CHAPTER TWELVE

Meteorite Ages

It is outside the scope of the present work to discuss the ages of meteorites and the associated implications. The theme is, however, of importance, and since the mass spectrometric techniques – which are the basis for most age determinations – have now reached high standards, it was felt that modern results on individual iron meteorites should be reported in the handbook section that follows. In order for the casual reader to comprehend the problematics better, there follows here a very brief survey of a few of the modern methods and their results. For general surveys and discussions the reader is referred to Kohman (1956), Patterson (1956), Houtermans et al. (1960), Signer & Nier (1962), Anders (1962; 1964; 1971c), Wänke (1966), Counsell (1967), Voshage (1968), Pasteels (1968), Wasserburg & Burnett (1969) and Olsson (1970). The following is largely based upon the discussions by Anders and by Voshage who have been constantly alert to the difficulties in age determinations and often have suggested new ways and interpretations.

Four important events in the history of meteorites can be dated by the mass spectrometric analysis of radioactive and stable nuclides, or, less frequently, by sophisticated low level counting techniques of radioactive nuclides*. They are (i) nucleosynthesis, (ii) solidification of the meteorite parent bodies, (iii) breakup of the parent bodies and (iv) fall of the meteorites. Nucleosynthesis may be dated by analyzing meteorites for the decay products of the extinct radioactive nuclides ^{129}I and ^{244}Pu; the solidification of the meteoritic material and formation of the minerals by determining long lived radioactive nuclides such as U, Th, ^{87}Rb, ^{40}K and their stable decay products; and breakup and fall by investigating cosmic ray produced nuclides, such as radioactive ^{36}Cl, ^{39}Ar or ^{40}K, and stable nuclides as well, e.g., of the light rare gases He, Ne, Ar, or of K.

Nucleosynthesis

A generation ago it was realized that radionuclides, with half-lives of 100 million years or less, might have been present in the early solar system if nucleosynthesis had taken place shortly before (Brown 1947). Interest centered around stony meteorites and silicate inclusions in iron meteorites. When ^{129}Xenon was found in extremely small concentrations of the order of 10^{-10} cm^3 STP/g or less it was interpreted as partly formed by β-decay from ^{129}I (half-life 17 million years, now extinct), partly from spontaneously fissioning ^{244}Pu (half-life 82 million years, now practically extinct) (Reynolds 1968; 1973). Methods to reveal the fission tracks from decaying nuclei have been described by Fleischer et al. (1967), Wasserburg et al. (1969a) and others. The tracks are best developed by etching silicate minerals with appropriate agents.

These and other observations, for example on the isotopic ratios of U, Pb and Os, indicate that the last nucleosynthetic event which contributed matter to the solar system and in which heavy and transuranium elements were also involved, occurred no more than a few hundred million years before the formation of the meteoritic minerals. It is now estimated, somewhat dependent on the underlying assumptions, that the major nucleosynthesis started about 8,500 million years ago, while perhaps the last 10% of the nuclides were formed only 150-200 million years before a significant part of the meteoritic matter had cooled down to temperatures at which diffusion losses of volatile ^{129}Xe were no longer possible.

It is generally supposed that the solar nebula formed by the gravitational collapse of an extended interstellar gas mass. As it contracted, its chance of absorbing additional matter (e.g., from supernovae) decreased as its diameter decreased, and finally the addition of freshly synthesized nuclides stopped to be of any significance. The system was finite from then on, and radioactive decay and chemical fractionation became the dominant processes. Early condensation removed the refractory elements, such as calcium, aluminum, titanium and uranium, and the platinum metals. Later it appears that nickel-iron was separated to varying extent from the remaining material, perhaps caused by its ferromagnetic properties. After final accretion that led to bodies of different compositions at different distances from the Sun, melting affected some but not all of the parent material. There is thus no evidence for melting in the carbonaceous chondrites Cl; yet, it appears that about 90% of the planetary matter – thus also Earth and Moon – was affected by melting and additional fractionation. Basaltic achondrites (i.e., howardites and eucrites) and most iron meteorites probably went through a stage of melting. (Grossman 1972; Grossman & Larimer 1974).

