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Studies of modern and ancient solar energetic particles

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Modern solar energetic particles (SEPs) have been studied for about 50 years by satellites and ground-based observations. These measurements indicate much about the nature of SEPs but cover too short a period to quantify the probabilities of very large solar particle events. Many SEPs have high enough energies to make nuclides in material in which they interact. Some nuclides measured in lunar samples have been used to extend the record about SEPs back several million years. Some new measurements of modern SEPs during the last solar cycle and new results for nuclides made by SEPs in lunar samples are presented and their implications discussed. Both the modern and ancient records need to be improved, and methods to get a better understanding of solar energetic particles are discussed. The SEP average fluxes from both sets of records are similar, and both sets can be used to show that huge fluxes of SEPs are very rare.

1. Introduction

There are many types of particles in the solar system. Most, such as those in the solar wind, have energies below an MeV and must be observed directly, either now in space or as implanted species in certain solar-system materials. Nuclides can be made in solar-system matter by both galactic-cosmic-ray (GCR) particles and solar energetic particles (SEPs). These "cosmogenic" nuclides allow us to study the energetic particles that made them as well as the history of the material in which the nuclides were made (e.g., Reedy *et al* 1983). GCR particles ($E \sim 1-10$ GeV) penetrate deep into matter and make many nuclides. The nature of GCRs is fairly well known.

Energetic particles are occasionally accelerated by various processes involving the Sun. SEPs only occur in rare events. The peak fluxes during a solar particle event (SPE) last only a few hours, and a SPE lasts only a few days to a week or two. SEPs have energies from ~ 1 MeV to hundreds and occasionally thousands of MeV with the flux usually dropping fairly rapidly with increasing energy (Smart and Shea 1989). The nuclei in a SPE are $\sim 98\%$ protons (Smart and Shea 1989), with a proton/ α -particle ratio of ~ 60 (Goswami *et al* 1988) and with small amounts of heavier nuclei (Tylka *et al* 1997). Before direct measurements of SEPs by spacecraft in the mid-1960s, some observations since 1942 were made using Earth-based instruments that detected ionization, neutrons, or radio disturbances caused by SEPs (Shea and Smart 1995). A few SPEs have very high fluxes and event-integrated fluences that are serious radiation hazards in space (Shea and Smart 1996).

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Most SEPs are stopped in less than a centimeter of solid matter. Some SEPs can induce nuclear reactions that produce high concentrations of certain nuclides near the very surface, such as in cosmic dust, meteoroids, and lunar samples (Reedy and Arnold 1972). Nuclides made by SEPs have been observed in many extraterrestrial samples and often are called solar-cosmic-ray-produced nuclides. Many SEP-produced nuclides have been observed in lunar samples (e.g., Reedy and Marti 1991; Rao *et al* 1994). When cross sections to unfold the lunar data are available, these SEP-produced nuclides have been used to infer the average fluxes of SEPs over various time periods determined by the half-life of the radionuclide or the surface exposure age of the lunar rock. Such fossil records enable us to study the long-term record of SEPs during the last 10^7 years. This paper reviews SEPs and what is known about them from both modern measurements of SEPs and the fossil record with SEP-produced nuclides.

2. Modern measurements

Table 1 lists average SEP fluxes for the four solar cycles from 1954 to 1996 for protons above four energies from 10 to 100 MeV and the approximate values of R_0 , the parameter for the best fit to the data using an exponential rigidity spectral shape (Reedy and Arnold 1972). The event-integrated fluences for SPEs from 1954 to 1997 are shown in Figure 1 along with the smoothed monthly sunspot number, an indicator of the level of solar activity. A solar cycle extends between consecutive minima of the smoothed sunspot number and is usually about 11 years long. The event-integrated fluences of SEPs have been compiled in detail by several authors for SPEs since 1954 until 1987 (e.g., Reedy 1977; Goswami *et al* 1988; Feynman *et al* 1990; Shea and Smart 1990).

The average fluxes from 1954 to 1964, solar cycle 19, are based on indirect measurements of relative SPE fluences and activities of 2.6-yr ^{22}Na and 2.7-yr ^{55}Fe in lunar rocks (Reedy 1977). These results for 1954–1964 need to be calculated again using better estimates of the relative SPE fluences for that period and newer cross sections for the nuclear reactions making ^{22}Na (e.g., Sisterson *et al* 1996). Preliminary calculations (e.g., Sisterson *et al* 1996) indicate that the average fluxes for 1954–1964 probably will be slightly (several tens of percent) smaller.

