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Radiation Ages and Gas-Retention Ages of Carbonaceous Chondrites and of Unequilibrated Ordinary Chondrites

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REVISED ABSTRACT

He, Ne, and Ar have been determined by mass-spectrometry in 25 carbonaceous chondrites, and in 12 unequilibrated ordinary chondrites. The occurrence of primordial inert gases, and the possibility of severe diffusion losses

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in certain carbonaceous chondrites leads to the following considerations: 1) U, Th-He ages cannot be estimated for the C1 and C2 - types carbonaceous chondrites; 2) only "minimum" ^3He -ages can be estimated for the C1 and C2-types carbonaceous chondrites; and 3) ^{38}Ar -ages cannot be estimated for any of the meteorites, except Karoonda.

The radiation ages of the carbonaceous chondrites and of the UOC are not grossly different from those of the ordinary chondrites. However, the following trends can be noted: 1) the ages of the C1 and C2 carbonaceous chondrites are on the average shorter than those of the ordinary chondrites; none of the former is greater than 15 Myr; 2) four, perhaps five C2 carbonaceous chondrites, Boriskino, Cold Bokkeveld, Haripura, Nawapali, and Nogoya come from a single collision 0.1-0.6 Myr ago, with the most likely date of 0.2 ± 0.1 Myr.

There is a rough correlation between the types of carbonaceous chondrites and K-Ar ages: C1 meteorites

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*give ages -1.5 Gyr; C2 meteorites of 0.6-4.6 Gyr; and (C3 + C4) meteorites of 2-4 Gyr.

The great majority of the UOC seem to have cooled to below 200-300°C some 2.5-4.5 Gyr ago. Among the L3 chondrites there is a rough anti-correlation between age and degree of recrystallization. This seems to imply that the more highly equilibrated chondrites come from greater depth inside the parent object than the UOC.

Radiation Ages and Gas-Retention Ages of Carbonaceous Chondrites and of Unequilibrated Ordinary Chondrites

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INTRODUCTION

The inert gases have been measured in recent years in several hundred ordinary chondrites, and useful information has been obtained pertaining to their origin from radiation and gas-retention ages estimated from such data.

It has been noted previously that the carbonaceous chondrites generally show lower K-Ar ages than the ordinary chondrites. Most authors have concluded that the carbonaceous chondrites nearly always suffered serious ^{40}Ar diffusion losses (cf. MASON [1]). It has also been noted that certain carbonaceous chondrites show unusually low radiation ages. In the case of Cold Bokkeveld, ANDERS [2] has confirmed by ^{26}Al measurements that the low age of ~0.2 Myr is not simulated by diffusion losses. So far, however, a systematic study of the inert gases of carbonaceous chondrites has been lacking. This seemed necessary to obtain firmer conclusions. In the present paper we present measurements of He, Ne, and Ar in three C1, fourteen C2, six C3, and one C4-type chondrite (we have adopted the classification by VAN SCHMUS and WOOD [3]). Our study, thus, comprises all but a few of the known carbonaceous chondrites.

The so-called unequilibrated ordinary chondrites (hereafter abbreviated as UOC) are chondrites with bulk compositions in the ranges of the H, L, and LL-group chondrites

(except for certain minor constituents such as carbon).

These meteorites are unusual in the following respects. UOC show large dispersions of olivine and orthopyroxene compositions; they have well-preserved chondrites and chondritic textures; they frequently contain igneous glass in chondrules; and they are systematically richer in carbon and the heavier primordial inert gases (WOOD [4]; MASON [5]; KEIL and FREDRIKSSON [6]; DODD and VAN SCHMUS [7]; DODD, VAN SCHMUS, and KOPPMAN [8]; HEYMANN and MAZOR [9]). Presently, some 24 UOC are known. We have determined the inert gases in 12 of these. With data available from the work of others (ESERHARDT, BUGSTER, GEISS, and MARTI [10]; HEYMANN [11]; HINTENBERGER, KÖNIG, SCHULTZ, and WÄNKE [12]; KIRSTEN, KRANKOWSKY, and ZÄHRINGER [13], VINOGRADOV and ZADOROZHNI [14], the number of UOC for which rare gas data are available is thus brought to seventeen. Hence, at least tentative conclusions should be possible.

EXPERIMENTAL PROCEDURES

Our procedures have been described elsewhere ([11]; HEYMANN and MAZOR [15]; these will not be repeated

in detail. The following are the salient features. Small samples (100 mg, occasionally about 50 mg) were melted for gas-extraction in a molybdenum crucible, which was placed in a water-cooled enclosure of Pyrex-glass. The melting lasted for 30 min. During this stage, H_2 released by the samples was pumped off through a hot Pd barrier. The remaining gas was purified on a hot Ti-getter. The early removal of H_2 yielded considerably lower background peaks on the masses 1, 2, and 3.