Several energy sources may have contributed to this heating of the proto-meteoritic material: gravitational

*Radioactivity from U- and Th-decay in iron meteorites is on a very low level and only rarely investigated. See, e.g., the autoradiographic study by Deutsch et al. (1956).

energy released by the accretion to planetary bodies, intense radiation from the early, and probably very active, Sun and, in particular, radioactivity which certainly was far more intense 4,500 million years ago than today. It has been suggested that, in addition, a substantial amount of energy was released by the radioactive decay of some now extinct nuclides, such as ^{26}Al with a half-life of 0.74 million years. This is, however, seriously doubted by Schramm et al. (1970). At present, a major and unsolved problem of meteorite research is that of determining in which proportions these different heat sources were active in performing the early chemical fractionation.

Solidification Ages

The final cooling, solidification and formation of the meteoritic minerals are the events that can be dated by the methods of physical geochronology. It is, however, more difficult to analyze meteoritic than terrestrial material because of the generally low content of radioactive elements and decay products in meteorites. Fortunately, it is usually possible to measure the age of a meteorite (or a rock) in more than one way by making use of more than one parent-daughter system. If the result of such independent analyses agree within experimental error, they are called concordant and give confidence that the calculated ages have real meaning in terms of actual time.

Age determinations of terrestrial, meteoritic and lunar materials have been made by analyzing the long-lived radionuclides ^{238}U, ^{235}U, ^{187}Re, ^{87}Rb and ^{40}K (Table 35). Extensive studies of terrestrial rocks have produced many concordant ages of up to about 2.8×10^9 years and also a few as old as 3.7×10^9 years (Baadsgaard 1973). Most stone and iron meteorites have proved to be significantly older, about 4.6×10^9 years, and similar high ages have now also been determined for the most ancient minerals and rocks of the Moon. See, e.g., Wetherill 1971.

Since rubidium-strontium determinations have proved very useful in the dating of meteorites, this method will be promptly introduced.

The nature of the Rb/Sr fractionation process is not quite certain, but the fractionation appears to have required high temperatures, near the melting point of the silicates. At these high temperatures diffusion of Rb and Sr across the grain boundaries of the various mineral components was still possible, but upon cooling diffusion gradually ceased. The Rb/Sr metod may be taken to date this somewhat imprecise event when diffusion of Rb and Sr came to a stop. It has turned out that the method within analytical error yields ages which almost coincide with ages that refer to the solidification of molten regions in the meteorite parent bodies.

At this time, the various elements and their isotopes by definition occurred with initial concentrations ($t = 0$). These, and the initial ratios, may be estimated in several ways. If the system remained closed ever afterwards – i.e., the minerals were not exposed to exchange or replacement (no remelting, recrystallization or weathering), – and if the minerals did not contain any radioactive elements, the initial ratios would remain unchanged. Various analyses thus indicate that the initial $^{87}Sr/^{86}Sr$ ratio was 0.700 ± 0.001 in both terrestrial, lunar and meteoritic samples.

Now, if ^{87}Sr or ^{86}Sr were added continuously by some radioactive process, the ratio would shift in time and we would have a radioactive clock. It turns out that only one known process adds to the original strontium reservoir: Rubidium-87 is radioactive and decays under emission of a beta particle (an electron) from the nucleus, whereby the next higher element strontium-87 is formed:

$$^{87}Rb \xrightarrow[47 \times 10^9 \text{ years}]{\beta^-} {}^{87}Sr$$

Rubidium only occurs in very low concentrations. It has two isotopes, of which the stable ^{85}Rb is about three times as abundant as ^{87}Rb. Geochemically, rubidium follows potassium and must be sought in potassium-bearing minerals, such as potash feldspar, where it occurs substitutionally, because its singly charged cation Rb^+ (1.45 Å) is of

Table 35. Important Radionuclides Used for the Determination of Mineral Ages or Solidification Ages (From Voshage 1968)

Radioactive parent	Abundance in naturally occurring element (%)	Half-life years	Modes of decay	Stable daughter nuclides
^{238}U	99.274	4.51×10^9	Uranium-Radium series	$^{206}Pb+8\,^4He$
^{235}U	0.720	0.71×10^9	Uranium-Actinium series	$^{207}Pb+7\,^4He$
^{232}Th	100	13.9×10^9	Thorium-series	$^{208}Pb+6\,^4He$
^{187}Re	62.93	43×10^9	β^-	^{187}Os
^{87}Rb	27.85	47×10^9	β^-	^{87}Sr
^{40}K	0.0119	1.3×10^9	89% β^-	^{40}Ca
			11% K-electron capture	^{40}Ar

a similar size as K^+ (1.33 Å). Rubidium is, however, less than 10^{-2} as abundant as potassium, and in meteorites usually occurs below the 1-10 ppm level. Since ^{87}Rb further has the very high half-life of 47×10^9 years, the radiogenic contribution of ^{87}Sr atoms from ^{87}Rb decay has been low, and the isotopic composition of common strontium has not changed much in geologic time.

