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Solar Emissions

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The SH1 session of the Pune ICRC dealt with the topic of solar emissions. In terms of which may be considered cosmic rays, this includes neutrons and γ-rays as well as the energetic particles directly detected in space. This rapporteur paper addresses the session SH1, but SH1.5 is addressed elsewhere. This constituted a total of forty-nine papers.

Gamma-Rays and Neutrons

Determining which high-energy emissions arise from the Sun itself vs. those that arise from interplanetary processes is still a subject of debate, the SH 1 sessions focused on (1) neutral particles from the Sun, i.e., neutrons and γ-rays, (2) interplanetary particles, including ions and electrons and (3) coronal mass ejections. Coronal Mass Ejections (CMEs), clearly not to be confused with solar cosmic rays, have been shown to be the accelerating agent for many, if not most, of the particles detected in space. The question surrounding interplanetary particles first revolves around their origin, i.e., Sun vs. interplanetary processes, and then how the accelerating process, whether flare or CME, produces the measured variety of spectral, composition and charge state signatures. The accelerating process in flares is more elusive than that for interplanetary particles since few of the accelerated particles can be detected. We know its existence from the neutral particles it produces as the charged particles interact with the solar atmosphere and also from the presence of particles of unusual composition and charge state in space (^{3}He rich events). Evidence for the potency of the process is revealed in the detection of secondaries above 1 GeV.

The paper by Ma et al. [1] was the only paper dealing with γ-ray detections. The cosmic burst spectrometer on the Chinese SZ-2 spacecraft has the potential to illuminate high-energy solar activity, for six months in 2001, that was present before the launch of RHESSI (February 2002) and after the unfortunate termination of the Compton Observatory (June 2000). The only other way solar γ-ray emission was addressed in this conference was in the context of other observations, such as helping to interpret neutron measurements. The large flares of 2001 April 2, 6 and 15 were observed with the GD on SZ-2, but detailed analysis is absent in the paper, although planned as future work.

Several papers were presented by the Solar Neutron Telescope collaboration [2-8], a global collaboration of scintillator-based high altitude neutron detectors that complement measurements with IGY and NM-64 neutron monitors. Some of these papers reported marginal detections of high-energy radiation that may be traceable to the Sun, but three papers by Watanabe et al. [5-7] and another paper by Matusbara et al. [3] reported the firmest conclusions.

Watanable et al. selected two large events for analysis. These were the events of 2003 November 2 [5] and 4 [7], part of a series of high-energy solar events in the 2003 October-November time frame. The 2003 November 2 solar neutron event (Fig. 1) was detected at the appropriate sub-solar station in Bolivia. This ground-level detections of neutrons exhibits an increase in a briefly delayed coincidence with the γ-ray intensity-time profile. The threshold, based on the particle-atmosphere transport model of Shibata [9], is on the order of 100 MeV. The detection is a combination of unattenuated neutrons from space to the ground, plus the count rate due to secondary neutrons generated in the atmosphere above the detector. The count rate due to both these channels is interpreted as being due to a plane-parallel beam of neutrons originating from the Sun with an unknown spectrum and an unknown production profile. Watanabe et al. used a few candidate production profiles to interpret the data, all yielding similar results. Roughly, the spectrum of solar neutrons from this event had a power-law-like spectrum with an E^{-8} shape. The energy contained in neutrons was of order 10^{26} ergs above 100 MeV, an interesting number, but not as important as that for the protons or ions that produced the neutrons.

A much larger event occurred two days later (Fig. 2) that yielded, in a similar analysis, a spectrum with an E^{-4} shape, with a fluence of 10^{27} neutrons above 30 MeV (extrapolating the spectrum downward from 100 MeV). The proton spectrum responsible for these neutrons would then have a spectrum of E^{-5} with an energy of 10^{30} ergs above 30 MeV, again assuming omnidirectional emission. This energy in high-energy protons is roughly 1% of the total flare energy for large events such as this. Extending such proton spectrum to lower energies would yield much larger energies in fast protons and ions, but we have no indication of the shape of the spectrum below 30 MeV.

