The Age of Meteorites

AND THEIR RADIOISOTOPE CHARACTERISTICS

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Meteorites are of particular interest to the person who is concerned with developing a satisfactory cosmology based on the specifications in the Bible. The isotopic characteristics of a meteorite may be interpreted to give the time of its fall to Earth, the variation of cosmic radiation intensity with respect to both time and position in the solar system, the duration of exposure to cosmic radiation, the length of time the meteorite has been in existence as a solid object, and a rough estimate of its thermal history. This information has significant implications for the creation of the primordial matter in the solar system.

SOURCE OF METEORITES

Meteorites were once regarded superstitiously as "stones from heaven." Classical Greeks supposed them to be objects that had fallen to Earth as a result of becoming loosened from their fastening on the celestial sphere. Approximately five hundred of these interesting objects fall on our planet in a typical year. About seventy percent of the falls are lost in the ocean. Of those meteorites that strike land, only about four out of one hundred fifty are recovered [1].

Data obtained from photographs of meteor trajectories establish that meteoroids, before striking Earth, orbit the sun in ellipses that usually range between Earth and Jupiter. The evidence strongly suggests that they originate from the asteroid belt between Mars and Jupiter. Some may be composed of material that was ejected from the moon when large craters were formed there [2].

COSMIC RAY EXPOSURE

Before entering Earth's atmosphere, meteoroids are subject to cosmic radiation. The high energy atomic nuclei that constitute the primary cosmic radiation break up some of the atoms in the outer portion of meteoroids. The formation of chlorine-36, tritium, nonradioactive isotopes of helium and hydrogen, and four free neutrons (by the impact of a cosmic ray proton with an iron-56 nucleus) is typical of these reactions:

$$H^1 + Fe^{56} \rightarrow Cl^{36} + H^3 + 2He^4 + He^3 + 3H^1 + 4n.$$

The neutrons released in this way react in turn with other atoms in the meteoroid to produce nuclear transmutations similar to those that take place in a nuclear reactor. The atoms formed as a result of cosmic radiation are classified by the term *cosmogenic nuclides.*

Thirteen cosmogenic nuclides ranging from H^3 to Co^{60} were identified in a fragment of Sputnik IV which had orbited 843 days. The United States Discoverer satellites, after a few days in orbit [3], have been found to contain detectable cosmogenic nuclides ranging from H^3 to Bi^{205}. Some cosmogenic nuclides are stable; others are radioactive. The half-lives of the principal radioactive cosmogenic nuclides found in meteorites are given in TABLE 1.

TABLE 1. Radioactive Cosmogenic Nuclides

NUCLIDE	HALF-LIFE	NUCLIDE	HALF-LIFE
V^{48}	16.1 days	H^3	12.5 years
Cr^{51}	27.8 days	Ar^{39}	269 years
Ar^{37}	35 days	Ti^{44}	~1000 years
Co^{58}	72 days	C^{14}	5730 years
Co^{56}	77 days	Ni^{59}	80 thousand years
Sc^{46}	85 days	Cl^{36}	400 thousand years
Co^{57}	270 days	Al^{26}	740 thousand years
Mn^{54}	313 days	Mn^{53}	2 million years
V^{49}	330 days	Be^{10}	2.7 million years
Na^{22}	2.58 years	K^{40}	1.31 billion years
Co^{60}	5.25 years		

TERRESTRIAL AGE

Radioactive cosmogenic nuclides permit a determination of the time since a meteorite fell. After the fall, it is shielded by Earth's atmosphere from further interaction with primary cosmic radiation, and there is a steady decrease in the radioactive levels that were built up as a result of cosmic radiation. Comparing the amount of radioactivity of a short half-lived cosmogenic nuclide with the radioactivity of a long half-lived nuclide in an old meteorite, and comparing this ratio with the corresponding ratio in a fresh meteorite, make possible an estimate of the length of time the old meteorite has been isolated from cosmic radiation. The period of time determined in this manner is known as the *terrestrial age.*

The nuclide pairs most commonly used for meteorite terrestrial age determinations are Ar^{39}/C^{14} and Ar^{39}/Cl^{36}. As can be seen from the data in TABLE 1, the ratio of Ar^{39} activity to Cl^{36} activity decreases by a factor of two for each 269 years since the date of fall. (The Ar^{39}/C^{14} *ratio* decreases about three percent less rapidly because the rate of C^{14} decay is greater than the rate of Cl^{36} decay.)

