Using Solar Neutrons to Understand Solar Acceleration Processes

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1. Introduction: Importance of Solar Neutrons for Understanding Solar Acceleration Processes

The development of an understanding of energetic-particle acceleration mechanisms has long been a goal of heliospheric physics. Although much progress has been made since the space-flight era began, many gaps in our knowledge remain. The largest gaps involve energetic-ion acceleration in solar flares. These ions are difficult to detect remotely if they do not have access to magnetic field lines that connect the corona to interplanetary space. Yet, 90% of all ions accelerated in large impulsive flares remain tied to the Sun on closed magnetic field lines (Hua and Lingenfelter, 1987) and those that do escape remain confined to spatially-limited magnetic flux bundles in interplanetary space limiting the ability to directly observe these ions. Whereas energetic electrons can be imaged indirectly through bremsstrahlung, gyrosynchroton radiation, and hard x-rays, energetic ions are nearly invisible except through their coupling to secondary neutral radiation in the form of gamma rays and/or neutrons.

Several recent studies (see, e.g., Miller et al. (1997); Ryan (2000); Hua et al. (2002); Murphy et al. (2007), and references therein) have shown that combined analyses of gamma rays and neutrons from solar flares are essential to adequately constrain the many parameters needed to account for the total number, energy spectrum, time dependence, and angular distribution of all ions accelerated. This combined analysis is also essential for constraining the magnetic and plasma structure of the flare neighborhood in the corona that control trapping and transport, such as the elemental composition, density and temperature scale height, magnetic loop structure, acceleration altitude, and the MHD and plasma turbulence near the flare site.

Because of sensitivity issues stemming from the necessity of measuring neutrons at 1 AU[1], to date, many more flares have been observed in gamma rays than in neutrons. This circumstance has put a filter on the types of impulsive flares that have been amenable to a joint neutron and gamma ray analysis. For the most part, these flares have been necessarily large. Another element of the observational filter stems from the fact that all previous neutron detections have been at energies larger than 25 MeV. However, all neutrons produced through interactions between accelerated ions and coronal plasma ions result from two dominant types of nuclear reactions: knock-on/charge-exchange, and spallation/ evaporation. In the first case, the emerging neutrons have a range of energies that extend up to that of the incident ion energy per nucleon, and in the second case, the neutron energy distribution is a Maxwellian having a temperature of several MeV. Lately, there has been a realization that even relatively low energy ions (E_i < 30 MeV/nucleon) can produce significant fluxes of low energy neutrons (E_n < 10 MeV). The most

[1] Neutrons in free space have a lifetime of ~15 minutes (Nieto et al., 2008). Therefore, most neutrons of moderate energy (less than few 10s of MeV) decay before ever reaching the Earth and are not detected.

significant reactions in this third class of reactions are the exothermic reactions induced by alpha particles involving isotopes ^{13}C, ^{25}Mg, and ^{26}Mg, (and their inverse reactions) and to a much smaller extent, of low threshold alpha reactions involving isotopes ^{14}N, ^{18}O, ^{22}Ne, ^{29}Si, ^{54}Fe, and ^{56}Fe (and their inverse reactions) (Share et al., 2010). Detection of the first reaction type will come from solar sites located preferentially near the limb of the disk to facilitate detection of the high-energy portion of the neutron spectrum. Because of the large pitch angles of trapped protons after initial acceleration, these ions preferentially convert to neutrons having directions perpendicular to the radial, yielding a higher detection probability at Earth if the flare is near the limb. On the other hand,