A question arises about the origin of the ground signal, since either neutrons or protons at the top of the atmosphere can produce a signal of secondary neutrons at ground level. Figure 3 is extracted and reassembled from the oral version of the Watanabe et al. presentation [5] and the print version of Gopalswamy et al. [10]. The left hand side shows the distribution over the solar disk of the claimed solar neutron events [5] while the right hand side shows the originating locations of proton-induced ground level events (GLE). Clearly the protons GLEs arise from magnetically well connected longitudes while the

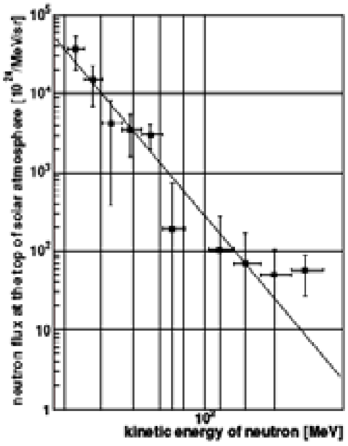

Figure 1. The solar neutron spectrum from 2003 November 2.

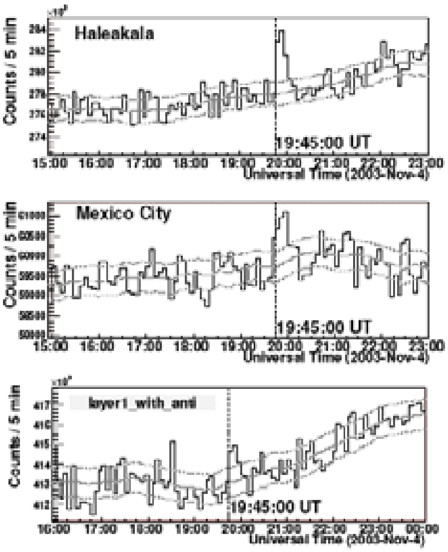

Figure 2. The count rates from the 2003 November 4 GLE.

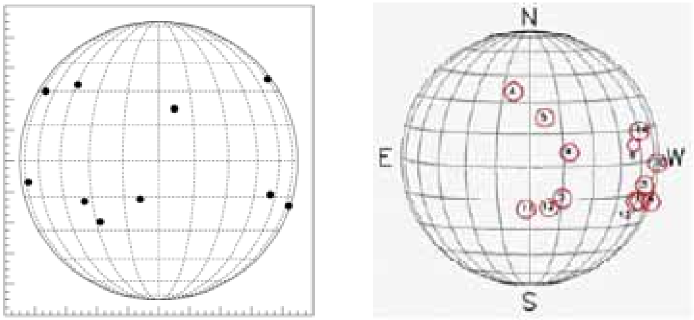

Figure 3. Distribution of neutron events (left) and GLEs (right).

neutron events are distributed rather uniformly within a low latitude range. This implies (1) that the reported neutron events are just that, neutron rather than proton-produced events and (2) that the emission pattern of neutrons is roughly isotropic, the only possibility when the parent particles interact with a highly stratified and spherically symmetric atmosphere such as the solar chromosphere and photosphere. Also, it clearly and logically seems that selecting large γ-ray flares as candidate solar neutron events is productive, but what about selecting solar flares that are associated with large interplanetary particle events? If the particles in space are related to the particles responsible for the neutrons then such a search should yield positive results. Although the search was not complete at the time of the conference, Matsubara et al. [3] observed no such relationship. A word of warning is in order because large solar events in any domain tend to exhibit emission in all other domains. In other words, the largest interplanetary proton event is statistically likely to produce solar neutrons, simply because of its size and intensity [11].