Ar (and the heavier elements Kr and Xe) were adsorbed on charcoal at liquid N_2 temperature while the isotopic compositions of He and Ne were determined with the mass-spectrometer. The absolute quantities of these gases were obtained by the method of peak-comparison, i.e. metered amounts of 3He , 4He and Ne ($\sim 70\% ^{20}Ne$) were added to the gas extracted from the samples, and the increase of the ion-current of the masses 3, 4, and 20 was recorded.

He and Ne were pumped off, and Ar admitted to the mass-spectrometer by warming the charcoal up to room temperature. After the isotopic composition was obtained, the absolute

amount of Ar was determined by peak-comparison with Ar-standards of atmospheric isotopic composition.

From the measured $^{36}\text{Ar}/^{38}\text{Ar}$ ratios, we concluded that the gas-purification was not satisfactory for mass-38 in the case of the C1 and C2 chondrites. The measured ratios of primordial Ar were systematically below those previously found by others (cf PEPIN and SIGNER [16]). Four carbonaceous chondrites were remeasured with a modified procedure, in which Ar was released at -80°C instead of at room temperature. This gave $^{36}\text{Ar}_p/^{38}\text{Ar}_p$ ratios in accord with the generally accepted value of about 5.3. Although many of the ^{38}Ar data could, thus, not be used, it is of little, if any concern for the present paper. Cosmogenic ^{38}Ar is masked in all the C1 and C2 chondrites by primordial ^{38}Ar anyway, hence it cannot be used for estimating radiation ages. No such difficulties were met for the C3 chondrites, or for the UOC.

The mass-discriminations were checked (we found about 2% per mass-unit for Ne; about 1% per mass-unit for Ar), and the appropriate corrections were made.

Each sample was remelted to monitor the completeness of the gas-extractions. In most cases, the extraction was virtually complete upon the first melting. The sample-melting system was outgassed after each run. Only traces of He, Ne, and Ar were obtained in the subsequent blank runs. These data were used for background corrections.

RESULTS

The data of individual runs are listed in Table I. Note the extremely low inert-gas content of Bells; there are serious doubts that our sample comes from a genuine meteorite. Note further that substantial amounts of primordial He, Ne, and Ar occur in many of the chondrites, and that there are often significant variations between two or more results of the same meteorite.

That the primordial gases vary in a carbonaceous chondrite was not unexpected. These variations seem to arise from structural characteristics similar to those of "gas-rich" ordinary chondrites such as Pantar. We have previously shown that Nogoya consists of "light" and "dark" portions, with the "dark" portion approximately an order of magnitude richer in primordial gas than the "light" portion

(HEYMANN and MAZOR [17]). From a simple visual inspection of Nogoya, we concluded that the two portions were not "cleanly" separated, i.e. that the "light" portions contain many "dark" inclusions. We surmised that other carbonaceous chondrites, especially of the C2-variety might contain similar structures, which have remained undetected because of the generally dark colour of the carbonaceous chondrites. In the present study, only small weights were available for sampling. Moreover, the two samples of Cold Bokkeveld came from two different sources; the four Mokoia samples came also from two different sources.

The variation of primordial Ar in the UOC is of a different nature [9]. Here the differences probably reflect portions with different degrees of recrystallization [18]. The two samples of Krymka, Bishunpur, and Chainpur come from different sources. Bremervörde is probably a "gas-rich" ordinary chondrite with sample 688 containing a somewhat greater proportion of "dark" material than sample 532 (DR. H. WÄNKE has informed us that his specimen of Bremervörde is a clear-cut "gas-rich" chondrite).

The duplicate runs show that the accuracy for cosmogenic

gases such as ^3He is fair-to-good (15-5%). However, there are large variations for Cold Bokkeveld (~25%) and Pollen (nearly a factor 2.5), which at present are unexplained. For Cold Bokkeveld with only $\sim 0.5 \times 10^{-8}$ cc STP/g of ^3He , inaccurate background corrections may be the cause, but this can certainly not be true for Pollen.

As customary, we will use the following symbols (no subscript always refers to the measured value of a given isotope) to distinguish the three components of the inert gases:

- c refers to the cosmogenic component
- p refers to the primordial component
- r refers to the radiogenic component

PRIMORDIAL GASES AND DIFFUSION LOSSES

The calculation of radiation and gas-retention ages is greatly encumbered by the primordial gases, and by the consideration that serious He diffusion losses may have occurred for the very finegrained C1 and C2 chondrites.

The average U and Th contents of ordinary chondrites of 0.01 ppm and 0.04 ppm show that these meteorites could have retained up to approximately 2×10^{-5} cc STP/g $^4\text{He}_r$ since 4-4.5 Gyr ago. Table II shows the currently known values of the two radioactive parents in a few carbonaceous chondrites; no data are available for the UOC, but it is a reasonable assumption that their U and Th contents are comparable to those of ordinary chondrites proper. It can be inferred from Table II that the maximum $^4\text{He}_r$ contents of carbonaceous chondrites cannot be grossly different from 2×10^{-5} cc STP/g.

