Solar Drivers of Interplanetary and Terrestrial Disturbances
ASP Conference Series, Volume 95, 1996
K. S. Balasubramaniam, Stephen L. Keil, and Raymond N. Smartt (eds.)

Constraints on Solar Particle Events from Comparisons of Recent Events and Million-Year Averages

Robert C. Reedy[1]

Group NIS-2, Mail Stop D436, Los Alamos National Laboratory, Los Alamos, NM 87545 USA

Abstract. Several sets of measurements of the fluxes of solar energetic particles (SEPs) above 10 MeV have been used to apply limits to huge solar particle events (SPEs) in the past. Direct measurements of SEPs are used to get event-integrated solar-proton fluences for SPEs since about 1965. Indirect measurements of SEPs in events from 1956 to 1963 have been used with radioactivities measured in lunar rocks to get event-integrated solar-proton fluences for the larger events back to 1956. A cumulative-probability plot of these event-integrated fluences for all energies above 10 MeV shows a fairly smooth trend from fluences of 10^7 protons/cm^2 up to the largest events (3×10^{10} protons/cm^2) but there are no events with higher fluences. Activities of radionuclides in the tops of lunar rocks were used to get average fluxes of solar protons for time periods from $\sim 10^4$ to $\sim 10^7$ years, which are similar to those over the last four decades. These proton fluxes from lunar radionuclides indicate that the long-term trend for huge events does not follow the modern trend for event fluences up to $\sim3\times10^{10}$ protons/cm^2, but that huge events (orders of magnitude larger than $\sim10^{11}$ protons/cm^2) have been very rare or nonexistent during the last $\sim10^7$ years.

1. Introduction

The intensities of protons in solar particle events (SPEs) are of concern to material and humans in space, especially those for the largest SPEs. As protons are about 98% of the particles in most big SPEs (e.g., McGuire et al. 1986), I will not worry about those particles in SPEs heavier than protons. SPEs like the one in August 1972 can deliver high, even fatal, doses to astronauts with minimal shielding in deep space (e.g., Letaw et al. 1989) and can seriously upset electronics on spacecraft not well within the Earth's magnetosphere (e.g., Adams & Gelman 1984). Some papers, especially a few decades ago, have even hypothesized that giant SPEs have affected life on Earth. A better understanding of very large SPEs are needed. Previous work on this subject will be reviewed and some new results presented.

Two types of measurements related to the intensities of solar energetic parti-

[1]Supported by NASA and the U.S. Department of Energy and done under auspices of the U.S. Department of Energy

cles (SEPs) are used here, those made since the early 1960s by energetic-particle instruments on spacecraft and those made of nuclides made in lunar samples by SEPs. I have often used both types of measurements for solar studies (e.g., Reedy 1977), including a couple of papers for major meetings on the history of the Sun (Reedy 1980; Reedy & Marti 1991). Both sets of measurements have some problems, such as the relatively short period of time over which good modern measurements have been made and the lack of good cross sections for unfolding the fossil lunar records. However, these data sets together can help to set some constraints on the fluences of particles in SPEs.

The work presented here is a preliminary report of work in progress. Much work is needed on both the modern and fossil records, but I suspect that the final conclusions will not be very different from those given here. I also want to report this work here as much of it has not been readily accessible by everybody interested in studying solar energetic particles, having often been in proceedings of meetings on specialized topics, such as lunar studies.

2. Measurements of Solar-Proton Fluences or Average Fluxes

2.1. Direct Solar-Proton Measurements, 1960s to Now

While many Earth-based observations have been made of the intensities of SPEs since the 1940s, comprehensive direct measurements by instruments on satellites in deep space have only been made since the 1960s (e.g., Shea & Smart 1990). To date, direct measurements of SEPs have been made for only three cycles of solar activity, sunspot cycles 20 (1964-1976), 21 (1976-1986), and 22 (1986-present). Some of the results early in this time period scattered widely, but the scatter among different sets of recent measurements is not too bad.