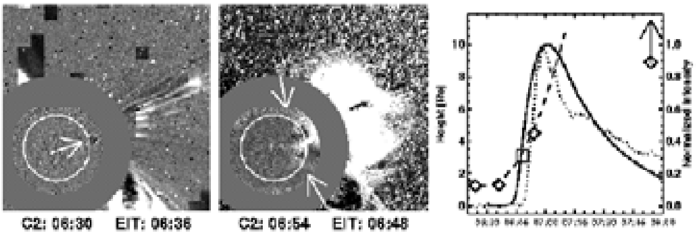

Figure 4. Development of the 2005 January 20 GLE CME.

Fig. 4 from Gopalswamy et al. [10] shows the development of a particularly fast CME that they interpret as the driving agent for the shock that accelerated protons in the most intensive GLE in a half century, the 2005 January 20 event. A selection of GLEs and their associated CMEs was jointly interpreted to show that the energetic particles are released at several solar radii from Sun center, the lowest of which was the 2005 January 20 event at 2.5 solar radii. These results are consistent with earlier studies that fit the release point to be in the range of 4 to 20 solar radii. This fitting is accomplished by computing the length of the Parker spiral and back propagating the first detected protons (momentum fixed by the local geomagnetic rigidity) from the time of detection. The speed and launch time of the associated CME over the resulting time difference yields the release height. A discussion in SH1.5, not covered here, revolved around the potential flare origin of the 2005 January 20 event [12].

Several papers were presented in SH1.2, interplanetary particles, that bear upon the flare/shock controversy. Fig. 5 shows the level of activity from the period of 2003 October/November [13]. Several particle increases can be seen in the plot.

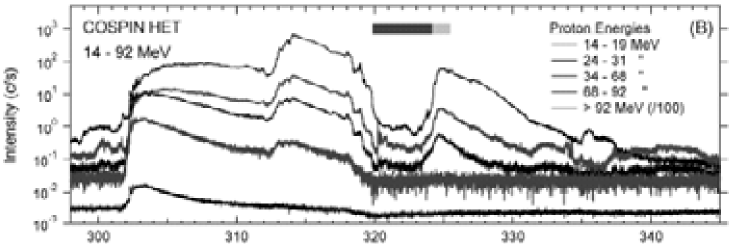

Figure 5. Energetic particle activity throughout Oct-Nov 2003

The spectra of protons in five of the particle events show remarkable similarity (Fig. 6) [14]. They can be characterized by a hard power law ($\sim E^{-1}$) that breaks above approximately 10 MeV into a softer spectrum, typically E^{-4}. The hard spectrum indicates saturation where the wave turbulence associated with the shock acceleration can carry no more particles, a so-called streaming limit [15]. Remarkably, the energy content of these particles is significant. After computing the energy densities of the particles and the driving CME, Mewaldt et al. [16] showed that the particle energy can be as large as 15% of the CME energy, making energetic particles a significant energy dissipation mechanism for the CMEs. The particle energy content is not always this large. In this sequence, the particles in one particular event was only 1% of the associated CME energy, but the fact that more than one energetic particle population represents ~10% of its associated CME energy is remarkable for a relatively short lived spherical shock, that suffers from rapid divergence or cooling. These numbers are consistent with the energy requirements for supernova shocks to be responsible for galactic cosmic-ray acceleration below the cosmic-ray spectrum knee at 10^{15} eV. Of the species of accelerated particles, protons carry the majority of the energy, i.e., 70%.

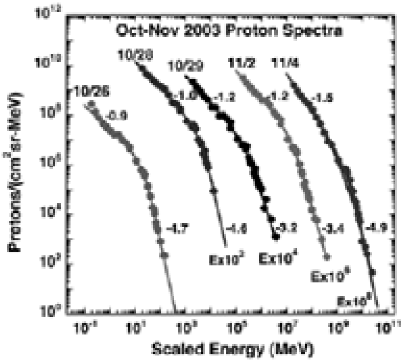

Figure 6. Spectra from five solar particle events. from 2003.