Initial strontium for the H6 chondrite Guareña has been carefully determined to be 0.69995±0.00015 by Wasserburg et al. (1969b). In achondrites, e.g., the eucrite Nuevo Laredo, with very low Rb concentrations, the $^{87}Sr/^{86}Sr$ ratio is still very close to the initial ratio. In the oceans of the Earth, a well-mixed sample, the ratio has increased slightly, to 0.708. In different chondrites the ratio ranges from 0.71 to about 0.80. On the other hand, different minerals extracted from the same meteorite (stone or iron meteorite) may show a range of, e.g., 0.730-0.768 (Weekeroo Station).

The ratio of $^{87}Sr/^{86}Sr$ can be plotted as a function of $^{87}Rb/^{86}Sr$ in an *isochrone* diagram (Figure 229A.) This diagram turns out to be one of the most useful concepts in geochronology; see, e.g., Sanz & Wasserburg (1969). It is based on the fundamental equation:

$$(^{87}Sr)_t = (^{87}Sr)_0 + (^{87}Sr)_R = (^{87}Sr)_0 + (^{87}Rb)_t \cdot (e^{\lambda t} - 1)$$

i.e., the total number of ^{87}Sr atoms after the lapse of time t equals the initial amount plus the radiogenic contribution. The equation is usually rearranged to:

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_t = \left(\frac{^{87}Rb}{^{86}Sr}\right)_t \cdot (e^{\lambda t} - 1) + \left(\frac{^{87}Sr}{^{86}Sr}\right)_0$$

in which the initial ratio $\left(\frac{^{87}Sr}{^{86}Sr}\right)_0$ and the age t are unknown, while the other members can be measured. $(^{86}Sr)_t$ is equal to $(^{86}Sr)_0$ since we assume a closed system. The decay constant λ and the half-life are tied together by the equation Half-life $= \frac{\ln 2}{\lambda}$.

At time $t = 0$, all components of the meteorite, regardless of rubidium content will have the same initial $\left(\frac{^{87}Sr}{^{86}Sr}\right)_0$ ratio and will plot on a horizontal line (Figure 229A).

After the lapse of time t, proportional amounts of ^{87}Rb, will have decayed to ^{87}Sr, and the points will now plot on a line forming an angle a with the horizontal, where $\tan a = e^{\lambda t} - 1$. In that way, one can calculate the age t from the slope of the line. Given two Rb/Sr systems, assumed to be of common origin but with different initial Rb/Sr ratios – i.e., two different silicate minerals from the same meteorite, – we can calculate not only their age but also the composition of the original strontium in them from the intercept on the ordinate axis. Many stone meteorites and a few iron meteorites (i.e., their silicate inclusions) have by now been measured, and it turns out that the majority fall upon the same straight line and thus are cogenetic, displaying ages of $(4.55 \pm 0.10) \times 10^9$ years. Kodaikanal is an important exception, page 728.

Theoretical estimates of the lifetime of the Sun on the main sequence give results that are compatible with these determinations but are more uncertain (Unsöld 1967).

Estimates of the solidification age by other pairs of radioactive parent and radiogenic daughter elements (Table 35) yield similar – but less accurate – results. A major anomaly has persisted within the $^{40}K/^{40}Ar$ dating until recently. Ages of certain iron meteorites ranged from 5 to 13×10^9 years (Stoenner & Zähringer 1958; Zähringer 1964). These ages were discordant with Rb-Sr and Re-Os ages for the same meteorites. It now occurs plausible that the $^{40}K/^{40}Ar$ ages were too high as a result of preferential loss of initial potassium from the meteorites during their terrestrial exposure to ground water (Bogard et al. 1968; Rancitelli & Fisher 1968; Kaiser & Zähringer 1968).

