NATURAL RADIOACTIVITY OF LUNA-24 AND APOLLO-16 SOILS

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Activity due to cosmic ray produced (^{26}Al + ^{22}Na) and natural ^{232}Th have been measured in lunar soil samples from Luna-24 drill core and Apollo-16 scoop by the β-γ coincidence technique. The (^{26}Al + ^{22}Na) activity is determined to be about 245 and $\leqslant$ 101 dpm/kg for 67481, 7 and 24087, 1 respectively. A comparison with their expected depth profile indicates an average irradiation depth on the moon of 5.4 ± 2.7 g. cm^{-2} for 67481 and $\geqslant$ 53 g. cm^{-2} for 24087, 1. ^{232}Th is found to be $1.5 \pm .4$ ppm in Luna-24 soil sample and negligible in the Apollo-16 soil.

INTRODUCTION

RADIONUCLIDES produced by cosmic rays in lunar samples have been studied in great detail recently resulting in a better understanding of the dynamical processes operating on the lunar surface as well as the long-term characteristics of solar and galactic cosmic rays (Lavrukhina & Gorin, 1973; Imamura *et al.*, 1974; Bhandari, 1976). Since in case of soils the amount of sample available has been usually small, such measurements, particularly in case of ^{26}Al, have been difficult. The present authors report here the attempts to measure ^{26}Al and ^{22}Na in small amounts of lunar soil and compare the observed activities with the expected depth profiles based on the Reedy-Arnold model (Reedy & Arnold, 1972).

EXPERIMENTAL TECHNIQUES

Two samples, one from 86–87 cm layer of Luna-24 core (24087) and another from Apollo-16 scoop (67481) weighing 162 and 228 mg respectively were counted on a β-γ coincidence spectrometer. The samples were evenly deposited on a 2.35 sq. cm area and the energy spectrum of gamma radiation in coincidence with β^+ were recorded. A thin window gas flow Geiger-Müller counter was used for detecting beta particles. The GM counter was kept in flush with a 12.5 cm × 12. 5 cm NaI (Tl) scintillator recording the gamma radiation. The details of this system are described in Bhandari *et al.* (1975). The resulting spectra showed a measurable activity in positron (511 keV) and 580 keV energy channels.

Out of the various radionuclides produced by cosmic rays, ^{26}Al and ^{22}Na are the major contributors of positrons and the contribution due to other radionuclides at the time of counting is atleast an order of magnitude smaller (Bhandari *et al.*, 1975). The 580 keV signal arises due to ^{208}Tl, a daughter product of ^{232}Th. When the concentration of ^{232}Th is large, Compton correction in the 511 keV peak becomes significant. These corrections have been made following the procedure discussed in Bhandari *et al.* (1975). The Compton contribution due to ^{232}Th in 511 keV peak is 71 ± 28 per cent and 9 ± 16 per cent of the signal in the case of lunar soils 24087 and 67481, respectively.

RESULTS AND DISCUSSIONS

The results are given in Table I for (^{26}Al + ^{22}Na). Because of the small amounts of samples available, the signal due to each of the two radionuclides could not be separated by their high energy gamma rays and the statistical errors in counting are large. However, it is still possible to derive some information on irradiation depths of these samples on the moon based on these data as discussed below. The amount of ^{232}Th could not be determined in 67481; in 24087 this is estimated to be 1.5 ± 0.4 ppm.

TABLE I

Counting data

Soil	Depth (cm)	Sample weight (mg)	Deposited area (cm^2)	Total counting time (min)	Gross counts (CPT)		(^{26}Al + ^{22}Na)*	
					0.511 (MeV)	0.580 (MeV)	Net CPT	dpm/kg
24087, 1	86–87 in core	162	2.35	30,056	4.3 ± 0.4	2.1 ± 0.3	0.59 ± 0.48	57 ± 45
67481, 7	Scoop	228	2.35	8,870	6.2 ± 0.8	1.6 ± 0.4	3.1 ± 0.95	245 ± 75
Background	—	—	5.25	15,840	2.3 ± 0.3	0.9 ± 0.2	—	—

*Mean time of counting : 15th May 1977.