With this criterion the meteorites of Table I fall into two categories: 1) those that do not contain detectable amounts of $^4\text{He}_p$, namely Bells, Cold Bokkeveld, Erakot, Haripura, Kaba, all the C3 and C4 chondrites except Vigarano, and all the UOC except Bremervörde (688); and 2) those that certainly contain $^4\text{He}_p$ (all the remaining meteorites). There are considerable doubts, however, that this simple division is tenable. Let us consider the evidence of Figure 1. It is seen that the C1 and C2 chondrites always contain detectable amounts of $^{20}\text{Ne}_p$, whereas only 1/3 of the remaining chondrites do (only 2 of the UOC, Bremervörde and Khohar

contain $^{20}\text{Ne}_p$). Even more remarkable is that the $^4\text{He}/^{20}\text{Ne}_p$ ratio of the C1 and C2 chondrites is always near 200-300, whereas the points of the remaining chondrites scatter, mainly above the curve. An especially telling piece of evidence is that what is considered a genuine $^4\text{He}_p/^{20}\text{Ne}_p$ ratio in a number of ordinary chondrites ("gas-rich") and enstatite chondrites is near the value 300 (cf [16]). Thus, it can be surmised that ^4He in the C1 and C2 chondrites is really $^4\text{He}_p + ^4\text{He}_c$.

The origin of ^4He in Bells, Cold Bokkeveld, Erakot, Haripura is, then, ambiguous. In the "gas-rich" chondrites of the C1 and C2 varieties, and in Vigarano, most of the ^4He is certainly $^4\text{He}_p$. Hence, we cannot estimate a U, Th-He age in any of these cases.

A similar dilemma arises for ^3He in the carbonaceous chondrites. Although the $^4\text{He}_p/{}^3\text{He}_p$ ratio in chondrites is known to be large ([16]; HINTENBERGER, VILCSEK, and WANCE [19]), ^3He cannot be neglected here, either because $^3\text{He}_p$ is large, or because ^3He is small. Moreover, there is evidence for diffusion losses of ^3He during or after the exposure era. ANDERS [20] has calculated ^{21}Ne production rates in carbonaceous chondrites. From his data one

expects $^3\text{He}_c / ^{21}\text{Ne}_c$ of ~ 10 in the C1, of ~ 7.5 in the C2, of ~ 6 in the C3 and C4 chondrites, and of ~ 5 in the UOC. These values are probably on the low side for the carbonaceous chondrites because of their small masses (cf [10]). Anyway, the $^3\text{He} / ^{21}\text{Ne}$ ratios of Alais, Al Rais (632), Cold Bokkeveld (673), Erakot, Kaba, Mighei, Sta. Cruz, and Grossnaja are at least twice as low as the expected values shown in Table III. The true $^3\text{He}_c / ^{21}\text{Ne}_c$ would be lower still if accurate corrections for the primordial components could be made. Such corrections are intractable, mainly because the corrections for $^3\text{He}_p$ from $^4\text{He}_p$ and corrections for diffusion losses are coupled in an unknown way, because the $^4\text{He}_p / ^3\text{He}_p$ ratio seems to depend markedly on the proportion of He lost [19], and because the ratios of Table III are only approximations.

It is useful, however, to calculate $^3\text{He}_c$ values by neglecting possible diffusion losses. In this sense, they are minimum values. For the C1 and C2 chondrites, and for Vigarano, we have considered ^4He to be wholly primordial; a $^4\text{He}_p / ^3\text{He}_p$ ratio of 2500 was adopted. No $^4\text{He}_p$ is considered to be present in the remaining meteorites. The results are shown in column 11 of Table 1.

The calculation of $^{21}\text{Ne}_p$ is less ambiguous. Cosmogenic neon is known to contain the stable isotopes in nearly equal proportions. Thus a good approximation for $^{20}\text{Ne}_p$ is $^{20}\text{Ne} - ^{21}\text{Ne}$, especially since the $^{20}\text{Ne}_p / ^{21}\text{Ne}_p$ ratio is about 340. The $^{20}\text{Ne}_p / ^{22}\text{Ne}_p$ ratio in chondrites is known to vary from $\sim 8 - 14$, with the larger values occurring in the so-called "gas-rich" meteorites. The $^{20}\text{Ne}_p / ^{21}\text{Ne}_p$ in chondrites varies also [17]. For chondrites with $^4\text{He} > 10^{-4}$ ccSTP/g, we have adopted a value of 354 (the value in the dark portion of Nogoya); for chondrites with $^4\text{He} < 10^{-4}$ ccSTP/g, we have used the atmospheric ratio of 338 (EBERHARDT, EUGSTER, and MARTI [21]). The results are tabulated in column 12 of Table I.

