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Solar-Particle Energy Spectra during the Large Events of October-November 2003 and January 2005.

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We present observations of the energy spectra and timing of some of the largest solar particle events of solar cycle 23, including the events of October-November 2003 and the January 20, 2005 event, using data from ACE, SAMPEX, and GOES. These spectra are all well fit by a double power-law form. The January 20 event had the hardest spectrum observed during solar cycle 23 and also reached the highest >100 MeV intensity level in ~30 years, reaching its peak intensity at 1 AU within minutes, almost without warning. The timing and energy spectrum of this event are consistent with RHESSI solar γ-ray data due to particles accelerated in the flare. On the other hand, if this event was accelerated by a CME-driven shock, it must have formed low in the corona and accelerated particles to GeV energies within minutes. This, the January 20 event provides several new challenges to models of SEP events at the Sun and in the heliosphere.

1. Introduction

The trailing years of solar cycle 23 have provided some of the largest solar energetic particle (SEP) events of the last decade, including the October-November 2003 "Halloween" period and the events of mid-January, 2005. The Halloween period included more than xx coronal mass ejections (CMEs) with speeds ranging up to 2600 km/sec, numerous interplanetary shocks, and five large SEP events. Data from ACE, SAMPEX and GOES-11 have been used to measure the energetic spectra of H, He, O, and electrons in these events over a wide energy interval (~0.1 to 100 MeV/nuc for ions and ~0.04 to 8 MeV for electrons). The October-November, 2003 data have been submitted for publication [1,2], along with measurements of heavier ions [3]. In this paper we summarize the characteristics of the proton energy spectra from the Halloween period, discuss the January 20, 2005 event, and compare them to some of the largest events of the space era.

The January 20, 2005 event was remarkable from several points of view. It was the largest ground-level event (GLE) measured in neutron monitors since 1956 [4], and had a very hard energy spectrum. It also was the most intense SEP event measured by NOAA's GOES satellites in their 29-year history (1976-2005). Finally, this event had a risetime that was faster than any of the large SEP events (proton intensity >100/cm^{2}sr-sec with energies >100 MeV) within the last 30 years. This rapid rise, coupled with the high intensity, means that if astronauts had been on EVA on the Moon, there would have very little warning before the maximum intensities were reached. Events of this nature need to be taken into account in planning astronaut operations and shelters on the Moon and in interplanetary space. In addition, the rapid rise places extreme requirements on models that accelerate SEPs by CME-driven shocks, because protons with energies >1 GeV must have been accelerated within minutes very low in the corona.

2. SEP Energy Spectra

The energy spectra were obtained by combining data from the ULEIS, EPAM and SIS instruments on ACE, the PET instrument on SAMPEX, and the GOES EPS sensor on GOES-11 (for more information see [1]). The spectra, extending from <0.1 to >100 MeV/nuc, were fit with two spectral forms: the double-power-law form of Band et al. [5] or the model of Ellison and Ramaty [6]. We find that the spectra at energies >50 MeV/nucleon in these events are fit better by the double-power law formalism [1,2]. In the January 20 event the proton spectra appear to be a power-law from <10 MeV to ~400 MeV. There is indirect evidence that the location and Q/M dependence of the breaks in these spectra may be related to the spectrum of proton-amplified Alfven waves created by particles escaping upstream from the shock [2,1,3].