In the study presented below, I have adopted for proton fluences during most of solar cycle 20 the event-integrated fluences from the Solar Proton Monitor Experiment (SPME) as published in Reedy (1977), which gave good agreement with short-lived radioactivities such as ^{56}Co measured in the tops of lunar rocks. For the rest of solar cycle 21 and all of solar cycle 22, I used the fluences from Goddard Space Flight Center (GSFC) instruments in Goswami et al. (1988). These fluences often differ by up to $\sim$50%, especially for energies integrated above 30 MeV, with the fluences in Feynman et al. (1990).

Very little work has been done on the big SPEs of solar cycle 22. A few event-integrated fluences for the biggest events in this period have been published (Reeves et al. 1992; Feynman et al. 1993). For 1989 until June 1991, I have adopted fluences for eight SPEs reported as private communications from H. Sauer of NOAA's Solar Environmental Laboratory (SEL) to M. Shea and D. Smart in 1991 and 1992 (reported in Shea & Smart 1992) and to me in April 1991. The few published fluences for 1989-1991 in Reeves et al. (1992) and Feynman et al. (1993) are in fairly-good agreement with the fluences adopted here. The large SPEs since 1989 have increased considerably the average flux of solar protons since 1964 (e.g., Feynman et al. 1993). The SPEs during solar cycle 22 are similar to those during solar cycle 19, about 30 years earlier, with only the August 1972 event of similar intensity from 1963 until 1989.

There is a need both to check the differences noted above for 1976-1986 and to complete the record for the current solar cycle 22. Los Alamos energetic-particle instruments in geosynchronous orbit (e.g., CPA, Reeves et al. 1992; SOPA, Belian et al. 1992) could be used to independently check solar-proton measurements back to 1976 and to study all SPEs during the current solar cycle. Preliminary results from the Los Alamos instruments at geosynchronous orbit indicate that there were several large SPEs from June 1991 until 1994.

2.2. Indirect Solar-Proton Measurements, Solar Cycle 19

A variety of indirect measurements (e.g., Shea & Smart 1990) provide estimates of the fluences of SPEs during solar cycle 19, which started with the big SPE in February 1956 with its large fraction of high-energy particles. There is much scatter in the fluences for these events. The protons in these SPEs made considerable amounts of radionuclides in rocks returned from the Moon by Apollo astronauts. Reedy (1977) showed that 78-day ^{56}Co in the tops of lunar rocks were in good agreement with solar-proton fluxes measured by the SPME for SPEs the few months before the rocks were returned from the Moon. Reedy (1977) then used 2.6-year ^{22}Na and 2.7-year ^{55}Fe measured in several lunar rocks along with relative fluences for SPEs during solar cycle 19 to determine the absolute intensities of solar protons from 1956 to 1962. The lunar radioactivities confirmed the indirect Earth-based measurements that the proton fluences during solar cycle 19 were very large.

Cross sections recently measured for the production of ^{22}Na are different than the cross sections used in Reedy (1977). The cross sections used for the production of ^{22}Na and ^{55}Fe need to be re-evaluated, and these evaluated cross sections used to re-determine proton fluences for 1956-1962. Preliminary calculations indicate that the new cross sections will lower the proton fluences, especially at lower energies, by several tens of percent. Such a study should also use a number of indirect measurements for the relative fluences in events during that period. However, the resulting fluences still will be fairly high, comparable only to those since 1989.

2.3. Long-Term Average Fluxes Using Lunar Radioactivities

Besides the short-lived radioactivities observed in lunar rocks mentioned above, there are a number of long-lived radioactive and stable nuclides made by solar protons that have been measured in lunar rocks. The use of such cosmic-ray-produced nuclides to study cosmic rays is discussed in Reedy (1977), Reedy & Marti (1991), and Rao et al. (1994). These nuclides can be made in significant amounts by solar protons, and their excess in the top centimeter of lunar rocks above the amounts made by galactic cosmic rays (GCRs) allows us to use them to study the fluxes of solar protons over the mean-lives of these radionuclides or over the time that the rock was exposed on the lunar surface.