Only in Karoonda is $^{38}\text{Ar}_c$ greater than 50%. In the remaining chondrites the cosmogenic component is masked by $^{38}\text{Ar}_p$. Accordingly, no $^{38}\text{Ar}_c$ -ages are calculated.

RADIATION AGES

We adopt as our working theory that the meteorites are fragments ejected by impacts from moderately large parent objects; that the meteorites did not suffer

significant mass-losses after they departed from their parent objects; and that the average cosmic-ray intensity was constant in space and time during the last 100 Myr. Perhaps the second point is not quite realistic for the friable carbonaceous chondrites. A number of authors contend that space-erosion is pertinent for stony meteorites. They argue that the cosmic-ray intensity inside these objects has increased during their exposure because of the continuous erosion of the surface by impacts of dust, atoms, and ions. Space-erosion has probably played a minor role for the ordinary chondrites and achondrites, but may have been more important for the carbonaceous chondrites.

Most workers seem to agree that the ^3He production rate in all varieties of stony meteorites is near 2.0×10^{-8} cc STP/g per Myr. This value is based on ^3H measurements in a number of ordinary chondrites (GBISS, OESCHGER, and SIGNER [22], GOEBEL and SCHMIDLIN [23]). These measurements show that the production rate is probably accurate within $\pm 20\%$. We have adopted the value as shown in Table III. For the $^{21}\text{Ne}_c$ production rate in the UOC we have adopted COBB's [24]

average value for chondrites, 0.38×10^{-8} cc STP/g per Myr. With this value we have recalculated ANDERS' [20] $^{21}\text{Ne}_c$ production rates for carbonaceous chondrites. The results are shown in Table III. The errors of these production rates cannot easily be ascertained. EBERHARDT et al [10] have shown that $^{21}\text{Ne}_c$ production rates in chondrites vary more than the $^3\text{He}_c$ rates, but their ingenious correlations cannot be used for the carbonaceous chondrites. Judging from $^{28}\text{Al}_c$ measurements by ROWE, VAN DILLA, and ANDERSON [25], it is concluded that variations by $\pm 50\%$ are not uncommon among ordinary chondrites. If carbonaceous chondrites are generally as low in mass as their recovered weights seem to suggest (the largest Lanced weighs 52 kg, but 10-100 g is more typical), significant fluctuations of the $^{21}\text{Ne}_c$ production rates must be anticipated (cosmic-ray secondaries escape more easily from very small objects).

As mentioned in the preceding section, $^3\text{He}_c$ -ages were calculated for the C1 and the C2 chondrites, and for Vigarano with the assumption that all ^4He is, in fact, primordial. All the remaining $^3\text{He}_c$ -ages were

calculated in the usual way, i. e. $^4\text{He}_p$ is considered negligible. For Bells, Cold Bokkeveld, Erakot, Haripura, and Kaba $^3\text{He}_c$ -ages were also calculated on the basis that ^4He is wholly radiogenic and cosmogenic. In some meteorites the $^3\text{He}_p$ correction is greater than ^3He actually present. In such cases the $^3\text{He}_c$ age is listed as > 0 Myr. The radiation ages are listed in Table IV, and are shown in the distributions of Figure 2.

No distinct trends show up for the three C1 chondrites. As expected, the $^{21}\text{Ne}_c$ -ages are considerably greater than the $^3\text{He}_c$ -ages.

The $^{21}\text{Ne}_c$ ages of the C2 chondrites range from 0.1 Myr (Haripura) to about 14 Myr (Kaba and Mokoia). The most interesting group is the one comprised by Boroskino, Cold Bokkeveld, Haripura, Nawapali, and Nogoya with ages of 0.1-0.6 Myr (Bells perhaps belongs to this category also). No other carbonaceous chondrites are found in this age-interval; in fact, among the several hundreds of ordinary chondrites for which inert gas data are available, there are only four with ages near this interval, and only one of these, Morland, is in the interval. This is remarkable, and seems to imply that

the five carbonaceous chondrites come from a single, or very few collisions. That the ages do not agree with a single value can be due to a number of causes. First, the known masses differ vastly, from 0.03 Kg of Bells to 4 Kg of Cold Bokkeveld. Second, the short ages are rather sensitive to errors in background corrections. It is curious that the uncorrected $^3\text{He}_c$ -ages of Cold Bokkeveld and Haripura are near 0.2 Myr. The $^{21}\text{Ne}_c$ -age of Cold Bokkeveld on the basis of the data by Kirsten et al [13] is near this value. ANDERS [2] finds an $^{26}\text{Al}_c$ -age of 0.1-0.2 Myr for Cold Bokkeveld. He has informed us that Nogoya gives an ^{26}Al -age of about 0.3 Myr. Hence, it seems that at least Cold Bokkeveld, Haripura, Nawapali and Nogoya come from a single collision about 0.2 ± 0.1 Myr ago.