A note may be added on the uranium-helium method, which was the earliest method applied for determination of the ages of meteorites (Paneth 1928). The helium content of a number of iron meteorites was determined, and, on the assumption that this helium was produced by the radioactive disintegration of uranium and thorium and had not leaked away in geologic time, ages ranging from one million years to 7,000 million years were obtained. Since the later figure greatly exceeded the age of the solar system as conceived at that time, the interpretation of these results was the subject of much controversy. Unfortunately, all the early results were in error for two reasons. Nearly all the helium in iron meteorites is produced by the spallation discussed below and not by U- and Th-decay (Bauer 1947), and the true uranium content of iron meteorites, as measured by neutron-activation analysis, is far lower (< 0.3 ppb) than the apparent contents measured by wet

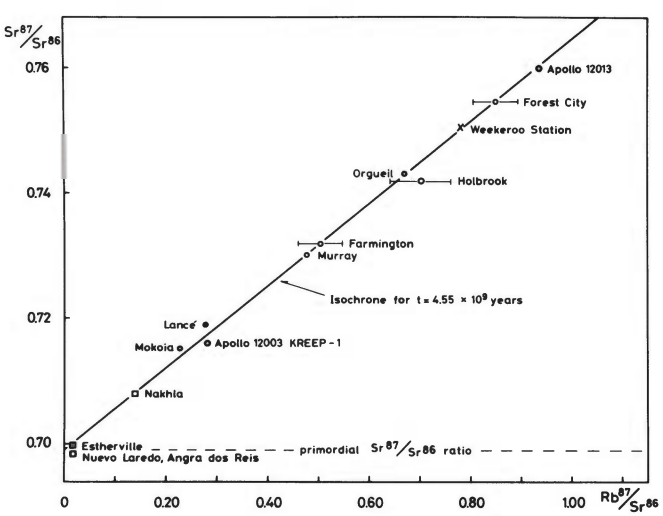

Figure 229A. Isochrone diagram for strontium-rubidium ages. Data for stone meteorites and for lunar rocks from the Apollo 12 mission. Also a few data (X) for silicate inclusions from iron meteorites. From Wasserburg & Burnett (1969) and NASA reports.

chemical analysis (< 100 ppb) (Dalton et al. 1953; Reed & Turkevich 1957). It appears that the U-He method is not very promising for the determination of solidification ages of iron meteorites.

Cosmic Ray Exposure Ages

While residing inside their parent bodies, the meteorites were effectively shielded from bombardment by the various particles that penetrate our solar system. Even the most energetic galactic cosmic rays (10^9 - 10^{10} electron volts per nucleon) will be stopped by some meters of silicates (mean free path for absorption about 150 g/cm^2); solar flare particles (10^7 - 10^8 electron volts) will be absorbed by some centimeters of material; and the least energetic solar wind particles (1000 electron volts per nucleon) will be absorbed by 1 μ of material.

However, when the parent bodies disintegrate by violent collisions, the meter-sized or smaller fragments become exposed to intense radiation and a whole array of new and usually radioactive atoms start being produced by a process called spallation – a generic term for nuclear reactions at energies above about 10 MeV. Spallation products cannot be heavier than the original nucleus and, therefore, in iron meteorites, the detectable products are practically limited to nuclides lower in mass than iron and nickel and, in stone meteorites, to nuclides lower in mass than silicon and sulfur.

By the application of very sensitive mass spectrometric methods it is possible to measure a significant number of the spallation-produced nuclides. Most important are the noble gases helium and neon and, in iron meteorites, also argon. The He-concentrations in irons are usually less than 50 $\times$ 10^{-6} STP cm^3/g, the Ne-concentrations less than 0.5 $\times$ 10^{-6} STP cm^3/g meteorite (Hintenberger & Wänke 1964). Other nuclides, such as potassium, which occur in concentrations of less than 5 $\times$ 10^{-9} g/g, can also be measured by mass spectrometric methods (Voshage 1967). Spallation-produced radioactive nuclides with half-lives between a few days and several million years are usually measured by radiochemical and low-level counting methods. See Table 36.