A concentration-versus-depth profile for a nuclide made by solar protons must be measured in the top few centimeters of a lunar rock, with measurements at the greater depths used to estimate the contributions from GCR particles in the top of the rock. The erosion rate for the surface of the rock, typically of the order of a millimeter of surface per million years, needs to be determined or estimated. The average flux and spectral shape of the solar protons making a nuclide can be determined from the measured concentration-versus-depth profile for the nuclide with the cross sections for the production of that nuclide.

The long-lived nuclides made by solar protons that have been measured in lunar rocks (and the references) are 1.5-Ma (1 Ma = 10^6 years) ^{10}Be (Nishiizumi et al. 1988), 5730-year ^{14}C (Jull et al. 1991), stable ^{21}Ne (Rao et al. 1994), 0.7-Ma ^{26}Al (Kohl et al. 1978), 0.30-Ma ^{36}Cl (Nishiizumi et al. 1989), 0.10-Ma ^{41}Ca (Klein et al. 1990), 3.7-Ma ^{53}Mn (Kohl et al. 1978), and 0.21-Ma ^{81}Kr (Reedy & Marti 1991). For several nuclides, such as ^{36}Cl, the cross sections needed to unfold the lunar measurements are only now being measured. For this work, I have adopted the proton fluxes reported by the original authors. Rao et al. (1994) have re-examined proton fluxes determined for ^{14}C, ^{26}Al, ^{53}Mn, and ^{81}Kr, and, except for ^{14}C where newer cross sections were used, their fluxes are not very different from the fluxes used here from the original papers.

3. Average Solar-Proton Fluxes over Various Time Periods

3.1. Reported Solar-Proton Fluences and Fluxes

The event-integrated solar-proton fluences above 10 and 30 MeV for SPEs since 1954 are showed with monthly smoothed sunspot numbers in Fig. 1. The large events in solar cycles 19 and 22 and the August 1972 event stand out above most other SPEs. The trend, as noted earlier (e.g., Shea & Smart 1990, Feynman et al. 1990) is for SPEs to occur almost anytime during a solar cycle except for a few years around the minimum in sunspot number.

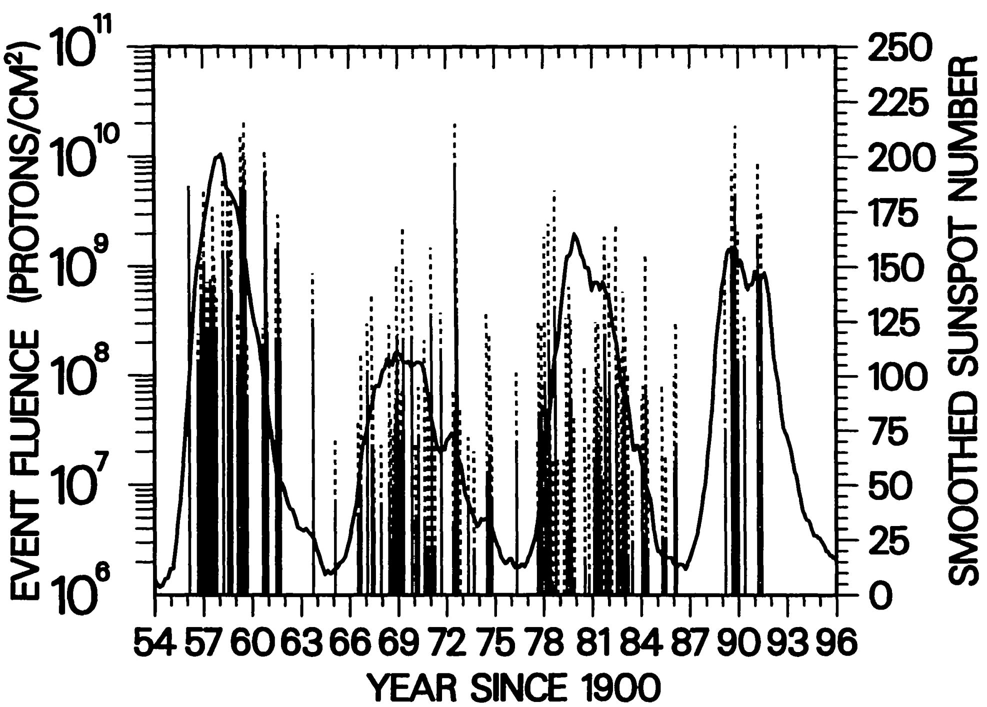

Figure 1. Smoothed monthly sunspot numbers (curve) and event-integrated solar-proton fluences above 10 (dashed lines) and 30 MeV (solid lines) for recent solar particle events