It is interesting in this respect that DUFRESNE and ANDERS [26] have discovered differences in mineralogy which seem to parallel the age-trend. The authors find that the insoluble minerals of Cold Bokkeveld and Haripura (ages ~ 0.2 Myr) consist among others of 13% olivine and 13% of a magnetic

spinel, whereas those of Mighei (age ~ 3 Myr) and Murray (age ~ 4.3 Myr) contain 50% olivine and only traces of spinel. It would be interesting to know whether all the C2 chondrites with ages < 1 Myr are of the Cold Bokkeveld-type, and those with ages > 1 Myr of one or more different types.

Like the ages of the overwhelming majority of the other stony meteorites, those of the C1 and C2 chondrites are several orders of magnitude smaller than the radiation ages of iron meteorites (0.2-2.0 Gyr). Most authors agree that this implies a different origin, with the stony meteorites coming from objects nearer to the orbit of the Earth. Grossly, the ages of the irons agree with collision lifetimes of debris from

Ring asteroids or Mars asteroids, whereas the ages of the stony meteorites are more nearly comparable to collision lifetimes of debris from the Moon, or from Apollo asteroids. That the known carbonaceous chondrites come to Earth directly from Mars, or from the distant asteroids can be ruled out on the basis of the present results. The objections against such an origin of the

ordinary chondrites, stated by ARNOLD [27], are equally, if not more pertinent for the C1 and C2 carbonaceous chondrites, whose ages are always less than 15 Myr (the ages of ordinary chondrites range up to about 60 Myr).

It seems thus certain that the C1 and C2 carbonaceous chondrites come either from the Moon, from an Apollo asteroid, or perhaps from a comet. A lunar origin of the stony meteorites was first suggested by UREY [29] on the basis of their short radiation ages. In one form or another his theory has been adopted by a number of workers, while others have argued against it; accepting, however, as they did that certain rare varieties of meteorites such as carbonaceous chondrites might well come from the Moon (cf [2]). The main objection against the lunar origin seems to be that it is somewhat difficult to imagine that an impact on the Moon could accelerate the friable carbonaceous chondrites to escape-velocities without reducing them to dust. Perhaps carbonaceous chondrites represent the freakish survivors of such collisions.

The ages of the C3 and C4 chondrites present no fresh clues. Among the seven cases, there are no ages < 1 Myr (if the $^{21}\text{Ne}_c$ -age of Grossnaja is counted only). With two ages near 50 Myr, these meteorites are more comparable to the ordinary chondrites in this respect.

No gross differences exist between the ages of the UOC and those of the ordinary chondrites proper (Figure 3). In fact, UOC-ages occur in or near all of the age-clusters, peaks, or intervals of the ordinary chondrites that have been proposed as having arisen from major impacts, such as at 4-6 and 20-25 Myr for the bronzite chondrites; or 7-13 and 16-31 Myr for the hypersthene chondrites. It has been suggested by various authors that the UOC come from nearer the surface of chondrite parent objects than ordinary chondrites proper. HEYMANN [11] has pointed out that the ordinary chondrites may have come to Earth in two steps. First, they were located on distant asteroids, perhaps one or a few Mars-asteroids, which were fragmented by collisions (substantial evidence points to a collision some 0.5 Gyr ago, involving a hypersthene object). Subsequently, a number of the asteroidal fragments of the original body, still of

considerable size were deflected by Mars into Earth-crossing orbits, such as those of the present Apollo-asteroids. Impacts on these fragments produced the meteorites that come to Earth. The fact that UOC are nearly always present among the major age-clusters of the ordinary chondrites seems to require that the collisions at those times involved the virtual destruction of an asteroid-fragment, with meteoritic debris produced from what were originally near-surface, as well as deeper locations of the original Mars-asteroid.

GAS RETENTION AGES

No U, Th-He ages were estimated for the C1 and C2 chondrites, for Vigarano and Bremervörde 688, because part, if not all ^4He is primordial. In the remaining cases, except for Karoonda, U contents were considered 0.011 ppm; Th contents 0.040 ppm (cf [11]). For Karoonda the U and Th data of Table II were used. ^4He was corrected for $^4\text{He}_c$ with $^4\text{He}_c / ^3\text{He}_c = 5.0$ [11].

K contents for the carbonaceous chondrites were taken from [1] except for Warrenton [29]. K contents for the UOC were taken from [8]. In the case of Prairie Dog Creek, for which no K measurement was available, a K

content of 800 ppm was assumed (the overwhelming majority of bronzite and hypersthene chondrites agree within $\pm 10\%$ of this value).