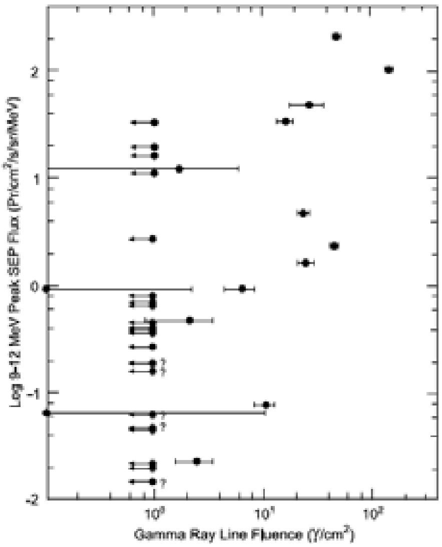

Figure 7. Correlation plot of SEP fluence vs. γ-ray fluence.

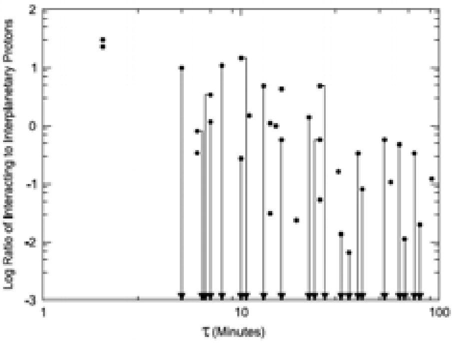

Figure 8: Ratio of γ-ray fluence to particle fluence vs. flare duration.

Cliver et al. [17] provided evidence that interplanetary shocks accelerate most of the ions one detects in space. In a plot, Fig. 7, prepared from several years of data that overlapped with the Solar Maximum

Mission, Cliver et al. showed that there exists little correlation between the intensity of ions measured in space with the intensity of γ-rays produced at the Sun. This supports the concept that once accelerated far from the Sun, ions do not, in significant numbers, produce a coronal signature, and conversely, that those ions whose presence in the low corona is evidenced by γ-ray emission, do not, in any significant number, escape to populate the interplanetary environment. What is still allowed is for lower energy particles produced in a flare to escape and then be accelerated to higher energies by a subsequent shock. The authros presented another plot (Fig. 8) that exhibits an anticorrelation between flare duration (a good indicator of CME presence) and the ratio of particles in the flare (from γ-ray emissions) to those detected in space. In other words, the longer duration the flare is, the more likely that it exhibits a CME and a large interplanetary energetic particle population compared to the population in the low corona inferred from γ-ray emissions.

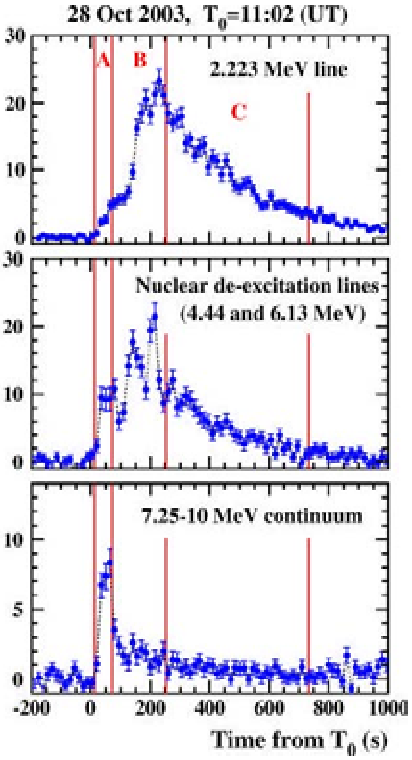

Figure 9. Period C corresponds to the period of hi-E neutron emission.

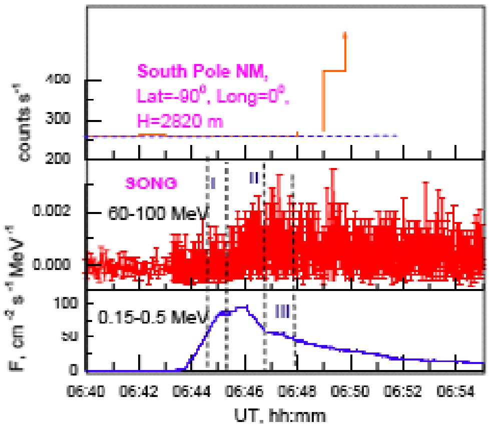

Figure 10. The prolonged high count rate on 2005 January 20 in the 60-100 MeV channel is a similar phase to that of Fig. 9.

