The Temporal and Spatial Variation in Cosmic Rays*

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Introduction

Meteorites are the only samples of material presently available which permit the study of cosmic ray intensities hundreds of millions of years in the past and hundreds of millions of kilometers distant from the earth. Meteorites fall to the earth at an estimated rate of about one each day. Of these about three are recovered each year and they furnish the material for the type of investigations described in this paper.

During its existence as a relatively small body in space, a meteorite is exposed to high energy cosmic-ray particles which produce radioactive and stable products by nuclear spallation reactions with the elements of the meteorites. From the measurements of a stable product and a radioactive product it is possible to estimate the length of the exposure in time. It has been found that meteorites have been exposed in space to cosmic rays for tens to hundreds of millions of years. As a result, practically all the radioactive products are in secular equilibrium with the cosmic radiation, at the time of fall, and hence the activities are proportional to the average cosmic ray intensity during a time comparable to the half-life. If the cosmic ray flux has been constant in time, then the ratio of the activities of two radioactive nuclides will be the same as the production rates of the same nuclides measured by high energy protons. The latter can be measured by accelerator produced protons.

Time Variation of Cosmic Rays

To study the time variation in cosmic radiation, chlorine-36 (308,000 year half-life) and argon-39 (270 year half-life) were measured in five dated

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fall iron meteorites. These observations test for the possible temporal variation in cosmic radiation during the last million years. The results are listed in Table 1. The average value for the five meteorites listed is 0.98 ± 0.08 which is to be compared to a production ratio. Unfortunately no satisfactory directly measured Cl^{36} production cross section exists. It is, however, possible to estimate an Ar^{36}/Cl^{36} production cross section ratio from a combination of measured stable argon contents of meteorites and argon production cross sections. Because Cl^{36} decays to Ar^{36} the Ar^{36}/Ar^{38} ratio in iron meteorites is:

$$\left(\frac{Ar^{36}}{Ar^{38}}\right)_{meteorites} = \frac{\sigma_{Ar^{36}} + \sigma_{Cl^{36}}}{\sigma_{Ar^{38}}} = 0.63 \qquad (1)$$

where σ refers to the production cross section. Then from the ratios

$$\frac{\sigma_{Ar^{36}}}{\sigma_{Ar^{38}}} = 0.144 \; ; \quad \frac{\sigma_{Ar^{39}}}{\sigma_{Ar^{38}}} = 0.51 \qquad (2)$$

as measured in iron targets it is possible to obtain:

$$\frac{\sigma_{Cl^{36}}}{\sigma_{Ar^{39}}} = 0.96 \qquad (3)$$

which is to be compared to the average value found for this ratio of 0.98 ± 0.08 in iron meteorites.

As these two values agree well within experimental error, it is concluded that the average intensity of cosmic rays during the last million years was the same, within 10% of the average value during the last thousand years.

Spatial Variation of Cosmic Rays

As we have heard earlier in this conference, the intensity of the low energy cosmic radiation exhibits a time variation that follows the 11 year cycle of solar activity. An increase in solar activity produces a marked decrease in the intensity of cosmic radiation in the 0.2 to 3.0 GeV energy range. The solar

Table 1

Argon-39 and Chlorine-36 in Dated Fall Iron Meteorites

Meteorite	Date of fall	Ar^{39} (dpm/kg)	Cl^{36} (dpm/kg)	Ar^{39}/Cl^{36}
Aroos	1959	16.3 $\pm$ 0.9	15.8 $\pm$ 1.7	1.03 $\pm$ 0.1
Bogou	1962	22.9 $\pm$ 0.3	24.0 $\pm$ 0.7	0.95 $\pm$ 0.05
Norfork	1918	14.1 $\pm$ 1.0	14.7 $\pm$ 1.5	0.96 $\pm$ 0.1
Sikhote Alin	1947	5.5 $\pm$ 0.6	6.3 $\pm$ 0.6	0.87 $\pm$ 0.1
Treysa	1916	22.1 $\pm$ 1.5	20.3 $\pm$ 2.0	1.09 $\pm$ 0.1
			Average value	0.98 $\pm$ 0.08

effect is attributed to modulation of the galactic cosmic radiation by the magnetic fields associated with the outward streaming plasma from the sun, the so-called solar wind. In addition, the solar wind should produce a spatial variation in the cosmic-ray intensity within the solar system such that the intensity increases with distance from the sun. This spatial variation should be observable in the cosmic-ray-produced radioactive spallation products in meteorites, since these objects have highly eccentric orbits with apogees of 3 or 4 astronomical units and perigees within the earth's orbit. The amount of a radioactive product with a short decay period is a measure of the intensity of cosmic radiation exposure to which the meteorite was subjected just before striking the earth, wheras the amount of a radioactive product with a long decay period determines the average cosmic-ray intensity over the meteorite's orbit. Thus, the ratio between the amounts of a short-lived product and a long-lived product gives a measure of the cosmic-ray intensity at one astronomical unit relative to that at several astronomical units from the sun.