The following decay constants were employed:

$$\begin{aligned}\lambda(\text{U}^{238}) &= 1.54 \times 10^{-10} \text{ yr}^{-1}; \lambda(\text{U}^{235}) = 9.8 \times 10^{-10} \text{ yr}^{-1}; \\ \lambda(\text{Th}^{232}) &= 4.99 \times 10^{-11} \text{ yr}^{-1}; \lambda_K = 0.583 \times 10^{-10} \text{ yr}^{-1}, \\ \lambda_B &= 4.74 \times 10^{-10} \text{ yr}^{-1}\end{aligned}$$

Like the radiation ages, the gas-retention ages shown in Table IV are only rough approximations. For the UOC, which are compositionally comparable to ordinary chondrites proper, the error of the U, Th-He ages from the adopted average U and Th contents alone may be as high as $\pm 25\%$, judging from the known U and Th contents of the ordinary chondrites. The U, Th-He ages of the C3 chondrites may be even more in error, inasmuch as there is no assurance that their U and Th contents are comparable to those of ordinary chondrites. In fact, the U, Th-He ages of the C3 chondrites are highly anomalous in that these are systematically greater than the K-Ar ages. This is unusual because ^4He diffuses faster than ^{40}Ar in ordinary chondrites, and probably also in

the C3 chondrites. The systematic difference seems to imply that either the U and Th contents of C3 chondrites are substantially greater than 0.011 ppm and 0.04 ppm, or that, contrary to what we have concluded, significant proportions of ^4He in these meteorites are $^4\text{He}_p$. Although reliable K measurements are available for most of the chondrites, it must be cautioned that these were always obtained with different samples than the ^{40}Ar data. For the sake of consistency we have employed K data for the carbonaceous chondrites from the work of one analyst, H. B. WILK, whenever possible. His results are always in good agreement with those obtained by others, which seems to imply that K does not vary by much (± 10 -15% perhaps) in any given carbonaceous chondrite. Among the K analyses of the UOC, five of which are from the work of WILK, only Manyah with 1830 ppm is highly unusual. The remaining values are not inconsistent with the chondritic average of about 800 ppm, which seems to imply that the K data are probably accurate within $\pm 20\%$ for our samples. Some caution must, however, be maintained, especially for the LL3 meteorites which are compositionally similar to the amphoteric chondrites. KAISER and ZÄHRINGER

[30] have found vast K variations in the latter.

A survey of the ages (Figures 3 and 4) reveals that there is a rough correlation between the types of carbonaceous chondrites and K-Ar ages: C1 meteorites give ages of 1-1.5 Gyr, C2 meteorites of 0.6-4.6 Gyr, and (C3 + C4) of 2-4 Gyr. However, the difference between C2 and (C3 + C4) is certainly not very pronounced, both varieties contain a substantial fraction of meteorites with ages only slightly lower than the accepted age of the solar system. The most consistent theory is that the carbonaceous chondrites were only slightly heated 4.5 Gyr ago, if at all, and that the extremely fine-grained nature of the matrix material, which evidently contains the potassium [1] makes the carbonaceous chondrites especially liable to lose $^{40}\text{Ar}_x$ by diffusion. This in turn is consistent with the general evidence for substantial He losses from these meteorites.

We have already mentioned the puzzle that the U, Th-He ages of the (C3 + C4) chondrites are always greater than the K-Ar ages.

The great majority of the UOC seem to have cooled to below about 200-300°C, the temperature interval in which $^{40}\text{Ar}_x$ retention changes from virtually complete

loss to virtually complete retention [20], between 4.5 and 2.5 Gyr ago. It is interesting in this respect that the concordant U, Th-He ages (agreement with K-Ar ages within about $\pm 20\%$) speak for the same general conclusion. Notable exceptions are Barratta, Carraraena, and Mezö-Madaras, all three of the L3-variety. (Clovis, from the work of HINTENBERGER et al [12] has a very low U, Th-He age of <0.1 Gyr; obviously this meteorite has suffered severe He-losses during the cosmic-ray exposure era. The K-Ar age of Tieschitz, given as 2.86 Gyr by [10] was recalculated with the K-content now available [8]. It has been noted before [11] that Barratta and Carraraena seem to have been definitely involved in a collision of a hypersthene parent object some 500 Myr ago. HEYMANN's [11] study of the hypersthene chondrites has further shown that the 500 Myr collision, while being the most prominent feature in the U, Th-He age distribution below 2 Gyr, is certainly not the only catastrophic collision for which there is evidence in this time-interval, a few earlier as well as a few more recent collisions are indicated by the data, but the ages of these are uncertain.

Mezo-Madaras, and perhaps Khochar and Farnallee, with concordant ages of about 1.5, 2.6, and 3.0 Gyr may have been involved in earlier collisions.

