CARBON-14 DEPTH PROFILES IN APOLLO 15 CORES;

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The depth dependence of radioisotopes in lunar core and rock samples can be used to study the production rates of various isotopes due to cosmic-ray effects. The study of radioisotopes of differing half-life can give an indication of variations of the galactic (GCR) and solar cosmic-ray (SCR) fluxes over different time scales (1). In this paper, we report on the study of ^{14}C ($t_{1/2}$=5,730 years) as a function of depth in lunar cores 15001/6 and 15008. The radioisotopes ^{10}Be, ^{36}Cl, ^{26}Al and ^{53}Mn have been measured in the Apollo 15 deep drill cores (2-6). These results confirm that the all radioisotopes show production due to both solar cosmic rays at shallow depths of a few g/cm^2 (except ^{10}Be), and also GCR production down to hundreds of g/cm^2 (2,5). Carbon-14 is produced by both solar and galactic cosmic rays (1).

The ^{14}C was extracted from samples of lunar soil (<1mm grain size) provided by the Lunar Sample Curator. The samples (0.02 to 0.15g) were placed in an alumina crucible with about 3g iron chips, to enhance combustion, and heated in air to 500°C using techniques developed for meteorites (7). The sample was then melted in an RF furnace in a flow of oxygen. All carbonaceous gases evolved were converted to CO_2 over Pt/CuO. The CO_2 was collected cryogenically and diluted to about 1 to 1.5cm^3 STP. The diluted gas was converted to graphite (8) for analysis by accelerator mass spectrometry. Details of the analysis and calculations are given elsewhere (7,9). Table 1 shows the results which we obtained.

Galactic Cosmic Rays: The profile from the deep drill core (15001/6) peaking at about 50g/cm^2 is typical of GCR-produced nuclides. For values up to 33 g/cm^2, the values obtained for the same depths for 15008 are slightly higher. The maximum observed production rate of about 34 dpm/kg is about 20% higher than the values predicted by calculations using the Reedy-Arnold lunar GCR flux model and ^{14}C production cross sections from Jull et al (10), which suggest a maximum of about 29 dpm/kg. The shape of the profile is similar to the expected profile (1) and to the profile obtained from the thick-target simulation experiment of Englert et al (11). Higher cross sections in the 25-200MeV range than those currently employed in the calculations could explain this difference, as the GCR flux is not expected to have changed over the time scale of interest.

Solar Cosmic Rays: The signal of SCR production of ^{14}C in the first few cm is quite clear in the surface core 15008. After subtraction of the GCR component, the maximum value of the SCR component observed, at a depth of 0-0.8g/cm^2, is approximately 15 dpm/kg. The profile (fig. 1) is similar to that expected from Reedy and Arnold (1). Best fits to the experimental data using the $^{16}O(p,X)^{14}C$ cross sections of (1) are obtained for 4-π SCR fluxes similar to those obtained for other radioisotopes in lunar samples (12). For any depth profile, there are several values of flux and R_o (SCR spectral rigidity parameter (1)) which fit the data. Our best fits favor a value of R_o between 70 and 100MV. At R_o=100MV, a flux of 85p/cm^2/s is obtained (the corresponding fluxes for R_o=70MV and 85MV are 260 and 135p/cm$^{2/s)}$. There is no evidencefor the very high surface (0-0.1cm) ^{14}C values observed by earlier work on rocks 12002 (13) and 12053 (14). Boeckl(13) explained his observation as due to a much higher SCR flux, CARBON-14 IN APOLLO 15 CORES: Jull, A. J. T. et al.

whereas Begemann et al (14) suggested a surface-correlated component. There is no evidence from our data for a greatly enhanced SCR flux in the last 10,000 years. The high flux (200p/cm^2/s for R_o) calculated by Boeckl (13) may be partially ascribed to an underestimation of the GCR component. It is more likely that the high very surface ^{14}C observed in rocks is due to an implanted surface-correlated component (15). Such a component would be unlikely to be observed in the core samples measured, as <1mm of lunar soil is gardened over 10,000 years (16), and our surface sample was from 0-5mm.

Our interpretations could be modified by improved cross section data. There are few direct measurements of cross sections for production of ^{14}C by spallation of oxygen. Sisterson et al (17) report some cross sections which are similar to the data that are used in the Reedy-Arnold model for this energy region. The excitation function in the range 25-150MeV for protons needs to be measured experimentally before the inferred solar-proton fluxes can be optimized.

References: (1.) R. C. Reedy and J. R. Arnold, J. Geophys. Res., 77, 537 (1972). (2.) C. P. Kohl et al, Proc. Lunar Planet. Sci. Conf. 9th, 2299 (1978) (3.) K. Nishiizumi et al, Proc. Lunar Planet. Sci. Conf 19th, 304 (1989) (4.) K. Nishiizumi et al, EPSL, 70, 157 (1984). (5.) K. Nishiizumi et al, EPSL, 70, 164, (1984). (6.) K. Nishiizumi et al, Proc. Lunar Planet. Sci. Conf. 19th, 305 (1989). (7.) A. J. T. Jull et al, Geochim. Cosmochim. Acta, 53, 1295 (1989). (8.) P. J. Slota et al, Radiocarbon, 29, 303 (1987). (9.) D. J. Donahue et al, Radiocarbon, 32, 135 (1990). (10.) A. J. T. Jull et al, Lunar Planet. Sci. XIX, 495 (1988). (11.) P. Englert et al., Lunar Planet. Sci. XIX, 303 (1988). (12.) R. C. Reedy and K. Marti, in "The Sun in Time", Univ. of Arizona Press, 1991. (13.) R. S. Boeckl, EPSL, 16, 269 (1972). (14.) F. Begemann et al, Proc. Lunar Sci. Conf. 3rd, 2, 1693 (1972). (15.) E. L. Fireman et al, EPSL, 32, 185 (1976). (16.) D. E. Gault et al, Proc. Lunar Sci. Conf. 4th, 3, 2365 (1974). (17.) J. M. Sisterson et al, Lunar Planet Sci. XXII, this volume.

Table 1: Carbon-14 in the Apollo 15 cores

Sample	Depth, g/cm^2	Wt.,g	^{14}C, dpm/kg
Shallow core:			
15008,227	0-0.8	0.099	41.1±0.6
15008,228	0.8-1.65	0.092	39.5±0.6
15008,229	1.65-2.5	0.111	37.7±0.5
15008,230	2.5-3.3	0.116	35.1±0.5
15008,231	3.3-5.0	0.092	31.3±0.6
15008,232	5.8-6.6	0.117	30.1±0.5
15008,233	7.4-8.3	0.103	30.7±0.5
15008,234	15.7-16.5	0.093	34.2±0.5
15008,235	32.2-33.0	0.107	36.0±0.5
Deep core:			
15006,284	1.15-2.0	0.019	37.0±1.7
15006,283	7.8-8.6	0.069	29.8±0.5
15006,282	16.0-16.8	0.070	30.7±0.8
15006,281	32.5-33.3	0.071	33.8±0.6
15005,566	82.5-83.3	0.103	32.5±0.5
15004,220	164.8-165.7	0.145	20.2±0.3
15001,370	330.5-330.8	0.148	10.0±0.3

Fig 1: ^{14}C profile in the Apollo 15 cores. The dashed line represents the calculated GCR component, the solid line is the combined GCR and SCR component.