On the other hand, the sun periodically emits large numbers of high energy particles accompanying prominent solar flares. If a meteorite should encounter such an intense particle flux shortly before striking the earth, the activity of a short-lived product would be greatly increased relative to that of a long-lived product.

The two isotopes of argon, Ar^{37} (35-day half-life) and Ar^{39} (270-year half-life), are ideally suited for these studies. The activity ratio Ar^{37}/Ar^{39} in the meteorites is determined and compared with the relative production cross sections for these isotopes measured with high energy protons and alpha particles on meteoritic material.

For these observations it is ncessary to analyze the meteorite shortly after the time of fall, preferably within a week. Six meteorites have been studied at Brookhaven over the last three years. Four were stone meteorites: Hamlet (Illinois, October 1959), Bruderheim (Canada, March 1960), Harleton

(Texas, May 1961), and Ehole (Angola, August 1961). Two were iron: Aroos (USSR, November 1959) and Bogou (Upper Volta, August 1962). With this number of observations extending over a period of diminishing solar activity, some comparisons of Ar^{37}/Ar^{39} ratios can be made with solar activity. The observed Ar^{37}/Ar^{39} ratios in the meteorite must be compared to the relative cross section ratio for these same isotopes produced inside a meteorite by the spectrum of cosmic-ray protons (87%) and alpha particles (13%). An evaluation of the cross section ratio for the stone meteorites is complicated because Ar^{37} is also produced by secondary particles on Ca^{40}. As a result the Ar^{37}/Ar^{39} ratio will depend upon the cosmic-ray energy spectrum and the depth of the sample in the meteorite. Experiments were carried out simulating the natural exposure of the meteorite as closely as possible. In the case of the Harleton meteorite a comparison was made for the whole meteorite and the iron phase.

Figure 1 summarizes the results for the six meteorites studied. As can be seen, the two iron meteorites and the iron phase of Harleton show an Ar^{37}/Ar^{39} ratio 20 to 30% lower than the predicted cross section ratio in each case. This variation can be interpreted as evidence for a gradient in cosmic ray intensity between the earth and the apogee of the corresponding meteorites at the time the meteorite fell. On the other hand, part of this variation could be temporal rather than spatial. It has been pointed out earlier in this conference by Professor Simpson that the low energy cosmic ray particles, especially those below 1.5 GeV, were depressed 10-20% during the period 1958-1962. As the Ar^{37} reflects the present flux while the Ar^{39} reflects the average flux, any change in flux due to the 11 year solar cycle will be present in the Ar^{37}/Ar^{39} comparison made. Hence part of the variation is due to this temporal variable and part due to a spatial gradient.

The stone meteorites Bruderheim and Harleton show a similar Ar^{37}/Ar^{39} variation as do the iron meteorites. On the other hand the stone meteorites Hamlet and Ehole show an Ar^{37}/Ar^{39} ratio higher than the production ratio. This is probably caused by the intense solar flares which in these two cases preceded the meteorites' arrival on earth and in both cases add to the Ar^{37} activity.

In conclusion the Ar^{37}/Ar^{39} ratios as measured in meteorites when compared to production rates measured with Accelerator protons, suggest that there is a 10-20% gradient in cosmic ray intensity in space between the earth and a point some hundreds of million of kilometers further from the sun, and that intense solar flares produce measurable effects on meteorites.

Fig. 1. Argon-37 and Argon-39 in recently fallen meteorites.

CROSS SECTION RATIO	1.8 ± .2	1.09 ± .05	1.8 ± .1	1.12 ± .06	1.8 ± .1	1.5 ± .1	1.09 ± .05	Ar^{37}/Ar^{39}
METECRITE	2.0 ± .3	0.9 ± .2	1.33 ± .13	0.84 ± 0.11	1.02 ± 0.13	1.65 ± 0.29	0.93 ± .09