The UOC open an interesting possibility for studying the 3-4 Gyr time-interval. It has been argued by various workers that degree of metamorphism is related to the depth at which these chondrites found themselves beneath the surface of the meteorite parent body, i.e. that the least recrystallized and equilibrated ones were nearer to the surface, and vice versa. One would expect that those nearer the surface cooled faster, hence show the greater U, Th-He and K-Ar ages. A test for this hypothesis is shown in Figure 5. The U, Th-He ages (which are more sensitive indicators of storage at higher temperatures than the K-Ar ages) are plotted along the vertical axis. Along the horizontal axis is plotted the quantity "percent mean deviation of olivine" taken from [8]. This quantity is proportional to the degree of unequilibration of the chondrites. There is no trend discernible among the H3 chondrites (Clovis must be discounted). However, there is a distinct trend among the L3 chondrites with decreasing U, Th-He ages for increasing degree of equilibration. With only two points,

no firm conclusions are possible for the LL3 chondrites, however, it is noteworthy that the more equilibrated chondrite Farnallee also has the lower U, Th-He age. Roughly, then, one can conclude that the gas-retention ages are not inconsistent with the hypothesis that the more highly equilibrated ordinary chondrites come, on the average, from greater depths in the parent objects than the more unequilibrated ordinary chondrites. This conclusion has interesting implications for the origin of all these meteorites.

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Table I. Inert Gas Contents of Carbonaceous Chondrites and Unequilibrated Ordinary Chondrites.
Units 10^{-8} ccSTP/g.

		Run No.	³ He	⁴ He	²⁰ Ne	²¹ Ne	²² Ne	³⁶ Ar	³⁸ Ar	⁴⁰ Ar	³ He _c	²¹ Ne _c
Carbonaceous Chondrites												
C1	Alais	639	4.6	4,370	14.3	1.5	3.3	50	9.6	386	2.9 ^b	1.46 ^e
	Ivuna	645	5.5	9,430	34.6	0.50	4.0	82	17.2	337	1.7 ^b	0.39 ^e
	Orgueil	644	6.1	10,800	31.2	0.80	4.3	77	15.9	518	1.8 ^b	0.71 ^f
C2	Al Rais	632	11.3	3,180	18.2	3.3	5.6	38	8.0	1,420	9.8 ^b	3.25 ^e
	Bells	691	0.02	15	0.75	<0.01	0.08	12.2	2.3	3,400	a	d
	Boriskino	683	4.8	11,800	55	0.33	5.3	46.4	9.0	610	0.1 ^b	0.17 ^f
	Cold Bokkeveld	638	0.44	1,760	7.2	0.10	0.90	17.8	3.5	294	>0.0 ^b	0.08 ^e
	Cold Bokkeveld	673	0.56	2,024	7.6	0.15	1.0	12.0	3.0	235	>0.0 ^b	0.13 ^e
	Erakot	681	5.3	1,890	8.9	1.6	2.8	37.5	8.2	1,250	4.5 ^b	1.58 ^e
	Haripura	635	0.45	2,500	7.9	0.05	1.0	31.5	6.3	576	>0.0 ^b	0.03 ^e
	Kaba	631	3.7	1,930	11.2	3.5	5.0	25.0	5.7	784	2.9 ^b	3.48 ^e
	Kaba	646	4.5	2,770	14.1	3.7	5.5	24.8	6.9	390	3.4 ^b	3.67 ^e
	Mighei	640	2.1	3,960	14.2	0.75	2.5	58.6	11.5	1,490	0.5 ^b	0.71 ^f
	Mokoia	633	56	89,400	352	4.3	31.0	19.0	3.8	1,170	20 ^b	3.27 ^f
	Mokoia	641	56	96,300	301	5.3	28.6	27.2	6.1	1,170	17 ^b	4.47 ^f
	Mokoia	674	52	94,600	285	3.6	25.8	22.5	4.7	1,330	14 ^b	2.77 ^f
	Mokoia	680	54	81,200	208	2.8	18.9	16.5	3.9	1,010	22 ^b	2.22 ^f
	Murray	643	13.1	31,400	151	1.6	14.3	89.9	18.2	805	0.5 ^b	1.16 ^f
	Nawapali	637	9.2	28,500	125	0.43	10.9	26.0	6.2	390	>0.0 ^b	0.05 ^e
	Nogoya-light	670	1.1	4,270	17.4	0.12	1.8	14.2	3.1	473	>0.0 ^b	0.07 ^e
	Nogoya-dark	671	16.0	48,300	252	0.80	21.6	58.1	12.6	1,400	>0.0 ^b	0.06 ^f
	Pollen	647	25.6	22,000	87.0	0.60	8.0	72.2	17.0	546	16.8 ^b	0.35 ^f
	Pollen	690	9.0	15,600	87.4	0.70	7.8	77.1	14.6	603	3.4 ^b	0.45 ^f
	Sta. Cruz	636	5.3	3,450	12.5	1.6	3.1	40.4	8.5	a	3.9 ^b	1.56 ^e
	Sta. Cruz	650	5.0	3,370	13.5	1.7	3.4	58	13.3	1,360	3.7 ^b	1.66 ^e

Table I. Inert Gas Contents of Carbonaceous Chondrites and Unequilibrated Ordinary Chondrites.
Units 10^{-8} ccSTP/g