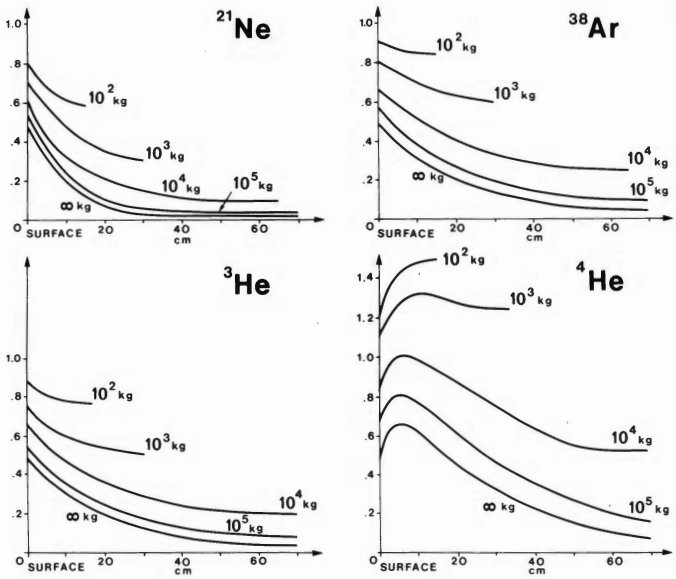

Figure 229B. Radial variation of ^{21}Ne, ^{38}Ar, ^{3}He and ^{4}He for spherical iron meteoroids of different mass as predicted from theoretical estimates. In each case the ordinate scale is chosen so that for an infinitesimally small meteoroid the amount would be unity (From Signer & Nier 1960).

Characteristic for the spallation-produced elements are their abundance ratios which are quite different from what is measured on terrestrial samples. The neon in iron meteorites thus occurs in the ratios ^{20}Ne : ^{21}Ne : ^{22}Ne ~ 1 : 1 : 1, while the corresponding ratios for atmospheric air is 90.9 : 0.26 : 8.8. Likewise, the ^{3}He/^{4}He ratio of iron meteorites ranges from 0.32 (near-surface, hard radiation) to 0.23 (interior, soft radiation), while the atmo-

Table 36. Some of the Methods Which Have Been Used to Measure the Cosmic Ray Exposure Age of Iron Meteorites

Method	Radio-active nuclide	Half-life years	Radiation on decay	Estimated production rate[1]	Measured activities[2] dpm/kg	Stable reference nuclides	Suitable for	Literature examples
^{3}He/^{3}H	^{3}H	12.3	β^-	12		^{3}He	Stones	Geiss et al. 1960
^{36}Ar/^{10}Be	^{10}Be	2.5$\times$10^6	β^-	0.31	4.1	^{36}Ar,He,Ne	Irons	Chang & Wänke 1969
^{10}Be/^{14}C	^{14}C	5,700	β^-	0.13	1.8		Irons	Kohman & Goel 1963
^{22}Ne/^{22}Na	^{22}Na	2.6	β^+, γ	0.11	2.1	^{22}Ne	Stones	Vilcsek & Wänke 1960
^{21}Ne/^{26}Al	^{26}Al	0.74$\times$10^6	β^+ (84%), γ	0.10	3.6	^{21}Ne	Irons	Lipschutz et al. 1965
^{36}Ar/^{36}Cl	^{36}Cl	0.31$\times$10^6	β^-	1	16	^{36}Ar	Irons	Vilcsek & Wänke 1961; Goel & Kohman 1963; Schaeffer & Heymann 1965
^{38}Ar/^{39}Ar	^{39}Ar	270-325	β^-	0.9	16	^{38}Ar	Irons	Begemann & Vilcsek 1969
^{41}K/^{40}K	^{40}K	1.3$\times$10^9	β^-, K-electron capture			^{39}K, ^{41}K	Irons	Voshage 1967
^{21}Ne/^{44}Ti	^{44}Ti	~ 200	β^+ (94%), active daughter	0.38	4.4	^{21}Ne	Irons	Lipschutz et al. 1965
^{53}Mn	^{53}Mn	~ 2$\times$10^6	X-ray	33	515		Irons	Herpers et al. 1969

1) The production-rate is estimated relative to ^{36}Cl. It is calculated for an iron alloy with 6.5% Ni at a depth of 100 g/cm^2 and a radius of 200 g/cm^2 (Honda & Arnold 1964).
2) The activities were measured on the fall Yardymly (24 November 1959); dpm/kg, disintegrations per minute per kg. The measurements were usually precise to ±10% (Honda & Arnold 1964).

sphere shows a ratio of 1.3×10^{-6}. The helium ratios in iron meteorites is dependent on the energy of the cosmic particles which produce the spallation nuclides. In small meteorites which are mainly exposed to the primary particles (hard radiation) the ratio is high. In the interior of larger meteorites, however, the primary particles are accompanied by low energy secondary particles which cause the $^3He/^4He$ ratio to shift to lower values. In other words, the measured ratios may serve as rough guides to the usually unknown depths of samples below the original exposed surfaces. See below and Table 37.

