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SOLAR-COSMIC-RAY VARIABILITY

Robert C. Reedy, Los Alamos Scientific Laboratory, Los Alamos, NM

The exposure of men and materials to radiation damage is a recognized problem in space exploration. Usually there is little need in space for much shielding against cosmic rays. However, there are occasional times, such as during early August 1972, when such large fluxes of energetic particles are emitted from the sun that astronauts in an Apollo-like spacecraft could be seriously injured, possibly fatally, from the radiation dose that they would receive. Thus, one important part of any space colony or space manufacturing facility will be thick walls for shielding against cosmic-ray particles (and meteoroids). The question considered here is what is the maximum flux of particles from solar events that should be considered in designing the shielding for a space habitation. The activities of various radionuclides measured in the top few centimeters of lunar rocks are used to examine the variability of solar-cosmic-ray fluxes over the last five million years.

Away from the trapped-radiation belts around the Earth, two types of energetic particles are encountered: the galactic cosmic rays (GCR) and the solar cosmic rays (SCR). Both types are mainly protons, but include about ten percent alpha particles and a couple of percent of heavier nuclei. The GCR particles have energies from several MeV to 10^{14} MeV or greater with an average energy of about 1 GeV. The flux of these particles is a few particles per cm^2 per second (1). The flux of GCR particles with energies below about 1 GeV varies several tens of percents during the eleven-year solar cycle, being diminished during periods of maximum solar activity. Measurements made on meteorites show that the average GCR flux over the last 4.5 Gy was not very different than the present-day flux.

The SCR particles have typical energies of tens of MeV, relatively few particles having energies above 100 MeV, and are emitted from the sun over periods of hours or days. Such solar events occur very infrequently, usually during periods of solar maximum. Over a typical solar cycle, the average omnidirectional flux of solar protons with energies above 10 MeV is about 100 protons/cm^2 sec (1,2), although the peak flux of protons above 10 MeV during the August 1972 solar event was about 10^6 protons/cm^2 sec (3). Near solar minimum, the flux of SCR particles is very low. Solar protons have been studied regularly only since 1956. Because of their low energies, SCR particles produce radionuclides only in the surface of objects in space. On meteorites this surface layer is ablated during passage through the Earth's atmosphere.

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The flux of solar protons for solar events during solar cycle 20 (1964-1974) is well known from satellite measurements, and the activities of 78-day ^{56}Co observed in lunar rocks were well predicted by the satellite data (2). The average flux of solar protons above 10 MeV during solar cycle 20 was about 82 protons/cm^2 sec, with 70% of these protons coming during August 1972 (1,3). The fluxes of protons during cycle 19 (1953-1963) were not well measured and estimates of the fluence for that cycle vary considerably (1,3). The activity of 2.6-y ^{22}Na in rock 12002 (2) implies an average cycle-19 flux of about 155 protons/cm^2 sec (above 10 MeV), about twice that measured for cycle 20.

Another important quantity describing the flux of particles during an SCR event is the spectral parameter which gives the energy distribution of the particles. The energy spectrum of solar protons is usually described by an exponential rigidity shape with R_o as the spectral parameter (1). The larger the value of R_o, the more high-energy-particles there are relative to low-energy particles. The energy distribution (and R_o) of the particles varies from event to event. The August 1972 flare was described with an R_o of about 100 MV, and the sum of the rest of the events for cycle 20 had a spectral parameter of about 55 MV. Including the August 1972 flare, cycle-20's average R_o was about 90 MV. The R_o for all events in cycle 19 was estimated from the ^{22}Na data to have been approximately 75 MV.

Spots on the surface of the sun were discovered by Galileo in about 1610. Starting about 1755, each eleven-year solar cycle has been given a number, the years of solar maximum in the middle of a cycle being those with the most sunspots. During the last 20 solar cycles, the sunspot numbers at solar maximum have varied by less than a factor of four (3). The annual-mean sunspot number at the maximum of cycle 19 was the largest ever observed, and was 71% greater than that for cycle 20. Thus it seems that sunspot numbers and SCR fluences are correlated. The sunspot data for the last 20 cycles are often interpreted as implying that the sun is very regular. However, there was a 70-year period from 1645 to 1715 when sunspots (and auroral displays in Scandinavia) appear to have been extremely rare (4). Unfortunately there are no appropriate radionuclides produced in lunar rocks with which to examine the SCR flux during this period. Over the last several thousand years, the production rates of ^{14}C in the Earth's atmosphere have varied, probably as the result of changes in solar activity. The activity of 5730-y ^{14}C in rock 12002 implies an average flux over the mean life of ^{14}C of about 200 protons/cm^2 sec (above 10 MeV) with an R_o of 100 MV (5), although there are several uncertainties in interpreting the measurements (the cross sections for the production of ^{14}C not being well known and some of the ^{14}C on the surfaces of lunar rocks possibly being of solar-wind origin). The activity of the 80 000-y ^{59}Ni in lunar samples produced by solar alpha particles is not very different from that predicted using present day alpha-particle fluxes (6).

