SOLAR COSMIC RAYS: FLUXES AND REACTION CROSS SECTIONS.*

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Cosmogenic nuclides in the outer centimeter of lunar samples have allowed us to determine the past fluxes of solar cosmic rays (SCR). While there has been much done on studies involving these SCR-produced nuclides (1), much still needs to be done to utilize or to confirm and extend existing measurements. Early measurements (e.g., 2) showed that solar-proton fluxes over the last $\sim$5–10$\times 10^6$ years weren't very different from those observed directly since the early 1960s. The Reedy and Arnold model (3) for calculating the production rates by SCR particles was developed then, but its application sometimes has been limited by the lack of cross sections for certain SCR-induced reactions. In the mid-1970s, more detailed SCR fluxes were determined from lunar rock measurements and other observations (e.g., 4,5). A more exact model (6) was reported for interpreting the lunar measurements but didn't change the earlier conclusions. A "status report" on SCR fluxes was presented at the *Conference on the Ancient Sun* in 1979 (7). Since then, there have been additional measurements, both of SCR-produced nuclides in lunar samples and of cross sections for SCR-induced reactions. Only a few of the needs discussed in (7) have been met; most have not. Now additional measurements also should be done. This paper gives the present status of SCR studies (see Table 1), emphasizing changes since 1980, and discusses what should be done to fully utilize the potential for lunar cosmogenic nuclides to determine past SCR fluxes.

The emphasis below will be on solar protons. The status for solar alpha particles hasn't changed much since (8). The cross sections of (9), used by (8) for the ^{56}Fe(α,n)^{59}Ni reaction, have been confirmed and extended by (10). The need here is for good measurements of the solar-α-particle-produced ^{59}Ni depth-versus-activity profile in the top few millimeters of lunar rocks.

<u>SCR-Related Measurements Since 1980</u>. Of the needs discussed in (7), additional cross sections for the production of ^{14}C and ^{81}Kr were emphasized. Cross sections for the ^{16}O(p,3p)^{14}C reaction have only been measured once, in 1961 (11), although they were revised slightly by (12) using better cross sections for the monitor reactions. The ^{14}C cross sections of (11) have been questioned and should be confirmed. For ^{81}Kr, additional cross sections, but only for $E_p \geq 150$ MeV, have been reported by (13) and evaluated by (14) but haven't been applied to lunar ^{81}Kr measurements. The lunar ^{26}Al results of (5) have been confirmed by (15), showing that higher fluxes deduced by (16) from their ^{26}Al measurements are probably incorrect. Direct measurements of the fluxes of SCR particles from 1973 to 1986 have been reported (17), extending direct observations to another 11-year solar cycle.

The biggest development in the field of cosmogenic nuclides recently has been accelerator mass spectrometry (AMS), which allows long-lived radionuclides to be measured with sensitivities that are orders of magnitude better than those with low-level counting. AMS contributed the measurements for ^{10}Be (18) and ^{36}Cl (19) in Table 1 plus some additional results for ^{26}Al and ^{10}Be (20). The use of ^{10}Be along with ^{26}Al and ^{53}Mn in lunar samples helps to restrict possible scenarios (rock erosion rates as well as the fluxes and spectra of the solar protons) that could explain the measurements (18). AMS measurements of ^{10}Be and ^{36}Cl in lunar samples have created the need for cross sections for proton-induced reactions to interpret these measurements (18,19). Because of the lack of cross sections for ^{36}Cl production by low-energy ($\lesssim$100 MeV) protons, no proton fluxes could be determined from the lunar-sample ^{36}Cl measurements (19). Some AMS measurements for the production of ^{26}Al have confirmed some estimated ^{26}Al cross sections (21).

