RECENT SOLAR ENERGETIC PARTICLES: UPDATES AND TRENDS. Robert C. Reedy[1], [1]MS-D436, Los Alamos National Laboratory, Los Alamos, NM 87545 (rreedy@lanl.gov); after 1 April 2002, at the Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131 (reedy@mail.cybermesa.com).

Summary: The event-integrated fluences of solar protons >10 to >100 MeV were determined for 21 events since 1996. The Sun has been very active starting in July 2000. Trends in these data and possible trends in future solar particle events are discussed.

Introduction: The fluxes of solar energetic particles (SEPs) are needed for many space studies, such as the study of the Sun and lunar samples, and applications, such as radiation damage to humans and experiments in space. These SEPs occur irregularly [1,2]. They are ~98% protons with energies usually of ~1-100 MeV, but they often have some particles with energies of ~1 GeV and higher. Studies of both modern and ancient fluxes of SEPs are needed to best understand them [2].

The present solar cycle, which started in 1996, has been a very active one since July 2000 with many solar events having high fluxes of SEPs, as first reported in [3]. Six additional large solar particle events (SPEs) have occurred since 25 May 2001, when [3] was written. These six more recent SPEs are included here, along with more details on the 15 earlier SPEs since 1996.

Recent meteorite falls could contain solar-proton-produced short-lived radionuclides [3]. Additional implications of SEPs, especially using these most recent data, and their effects are discussed here.

Event-Integrated Solar-Proton Fluences:

Sources of the data. The websites for solar-proton-flux data from the GOES geosynchronous satellites (through 17 December 2001) and the IMP-8 interplanetary satellite (through 11 November 2000) were used to determine solar-proton fluences for 21 SPEs since 1996. The proton energies were from >10 MeV to >100 MeV (for GOES) and to >60 MeV (for IMP-8). Some weaker SPEs were ignored.

SEP fluences during the current solar cycle. The omnidirectional (4π) proton fluxes integrated over the SPEs since 1996 are given in Table 1. The event-integrated solar proton fluences measured for the 14 July 2000, 9 November 2000, 25 September 2001, 5 November 2001, and 23 November 2001 SPEs were among the dozen or so most intense SPEs since 1954. The preliminary integral fluences (in protons/cm^2) since 1996 are 5.6×10^{10} for energies >10 MeV, 1.1×10^{10} for >30 MeV, and 2.9×10^{9} for >60 MeV. These fluences correspond to a spectral shape with an exponential rigidity parameter R_0 [1] of about 70 MV, slightly softer but typical for recent solar cycles [2].

Table 1. Fluences of solar protons integrated over 21 solar particle events since 1996. Date is the month, day, and year of the peak flux. The fluences F are in units of protons/cm^2 (where E means power of 10, i.e., 4E9 = 4×10^9). The energies above which the fluences were integrated (10, 30, and 100) are in MeV.

Date (mm/dd/yyyy)	F (>10)	F (>30)	F (>100)
11/7/1997	4.0E8	1.3E8	2.7E7
4/21/1998	1.5E9	3.5E8	4.9E6
5/4/1998	7.0E7	2.5E7	3.6E6
8/26/1998	4.5E8	5.0E7	2.5E7
11/14/1998	1.3E8	3.2E7	1.9E7
7/14/2000	1.1E10	3.2E9	2.0E8
11/9/2000	9.1E9	2.7E9	1.7E8
11/26/2000	4.9E8	5E7	1E6
1/29/2001	3.3E7	4E6	1E5
3/29/2001	4.3E7	5E6	6E4
4/3/2001	6.6E8	1.1E8	3E6
4/11/2001	2.6E8	3.5E7	9E5
4/18/2001	2.0E8	6E7	6E6
5/8/2001	3.4E7	3E6	2E4
5/20/2001	5E6	2E6	2E5
6/15/2001	2.1E7	2.6E6	6E4
8/16/2001	2.9E8	9.8E7	9E6
9/25/2001	7.4E9	1.2E8	3.0E7
10/2/2001	9.8E8	6.5E7	6E4
11/5/2001	1.5E10	3.0E9	1.0E8
11/23/2001	8.1E9	8.0E8	4.5E6

Dividing these fluences by the number of seconds in 5 years yield average omnidirectional proton fluxes of 356 and 69 protons/cm^2/s for >10 and >30 MeV, respectively. These average fluxes are similar to those seen since 1954 and much higher than those from 1965 through 1986 [2]. Even if no SPEs occurred in the remaining 6 years of the present solar cycle, its average fluxes would still be about average.