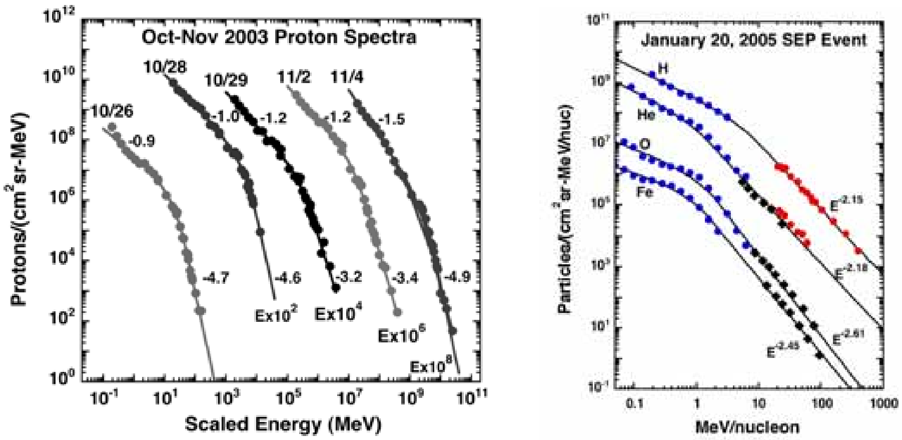

Figure 1. (Left) Fluence spectra for the Oct.-Nov. 2003 events (from [2]) fit with the Band et al. shape [5]. Spectral indices above and below the break are indicated. (Right) The 20 Jan. 2005 event had a double power-law shape with a very hard spectrum. Data are from ACE, SAMPEX and GOES-11 [1,2].

3. SEP Timing and Intensities

At 636 UT on January 20 an X7-class flare began, the last of five X-class events within a week. The soft x-ray emission peaked soon after 700 UT. The neutron-monitor response at McMurdo (energy ≥0.5 GeV) began at 0649 UT, peaking within ~5 minutes [7]. The >100 MeV protons peaked at ~707 UT, consistent with their lower velocity. Figure 2 compares time profiles of >100 MeV protons from GOES-11 with GOES-12 x-ray profiles. Note the similarities of the time profiles and that the x-ray flare provides only a few minutes warning before the maximum high-energy SEP intensities at Earth. The right panel of Figure 2 compares intensity profiles from the largest SEP events of the last 20 years. Note that in typical large events it takes several hours to reach maximum intensity. The January 20 event stands out as the fastest-rising large event we could identify. The fast rise is due in part to good magnetic connection (W61°) but this event must have also been accelerated quickly and experienced less scattering than most large SEP events. If there had been astronauts on a "Moon-walk" during this event, little warning would have been possible (SEP protons can be shielded against if shelter is near). Thus, the January 20 event is an example of an SEP event that NASA should consider in planning astronaut activities and shelters once they return to the Moon during the next decade. The February, 1956 event, which was ~5 times as intense, had similar characteristics [7].

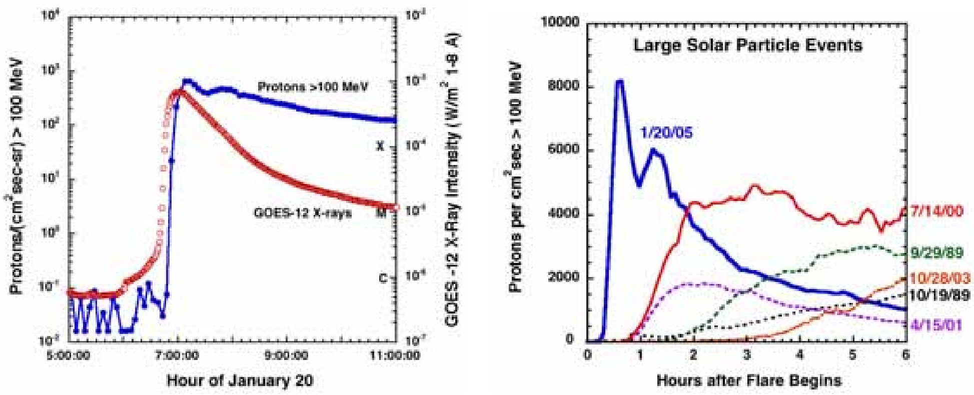

Figure 2. (Left) A comparison of x-ray and >100 MeV proton onsets from the January 20, 2005 event. (Right) The January 20 event reached peak intensity much faster than any of the largest SEP events of the past 30 years.