In large flares, one sometimes observes an extended period of high-energy γ-ray emission [18, 19]. This is a phase of a large flare that has a late onset compared to the impulsive phase but can extend for many hours [20]. Because of the nuclear signature in the γ-ray spectrum, one expects the production of high-energy neutrons to accompany the production of pions, as seen in the γ-ray spectrum. Bieber et al. [21] (Fig. 9) reported the analysis and modeling of a GLE neutron event at the Tsumeb station that could only be well fit with an exponential-like K_2 Bessel function of parent protons that started no earlier than a few minutes after the onset of the impulsive phase. The emission also extended for at least 10 minutes at GeV neutron energies as indicated by the two rightmost lines in Fig. 9. The hi-E neutron intensity (after correcting for velocity dispersion) occurred on the declining part of the intensity curve for all parts of the γ-ray emission, except for around 10 MeV. This behavior is consistent with other long duration γ-ray flares, except here it is apparently plainly visible in the form of hi-E neutrons. Struminski [22] performed a similar analysis and recognized that this hi-E neutron behavior requires a late and prolonged production when modeled with the count rate in the INTEGRAL SPI instrument.

Kuznetsov et al. [23] identified high-energy γ-ray activity in the 2005 January 20 flare event (Fig. 10) that also produced an intense solar proton GLE. The γ-ray data came from the SONG experiment on the CORONAS spacecraft that has sensitivity up to 200 MeV photons. A spectral feature in the tens of MeV range arose and persisted for a few minutes, consistent in duration and onset with the GLE, after correction for velocity dispersion. Kuznetsov et al. interpreted this as "leakage" of the solar flare protons that produced the neutron pions giving rise to broadened π^0 decay γ-rays. Indeed, this is a prime example of the source of the confusion that is possible when searching for the origin of GLE protons. The January 20 GLE, interpreted and reported in the SH1.5 session, was impulsive, intense and brief. The velocity dispersion and event durations in γ-rays and the GLE increase allow for interpretations either as flare-particle leakage or low altitude coronal shock acceleration. Other GLE increases are more clearly separable from their associated flares [24].

Because no composition data exist at these energies (GLE), it is difficult to attribute by means other than timing the origin of GLE protons and ions. Impulsive phase ions, through their γ-ray spectra, are rich in heavies relative to the composition of the corona. An impulsive event such as 2005 January 20 should exhibit a hi-*Z* abundance of ions detected in space. No such capability exists. The anticipated launch and operation of PAMELA may provide such data [25]. It will be able to measure isotopes of He through C, which should be sufficient to establish whether the composition of the 1 GeV ions is similar to that of the 20 MeV ions producing the γ-rays or the quiescent solar corona.

Interplanetary Particles

The study of interplanetary particles, being distinct from those detected in flares through γ-ray and neutron emission, has advanced considerably in recent years, both from new data and new analyses and perspectives. The conventional wisdom that impulsive events and gradual events constitute two independent classes of particle events has fallen away with features of one appearing in the data of the other. At this conference some important results about variability and composition were presented. An overarching question is how the particles in interplanetary space are related to those detected in flares.

Király et al. [26] conducted a variability study of interplanetary particles as a function of energy. At the highest energies, particle events are rare but as one descends in energy toward suprathermal energies, the frequency tends to increase with fewer large excursions in amplitude. Király et al. quantified this characteristic showing in Fig. 11 a strong correlation between a flux variability index and energy band.