<u>Measurement Needs – 1989 Version</u>. The needs now for the study of SCR fluxes in the past are similar to those discussed by (7), with the emphasis on cross sections but still a need for some lunar-sample measurements. Proton cross sections that should be measured include: (1) ^{14}C from oxygen (best if $E_p \approx$ 40–50 MeV) to confirm those of (11), and from Mg, Al, and Si from $\approx$50–60 MeV to $\sim$100 MeV; (2) ^{81}Kr near and above the reaction thresholds with Sr ($\approx$60 MeV) and Zr ($\approx$80 MeV); (3) ^{10}Be from $\approx$40 MeV to $\sim$100 MeV for oxygen and with $E_p \gtrsim$ 50–60 MeV from Mg, Al, and Si; and (4) ^{36}Cl from Ca for $E_p \gtrsim$ 45 MeV and from K starting at 20–25 MeV. We are looking for previously-irradiated targets that could be used for these measurements and for accelerators at which such cross sections could be measured. A consortium of investigators interested in such low-energy proton cross sections is being organized.

Additional measurements of SCR-produced nuclides in lunar samples are also needed. Another ^{14}C depth-versus-activity profile should be measured to confirm the results of (22). Good ^{81}Kr, ^{36}Cl, and ^{59}Ni profiles should be measured in the tops of hard lunar rocks. It would be good if ^{26}Al, ^{10}Be, and ^{53}Mn profiles are also determined in these samples. The rocks used for such studies should be well documented to have been horizontal on the Moon's surface with a known, especially simple exposure history. To get additional time periods beyond the half-lives given in Table 1, SCR-produced nuclides in rocks with known, fairly short ($\lesssim 10^7$ years) exposures also could be studied. Such a co-ordinated program of lunar-rock and cross-section measurements plus more contemporary SCR-particle observations would confirm and extend the fluxes given in Table 1 and help to better understand the nature of energetic particles from the Sun now and in the past (23).

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Table 1. Solar-proton integral fluxes and spectral shapes (in rigidity, R_o, usually between 10 and 30 MeV) averaged over various time periods (last three 11-year solar cycles or lengths of time into the past) as determined from direct measurements (1965-1986) or lunar-rock radioactivities. Fluxes are in protons / (cm^2 s); the four energies are in MeV. References are given for the cross sections used to unfold the data and for the measurements and the solar-proton flux determinations.

Time Period	Data Source	Cross Section References	Flux References	R_o (MV)	----- $E > 10$	Integral $E > 30$	Fluxes $E > 60$	------ $E > 100$
1976-1986	IMP-8[a]	–[b]	(17)	40	63	5	0.6	~0.2[c]
1965-1975	SPME[d]	–[b]	(4,17)	90	92	30	8	–[c]
1954-1964	^{22}Na, ^{55}Fe	(3)	(4)	100	378	136	59	26
$\sim 10^4$ y	^{14}C	(11)	(22)	100	[≈200][e,f]	≈72[f]	≈26[f]	≈9[f]
$\sim 3 \times 10^5$ y	^{81}Kr	(25)	(26)	~150	–[e]	–[e]	~18[g]	~9[g]
$\sim 5 \times 10^5$ y	^{36}Cl	(19)	(19)	–	–[e]	–[g]	–[g]	–[g]
$\sim 10^6$ y	^{26}Al	(3)	(5)	100	70	25	9	3
$\sim 2 \times 10^6$ y	^{10}Be	(27)	(18)	≳70	[≲150][e,g]	~35[g]	~8[g]	~2[g]
$\sim 5 \times 10^6$ y	^{53}Mn	(28)	(5)	100	70	25	9	3

[a] Goddard Space Flight Center experiment on the IMP-8 satellite.
[b] Solar-proton fluxes directly measured.
[c] Not measured (1965–1973) or sometimes not reported (1973–1986).
[d] Solar Proton Monitor Experiment on several satellites (24).
[e] Energy is below main reaction thresholds. Fluxes in [ ] are extrapolations from higher energies.
[f] Needs some additional cross sections to check those used to unfold the measurements.
[g] Few or no cross sections available for unfolding the lunar-radioactivity measurements.