There are two sets of solar-proton average fluxes using different instruments given in Table 1 for the next two solar cycles. For both periods, there are some disagreements for the fluxes averaged over the 11-year solar cycle. These results suggest that these average fluxes are usually good to $\sim 30\%$ or so. For SPEs with very high fluxes, measured fluxes could be more uncertain because of dead-time effects (e.g., Tylka *et al* 1997). Measurements during times with many very-high-energy protons could be affected by protons entering through the sides or collimators of detector systems (e.g., Reeves *et al* 1992). Some work needs to be done to check these fluxes and to try to reduce their uncertainties. The event-integrated fluences of Reedy (1977) and Goswami *et al* (1988) are used for the 1954–1996 averages in Tables 1 and 2 and in Figure 1 for 1954 to 1986. The average fluxes for solar cycles 20 and 21 (1965–1986) are much less than those for solar cycle 19. This variation among SEP fluxes for individual solar cycles makes it hard to get good estimates for the long-term average fluxes of SEPs.

The values for the solar cycle 22, 1986–1996, are preliminary ones from databases for energetic-particle instruments on the GOES and IMP-8 satellites. The fluences for some

of the larger events have been published for GOES (Shea and Smart 1992) and IMP-8 (Feynman *et al* 1993) data. There are some differences in the event-integrated fluences for SPEs in these data sets, and averages, when available, were usually used here. For three of the four largest events in 1989, the event-integrated fluences of Reeves *et al* (1992) >10 MeV are within 50% of those from the other two data sets. The >10 MeV fluence for the other event (29 September 1989) in Reeves *et al* (1992) is about twice those of the others. Event-integrated proton fluences for the largest events during this last solar cycle are among the largest observed during the last five decades (Reeves *et al* 1992; Feynman *et al* 1993; Shea and Smart 1992, 1994). These data show that solar cycle 22 needs to be included in any study predicting SEP fluences in space, such as was done recently by Feynman *et al* (1993).

The fluences for the 11 November 1997 solar particle event, especially >30 MeV, are very preliminary values from peak fluxes >10 MeV in the database for the GOES satellites at geosynchronous orbit. A more complete set of intensities of event-integrated fluences and average fluxes of SEPs from 1954 until 1998 is being prepared (Reedy *et al* 1999).

As shown in Figure 1, the largest SPEs since 1954 had event-integrated proton fluences $\leq 3 \times 10^{10}$ protons/cm² for energies >10 MeV. Solar particle events of this size are serious radiation hazards to people, spacecraft, and instruments in deep space, especially away from the Earth's atmosphere and strong geomagnetic field (Shea and Smart 1996). It is hard to set good limits on huge SPEs using the present sets of direct measurements of SEPs. Other records for SEPs, such as nuclides made by SEPs in lunar samples, have been used to extend our database for the average fluxes of SEPs.

3. Ancient records

The best records of solar energetic particles in the past are some nuclides made and preserved in the top layers of lunar samples. SEP-produced nuclides have been studied since the first lunar samples returned by Apollo 11 in 1969. These nuclides represent various time periods in the past (see Table 2), as determined by the mean-life of a radionuclide and/or the surface exposure age of the lunar sample. The interpretations of the depth-versus-concentration profiles of nuclides made by SEPs in lunar rocks and cores have provided average fluxes and spectral shapes of solar protons for various time periods back to ~ 5 Myr. Much work has been done measuring and interpreting these records, but more work needs to be done.

It should be noted that, even a few years ago, not many cross sections existed for unfolding the records of most SEP-produced radionuclides, such as 5730-yr ¹⁴C and 0.3-Myr ³⁶Cl (Reedy and Marti 1991). Several groups have measured or are now measuring the needed cross sections and also some cross section to confirm older measurements (e.g., Michel *et al* 1996; Sisterson *et al* 1996, 1997a,b). Preliminary studies with the newest cross sections show that the results for SEP average fluxes over various time periods are not likely to change much due to the cross sections used to interpret the data.