Terrestrial ages that have been determined for iron meteorites extend to about 3,000 years but are usually below 2,000 years. Only rough estimates of terrestrial age can be made for stony meteorites, because small quantities of appropriate activities are involved. Nearly all the determinations that have been made range between 3,000 and 5,000 years and are uncertain, with $\pm$ 2,000 years. A few stony meteorite terrestrial ages in excess of 20,000 years have been reported [4]. Stony meteorites may not be significantly different from iron meteorites with respect to terrestrial age.

The paucity of terrestrial ages greater than 3,000 to 5,000 years has been taken to indicate that reworking of our planet's surface has made earlier meteorite falls unavailable. It is unlikely that meteorite "finds" would include any cosmic objects that may have struck Earth before the Noachian Flood.

COSMIC RAY EXPOSURE AGE

The rate at which cosmogenic nuclides are produced in meteoroids can be estimated from measurements of the cosmic ray intensity in artificial satellites, from the number of cosmogenic nuclides that have developed during flight time in artificial satellites, and from the relative concentration of radioactive cosmogenic nuclides in meteorites at the time of fall. The last method, the most direct, has important cosmological considerations.

The rate at which a radioactive cosmogenic nuclide is formed in a meteoroid depends on the intensity and energy characteristics of the cosmic radiation to which it is exposed. The rate at which this nuclide disappears depends only on the half-life and the amount present. (If the amount is doubled, the number of atoms that disintegrate in a given time also doubles.) The concentration of each cosmogenic radioactive nuclide tends to a level at which the number of atoms disintegrating in a given time equals the number formed within the same time and period. When this condition is established, the nuclide is said to be in radioactive equilibrium. Equilibrium cannot be attained (and has no practical meaning) if the cosmic ray intensity does not remain essentially constant over several half-lives [5].

The time required to reach equilibrium for the nuclides listed in TABLE 1 ranges from 60 days to 5 billion years. In the meteorites that have been analyzed, these nuclides are found to be in approximate equilibrium consistent with one another to an extent indicating that the cosmic ray flux varies by less than a factor of two throughout the meteoroid orbit and that its long-term average has not changed more than fifty percent over the past several million years [6].

As I explained above, if a cosmogenic radioactive nuclide is in equilibrium, its rate of decay is equal to the rate at which it has been formed by cosmic radiation. On the other hand, the concentration of a nonradioactive cosmogenic nuclide is the total number of such atoms that have been formed during cosmic ray exposure. Comparison of a pair composed of a stable member and a radioactive member, each of which has the same formation probability (or a known formation probability ratio), makes possible the estimation of the length of time a meteorite has been exposed to cosmic radiation. The concentration of the radioactive member indicates the rate at which the pair has been produced. The concentration of the nonradioactive member indicates the total exposure. The exposure age, or length of time the process has been going on, is then readily determined, but subject to the assumption that the cosmic radiation has remained essentially invariant during this time.

Stable radioactive pairs that have been used for exposure age determination are He^3/H^3, Ar^{36}/Cl^{36}, Ar^{38}/Ar^{39}, and Ne^{21}/Cl^{36}. Since K^{41} and 1.31 billion years K^{40} are cosmogenic in meteoroids, the pair K^{41}/K^{40} has also been used, although there are uncertainties concerning the equilibrium of cosmogenic K^{40} and contamination with primordial K^{40}. Determinations based on the pairs Ar^{36}/Cl^{36}, Ar^{38}/Ar^{39}, and Ne^{21}/Cl^{36} agree on exposure age of 0.53 ± 0.01 billion years for the meteorite Aroos, whereas the He^3/H^3 pair has yielded 0.8 billion years [7]. Most cosmic ray exposure age determinations for stony meteorites are made with helium-3 (He^3) [8].

Exposure ages for stony meteorites cluster at 5, 7, 20, and 22 million years, whereas those for iron meteorites cluster at 270, 550, and 700 million years [9]. The difference between the exposure ages of these two groups of meteorites may be taken to indicate uncertainties in the interpretation of the data from which exposure ages are determined. It may also be taken to indicate marked differences in the cosmic or creative processes by which these two classes of meteorites have been formed.