CPT = Counts per thousand minutes.

Expected Depth Profiles — We may compare these activities with the expected depth profiles based on the Reedy-Arnold model. For this purpose we have calculated ^{22}Na and ^{26}Al depth profiles shown in Fig. 1 based on the target element composition of these soils listed in Table II.

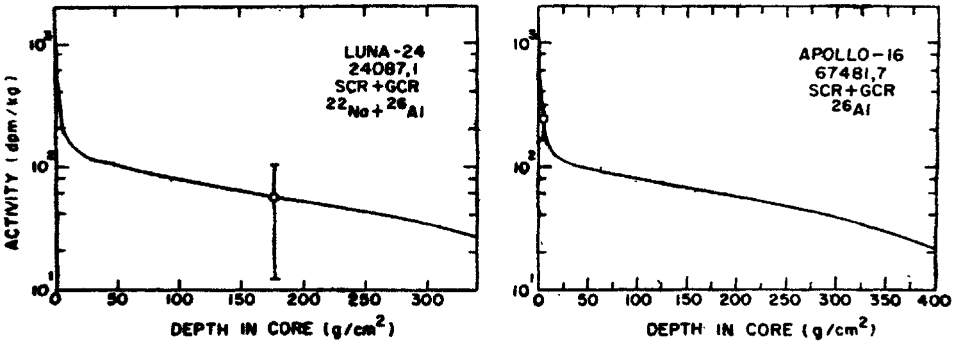

FIG. 1. Depth profiles of (^{26}Al + ^{22}Na) in Luna–24 core and of ^{26}Al in Apollo–16 soil, corrected for their decay to the time of measurement (15 May 1977). The experimental points give the most probable irradiation depths.

TABLE II

Adopted chemical composition

Sample	% by weight			
	Mg	Si	Al	Na
24087[a]	5.82	21.37	6.24	0.22
67481[b]	3.90	21.20	13.90	0.32

[a]Blanchard *et al.* (1977); Murali *et al.* (1979)
[b]Wänke (1974).

The Apollo–16 chemical composition has been taken from analysis of similar soils (Wänke, 1974) and Luna–24 soil composition is based on the work of Murali *et al.* (1979) and Blanchard *et al.* (1977). Following Reedy and Arnold (1972), we have taken a long-term average galactic cosmic ray proton flux (>1 GeV) of 1.7 protons/(cm^2. sec. 4π sr) for the calculation of the activity of ^{26}Al. For the calculation of ^{22}Na activity the proton fluxes over the last decade covering solar cycle 20 from the available data of measured fluxes (Lezniak & Webber, 1971; Moraal, 1976; Hsieh *et al.*, 1971; Garcia-Munoz *et al.*, 1975 *a,b,c*, 1977) were used. The high energy (> 1 GeV) data are limited but upto about a hundred MeV, measurements have been made during brief solar quiet times for all the years covering solar cycle 20 (i.e., during 1965–76). These were taken to represent the mean annual GCR fluxes. In view of the hysteresis effect, observed at low energies, particularly during solar maximum (Van Hollebeke *et al.*, 1972; Burger & Swanenburg, 1973), only the high energy observations were used for extrapolating the GCR spectra for energies > 1 GeV, guided by the limited high energy measurements, modulation models, the GCR theoretical interstellar spectrum and 1973 GCR interplanetary spectrum (Garcia-Munoz *et al.*, 1975*b*). The spectrum beyond 20 GeV for all the years was assumed to have the form as given below (Wolfendale, 1975) :

$$\frac{dJ\,(E)}{dE} = KE^{-2.65}$$

The spectra for the respective years should be representative of GCR fluxes in the interplanetary space at 1 A. U. From these spectra fluxes (> 1 GeV) were obtained. These are listed in Table III. The errors in experimental measured fluxes (which are of the order of 5 to 10 per cent around 1 GeV) and in extrapolation have not been taken into account in Table III and, therefore, the values of annual mean GCR fluxes are expected to be correct only within ± 10 per cent. It is seen that the annual mean fluxes vary between 1.32 in 1970 to 2.36 in 1976. These data lead to a mean flux (> 1 GeV) during the solar cycle 20 of 1.9 protons/cm^2. sec. 4π s compared to the long-term average of 1.7 protons/(cm^2. sec. 4π s r) adopted by Reedy and Arnold (1972). The latter probably also represents mean GCR flux during solar cycle 19. The solar cycle 20 fluxes inversely correlate with the yearly Zürich smoothed mean sun-spot numbers with a phase lag of about one year as expected (Fig. 2).