The fluences for SPEs during each of solar cycles 19 through 22 were used to get proton fluxes averaged over each of these four solar cycles. These recent fluxes and those determined for various time periods into the past from lunar measurements are given in Table 1.

Table 1. Average Solar-Proton Fluxes above Various Energies[a]

PERIOD	DATA	E>10	E>30	E>60	E>100
1986-91	SEL	312	66	20	6
1976-86	GSFC	63	5	~1	—
1965-75	SPME	92	30	8	—
1954-64	Lunar	378	136	59	26
1954-91	Above	195	58	22	~9
~ 10^4 y	^{14}C	~145[b]	~45	13	4
~0.2-Ma	^{41}Ca	~120[b]	~28	~7	~2
~0.3-Ma	^{81}Kr	~145[b]	—[b]	—[c]	—[c]
~0.5-Ma	^{36}Cl	—[c]	—[c]	—[c]	—[c]
~1-Ma	^{26}Al	70	25	9	3
~2-Ma	^{10}Be	~115[b,c]	~35	~8	~2
2-Ma	^{21}Ne	68	21	6	2
~5-Ma	^{53}Mn	70	25	9	3

[a] Omnidirectional fluxes in protons/(cm^2 s); Energies in MeV. [b] Energy is below main reaction thresholds. [c] Few or no cross sections available.

While the average fluxes in Table 1 scatter some, especially for the four recent solar cycles, they generally are relatively similar. Especially noteworthy is that the modern average (1954-91) and those from the lunar fossil records are not very different. Thus, solar particle events similar to those observed during the last four decades can account for the solar-proton-produced nuclides made in lunar samples over the last $\sim 10^4 - 10^7$ years.

3.2. Probabilities of Giant Solar Particle Events

Using the event-integrated fluences from the database used above, the distribution of the number of events above a given fluence can be studied as a function of the fluence in that event. These cumulative probabilities are shown in the upper-left part of Fig. 2. The probability of events with fluences around 10^7 protons/(cm^2 s) is a lower limit as some events of this size are missing, especially for solar cycle 19. The probability for a fluence of 3×10^{10} to 10^{11} protons/cm^2 is also a limit assuming that less than 1 such event occurred since 1954, although none of this size were observed. The trend for these modern solar particle events with event fluence F is $F^{-0.4}$ and is shown as the solid line that is extrapolated to larger events with a dashed line. The modern fluences are well enough determined that we can see that such an extrapolation for F > 10^{11} protons/cm^2 (the dashed line) is not justified.

The average fluxes from various fossil records of solar particles confirm that giant SPEs are very rare. In Fig. 2 are four sets of limits using the average solar-proton fluxes determined from lunar radioactivities. For each set, an extreme