The formation of cosmogenic nuclides is limited to a depth within approximately one meter, because of absorption of cosmic radiation by the meteoroid mass. The pre-atmospheric size and shape of a meteorite body can be determined from contours for equal concentration of a cosmogenic nuclide [10]. Since the formation of cosmogenic nuclides is a surface phenomenon for objects greater than a two-meter effective diameter, the range over which exposure ages are distributed has been taken to suggest that meteoroids are fragments of larger bodies that were broken up at various times during the history of the solar system. Accordingly, the cosmic ray exposure age is often referred to as the parent body break-up age.

SOLIDIFICATION AGE

Meteorites contain the same primordial radioactive elements that are found in Earth minerals and can be analyzed by the procedures that have been developed for determining radioisotope ages of terrestrial material. Considerations involved in the interpretation of these radioisotope ages have been treated elsewhere and need not be reviewed here [11]. If the necessary simplifying assumptions of decay rate constancy and chemical isolation during the time involved are satisfied, a daughter/mother radioisotope age for a meteorite will represent the time that has elapsed since the mother and daughter elements were chemically fractionated — i.e., the time the meteorite has been in its present solid state and the accumulating daughter products have been maintained at local sites in association with their parents. Both stony and iron meteorites give evidence of having been in a molten state at some time previous to their encounter with Earth. The radioisotope ages indicated by the daughter products, which appear to have accumulated in various mineral grains of these meteorites, are therefore described as solidification ages.

Crystallization out of a given molten mass may be expected to extend over a period of time that depends on the cooling rate. Accordingly, solidification ages for portions and mineral components derived from a unit of molten material may extend over a range of cooling time. If this range is less than the precision of solidification age determinations, it will not be discernible.

Rubidium-strontium solidification age determinations for stony meteorites may be determined within a precision of $\pm$ 0.2 billion years. The best values that have been obtained range between 4.46 and 4.70 billion years.

Rhenium-osmium ages for "stones" average 4.0 ± 0.8 billion years. The Pb^{207}/Pb^{206} technique yields ages ranging from 4.02 to 4.65 billion years. The Pb^{207}/Pb^{206} ages present an unsolved problem, because most stony meteorites do not contain enough uranium to account for their radiogenic lead. The average of Pb^{207}/Pb^{206} ages for those that do contain adequate supporting uranium is 4.6 billion years [12].

Pb^{207}/Pb^{206} age determinations on iron meteorites cluster around 4.60 billion years [13].

The weighted average of the Pb^{207}/Pb^{206} meteorite solidification age determinations that are considered to be most reliable is 4.550 ± 0.030 billion years [14]. This value is often referred to as "the age of meteorites."

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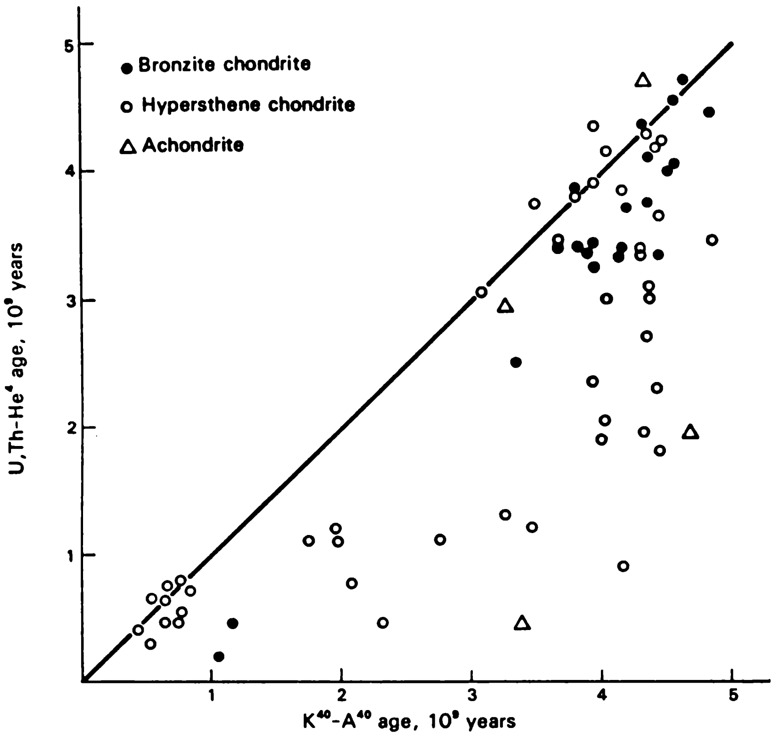
GAS RETENTION AGE