TABLE III

Computed GCR proton fluxes (> 1 GeV) at 1 A.U. during solar cycle 20

Year	4π integral proton flux (> 1 GeV)/(cm^2. sec).
1965[a,b,c]	2.23
1966[b]	1.97
1967[a]	1.57
1968[b]	1.62
1969[a,c]	1.48
1970[c]	1.32
1971[c]	1.66
1972[c]	2.04
1973[c,g]	1.95
1974[c,c,g,]	2.06
1975[f]	2.23
1976[e]	2.36

Solar cycle 20 average proton flux (> 1 GeV) = 1.9 protons/cm^2. sec. 4 π sr.
[a]Hsieh *et al.* (1971); [b]Bedijn *et al.* (1973); [c]Garcia-Munoz *et al.* (1975*b*); [d]Mckibben (1977); [e]Garcia-Munoz *et al.* (1977); [f]Garcia-Munoz *et al.* (1975*a*); [g]Garcia-Munoz *et al.* (1975*c*)

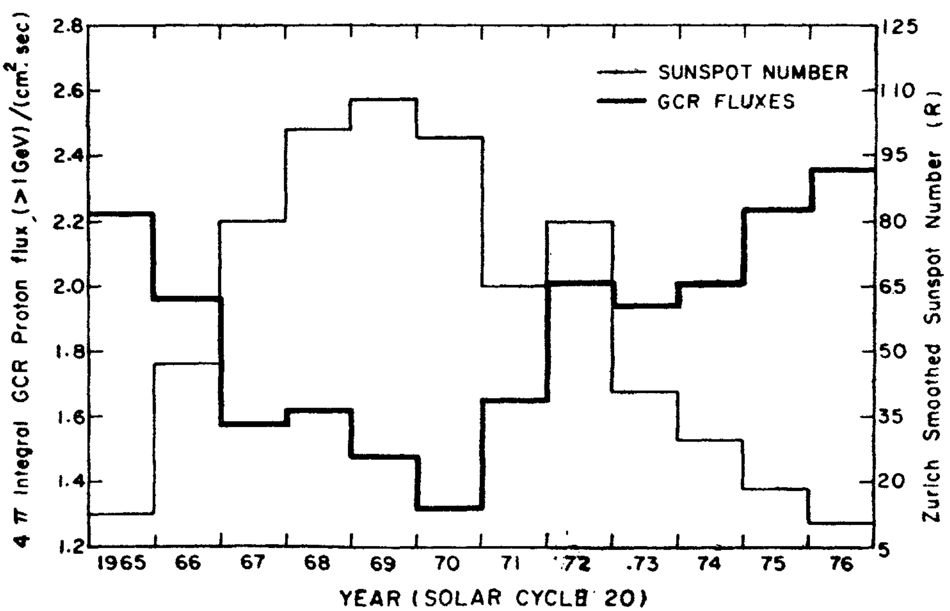

FIG. 2. Annual average GCR proton fluxes (protons/cm^2. sec. 4π sr) during solar cycle 20. The Zurich smoothed sunspot numbers for different years are also shown.

The solar cycle 19 was a very active period of solar activity compared to solar cycle 20 in particular, and all the previous cycles since 1750. Solar cycle 19 had the largest peak sunspot numbers (Zürich smoothed sunspot number ~ 200) as compared