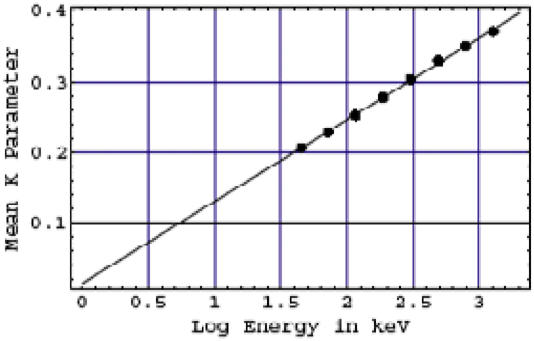

Figure 11. A variability index correlation with particle energy.

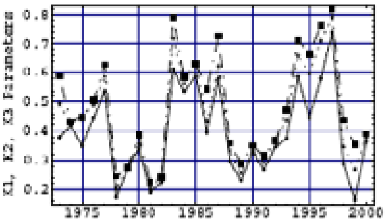

Figure 12. Variability index vs. date for three energies.

They also showed in Fig. 12 that the index was higher during solar minimum, i.e., significant events are always occurring but become less frequent during solar minimum.

There were some, perhaps conflicting, studies presented on primordial or ancient solar activity as witnessed in cosmic-ray exposure of meteorites. Das et al. [27] from an investigation of rare isotopes in chondrites, such as ^{21}Ne, concluded that the data were consistent with a steady cosmic-ray exposure. Whereas others [28] in studying ^{10}Be abundances in meteorites concluded that the meteorites were exposed to an intense and hard proto-Sun energetic particle spectrum. Finally, Ustinova et al. [29] reported that the spectrum that the meteorites were exposed to was more “flare-like” in composition as opposed to that of the solar corona. Clearly, this field calls out for more study. The implications of intense and frequent flaring of the proto-Sun would have significant impact on stellar astrophysics.

Due to limitations of the technology, composition experiments have historically been confined to iron and below (atomic number). However, with the ACE mission much higher *Z* elements can be identified and studied [30]. The flux of such heavy elements is very low and good statistics can only be acquired by summing over many events. Leske et al. [31] reported results from a trans-Fe study showing that the composition at large atomic number is consistent to within a factor of two with solar system abundances (Fig. 13). Some significant event-to-event variation could not be ruled out, however. If “flare-like” heavy element abundances seen below Fe extend to the trans-Fe domain, it would place stronger constraints on the injection and acceleration processes at work in SEPs.

So-called ^{3}He-rich events have for many years been associated with flares directly—the idea being that some fraction of flare particles escape into interplanetary space. The inference is thus that flare particles are rich in ^{3}He as well as hi-*Z* ions and electrons, all seen in classical ^{3}He-rich events. Gómez-Herrero et al. [32] presented data from the 2003 August 19 particle event showing that ^{3}He as well as ^{4}He spanned the energy range from 4 to over 60 MeV with basically the same power-law spectrum (–2.90), while protons had a distinctly softer spectrum (–3.22) (Fig. 14). The intensity of ^{3}He persisted at a level of 50% of that of ^{4}He for a duration of ~two days. However, at the beginning of the event the composition was slightly richer in ^{3}He, but the spectral index of ^{4}He continued to soften with time.

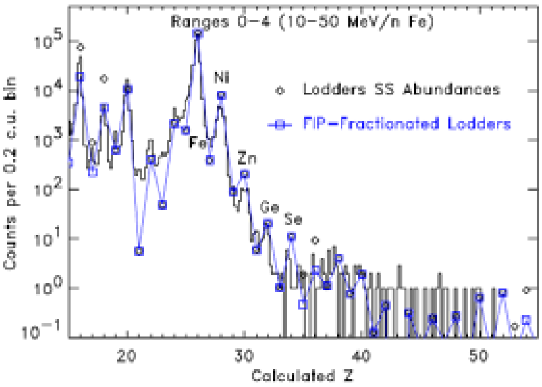

Figure 13. Mission average Z spectrum of SEPs.