3a. The SEP record in lunar samples

The energies of solar energetic particles are low enough that most SEPs are slowed down and stopped by ionization energy losses in matter before inducing a nuclear reaction (Reedy

and Arnold 1972). SEPs are usually stopped in the top centimeter or so of solid matter. The flux of SEPs drops rapidly with depth, so that the concentrations of SEP-produced nuclides decrease rapidly with increasing depth. These nuclides are also made by GCR-particles with a production profile that increases slowly with increasing depths to depths of tens of centimeters (Reedy and Arnold 1972).

An example of the concentration-versus-depth profile of a radionuclide in a lunar sample is shown at the top of Figure 2 for 0.3-Myr ^{36}Cl measured in lunar rock 64455 (Nishiizumi *et al* 1995). The decrease in the concentration of ^{36}Cl in the top few g/cm^2 (about a centimeter) is characteristic of production by SEPs. The solid curve near the top of Figure 2 is the GCR production profile of ^{36}Cl calculated using LCS, the LAHET (Los Alamos High Energy Transport) Code System (J Masarik, priv. comm., 1997), see Reedy and Nishiizumi (1998) for details. Subtracting the GCR contribution from the measured concentrations, one gets the contribution from SEPs shown as the lower set of symbols. For ^{36}Cl , the SEP-produced component is about the same as the GCR one near the very surface but drops rapidly to low values at the bottom of rock 64455 ($6 \text{ g}/\text{cm}^2$, which is about 2.2 cm for the $2.74\text{-g}/\text{cm}^3$ density of rock 64455).

The SEP profile is converted to the incident flux and spectral shape of SEPs (assumed to be protons) using cross sections for the main nuclear reactions making ^{36}Cl from the major target elements. Most ^{36}Cl is made from calcium, such as the $^{40}\text{Ca}(p,n4p)^{36}\text{Cl}$ reaction, with some ^{36}Cl made from potassium, titanium, and iron. Good cross sections for making ^{36}Cl from calcium and potassium have only been recently measured. The cross sections of Sisterson *et al* (1997b) were used to interpret the SEP profile for ^{36}Cl (Reedy and Nishiizumi 1998).

The incident spectral shape of SEPs was assumed to be that for an exponential in rigidity, $dJ/dR = k \times \exp(-R/R_0)$, where R is rigidity (momentum per unit charge) and R_0 determines the spectral shape (Reedy and Arnold 1972). Other spectral shapes, such as power laws in energy or rigidity, did not give better fits. As shown in Figure 2, three values of R_0 give reasonable fits to the SEP profiles for ^{36}Cl in 64455. The one with the largest fraction of low-energy protons, $R_0=60$ MV, fits the near-surface points better, but the harder ($R_0 = 80$ and 100 MV) spectra are better for the deeper points in Figure 2. However, a slight ($\sim 5\%$) increase in the GCR component would move the deepest points determined for the SEP component lower, to near the calculated curve for 60 MV.

The measured ^{36}Cl profiles in lunar core 15008 and lunar rock 74275 have also been studied (Reedy and Nishiizumi 1998). For $R_0=100$ MV, the best-fit fluxes >10 MeV are $124 \text{ protons}/\text{cm}^2/\text{s}$ for 15008 and $95 \text{ protons}/\text{cm}^2/\text{s}$ for 74275, higher than the same spectral shape for 64455. The best fit fluxes >10 MeV for ^{36}Cl in these three lunar samples varied and the values of R_0 also varied. However, most of these fits gave the integral fluxes given for ^{36}Cl in Table 2. There is much scatter in the fluxes >10 MeV and some spread in those >100 MeV, but most fits had integral fluxes >30 and >60 MeV close to those in Table 2.

The results for a given nuclide or set of nuclides for a given profile can also vary, as indicated in Table 2 for the four sets of results using 0.7-Myr ^{26}Al and 1.5-Myr ^{10}Be , depending on the sample measured or the interpretation procedure. While these variations are usually not very great, they are large enough that the reasons for variations in the results for SEP-produced nuclides need to be examined. The sources of uncertainties in

studies of such nuclides also need to be better characterized. Such uncertainties are hard to determine quantitatively because of the nature of the data for SEP-produced nuclides and how such data are interpreted.

3b. Factors affecting the interpretation of the SEP record

Lunar samples are very well suited for studies of the fossil records of SEPs, having been in a known orbit on a body with no atmosphere and very weak magnetic fields. Meteorites are not used for such studies because of their generally-unknown orbits and fairly-large amounts of ablation that remove the outer surfaces where nuclides are made by SEPs.