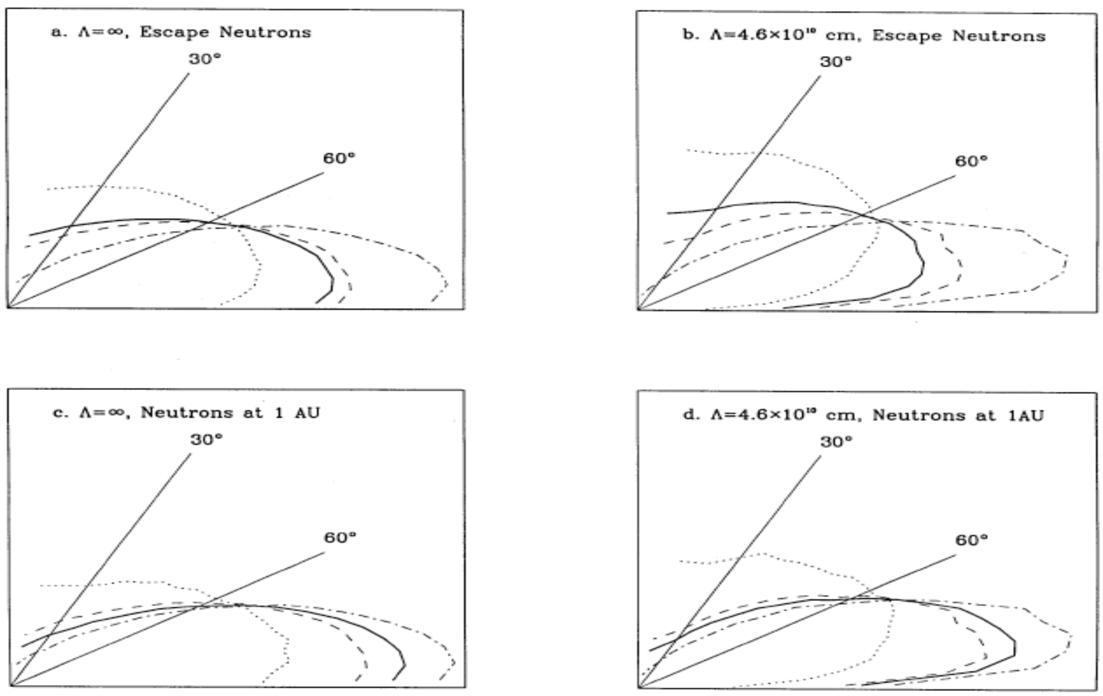

Figure 1. Zenith angular dependence of escaping neutrons (top two panels); zenith angular dependence of neutrons at 1 AU (bottom panels). Left panels have no ion pitch angle scattering; right panels are for saturated pitch angle scattering. Figures from Hua et al., (2002).

detection of low energy neutrons in the second and third class of reactions, which is only possible at distances much closer to the Sun than 1 AU is facilitated from flare sites nearer to disk center because boil-off neutrons from highly excited spallation nuclei and exothermic reactions are nearly isotropic. Here, the coronal escape probability is maximum in the radial direction where the neutrons will encounter a reduced column density of overlying coronal protons. This difference in the neutron angular distribution of escaping neutrons is illustrated in Figure 1, from simulations carried out by Hua et al. (2002).

In summary, the objectives of studying solar neutrons is to fill the gaps in our understanding of ion acceleration, trapping, and transport in the corona during solar flares. This can be accomplished through analysis of combined neutron, gamma ray, extreme ultraviolet (EUV), radio wave and energetic particle data sets. The significance of these studies is to: 1) better understand magnetic reconnection as revealed in solar flares and coronal mass ejections; 2) to understand the plasma processes that accelerate and transport particles; and 3) to explore the full range of flares that produce neutrons. Up to now, only the very largest impulsive flares have been amenable for study at 1 AU. All of these objectives are specifically called out in the 2005 Heliophysics Roadmap for Science and Technology.

2. Current and Potential New Measurements of Solar Neutrons

At present, the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) spacecraft (Lin et al., 2002) provides the most comprehensive source of high-energy X-ray and gamma-ray data that are suitable for studies of ion acceleration in solar flares. Solar-flare neutrons have for some time been, and are currently, monitored by ground-based neutron detectors (e.g., (Ryan, 2000) and references therein]) The only source of solar neutron data from space at present is the Neutron Spectrometer (NS) sensor of the Gamma-Ray and Neutron Spectrometer (GRNS) instrument (Goldsten et al., 2007) on the MErcury Surface, Space ENvirnoment, GEochemistry, and Ranging (MESSENGER) spacecraft (Solomon et al., 2007). This spacecraft is presently orbiting the Sun between 0.30 AU and 0.55 AU en route to orbit insertion about Mercury in March 2011. Between now and the end of the mission, the MESSENGER orbit will decrease from its present aphelion of 0.55 AU to that of the aphelion of Mercury, 0.47 AU. Its orbit about the Sun is presently scheduled to last one Earth year beyond orbit insertion now, scheduled for 18 March, 2011. However, the termination date of the MESSENGER mission is presently under consideration to be extended for at least one additional year to include the period up to solar maximum.