Solar-Proton Average Fluxes and Event-Integrated Fluences: These latest solar-proton fluxes continue the trend for modern (since 1954) solar-proton fluxes compared to fluxes determined from nuclides made in lunar samples by SEPs. As reported in [2], averaged solar-proton fluxes for periods less than 1 Ma ago are higher than for 1-5 Ma. The average

fluxes since 1954 continue to be higher than for almost all time periods from 10 ka to 5 Ma ago [2].

The recent SPEs also continue the trend of there being no SPEs with event-integrated fluxes above 10 MeV of more than about 3×10^{10} protons/cm^2 [2]. Using the data in [2], [4] showed a similar high-fluence cut-off for fluences >30 MeV, which these authors noted is consistent with their SPE fluences estimated since 1561 using nitrates measured in polar-ice cores.

Implications for Space Applications: The fact that the present solar cycle seems to be a very active one means that humans and experiments in space will probably continue to be subjected to large fluxes of solar protons.

The gamma-ray and neutron spectrometers on Mars Odyssey were exposed to several large SPEs since it was launched on 7 April 2001. Usually the gamma-ray spectrometer (GRS) was off during these SPEs. The GRS was on during the 16 August 2001 SPE (which was not a very large SPE) but shut itself off when the energy deposited in the Ge detector by the solar protons became too high for the electronics. On 18 August, when the GRS was commanded to turn back on, the background was high due to some energetic protons. Many gamma-ray lines were also seen from radionuclides made by solar protons in and near the germanium GRS, such as in the titanium can. Fortunately, the solar protons did not induced much resolution degradation in the GRS spectra. Based on trends for previous solar cycles, large SPEs can occur up to two year before the next solar minimum in about 2007 [5]. Thus additional SPEs can be expected anytime during the next 3 years when the GRS is collecting data at Mars.

Future Trends: A big question is what solar-proton fluxes should be expected in the future. Many people have looked for cycles in solar activity. The trend of there possibly being high-fluence SPEs for all but the four years around solar minimum [5] was noted above for Mars Odyssey. The 11-year sunspot cycle and 22-year cycle in the Sun's magnetic fields are well established cycles.

Some people feel that there is a cycle of ~80-88 years, often called the Gleissberg cycle [e.g., 4]. The last Gleissberg minimum in solar activity was about 1910. If such a Gleissberg cycle exists, we should be in a period of low activity. However, the last two solar cycles (since 1986) have been far from ones of low solar activity. Thus the trend since about 1580 of there being ~80-year Gleissberg cycles in solar activity appears to have ended.

Noting the current period of high solar activity, [6] speculated that maybe the Sun is entering a prolonged period of high solar activity, such as the "Grand Maximum" that occurred from about 1050-1250 [7]. If so, huge solar particle events could be a space hazard for a while.

The solar-proton fluences reported here suggest that high fluences of solar proton could continue, very likely for three more years and possibly for longer periods. The Sun appears to be as unpredictable as ever!

Acknowledgments: This work was supported by NASA and done under USDOE auspices.

References: [1] Reedy R. C. and Arnold J. R. (1972) *JGR, 77,* 537-555. [2] Reedy R. C. (1998) *Proc. Indian Acad. Sci. (Earth Planet. Sci.), 107,* 433-440. [3] Reedy R. C. (2001) *Meteoritics & Planet. Sci., 36, Suppl.,* A172. [4] McCracken K. G. et al. (2001) *JGR, 106,* 21585-21598. [5] Feynman J. et al. (1990) *J. Spacecraft Rockets,* 27, 403-410. [6] McCracken K. G. et al. (2001) *JGR, 106,* 21599-21609. [7] Eddy J. A. (1976) *Science, 192,* 1189-1202.