Only lunar samples with a well-documented record on the lunar surface should be used for studies of SEPs in the past. Their exposure histories need to be well known. The best lunar rocks are ones with a simple cosmic-ray exposure history since they were placed on the lunar surface from a great depth in the Moon by an impact. Lunar cores should not have been recently disturbed. The orientation of the sample on the Moon's surface should be known as well as the location of any objects (such as boulders and mountains) that could shield the sample from cosmic-ray particles.

The cosmogenic-nuclide measurements should be used to test the lunar-sample's exposure history. The activities of radionuclides and concentrations of stable nuclides can be compared to expected production rates, especially in the deeper subsamples. Several measurements of nuclides that are made readily by SEPs in subsamples at and near the bottom of a lunar rock would provide a check that the rock was not flipped over at some time during its surface exposure.

The many subsamples used for analysis should be for a wide range of depths (with many near the surface) and from a surface with a known location, shape, and orientation (best if horizontal) on the Moon's surface. All parts of each subsample should have the same range of depths below the surface. A slice should have the same depths for the entire area and not have variable thicknesses.

The depth of each subsample below the surface needs to be known in units of the grams of material above the subsample per unit area (g/cm^2). For many samples, this requires a good knowledge of the density of the sampled material. Rock densities vary, with rock 64455 being $2.74 \text{ g}/\text{cm}^3$ and rock 74275 being $3.36 \text{ g}/\text{cm}^3$. Densities for lunar cores should be the ones related to sampling, such as the compacted density of $1.65 \text{ g}/\text{cm}^3$ used for samples of 15008.

The composition of each subsample should be known for the target elements making the SEP-produced nuclides of interest. Usually there is little elemental variation among subsamples, but occasionally there can be some variability in composition. Usually the analyses assume an average composition and no variation among subsamples. If elemental production rates are known, the measured activities of each subsample could be adjusted to the average composition.

Some of the spread among various groups measuring a given nuclide could be the atom or activity scales used to get the measured concentration of that nuclide. Generally this variation should be small due to the use of good standards. Analyses of interlaboratory standards by the laboratories doing work on cosmogenic nuclides indicate that the reported concentrations should usually be reliable.

The measured concentrations need to be corrected to get that due only to SEPs. The main correction usually is for the production of that nuclide by GCR particles. Corrections for GCR production can be made and tested if one has a deep sample where SEP production is negligible, in which case a GCR production profile is needed to correct the samples closer to the surface. In many samples, such deep subsamples are not available (e.g., the small rock 64455) or were not taken. In those cases, good models for GCR production, such as LCS, are needed. Most GCR models are for a slab geometry. Some 3-D calculations done with LCS for hemispheric rocks on top of the lunar surface show that the GCR production rates vary depending on the size of the rock but that the shape of the profile as a function of depth is similar to that for a slab geometry (Reedy and Masarik 1995).

For 0.1-Myr ^{41}Ca (Fink *et al* 1998), and possibly ^{36}Cl , production by neutron-capture reactions with thermal neutrons needs to be considered. Neutron-capture production of ^{36}Cl is not expected to be important in samples like 74275 and 15008 with high concentrations of neutron-capturing elements like Fe and Ti (although Cl should be measured in such samples). In 64455 with its low Ti and Fe, it was estimated that 30 ppm of Cl would contribute ~ 0.5 atoms/min/kg of ^{36}Cl .

In some cases, such as ^{10}Be and ^{26}Al in 74275, corrections need to be made for pre-exposure production before being brought to the lunar surface. There can be some uncertainty in the time and depth of the previous exposure and in the rock's orientation at depth (e.g., Fink *et al* 1998).

Production by solar alpha particles for most solar-proton-produced nuclides is expected to be much less than 10% of the total SEP production (Reedy 1998). The main exception is 76-kyr ^{59}Ni , which is made in low yields by protons, because nickel is very rare in lunar samples, but readily made by the $^{56}\text{Fe}(\alpha, n)^{59}\text{Ni}$ reaction (Lanzerotti *et al* 1973).

The incident solar protons are usually assumed to have an exponential-rigidity spectral shape, which works fairly well for most modern measurements (e.g., Reeves *et al* 1992). However, it has not been shown that this is the best shape for unfolding SEP records. An exponential in rigidity generally gives good fits to the fossil SEP profiles. Other simple spectral shapes, such as power laws in energy or rigidity, generally do not give better fits to SEP-produced nuclides.