The radioactive spallation products are usually short-lived. If the cosmic ray flux is assumed constant, they will soon reach secular equilibrium; and their stable decay products begin to accumulate at constant rates. The assumption of constant cosmic ray flux appears valid for the last many million years – and possibly also way back in geologic time. The problem, however, is complicated, as the meteorites in their orbital travel pass through a significant part of the solar system and thus integrate cosmic ray effects in both time and space. In addition, many meteorites may have broken up more than once, thus exposing new surfaces to cosmic rays.

The total amount of radiation received by a particlar meteorite sample can be calculated from the accumulated amount of a stable isotope. To perform the calculations it is necessary to make several assumptions, for example, about (i) the cosmic ray intensity and spectrum along the meteorite's orbit, (ii) the shielding effect which depends on the distance of the sample from the preatmospheric surface of the meteorite, (iii) the production cross section as a function of energy for all spallation processes leading to a particular cosmogenic nuclide and (iv) the initial content of the nuclide in question. It is important to note here that practically all helium, neon and argon in iron meteorites were produced by spallation. Only Washington County, with a surprising excess of noble gases, is apparently an exception (Hintenberger et al. 1967).

Table 37. The Concentration Ratios of the Spallogenic Noble Gas Nuclides Vary with the Depth Below the Irradiated Surface (Voshage 1968).

	Effective radiation hardness	
Ratio	very hard radiation (near-surface material)	very soft radiation (interior material)
$^3He/^4He$	0.315	0.235
He/Ne	105	190
$^4He/^{21}Ne$	230	460
$^{38}Ar/^{21}Ne$	4.05	6.4

In relatively small iron meteorites which are exposed to radiation from all sides (4π) the production rate of spallogenic ^{21}Ne is about 1×10^{-8} cm^3 STP per gram meteorite per 100 million years. A rough estimate of the cosmic ray exposure age may therefore be obtained by measuring the amount of ^{21}Ne. Near-surface samples from larger meteorites have only been irradiated from one side (2π) so the production rates are only about half of those from small meteorites. The interior of large meteorites, such as Cape York and Gibeon, have too little noble gas for detection. See Appendix 7.

Eberhardt et al. (1963) have pointed out that nuclides produced by neutron capture reactions should be sensitive indicators of depth in a meteorite. Thus a plot of a spallogenic nuclide, e.g., ^{26}Al, against a neutron capture product, e.g., ^{60}Co, is essentially a plot of the spallation production rate versus depth. The proposed method has been demonstrated to work on the recent falls, Allende and Murchison (Cressy 1972).

For iron meteorites, Signer & Nier (1960) have developed a useful method for determining both the age and distance below the surface from noble gas data alone. Their method is based upon the principle that the production cross sections of various nuclides in irons differ in their energy dependence. Some nuclides, such as ^{21}Ne, are made mainly by high energy primaries; others, such as ^4He, are also made in appreciable yield by low energy secondaries. Consequently, the $^4He/^{21}Ne$ ratio increases with distance below the preatmospheric surface and can serve as a depth indicator. See Table 37.

A particularly favorable case for the measurement of exposure age is that in which the stable element is the daughter of the radioactive one and relatively little of the stable nuclide is produced directly by cosmic rays. For elements below iron the only useful pair is ^{36}Cl and ^{36}Ar. It has been found that 80% of the ^{36}Ar results from the decay of ^{36}Cl, and 20% of the ^{36}Ar is produced directly by spallation reactions. Age determinations based on this pair range from 9 million years to 550 million years (Chang & Wänke 1969).