The Neutron Spectrometer aboard MESSENGER is sufficiently sensitive to solar neutrons as to complement the measurements of solar flare gamma rays that are now provided by RHESSI. The energy range of the MESSENGER NS covers the maximum flux portion of the neutrons generated by ions accelerated during solar flares, between 0.5 and 7.5 MeV. This range nicely brackets the maximum flux portion of flare neutrons that was simulated by Murphy et al. (2007), as shown in Figure 2. This new NS data set will then effectively provide a separate scientific mission of opportunity for MESSENGER that could function as an active addition to the Heliophysics Great Observatory.

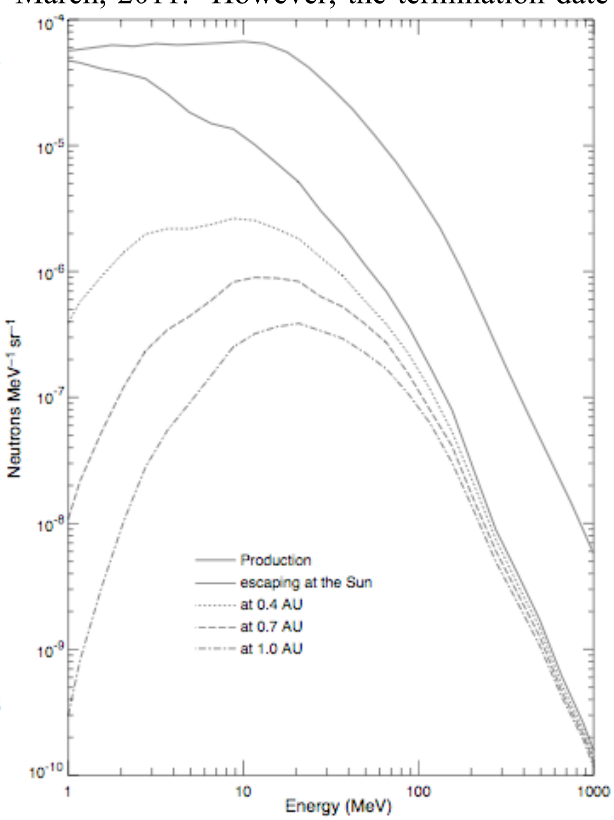

Figure 2. Energy spectrum of neutrons at various stages of production and propagation to 1 AU (from Murphy et al., 2007).

A neutron and gamma-ray spectrometer were included as part of the baseline mission design for the Solar Probe Plus (SPP) mission (STDT, 2008). However, the final instrument selection that took place in mid-2010 did not include either instrument. For the neutron measurements in particular, the SPP mission easily provides the best opportunity for making robust measurements of solar neutrons because the close distance of SPP to the sun (~0.05 AU) results in an increased sensitivity for 5 MeV neutrons by six orders of magnitude from 1 AU[2]; the SPP mission provides for a factor of ~800 increased sensitivity from 0.3 AU, which is the minimum distance achieved by the MESSENGER NS.

Finally, neutron and gamma-ray instruments are listed as potential measurements for the Solar Sentinels mission, which would approach the sun with a distance of 0.25 AU (Solar Sentinels STDT, 2006).

3. Observations of Neutrons at 0.48 AU with the MESSENGER NS

A recent report by Feldman et al., (2010) illustrates the type of interplanetary-space neutron measurements that can be made with the MESSENGER NS. On 31 December 2007, neutrons were detected by the MESSENGER NS during an M2 flare (see Figures 3 and 4). This flare contained multiple acceleration episodes as seen in Type III radio bursts. After these bursts ended, both the energetic-particle and neutron fluxes decayed smoothly to background with an e-folding decay time of 2.84 hours, spanning a nine-hour time period. This time is considerably longer than the mean lifetime of a neutron, which indicates that either the observed neutrons were generated in the spacecraft by solar-energetic-particle protons, or that they originated on the Sun. As part of this study, Feldman et al. (2010) investigated the possibility that the detected neutrons might have been generated on the spacecraft due to energetic ion interactions with spacecraft material. Unfortunately, the MESSENGER spacecraft does not have any instruments to measure energetic ions having energies greater than about 30 MeV per nucleon, which is the general threshold energy for producing neutrons. The MESSENGER NS is sensitive to energetic charged particles, but at present the response of the NS is not sufficiently modeled to discriminate between energetic electrons or ions. Even with these limitations, a full spacecraft particle transport model that was validated with neutrons measured at Mercury (Lawrence et al., 2010), was used to determine that if all the NS detected charged particles were ions (instead of the more likely mix of electrons and ions), then at most only 20% of the detected neutrons could have been locally generated. As a consequence, Feldman et al. (2010) concluded that a likely explanation of their long duration is that energetic ions were accelerated over an extended time period onto closed magnetic arcades above the corona and then slowly pitch angle–scattered by coronal turbulence into their chromospheric loss cones. Because of their relatively low energy loss in the Neutron Spectrometer (0.5–7.5 MeV), most of these neutrons beta decay to energetic protons and electrons close to the Sun, thereby forming an extended seed population available for further acceleration by subsequent shocks driven by coronal mass ejections in interplanetary space.