Often, as above for ^{36}Cl , a fairly-wide range of spectral shapes can give good fits. Several radionuclides, especially ^{10}Be , have been shown to be sensitive to the spectral shape of solar protons (Nishiizumi *et al* 1988). The low concentrations of SEP-produced ^{10}Be measured in lunar rocks requires that the incident SEPs not have many high energy particles (e.g., Nishiizumi *et al* 1988; Fink *et al* 1998). Thus, recently, ^{10}Be and ^{26}Al have often been used together to get the average SEP flux over the last ~ 1 Myr (e.g., Michel *et al* 1996; Fink *et al* 1998).

Almost all calculations have used the slab or hemispherical geometries with the SEP model of Reedy and Arnold (1972). Calculations using an irregular shape for rock 68815 (Russ and Emerson 1980) gave results not very different than those using the Reedy-Arnold model. Some 3-D calculations using Monte Carlo codes, such as the LAHET code (Masarik and Reedy 1996), should be done of solar protons irradiating irregularly-shaped lunar rocks.

Most models used for production of nuclides by solar protons (e.g., Reedy and Arnold 1972) only consider the slowing and stopping of the protons by ionization energy losses.

The relations used for the slowing of protons in matter are well determined (e.g., Janni 1982). Some comparisons done with the model of Reedy and Arnold (1972) and with LAHET gave good agreement for fluxes of solar protons at depth. LCS calculations also showed that production by secondary neutrons is not important except for very hard ($R_0 \gtrsim 200$ -MV) solar-proton spectra (Masarik and Reedy 1996).

For some nuclides (e.g., ^{41}Ca and 0.2-Myr ^{81}Kr), there is still a need for the measurement of more cross sections for the main proton reactions making these SEP-produced nuclides. Some cross sections for proton reactions making some SEP-produced nuclides (e.g., neon) need to be checked with some additional measurements. Measurements of cross sections for neutron-induced reactions are needed to help get better calculated production rates for GCR particles, which are mainly neutrons in lunar samples.

Some systematic studies are needed where many SEP-produced nuclides are studied in a few good rocks (e.g., 68815 and 64455) or cores (such as 15008). Any trend in SEP fluxes determined from several nuclides in a given sample would eliminate most of the effects due to the sample and help to study the other effects. A best fit for the SEPs making one or several nuclides could also be determined using several lunar samples, such as was done above for ^{36}Cl in lunar rocks 64455 and 74275 and lunar core 15008.

3c. Summary of the SEP fossil record

Lunar SEP-produced nuclides give only an average flux of solar protons over the radionuclide's mean-life or the sample's surface-exposure age. While the uncertainties in these average fluxes are not well characterized, these fluxes are known well enough (better than a factor of two) to be of much value in studies of lunar samples and ancient solar energetic particles. Better average fluxes of SEPs in the past should be determined soon as some of the factors above are better understood and improved models, such as for GCR production, are developed. There exist many good profiles for SEP-produced nuclides that should be re-examined. Some SEP-produced nuclides not usually measured (e.g., ^{41}Ca and ^{81}Kr) should have good profiles measured in some of the better-studied lunar samples.

The fluxes >30 and >60 MeV are better determined than those >10 MeV, as indicated in fits to individual profiles (as for ^{36}Cl above) and by the smaller spread among results in Table 2 for ~ 1 –5 Myr. The trend for these >30 and >60 MeV fluxes in Table 2 suggests that the average flux of SEPs over the last few million years is less than that for more recent periods, including the last four solar cycles (1954–1997).

4. Conclusions

Both the modern and ancient records for SEPs have been fairly quickly reviewed above. The SEP record from 1954 to 1964 is a little uncertain, and reported SPE fluences often are different by factors of several. Earth-based measurements need to be examined to give good fluences, especially relative ones. These data sets can then be used with lunar short-lived radioactivity measurements, as in (Reedy 1977), to check the absolute fluences and average fluxes for this period. The modern record is fairly good since 1965, although several reports of event-integrated fluences (e.g., Goswami *et al* 1988; Feynman *et al* 1990) differ for some events by $\sim 50\%$ or more. More data sets that can be used to get modern

SPE fluences need to be studied to improve the recent record. The measurements of SEPs since 1987 need to be carefully analyzed to get average SEP fluxes and SPE fluences for this period of several very large solar particle events.