Another method of age determination, and perhaps the most accurate one, is based upon the ratios furnished by

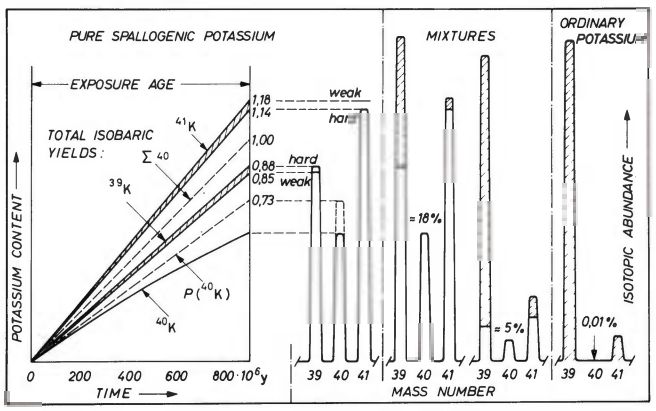

Figure 229C. The $^{41}K/^{40}K$ method for determination of the cosmic-ray exposure age of iron meteorites. The line marked Σ40 indicates the total production of spallogenic nuclides with mass number 40 (^{40}K, ^{40}Ar and ^{40}Ca), while P (^{40}K) indicates the production of ^{40}K alone. The curve marked ^{40}K indicates what remains of ^{40}K, after increasing amounts have undergone radioactive decay. To the right, four examples of the isotopic composition of meteoritic and ordinary potassium. (Courtesy H. Voshage)

the radioactive nuclide ^{40}K and the two stable nuclides ^{41}K and ^{39}K (Voshage 1962; 1967). The total amount of potassium in iron meteorites is extremely low, but a major part of it has been produced by cosmic ray spallation. The concentrations of the *stable* nuclides ^{39}K and ^{41}K increase linearly with time, but the concentration of the radioactive ^{40}K increases more slowly because some nuclei are lost by radioactive decay to ^{40}Ca and ^{40}Ar. The production rates of the nuclides ^{41}K:^{40}K:^{39}K are (1.18-1.14):1.00:(0.85-0.88), where the indicated variation is caused by the effective radiation hardness. See Figure 229C. For comparison, the isotopic ratios of terrestrial potassium are 93.08:0.01:6.91 at right in the figure, and it is, therefore, also possible to correct the measured mass spectrum for terrestrial – or preterrestrial – contamination with nonspallogenic potassium. Short cosmic ray exposure ages, below say 50 million years, are not easily measured by this method, since the typical ratios require considerable time for their development. Spallogenic potassium is only produced in very small amounts in stone meteorites because there are few target nuclei present with masses above potassium. Also, in stone meteorites the concentration of initial potassium is so high that it will swamp any additional cosmogenic spallogenic potassium entirely. Therefore, the $^{41}K/^{40}K$ method is excellently suited for iron meteorites and, moreover, very precise. Presently, the measuring apparatus for potassium and for noble gases is being improved so that in the future the method can be expected to yield still more, and more accurate, data (Voshage, personal communication). A selection of presently available cosmic ray $^{41}K/^{40}K$ ages is presented in the last column of Appendix 7. The range is from 90 to 2,275 million years.

Bauer (1947) suggested that, in iron meteorites, an apparent inverse ratio of helium content with mass could be interpreted on the assumption that most, if not all, helium was of cosmogenic origin – i.e., produced by spallation of iron atoms and not of radiogenic origin i.e., produced by radioactive decay of U and Th*. This has later been proved correct (e.g., Paneth 1954; Signer & Nier 1962; Bauer 1963). The concentration of the cosmogenic helium is proportional to the intensity of the cosmic radiation and to the length of time during which the meteorite was exposed. The $^{3}He/^{4}He$ ratio of the cosmogenic helium depends on the size of the meteorite and the position of the measured sample within the meteorite. The studies of Grant, e.g., indicated that it had a preatmospheric mass of about 2000 kg and, at a point halfway from the center to the meteoric surface, had a ^{4}He concentration of 19.8×10^{-6} STP cm^3 per g and a $^{3}He/^{4}He$ ratio of 0.27.

Particularly large spallogenic helium concentrations have been found in small meteorites with a high cosmic ray exposure age, e.g., Deep Springs, Clark County and Washington County. On the other hand, the very low, almost undetectable, helium levels of, e.g., Cape York, Gibeon and Campo del Cielo must be due to sampling the shielded interior of once very large meteorites. For a possible interpretation of the widely varying $^{3}He/^{4}He$ ratios (0.09-0.30) the reader is referred to the discussions by Schultz (1967) and Buchwald (1971d).

