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Cosmogenic Carbon-14 in Meteorites and Terrestrial Ages of "Finds" and Craters

Abstract. Carbon-14 has been measured in several stone and iron meteorites. For "falls," the C^{14}/Al^{26} ratios in stones and the C^{14}/Cl^{36} ratios in irons are consistent with constant irradiation. The stone "finds" have radiocarbon ages of up to $\geqq$ 21,000 years. The Henbury craters are apparently $\leqq$ 7,000 and the Odessa craters $\geqq$ 11,000 years old.

The study of stable and radioactive nuclides in meteorites from bombardment by cosmic radiation in space (*1*) has given valuable information on the relative intensity of cosmic radiation in the past (*2*) and on the histories of meteorites (*3*). The possible occurrence of C^{14} in meteorites was first mentioned by Bauer (*4*), and it has been recognized that its half life of some 5000 years would make it particularly useful for dating the falls of meteorite "finds" (*5*). Its observation in both a stone and an iron meteorite has recently been reported (*6*), and we present herewith the results of additional measurements. The results on "falls" supplement previous information on the past cosmic-ray intensity, and those on "finds" illustrate the utility of C^{14} for determination of terrestrial ages of meteorites.

The techniques are described elsewhere (*6, 7*). From stone meteorites (10 to 20 g), carbon is recovered as CO_2 by fusion with an oxidizing flux. Iron meteorites (200 to 400 g) are decomposed in a closed system by HNO_3, and the evolved CO_2 is absorbed in NaOH and precipitated as $BaCO_3$. The CO_2 is carefully purified with special care to remove radon. The pure CO_2 serves as the counting gas in proportional counters of various sizes, similar to those of Stoenner *et al.* (*8*). Conventional anticoincidence and shielding techniques are used to reduce backgrounds. Special alpha-particle monitoring circuitry indicates the absence of radon contamination. Counters with volumes (including dead-space) of 11 to 82 ml with CO_2 at about 76 cm-Hg have backgrounds from 0.20 to 0.45 count/min and counting yields of 44 to 65 percent as determined with National Bureau of Standards standard C^{14} and checked with biological carbon.

The results, in terms of meteorite specific C^{14} activity, are given in Table 1. Specimens differentiated by "I" and "II" in the table came from the same piece of meteorite; the agreement between such duplicates gives confidence in the techniques. The negative results (Potter, Sardis) demonstrate absence of appreciable contamination from terrestrial radiocarbon. Limits for inactive samples are calculated by adding two standard deviations (computed from counting statistics only) to the net counting rate, if positive, or to zero, if negative.

The production rate of a nuclide in a specimen should vary with the size of the meteoroid and the position of the specimen within it. It is therefore surprising that the range of variations observed in stone "falls" is so small. A mean value of the C^{14} activity level in stone "falls" is calculated as 63 ± 10 disintegrations per minute per kilogram (dpm/kg), the uncertainty index being the standard deviation characterizing the spread of the individual values. From the data of Rowe *et al.* (*9*), the mean Al^{26} content of stones is 52 ± 5 dpm/kg, giving a C^{14}/Al^{26} ratio of 1.2. Qualitative arguments (*6*) show that this is roughly consistent with expectations based on a constant cosmic-ray intensity.

For the calculation of the terrestrial ages of stone "finds," recorded in Table 1, the value 63 ± 10 dpm/kg was assumed for all at the time of fall. Simultaneous measurements of additional radionuclides should permit separate estimates for each. It is interesting that four of the six stone "finds" are fairly old (*10*).

For the iron "falls," Aroos (=Jardymlinsky) and Sikhote Alin, the Cl^{36} contents have been measured (*11*) to be 21.0 ± 0.4 and 15.0 ± 0.4 dpm/kg, respectively. In both, the ratio C^{14}/Cl^{36} is close to 0.10. Arnold *et al.* (*2*) give 0.13 as a theoretical production-rate ratio estimate. The closeness of these values makes it appear that the cosmic-ray intensity averaged over the mean lives of these two nuclides has been about the same. Carbon-14 integrates over a time span essentially missed by the radionuclides considered in the survey of Arnold *et al.* (*2*).

Table 1. Carbon-14 in Meteorites

Meteorite and place of fall or find	Year fell or found	Recovered mass (kg)	[Carbon-14] (dpm/kg)	Terrestrial age (years)
		Stone falls		
Bruderheim, Alberta, Canada	1960	303	63 ± 5	
Forest City, Iowa	1890	122	I: 47 ± 6	
			II: 51 ± 7	
			Av: 49 ± 5	
Harleton, Texas	1961	8.36	57 ± 5	
Holbrook, Arizona	1912	218	I: 63 ± 4	
			II: 58 ± 3	
			Av: 60 ± 3	
Kunashak, U.S.S.R.	1949	200	71 ± 5	
Modoc, Kansas	1905	211	59 ± 4	
New Concord, Ohio	1860	220	73 ± 5	
Richardton, N. Dakota	1918	100	78 ± 6(*6*)	
		Stone finds		
Achilles, Kansas	1924	16	I: 55 ± 11	
			II: 58 ± 11	≤5,200
			Av: 56 ± 8	
Coldwater, Kansas	1924	11	39 ± 3	4,000 ± 1,400
Hugoton, Kansas	1927	350	36 ± 4	4,700 ± 1,600
Plainview, Texas	1917	700	61 ± 4	≤3,500
Potter, Nebraska	1941	261	−0.2 ± 2.2 [≤4.5]	≥21,000
Selma, Alabama	1906	105	29 ± 2	6,500 ± 1,400
		Iron falls		
Aroos, U.S.S.R.	1959	150	1.80 ± 0.25	
Sikhote Alin, U.S.S.R.	1947	large	1.66 ± 0.33	
		Iron finds		
Henbury, Australia	1931	large	I: 1.20 ± 0.36(*6*)	
			II: 1.44 ± 0.22	≤7,000
			Av: 1.37 ± 0.18	
Odessa, Texas	1922	large	0.22 ± 0.10 [≤0.42]	≥11,000
Sardis, Georgia	1940	800	0.01 ± 0.13 [≤0.28]	≥16,000

Terrestrial ages of irons would probably be reflected better by the C^{14}/Be^{10} ratio than by the absolute C^{14} content. Pending completion of Be^{10} determinations in the same specimens (*12*), we can use the C^{14} activity to obtain rough limits on the ages of the iron "finds." The activity in Odessa is not sufficient to be regarded as definite.