Many faunal species on Earth have become extinct during periods of reversals in the polarity of the geomagnetic field and Reid et al (7) have argued that such extinctions were caused by large fluxes of solar protons. (They propose that, without a geomagnetic field, the solar protons reach and ionize the stratosphere, producing NO which then destroys the ozone layer.) To get significant ozone depletions during such reversal periods (which last perhaps one thousand years or more), they require solar flares one or two orders of magnitude more intense than that of August 1972. Six cases of species extinctions have occurred during polarity reversals during the last 2.5 My (7). This time period is intermediate between the mean-lives of 0.74-My ^{26}Al and 3.7-My ^{53}Mn. The ^{26}Al and ^{53}Mn activities measured in the tops of lunar rocks 12002 and 14321 imply average solar-proton fluxes of about 80 and 90 protons/cm^2 sec, respectively, and R_o values of 100 MV (8). (The ^{53}Mn result has some uncertainty because the erosion of the rock's surface significantly changes the activity profile produced by solar protons and the erosion rate must be fairly well known to determine the incident SCR flux (8).) The SCR-produced activities in lunar rocks suggest that superflares significantly larger than the flare of August 1972 could not have occurred very frequently during the last million years.

Additional measurements of radioactivities in lunar samples and of cross sections for certain reactions would help in further unfolding the history of the solar cosmic rays. There are only a few other long-lived radionuclides produced by the low-energy SCR particles which could be used for such studies (e.g. 12.3-y ^{3}H and 21 000-y ^{81}Kr). Several lunar rocks are available with short surface exposure ages determined by GCR interactions, and the activities of radionuclides in their top surfaces could be used to study the SCR fluxes during the surface-residence times of these rocks (9).

Although the sun may not be as regular as often believed (the irregularity viewpoint also being shared by astrophysicists trying to explain the very low observed solar neutrino flux), measurements of radionuclides in the top surfaces of lunar rocks show no major irregularities in the SCR fluxes averaged over several time periods. In all likelihood, the distribution of solar-proton fluxes is log-normal, although the possibility of superflares occurring can not be excluded. Thus space colonies will probably not be exposed to fluxes of solar particles significantly greater than those observed during the last 20 years, and the data for these recent solar events could be used in planning shielding requirements.

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DISCUSSION (Reedy Paper)

SPEAKER 1: One detail, Bob. The 20th Century depression of the carbon-14 is not due to a decrease in production. It's due to industrial burning of fossil fuel. As far as we know, which is a considerably big uncertainty, that falloff in the 20th Century matches what's calculated from the models for the burning of fossil fuel. I would guess that the production is not particularly different.

REEDY: Well, it looks like some of the similar cycles that one has seen. I'll accept your comment.

SPEAKER 1: There is a perfectly known cause which would certainly make a contribution of this order of magnitude.

SPEAKER 2: Make a comment, too, that you really don't know that you won't sporadically once every 100 or 1000 years have a really giant super-flare.

REEDY: You can't exclude it, no.

SPEAKER 2: You can't exclude it, and hence it would be prudent to have in any such space colony little shelters because, after all, one of the happy properties of solar flares is that they don't last very long.

REEDY: Several days would be wise, but they are not going to get them every decade or every 100 years. I think that's the point I wanted to make. A lot of people say that the solar cosmic rays have only been studied for 20 years and in a sense, that's not really true.

SPEAKER 3: In the Ames study, the shielding design was based I think, largely on a flare that occurred in 1952, which was supposed to be an alltime biggy, and even to the extent that it was penetrating to the Earth at the equatorial region. Now I don't know, you didn't mention such a flare.

REEDY: I knew there was some earlier ones before 1956 that had ground-level events; I'm not really aware of the parameters on that.

SPEAKER 3: The other point is that, of course, the thing that burns you is the relativistic protons that come out very high energy and very fast so you don't have much warning and shelter approach is difficult under those circumstances. You have to have some kind of precursor event which tells you that there's going to be a flare.

DISCUSSION (Reedy Paper)

REEDY: Usually in a solar flare there are very few relativistic protons.

SPEAKER 3: Again, I refer to the baseline event that we were using.

REEDY: These things decay very steeply with increasing energy, at least all that have been really studied.

SPEAKER 4: Even relativistic protons take some time to defuse and you do get light and X-ray emission which travels with the velocity of light. So there is some time.