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[2] This rough scaling assumes that the detected neutron flux scales as $F \sim e^{-(t/\tau)}/D^3$, where t is the neutron time-of-flight from the sun to the sensor, τ = 886 seconds is the neutron lifetime (Nieto et al., 2008), and D is the distance from the sun to the measurement. The factor of $1/D^3$ is included to account for the time spreading of the neutrons ($1/D$) and an areal flux factor ($1/D^2$). A full sensitivity analysis requires a detailed understanding of a given instrument sensitivity and mission profile (e.g., time spent at a given sun distance) and is beyond the scope of this white paper.

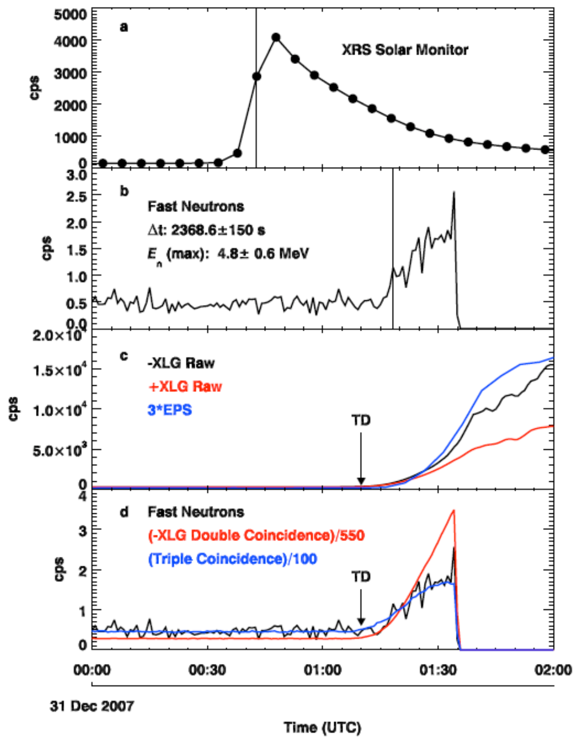

Figure 3. (a) Response of the MESSENGER X-ray Spectrometer (XRS) solar monitor to X-rays during the 31 December 2007 solar flare. (b) NS detector response to fast neutrons produced by the solar flare. (c) Rates of energetic particle counts at MESSENGER measured using the two Li-glass (LG) scintillators and the MESSENGER Energetic Particle Spectrometer (EPS) EPS detector. (d) An overlay of fast-neutron, lithium glass double-coincidence, and lithium glass/borated plastic triple-coincidence counting rates before a data dropout due to an instrument safing from high rates. The energy range of the EPS is 65 keV to 1.0 MeV; the energy range of the single raw LG counting rates for electrons is from 300 keV to about 2 MeV and protons up to about 30 MeV; the energy range of the double-coincidence rates for electrons is from about 2 to 20 MeVand protons from about 30 to 120 MeV; and the energy range for triple-coincidences of electrons is greater than about 20 MeV and protons greater than about 120 MeV (figure taken from Feldman et al., 2010).