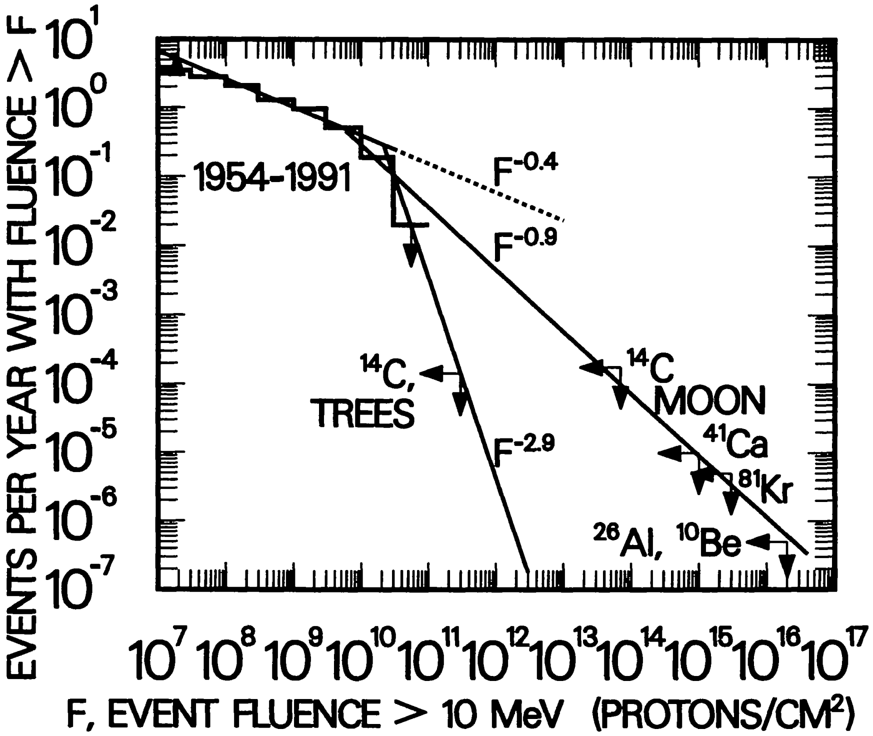

Figure 2. Probabilities of solar particle events with fluences above a given value occurring per year versus the fluence for both modern events and for limits determined from various fossil records

assumption was made that all of that nuclide was made by one huge SPE at one half-life of that radionuclide ago. These four limits define a line that drops much steeper with F than did the extrapolation line for modern events. These points are really very large limits because, as shown in Table 1, the distribution of modern SPEs can account for the activities of these radionuclides without the need for any extra giant events.

An even better limit on giant SPEs was determined by Lingenfelter & Hudson (1980) from the lack of major spikes in activities of ^{14}C in tree rings over the last 7000 years. This point is a stronger limit but only covers the past 7000 years.

4. Conclusions

Fluences and average fluxes of solar protons for the last four "11-year" solar cycles and for various time periods over the last few million years have been used to study the nature of solar particle events and to set some limits on SPEs with giant particle fluences.

Both the modern and fossil data sets need work. Better fluences for solar cycle 19, 1954-1964, could be obtained by using better cross sections to unfold lunar radioactivities and several sets of indirect measurements for relative event fluences during this period. Some discrepancies for proton fluences measured during 1976-1986 need to be examined. Very little has been done on cataloging the SPEs during the current solar cycle, especially events since June 1991. Continued measurements of solar energetic particles are needed to extend our limited data set for modern solar energetic particles.

The long-term record from the nuclides made in lunar rocks by SEPs is being improved. New cross sections for most of the nuclides in Table 1 are being or will be measured (J. Sisterson & R. Michel, private communication, 1995). Some new measurements are being made of these solar-proton-produced radionuclides in lunar rocks. One rock, 64455, is being studied for such nuclides and appears to have had a low erosion rate (K. Nishiizumi, private communication, 1995), which will improve our ability to unfold the measurements to get solar-proton fluxes.

While the situation for the study of SEPs, both modern and ancient, should improve over the next decade, there is much that can be learned from the work that already exists. The basic trends for particle fluences in SPEs is fairly well established. Using a database similar to the one used here, Feynman et al. (1993) have constructed an updated model for interplanetary proton fluxes, in their JPL 1991 model. While they did not use fluences for solar cycle 19, the inclusion of SPEs since 1989, which are very similar to those for solar cycle 19, is a big improvement over some previous models that ignore "anomalously large" events such as that in August 1972.

Using the tree ring ^{14}C results and also the lunar measurements for ^{26}Al and ^{53}Mn, Lingenfelter & Hudson (1980) concluded that "there is a maximum proton fluence (> 10 MeV) from a solar flare on the order of 10^{10} p/cm^2, above which the size-frequency distribution steepens sharply." The work presented here supports their conclusion.