The fossil record is also improving, with new measurements of SEP-produced nuclides in lunar rocks and of the cross sections for making these nuclides. Better models to correct for production by GCR particles are also being developed. Within a few years, many newer and better average fluxes should be available from the lunar fossil record for SEPs. Average SEP fluxes for the nuclides in Table 2 should soon be better known.

High intensities of solar energetic particles are serious radiation hazards in space. Modern and ancient measurements together have been used to show that huge solar particle events (event-integrated fluences $\gtrsim 10^{11}$) should be very rare (Reedy 1996). However, the record for SEPs is not complete. More work is needed on both the modern and ancient records.

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Table 1. Solar-proton integral fluxes during last four solar cycles

Time Period	Data Source	Flux References	R_o (MV)	----- E>10	Integral E>30	Fluxes# E>60	----- E>100
1986-1996	Several	This work	≈ 65	≈ 152	≈ 31	-†	-†
1976-1986	GSFC	Goswami <i>et al</i> 1988	40	63	5	0.6	$\sim 0.2\dagger$
1976-1986		Feynman <i>et al</i> 1990	57	52	8.6	-†	-†
1965-1975	SPME	Reedy 1977	90	92	30	8	-†
1965-1975		Feynman <i>et al</i> 1990	86	64	20	-†	-†
1954-1964	$^{22}\text{Na}^@, ^{55}\text{Fe}$	Reedy 1977	100	<u>≈ 378</u>	<u>≈ 136</u>	<u>≈ 59</u>	<u>≈ 26</u>
1954-1996		(See text)	83	≈ 171	≈ 50	≈ 19	≈ 7

Omnidirectional fluxes in protons/cm²/s; energies in MeV.

† Not measured (1965-1973), not reported (1973-1986), or not determined (1986-1996).

@ Using an older set of cross sections slightly different from newer ones.

Table 2. Average solar-proton fluxes for various time periods

Time Period	Data Source	Flux References	----- E>10	Integral E>30	Fluxes# E>60	----- E>100
1954-1996	Modern	(See text)	171	50	19	7
10^4 yr	^{14}C	Jull <i>et al</i> 1998	$\sim 103\dagger$	42	17	7
2×10^5 yr	$^{41}\text{Ca}^*$	Fink <i>et al</i> 1998	$\sim 200\dagger$	≈ 56	≈ 16	≈ 4
3×10^5 yr	$^{81}\text{Kr}^*$	Reedy & Marti 1991	$\sim 160\dagger$	$\sim 48\dagger$	~ 15	~ 4
5×10^5 yr	^{36}Cl	Reedy & Nishiizumi 1998	$\sim 70\dagger$	30	12	≈ 5
10^6 yr	$^{26}\text{Al}^@$	Kohl <i>et al</i> 1978	70	25	9	3
10^6 yr	$^{26}\text{Al}, ^{10}\text{Be}^@$	Nishiizumi <i>et al</i> 1995	100	26	7	2
10^6 yr	$^{26}\text{Al}, ^{10}\text{Be}$	Michel <i>et al</i> 1996	55	24	11	5
10^6 yr	$^{26}\text{Al}, ^{10}\text{Be}$	Fink <i>et al</i> 1998	89	32	12	4
2×10^6 yr	^{21}Ne	Rao <i>et al</i> 1994	68	21	6	2
5×10^6 yr	^{53}Mn	Kohl <i>et al</i> 1978	70	25	9	3

Omnidirectional fluxes in protons/cm²/s; energies in MeV.

† Energy is below main reaction thresholds.

* Need some (^{41}Ca) or many (^{81}Kr) key cross sections.

@ Using older sets of cross sections slightly different from newer ones.

Figure 1. The event-integrated proton fluences above 10 and 30 MeV near the Earth for solar particle events (vertical solid and dashed bars) and the smoothed monthly sunspot number (continuous curve) are shown as a function of time since 1954.

Figure 2. Measured ^{36}Cl activities (top symbols), calculated GCR production rates (solid line), inferred solar-proton ^{36}Cl production rates (lower symbols), and three sets of best fit production rates for various solar-proton exponential-rigidity spectral shapes (R_o) and integral fluxes above 10 MeV (lower curves) as a function of depth in lunar rock 64455.