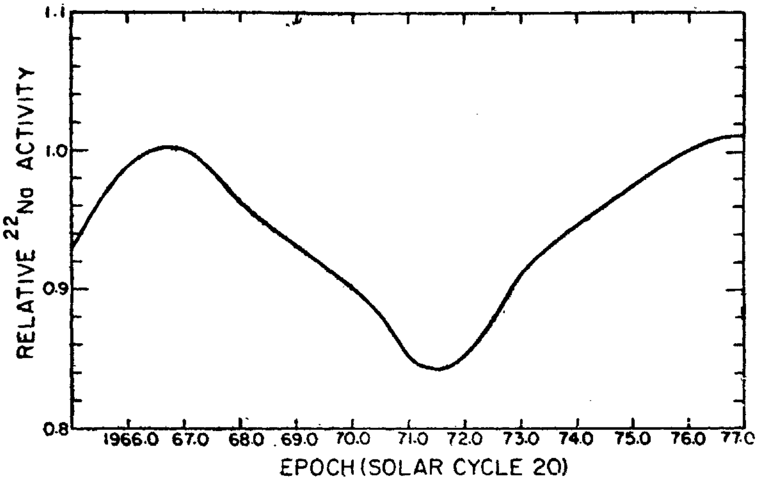

FIG. 3. Solar cycle effect on ^{22}Na activity during 1965–76, taking the average production during solar cycle 20, (GCR proton flux = 1.9 protons/(cm^2. sec. 4π sr)) to be unity.

to 110 of solar cycle 20 (Reedy, 1977) but the GCR fluxes (> 1 GeV) are different by only about 12 per cent.

Based on the annual mean fluxes (Table III), we have calculated the variation of ^{22}Na activity during various years. This is shown in Fig. 3. The ^{22}Na activity at the time of Luna-24 collection should be equivalent to that produced by 2 protons (> 1 GeV)/(cm^2. sec. 4π sr.).

The ^{22}Na depth profile in the Luna-24 core is calculated based on these GCR proton fluxes following the method of Reedy and Arnold (1972) shown in Fig. 1. The ^{22}Na in Apollo-16 soil at the time of counting was too small, because of decay during the time elapsed after sample collection and therefore, the observed 511 keV peak is mainly due to ^{26}Al. In Luna-24 sample, however, ^{22}Na contribution is significant. Depth profiles given in Fig. 1 show the expected (^{22}Na + ^{26}Al) at the time of counting of these samples. The observed activity is also shown for comparison.

Although the counting errors are large because of small amount of samples available, they allow us to estimate the irradiation depths of the two samples on the moon. The activity of 245 ± 74 dpm/kg in the Apollo-16 scoop sample corresponds to the mean shielding depth of 5.4 ± 2.7 g.cm^{-2} whereas the activity of 57 ± 45 dpm/kg in 24087 corresponds to a shielding depth of $\gtrdot$ 53 g. cm^{-2}. The density of core soil varies between 1.4 to 1.7 g. cm^{-3} (Apollo-16 preliminary science report). Taking average value of 1.55 g. cm^{-3}, we obtain their depths to be equal to 3 ± 1.5 cm and $\gtrdot$ 35 cm for the Apollo-16 and Luna-24 samples respectively. Whereas in case of Apollo samples, the deduced average depth is consistent with the scoop size, the situation with Luna-24 sample is somewhat complicated. The actual depth of the sample 24087 from the top of the core tube is 86 cm. The tube was empty upto a depth of 47 cm and was scantly filled upto 58 cm. From 58 to 73cm the core tube, according to Barsukov *et al.* (1977), contained only coarse grains. Bogard and Hirsch (1977) have discussed the problem of real sample depths on the moon. The following three possibilities have been suggested to explain the smaller recovered core length (140 cm) compared to the depth of penetration (223 cm) : (1) shortening due to compaction; (2) expansion due to large diameter of the core tube compared to that of the bit; and (3) incomplete sampling. Unlike the case of rare gases. the pre-irradiation effects are not present in case of ^{26}Al. The ^{26}Al measurements can be used to determine the actual sample depths on the moon, with the help of a suitable model for depth profile of ^{26}Al such as the Reedy-Arnold model (Reddy & Arnold,, 1972). If the level of 58 cm is assigned to the lunar surface, then our results indicate that some part of the soil was not contained in the core tube. Furthermore, as discussed by Bogard and Hirsch (1977) if the core was not taken vertically, but at an angle of 30°, our results would indicate a loss of upper 10 cm of core material.

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