Acknowledgments. I thank my co-authors on previous papers and others who provided much of the data used in this paper and to various colleagues, including R. Belian, T. Cayton, G. Reeves, D. Lal, M. Shea, and D. Smart, who have encouraged me to do this work.

References

Adams, J. H., & Gelman, A. 1984, IEEE Trans. Nucl. Sci. NS-31, 1212-1216

Belian, R. D., Gisler, G. R., Cayton, T., & Christensen, R. 1992, J. Geophys. Res 97, 16,897-16,906

Feynman, J., Armstrong, T. P., Dao-Gibner, L., & Silverman, S. 1990, J. Spacecraft Rockets 27, 403-410

Feynman, J., Spitale, G., Wang, J., & Gabriel, S. 1993, J. Geophys. Res. 98, 13281-13294

Goswami, J. N., McGuire, R. E., Reedy, R. C., Lal, D., &

Jha, R. 1988, J. Geophys. Res. 93, 7195-7205

Jull, A. J. T., Donahue, D. J., & Reedy, R. C. 1991, in Lunar and Planetary Science XXII (Lunar & Planetary Institute, Houston), pg 639-640

Klein, J., Fink, D., Middleton, R., Vogt, S., Herzog, G. F., Reedy, R. C., Sisterson, J. M., Koehler, A. M., & Magliss, A. 1990, in Lunar and Planetary Science XXI (Lunar & Planetary Institute, Houston), pg 635-636

Kohl, C. P., Murrell, M. T., Russ III, G. P., & Arnold, J. R. 1978, in Proceedings of the Ninth Lunar and Planetary Science Conference (Pergamon Press), pg 2299-2310

Letaw, J. R., Silberberg, R., & Tsao, C. H. 1989, Adv. Space Res. 9 (#10), 285-291

Lingenfelter, R. E., & Hudson, H. S. 1980, in The Ancient Sun (Pergamon Press), pg 69-79

McGuire, R. E., von Rosenvinge, T. T., & McDonald, F. B. 1986, Astrophys. J. 301, 938-961

Nishiizumi, K., Imamura, M., Kohl, C. P., Kobayashi, K., Yoshida, K., Yamashita, H., Reedy, R. C., Honda, M., & Arnold, J. R. 1988, in Proceedings of the Eighteenth Lunar Science Conference (Cambridge Univ. Press), pg 79-85

Nishiizumi, K., Kubik, P. W., Elmore, D., Reedy, R. C., &

Arnold, J. R. 1989, in Proceedings of the Nineteenth Lunar Science Conference (Lunar and Planetary Institute, Houston), pg 305-312

Rao, M. N., Garrison, D. H., Bogard, D. D., and Reedy, R. C. 1994, Geochim. Cosmochim. Acta 58, 4231-4245

Reedy, R. C. 1977, in Proceedings of the Eighth Lunar Science Conference (Pergamon Press), pg 825-839

Reedy, R. C. 1980, in The Ancient Sun (Pergamon Press), pg 365-386

Reedy, R. C., & Marti, K. 1991, in The Sun in Time (Univ. Arizona Press), pg 260-287

Reeves, G. D., Cayton, T. E., Gary, S. P., & Belian, R. D. 1992, J. Geophys. Res. 97, 6219-6226

Shea, M. A., & Smart, D. F. 1990, Solar Phys. 127, 297-320

Shea, M. A., & Smart, D. F. 1992, Radiocarbon 34, 255-262

Group Discussion

Ahluwalia: Over the time scales of 10^4Y to 10^6Y, is there any evidence of super nova explosion nearby, in your data?

Reedy: The lunar records are integral, with the time sampled by a radio nuclides with times since now depending on the radionuclides' half-life, so it is very hard to see a spike. No spikes have been seen to date in the lunar records. Many terrestrial records of cosmic-ray-produced radionuclides are differential and show changes over short periods. Most fluctuations are caused by terrestrial inputs, such as temperature. A pair of spikes in ^{10}Be suggests non-terrestrial origin of about 35 and 65 k Yr ago in ice core and deep-sea core records.