large SEP events is ~ 1.8 x 10^{32} egs (see also [23]). If we assume a kinetic energy of 1 x 10^{32} ergs for the 5 December 2006 CME then our estimate of $E_{SEP} \approx 3 \times 10^{29}$ ergs amounts to only 0.3% of the assumed CME kinetic energy, certainly not an unreasonable fraction for this prime acceleration region close to the Sun. A somewhat slower CME speed could also be accommodated if the CME was launched earlier than ~1020 UT.

The above comparison depends on our estimated yield of the ENA production due to charge-exchange with heavy coronal ions like O^{+6}, which is very uncertain. If these cross sections should turn out to be significantly overestimated, the efficiency required of SEP acceleration would increase correspondingly (note also that CME kinetic energies up to ~10^{33} ergs have been observed [24].

IV SUMMARY AND CONCLUSIONS

RHESSI observations of the neutron-capture line in the 5 December 2006 lead to improved estimates of the spectrum of flare-accelerated protons and of ENA production in the 5 December 2006 event. These imply that if flare-accelerated protons are the cause of most of the ENA production they must be created at >2 Rs to escape the Sun in sufficient numbers. This suggests that escaping rather than trapped flare particles are more likely to have been responsible. It is also shown that the observed ENA emission, if due to CME-shock accelerated particles, would only require a small fraction (~0.3%) of the kinetic energy of the typical $\sim 10^{32}$ erg CME responsible for most large SEP events. Furthermore, the timing of the ENA emission is also plausible if the CME travels at speeds close to 1500-2000 km/s. More detailed modeling of both flare and shock-accelerated ENA production would be very helpful in interpreting these observations.

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

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Figure Captions

Figure 1: Time history of low-energy protons measured by LET-B during 5 to 7 December 2006. The onset time and location of two X-class flares are indicated. The arrow points to a burst of particles preceding the main SEP event.

Figure 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 with the onset of STEREO type-II and type-III radio bursts (adapted from [1]).

Figure 3: RHESSI light-curves for the December 5, 2006 flare in three energy bands, scaled for clarity. The 50–100 keV light-curve (black) and the 300–500 keV light-curve (blue, background-subtracted) are primarily electron bremsstrahlung continuum emission, while the 2215–2230 keV light-curve (red, background-subtracted) is dominated by the 2.223 MeV neutron-capture line. The green dashed line signifies when RHESSI came out of eclipse, showing that RHESSI likely missed part of the emission. The 50–100 keV light-curve has data removed when the instrument had high deadtime.

Figure 4: ENA spectrum measured by LET-A and LET-B during the 5 December 2006 solar event, based on particles with arrival directions within ±10° of the Sun and derived solar emission times between 1015 and 1145 UT (from [1]). The >5 MeV points could include contributions from neutron-decay protons (see text).

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

Figure 6: The attaenuation factor for 3.2 MeV ENAs produced at a given heliospheric radius (for an E79 flare with ENAS directed towards Earth). Possible ENA production locations are indicted. **(Hope to change this to 3 MeV curve)**

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