Assuming that the neutron monitor response is due to protons with ~2 GeV that traveled 1.2 AU, the protons take ~2.5 minutes longer than light to reach Earth. Subtracting 2.5 minutes from their onset time at 649, the first high-energy protons must have left the Sun at 0647 (viewed from Earth). RHESSI observed nuclear γ-ray emission from ~0643 to 0649 UT (G. Share, personal communication). Thus, the first high-energy protons observed at Earth left the Sun at about the time of maximum γ-ray emission (see Figure 3).

The CME from this event was first observed by SOHO/LASCO at 0654. Unfortunately, subsequent LASCO images were totally obscured by high-intensity solar-particle “snow”, so CME velocity measurements were not possible from SOHO alone. Using other data, Simnett and Roelof [8] and Lin et al. [9] estimated a CME velocity of ~2500 km/s. Figure 3 shows the height of the CME leading edge versus time for a constant velocity of 2500 km/s. At the time the first high-energy particles were (apparently) released from the Sun, the CME was below 1.5 solar radii, having left the Sun ~7 minutes earlier. A challenge to shock acceleration models is to form a shock very low in the corona (≤1.5 Rs; e.g. [10]), and accelerate particles to GeV energies within minutes (see, e.g. [11]). Ionic charge state measurements place further restrictions [12].

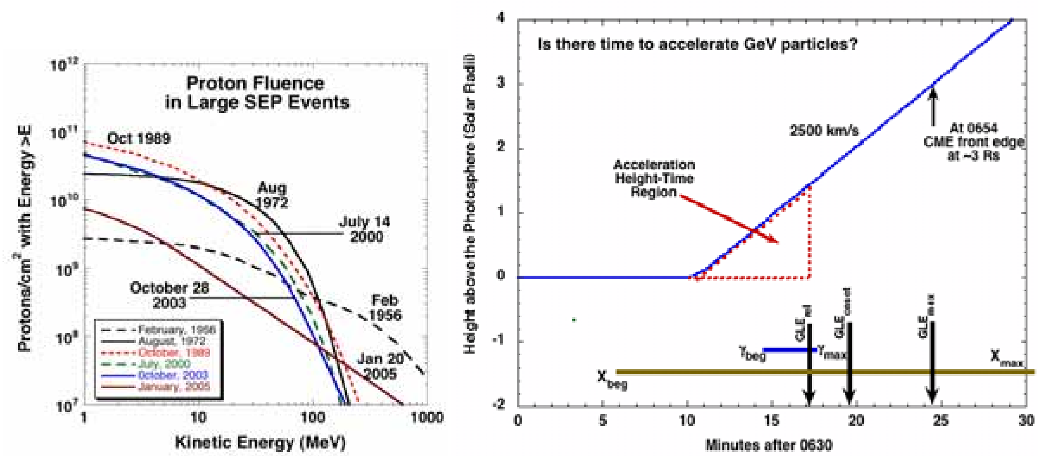

Figure 3. (Left) Fluence spectra of some of the largest SEP events of the last 50 years [1]. (Right) If the January 20, 2005 event was accelerated by a CME-driven shock, it formed low in the corona and reached GeV energies in minutes.

4. Summary

The proton spectra in the five Halloween events as well as the January 20, 2005 event are well fit by a double power-law form [1,2,3]. The January 20 event had the hardest spectrum observed during solar cycle 23 and also reached the highest >100 MeV intensity observed at 1 AU in ~30 years. It reached its peak intensity at 1 AU within minutes, almost without warning. The timing and energy spectrum of the January 20 event are consistent with RHESSI solar γ-ray data due to particles accelerated in the flare [9]. This event appears to be similar to the February 1956 event, which was ~5 x as intense and also had a very hard energy spectrum (Figure 3) and fast rise time. If the January 20 event was accelerated by a CME-driven shock, it must have formed low in the corona and accelerated particles to GeV energies within minutes [12]. This event therefore provides several new challenges to models of SEP events at the Sun and in the heliosphere.

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