It has been shown previously that most iron "finds" contain no detectable Ar^{39} (H = 325 years) (*13*) and thus are at least about 1000 years old. The present results show that stone "finds" with terrestrial ages of thousands of years are not uncommon, and that some craters associated with iron meteorites (Henbury and most probably Odessa) have ages in the range of applicability of dating by C^{14} measurements.

Measurements of pertinent cross sections and production-rate ratios in accelerator targets are under way, and should provide a basis for more quantitative interpretation with respect both to the past cosmic-ray intensity and to the terrestrial ages of "finds" and associated impact phenomena (*14*).

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Measurement of Membrane Potentials in Neurospora

Abstract. Microelectrodes were used to record intracellularly from the filamentous fungus *Neurospora crassa*. Under standard conditions membrane potentials averaged 127 mv, inside negative. The potentials were potassium-sensitive, and depended upon the distance of the cells from the growing margin of the colony. In addition, the potentials were quickly reduced to about 30 mv in the presence of low concentrations of sodium azide or the polyene antibiotic nystatin.

The convenient size of *Neurospora* hyphae suggested that, unlike the cells of most other microorganisms, they might permit direct electrophysiological measurement of membrane properties. Such properties could then be correlated with cell growth and with the structure and permeability of the cell membrane, by using genetic and biochemical techniques not readily applicable to the tissues of higher organisms.

Neurospora hyphae are divided into "cells" by incomplete septa, and in growing colonies the cytoplasm streams continuously toward the advancing hyphal tips. Electron microscopic studies (*1*) have demonstrated the presence of a highly convoluted 75A unit membrane directly beneath the chitinous cell wall. Unlike the alga *Nitella, Neurospora* has no large central vacuole to complicate the interpretation of electrophysiological data (*2*).

In the present study, 1-day cultures of wild-type *N. crassa*, Perkins strain, mating type *a*, were grown at 25°C on minimal agar (*3*) covered with cellophane. Squares of cellophane with cells affixed were removed from the growth medium, washed, transferred to the recording chamber, and covered with the desired bathing fluid. Many hyphae reached diameters of 10 to 15 μ, and glass micropipettes with tip diameters less than 1 μ could be used to record intracellularly. The pipettes were filled with 3M KCl and had resistances between 20 and 35 megohms. All recordings were made with a direct-coupled amplifier. It was possible to keep individual cells impaled for more than half an hour without loss of membrane potential or cessation of normal cytoplasmic streaming. In general, however, cells were punctured in fairly rapid succession over a 30-minute period, and their membrane potentials were averaged to give the results discussed below. Usually the potentials were stable to within a few millivolts, but occasionally spontaneous depolarizing deflections occurred which were 10 to 50 mv in amplitude and 0.05 to 2 seconds in duration. The nature of these deflections is unknown and is being investigated.

The magnitudes of the stable potentials were found to depend mainly on two experimental parameters: the ionic composition of the surrounding fluid, and the distance of the cells from the margin of the colony. In an arbitrary reference medium (*4*) and at the optimal distance (8 mm) behind the growing hyphal tips, the average membrane potential for 88 cells was 127 mv (standard deviation, ±10 mv), inside negative relative to a reference electrode in the surrounding fluid. There was a gradual decline in average potential toward the center of the colony and, toward the

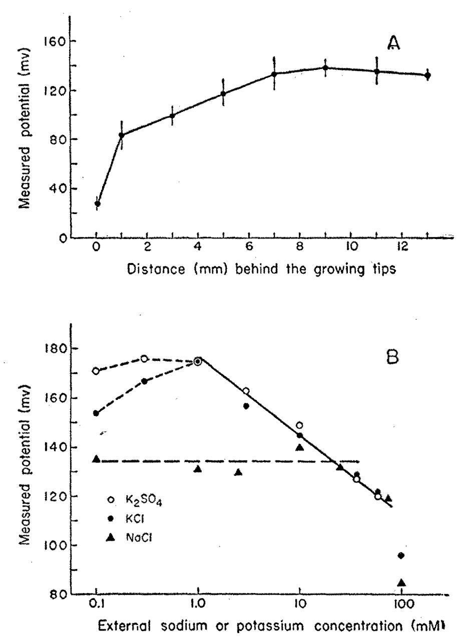

Fig. 1. *A*, Relationship between membrane potential and the location of cells in the colony. Points are averages for 5 to 15 cells measured in the reference medium (*4*). Vertical bars indicate ± S.D. *B*, Effect of sodium and potassium on the membrane potential. Filled circles or triangles indicate variation of potassium chloride (●) or sodium chloride (▲) in the reference medium. Open circles denote the concentrations of potassium added as sulfate to a medium containing 25.3 mM sodium, as sulfate, and 1 percent sucrose. A new population of cells was studied in each medium, and each point represents the average potential for 5 to 15 cells located 8 mm from the growing tips. Standard deviations (not shown) were approximately ± 10 mv. In both *A* and *B* potentials are uncorrected for pipette tip potentials. The cells were negative inside, relative to a reference electrode in the surrounding fluid.