Attempts have been made to explain the differences which are indistinctly apparent among exposure ages of the various classes of meteorites. No doubt, stone meteorites display systematically smaller ages than the iron meteorites, ranging from <1 to perhaps 200 million years. Iron meteorites apparently range from 1 to more than 2,000 million years, and several clusters have been postulated. See, e.g., Voshage 1967; Jaeger & Lipschutz 1967b; Anders 1971b. See also the data arranged by class in Appendix 7.

Terrestrial Ages

From the many stable and radioactive nuclides produced by the cosmic ray bombardment discussed above, it is also possible to deduce the approximate age of a find, the so-called terrestrial age. Let us, for example, assume that we have already measured the cosmic ray exposure age from a pair of nuclides. We would then expect that other nuclides had been produced in compatible amounts which could be predicted from experimentally determined production rates, depth of shielding, etc. However, actual measurements show that, in a number of cases, the concentraton of short-lived radionuclides, such as ^{39}Ar, ^{14}C and ^{36}Cl, is significantly lower than calculated.

This fact may be understood when we remember that, after the fall of the meteorite, it is shielded from cosmic rays by the Earth's atmosphere, so that any radioactive species will from now on decay with its characteristic half-life: $N = N_0 \cdot e^{-\lambda t}$. In this equation there are two unknowns, the initial concentration N_0 and the time t; N can be measured and λ is the known half-life of the radionuclide. The N_0 will, due to shielding and cosmic ray age, vary from meteorite to meteorite. However, one can calculate it from the observed level of a second radionuclide of long half-life, e.g., ^{26}Al, and from calibration data on freshly fallen iron meteorites. Incidentally, the activities of a number of radionuclides at the time of fall are now so well known, that an activity measurement may be used to decide whether a newly reported meteorite is really an observed fall or, indeed, a meteorite at all.

Early measurements by Vilcsek & Wänke (1963) showed that the terrestrial age of many iron meteorites must be much higher than generally assumed. Only one meteorite, Keen Mountain, showed some ^{39}Ar activity (~ 2 disintegrations per minute per kg), indicating that its terrestrial age was of the order of one or two ^{39}Ar halflives. Twenty-five other meteorites had nondetectable activities, suggesting ages about five ^{39}Ar half-lives – i.e., above 1,500 years.

*Whereas the helium from uranium and thorium decay is all ^{4}He (See Table), the spallogenic (or cosmogenic) helium is a mixture of ^{3}He and ^{4}He in the ratio of about 1:3. An isotopic analysis of the helium in meteorites thus furnished the test to distinguish between the modes of origin.

Turning then to radionuclides with longer half-lives, the meteorite Carbo, e.g., still shows some ^{14}C activity – 0.7 dpm/kg (Kohman & Goel 1963) – and significant ^{36}Cl activity – 5-8 dpm/kg (Honda & Arnold 1964; Chang & Wänke 1969). These data have enabled various workers to estimate Carbo's terrestrial life to about 100,000 years. Still higher ages have been suggested for the iron meteorites Kenton County, Clark County, North Chile, Skookum Gulch and Muonionalusta. Two, Tamarugal and Ider, were found to contain almost no ^{36}Cl, results which have been interpreted to indicate ages greater than one million years.

However, the metallographical examination does not always support these estimates. For example, fusion crust and heat-affected α_2 zones may still be detected on Carbo, Clark County and North Chile which, together with the estimated ages, indicate the incredibly low corrosion rates of about 1 mm per 100,000 years. The question deserves some attention, and the reader is referred to the survey in Appendix I where preserved fusion crusts and α_2 zones are indicated in column 14. A correlation between the terrestrial age, the "average" climatic condition of the locality, the depth of burial and the preservation of α_2 zones and fusion crust would be expected to be found in a thorough systematic examination.

Even pure truth, which has no application whatsoever, elevates life. From a practical point of view it is quite irrelevant whether the earth turns around the sun or the sun turns around the earth. All the same, Galileo and Copernicus, by their discoveries, lifted human existence to a higher level. The same may one day be said for our moonshots. Science is life-oriented.

A. Szent-Györgyi, *The Crazy Ape*, 1970