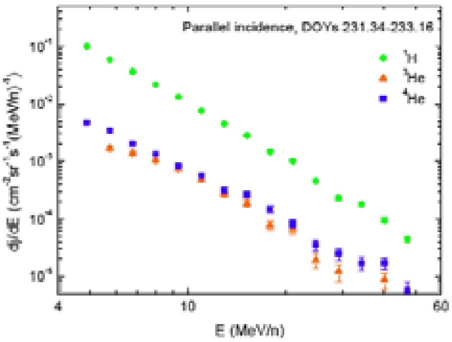

Figure 14. Proton, ^{4}He and ^{3}He energy spectra.

von Rosenvinge et al. [33] presented analysis of four events, that include 1997 November 6 and three other GLEs. Three of them have, as measured by event-averaged atomic number, so-called “impulsive” compositions, while the fourth, 1998 August 24 has a composition normally attributed to “gradual” events. The events with “impulsive” compositions exhibited, at the extreme, a 10× increase in Fe abundance as compared to gradual events. It is conceivable and perhaps likely that these heavy-rich events were seeded by previous activity that was impulsive-like. If not, then one must consider acceleration or injection models that exhibit a wide variation in the efficiency of accelerating higher *Z* ions [34].

Weidenbeck et al. [35] studied the abundance of ^{3}He over a period of 1999 to the present searching for time-varying injection of ^{3}He into the heliosphere. The results from an energy range from 200 keV to 16 MeV/nucleon indeed showed a variation consistent with solar activity. This conforms to the idea that flare or impulsive-SEP frequency follows the solar cycle even at individually unobservable levels, i.e., from events that are too small to individually detect. In fact, the period of 2003 October 15-19 is labeled as not being ^{3}He-rich but it still registers quiescent ^{3}He in measurable quantities, presumably from unresolved small flares or impulsive-SEP events. This relates to another question in solar physics, that being how the corona is heated. The idea of nanoflares [36] producing numerous low-energy ions that dissipate their energy in the corona is supported by detection of unresolved solar events with a telltale signature in ^{3}He emission. If a quasi-steady flux of solar neutrons is detected, sometime in the future with Solar Orbiter or Solar Sentinel, this could help to quantify the contribution of energetic ions to the energy budget of the corona.

Particle Acceleration and Coronal Mass Ejections

The two sessions SH1.3 and SH1.4, *Particle Acceleration near the Sun* and *Coronal Mass Ejections* were closely related. In terms of interplanetary shock acceleration, the subject matter was largely interchangeable. Two of the specific questions surrounding the acceleration of energetic particles by CME-related shocks are “What is the extent of the ability of CMEs to accelerate particles?” and “How do they do it so efficiently?” Cliver et al. [37] addressed the former question by examining the unusual event of 2001 August 16 (Fig. 15). This event was attributed to a CME ejected in a direction diametrically opposed to the earth. This extraordinary event produced a rather abrupt increase in particles starting 40 minutes after the inferred CME liftoff time on the backside of the Sun. The authors are confident from null observations on the visible disk that the receding shock was solely responsible for the >400 MeV proton increase, the idea being that acceleration was taking place shortly after liftoff, but it required 40 minutes to find a connecting field line to earth, after which both high (>400 MeV) and lower (>10 MeV) energy protons exhibited a prompt increase.

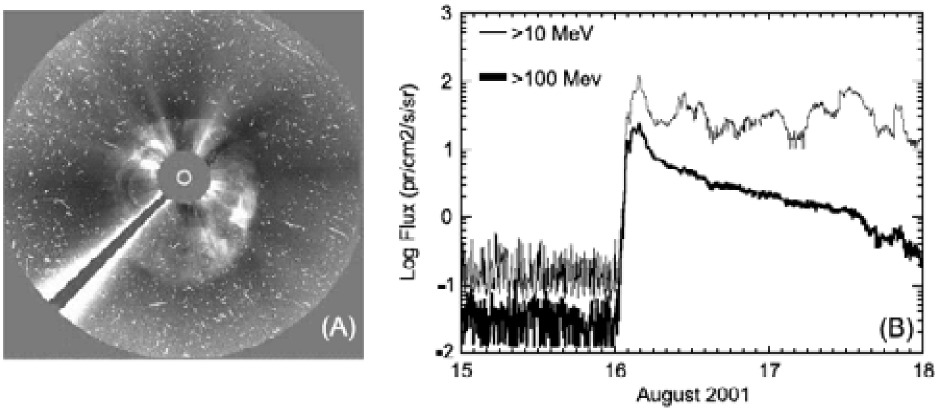

Figure 15. The halo CME of 2005 April 16 and the associated SEP event.