Radioisotope ages given by the ratio of radiogenic Ar^{40} to parent potassium or radiogenic He^4 to parents uranium and thorium could also indicate the time of solidification if the material were subsequently maintained at a temperature low enough to prevent diffusion loss of gas. Heating that is due to impact, close approach to the sun, or descent through Earth's atmosphere — and also slow cooling after solidification — may be expected to reduce K-Ar and U-Th-He ages below the corresponding Rb-Sr, Re-Os, U-Pb, Th-Pb, and Pb^{207}/Pb^{206} ages. Since helium diffuses more readily than argon, K-Ar ages should be reduced less than U-Th-He ages, unless there has been sufficient heating to produce complete degassing. Because of the foregoing considerations, meteorite age determinations based on Ar^{40} and He^4 are classified as gas retention ages.

Gas retention age determinations have been limited to stony meteorites and range between approximately 0.5 billion years and the 4.5 billion year "age of meteorites" (FIGURE 1). For about half the meteorites on which data are available, the U-Th-He age is less than the K-Ar age, and in no case is it significantly greater [15]. The gas retention ages plotted in FIGURE 1 provide opportunity for emphasizing that a basic radioisotope age is merely a convenient means of expressing the ratio of a daughter/mother pair of nuclides. Considerations independent of the daughter/mother ratio measurement are required to determine whether or not a correlation exists between radioisotope age and real time. FIGURE 1 shows that in some cases Ar^{40}/K^{40} ages correlate with He^4/U or He^4/Th ages. When such correlation exists, there is a firmer basis for suspecting that these radioisotope ages might provide some indication of the real time lapse since an event in the history of the mineral involved.

FIGURE 1. Gas-retention ages of 69 stony meteorites: a comparison of results obtained by the U,Th-He^4 and K^{40}-Ar^{40} method. (Courtesy John A. Wood, *Meteorites and the Origin of Planets,* p. 62, McGraw-Hill Book Company 1968.)



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EXTINCT RADIOACTIVITY

Iodine-bearing minerals in meteorites are found to contain xenon, which has an abnormally high ratio of Xe^{129}. The excess Xe^{129} appears to be the daughter product of extinct 16-million year half-life iodine-129 (I^{129}) [16].

A study of fission-product components of xenon in one meteorite has given evidence for fission products at least fifteen times greater than can be accounted for by the uranium content. The only likely source for these fission products is extinct 76-million year half-life plutonium-244 (Pu^{244}) [17]. Additional evidence for extinct Pu^{244} has been provided by the crystal structure damage produced by fission products in meteorites. The atoms produced by a fission reaction have sufficient kinetic energy and mass to dislocate the crystal structure over a considerable distance from their point of origin. With proper etching techniques, these dislocation paths become visible under a microscope and are described as fission tracks. Data have been reported on two meteorites that contain fossil fission-track densities much too high to be accounted for by the uranium present. Spontaneous fission products from Pu^{244} appear to be the only reasonable cause of these excess fission tracks [18].

A meteorite that contains fission tracks from now undetectable Pu^{244} has most likely been in existence at a temperature below approximately 800° C for a time at least in the order of ten Pu^{244} half-lives — 760 million years. Higher temperatures would destroy the tracks; a shorter time would leave a detectable amount of Pu^{244}. For similar reasons, the evidence for the prior existence of I^{129} implies a history of meteoroid bodies in solid form extending over more than 160 million years.

CONCLUSION

The foregoing meteorite observations must be satisfactorily accommodated by a successful cosmogony. Cosmogonies based on the testimony given by Moses have either included meteorites in a general creation of matter at the beginning of the Genesis Creation week, placed their origin on the fourth day of Earth's history along with the moon, sun, and other stars, or presumed them to have originated from a creative episode which took place at a remote time before the events of Creation week.

A cosmogony that limits the existence of the matter which makes up meteorites to a duration period of only several thousand years should offer plausible reasons for the creation of meteorites with the radioisotope features that characterize them. On the other hand, a cosmogony that allows the most obvious interpretations of meteorite radioisotope data should be supported by biblical evidence that the creative activity which took place during the Genesis Creation week was principally confined to planet Earth.

Since God is the author of both nature and revelation, we should expect to develop a cosmogony that accounts in a manner intellectually acceptable for the observations on meteorites as well as for the specifications of revelation.

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