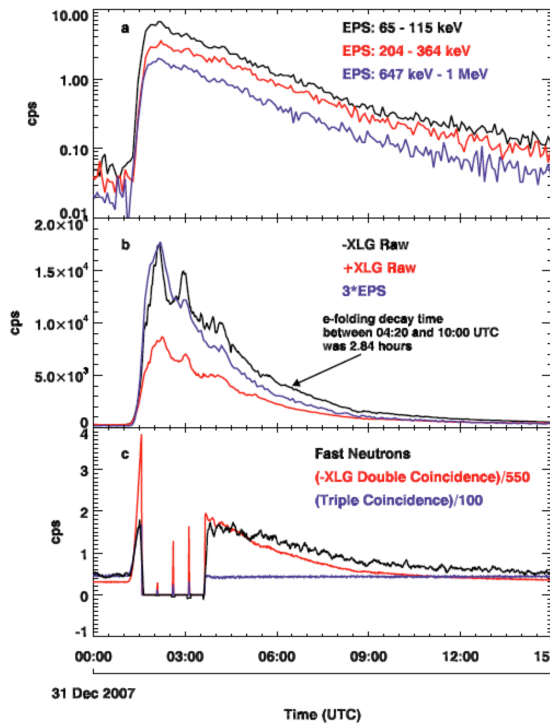

Figure 3. (a) Time-dependent counting rates of energetic electrons measured with the MESSENGER EPS detector. The top (black) curve is for 65 to 115 keV, the middle (red) curve is for 204 to 364 keV, and the bottom (blue) curve is for 647 keV to 1 MeV. (b) Rates of energetic particle counts at MESSENGER measured using the two Li-glass scintillators and the EPS detector. The EPS counting rates have been scaled to match that registered by the LG scintillator. (c) An overlay of fast-neutron (black curve), double-coincidence (red curve), and triple-coincidence (blue curve) counting rates throughout the entire fast-neutron event. The three vertical lines during the safe mode record three failed attempts to exit the safe mode before the BP counting rate dropped below the preprogrammed safe level. (figure taken from Feldman et al., 2010).

In response to the Feldman et al. (2010) study, Share et al. (2010) have suggested that the most likely explanation for the detected neutrons is that they were generated locally on the spacecraft from flare-related ions and alpha particles. The particular concerns of

Share et al. (2010) include the following: 1. The inferred number of accelerated protons at the Sun for this M2-class flare was 10X larger than any flare observed to date; 2. The onset and duration of the 'solar' neutron count rate was similar to that of the solar energetic particles (SEPs) (albeit with some exceptions); and 3. They argue that Feldman et al. (2010) underestimate the local neutron production from energetic ions. There is clearly more work to be done to sort out and understand these conflicting interpretations of the MESSENGER measurements.

Further progress can be made in understanding and resolving these discrepancies through multiple tasks: 1) Further modeling of the MESSENGER NS and spacecraft can be carried out to understand the response of the NS to charged particles (to help discriminate between energetic electrons and ions), as well as better understand the local generation of neutrons. 2) The ability to distinguish between solar and local neutron production will be helped considerably after Mercury orbital insertion with the aid of the 12-hour orbital period, which should effect a significant modulation of SEP protons incident on the spacecraft during flare events. Specifically, one can monitor the modulation of SEP protons by the Mercury magnetosphere using its simultaneously measured plasma and fields structure by onboard plasma, magnetic field, and energetic particle experiments and determine if any detected neutrons have or do not have a similar modulation. 3) Now that the sun is becoming more active, many more flare events will be detected with the MESSENGER NS. It is likely that future events will have coincident energetic particle measurements from other spacecraft assets such as STEREO and/or ACE. Starting in March 2011, the MESSENGER spacecraft will be in orbit about Mercury for at least one Earth year. If the mission proceeds nominally, it will have enough fuel to enable an extended mission of up to a few years. Therefore, there will be ample opportunity to measure multiple solar flares with possible neutron detections.

4. Future of Solar Neutron Studies

Measurements of solar neutrons provide a unique opportunity to enhance our understanding of solar acceleration processes in all types of flares having an expanded range of strengths. The only mission currently operating that can provide any information about solar neutrons in the neutron energy range of 0.5 – 10 MeV is the MESSENGER mission. However, since it is a planetary exploration mission, there is no explicit funding to carry out the analysis and modeling tasks described in Section 3. In particular, as more neutron events are detected, more effort will be needed to analyze and interpret these events along with comparative event studies. The required funding for such studies should be modest and on the order of standard Science, Research and Technology (SR&T) grants.

Second, flight opportunities for neutron detectors to fly inside of 0.3 AU should be strongly encouraged. SPP clearly provided the best opportunity likely to be seen in a generation, as it will be traveling to within 9.5 R_s (or 0.05 AU). If other such flight programs are proposed (e.g., Solar Sentinels, which may fly to within 0.25 AU), a neutron instrument should be strongly considered. In summary, to fully understand solar acceleration mechanisms, it is required to have robust neutron measurements in concert with coordinated observations of gamma-rays, energetic ions and electrons, EUV, and radio waves.

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