As far as improving the efficiency of particle acceleration, two theoretical papers reported progress in that direction. Shock acceleration models are tested by the rapid acceleration of GLE protons to energies > 1 GeV in a few minutes, especially when the shocks are not well formed because the Alfvén speed is so high in the low corona (making the CME front sub-Alfvénic). Kotá et al. [38] used the compression and distortion of the IMF ahead of the shock to create a “reflecting barrier” to energetic particles. Such a barrier could retain the particles close to the shock before the development of a strong upstream wave field and partake in quasi-perpendicular shock acceleration. The net result of their simulations was that ~MeV ions were accelerated almost instantaneously, by way of the quasi-perpendicular shock set up by the field distortion and that 500 MeV ions were accelerated in 10-20 minutes by way of the now-restricted field-aligned diffusion. These are time scales that agree with observations of GLE onsets.

In a related paper, Li and Zank [39] presented a model that employs a common phenomenon, that being the presence of multiple and successive shocks associated with energetic particle acceleration. The gain in efficiency of particle acceleration is realized by the fact that a leading shock downstream region is the upstream region of the accelerating shock. The leading shock produces an upstream wave field that is necessary to scatter the particles back into the accelerating shock. Although the particles themselves are capable of generating that wave field, this takes time. If such a turbulent field is already present from the passage of a preceding shock, the process is accelerated [40].

One of the interesting papers on CMEs includes that of Simnett and Kahler [41] who showed evidence that SMEI, a very wide field imager of coronal and interplanetary transients, detects CMEs that do not appear at lower altitudes in LASCO imagers. This suggests that the CME might be collecting material as it progresses, increasing its visibility. The other alternative is that the CME is concentrating its own material in a manner that would increase visible contrast, making it more detectable farther from the Sun.

The effects of CMEs on terrestrial phenomena were reported by Tripathi and Mishra [42], who demonstrated what one would expect, that CMEs directed directly toward earth, also known as halo CMEs, produce the largest geomagnetic storms. Similarly, Kodaira et al. [43], using data from USERS and SERVIS-1 spacecraft [44], reported a five-fold increase in trapped proton fluxes during the 2003 October solar activity.

Instrumentation

Finally, two new instruments or instrumental techniques were presented. Karpov et al., [45] reported that the BAKSAN EAS array can be used to detect solar protons. They showed that this instrument, through the detection of secondary muons, is considerably more sensitive than neutron monitors at their geomagnetic cutoff, approximately 6 GV. The ability to efficiently measure muons was further demonstrated by Navia et al. [46] who showed that atmospheric muons register the onset of CMEs, similar to that of neutron monitors. Moser et al. [47] presented a description and simulations of an inner heliosphere neutron telescope, FNIT, designed to detect and measure solar neutrons below 10 MeV, an undetectable energy at 1 AU. One goal of such an instrument is to detect the presence of a quasi-continuous emission of neutrons indicative of low level flaring that might be responsible for heating the corona. Such a measurement would complement observations of ^{3}He in interplanetary space, another proxy for low level flaring accompanied by impulsive particle emission.

The next ICRC in Mexico will take place after the deployment of the STEREO mission. The new observations of CMEs and energetic particles will shed new light on some of these nagging problems. We will know better how these phenomena extend throughout interplanetary space and how their properties vary according to the position of the observer. We also hope that the RHESSI mission is still successfully observing and imaging flares. Coupled with new theoretical work on understanding the peculiar selectivity of the particle acceleration and/or injection problem, the next few years should be exciting times for studying high-energy solar phenomena.

Acknowledgements

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