		Run No.	^3He	^4He	^{20}Ne	^{21}Ne	^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar	$^3\text{He}_c$	$^{21}\text{Ne}_c$
Carbonaceous Chondrites												
C3	Felix	652	91	2,500	18.6	15.2	17.7	118	23.8	2,300	91 ^c	15.2 ^a
	Grossnaja	653	1.2	1,760	7.1	0.60	1.4	24	4.9	797	1.2 ^c	0.60 ^a
	Lancé	649	6.3	1,630	5.3	1.6	2.1	137	26.3	1,690	6.3 ^c	1.6 ^e
	Ornans	634	37	2,400	6.3	4.8	5.9	57	11.0	2,250	37 ^c	4.8 ^e
	Vigarano	654	8.3	4,450	16.1	1.8	3.2	31.0	6.2	2,240	8.3 ^c	1.8 ^e
	Warrenton	648	58	2,200	10.0	7.4	9.5	103	20.4	2,830	58 ^c	7.4 ^e
C4	Karoonda	630	85	2,660	15.9	16.8	18.5	3.8	2.7	1,390	85 ^c	16.8 ^e
	Karoonda	657	83	2,850	14.8	14.8	16.8	4.3	2.1	1,430	83 ^c	14.8 ^e
Unequilibrated Ordinary Chondrites												
H3	Bremervörde	*	20.6	2,370	10.2	4.3	5.4	10.1	2.5	a	20.6 ^c	4.3 ^e
	Bremervörde	688	21.7	4,200	19.1	3.8	5.4	5.9	1.4	2,830	21.7 ^c	3.8 ^e
	Prairie Dog Creek	675	44	1,520	7.4	8.3	8.4	8.4	2.3	4,700	44 ^c	8.3 ^e
L3	Krynka	*	42	2,030	a	9.1	a	64	13.2	a	42 ^c	9.1 ^a
	Krynka	665	50	2,370	13.6	11.5	12.6	37	8.1	4,070	50 ^c	11.5 ^a
	Bishunpur	*	13.2	1,680	4.1	3.7	3.3	60	11.6	a	13.2 ^c	3.7 ^e
	Bishunpur	663	14.7	1,700	6.6	3.2	3.5	39	7.7	3,930	14.7 ^c	3.2 ^e
	Manych	667	15.0	600	4.5	2.4	2.8	15.6	3.3	4,830	15.0 ^c	2.4 ^e
	Khojar	664	16.0	870	27.3	6.0	8.3	25.6	5.3	1,830	16.0 ^c	6.0 ^e
	Mező-Madaras	666	52	690	11.1	11.1	12.7	16.3	4.3	660	52 ^c	11.1 ^a
	Carraweena	686	6.9	187	4.1	3.0	3.3	3.9	0.93	600	6.9 ^c	3.0 ^e
	Barratta	687	16.0	200	4.6	3.0	4.2	4.9	1.2	377	16.0 ^c	3.0 ^e

Table I. Inert Gas Contents of Carbonaceous Chondrites and Unequilibrated Ordinary Chondrites.
Units 10^{-8} ccSTP/g

	Run No.	^3He	^4He	^{20}Ne	^{21}Ne	^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar	$^3\text{He}_c$	$^{21}\text{Ne}_c$
LL3 Chainpur	*	42	1,840	10.0	8.4	9.8	60	12.3	a	42^c	8.4^a
Chainpur	627	48	2,080	13.8	10.6	11.8	51	10.5	4,940	48^c	10.6^a
Parnallee	668	8.6	1,000	4.4	3.2	3.9	13.8	2.9	2,720	8.6^c	3.2^e

Notes * These runs have no numbers.

a Not measured

b ^4He assumed wholly primordialc ^4He assumed radiogenic + cosmogenic

d very small

e from $^{20}\text{Ne}_p = ^{20}\text{Ne} - ^{21}\text{Ne}$, with $^{20}\text{Ne}_p / ^{21}\text{Ne}_p = 338$

f from " " " " " = 354

Table II

Uranium and Thorium Contents of Carbonaceous Chondrites

Meteorite	Type	Uranium, ppm	Reference	Thorium, ppm	Reference
Orgueil	C1	0.008	[31]		
Orgueil	C1	0.0242	[33]	0.0648	[33]
Mighei	C2	0.021)	[32]		
		0.008)			
Nokoia	C2	0.0140	[33]	0.0605	[33]
Murray	C2	0.018)	[32]		
		0.028)			
		0.015)			
Karoonda	C4	0.0137	[33]	0.0566	[33]

Table III

Production Rates of $^3\text{He}_c$ and $^{21}\text{Ne}_c$, units 10^{-8} ccSTP/g per Myr

Type	$^3\text{He}_c$	$^{21}\text{Ne}_c$	Reference	$^{21}\text{Ne}_c$	$^3\text{He}_c/^{21}\text{Ne}_c$
C1	2.0	0.20	[20]	—	10.0
C2	2.0	0.27	[20]	—	7.4
C3, C4	2.0	0.32	[20]	—	6.2
M3, L3, LL3	2.0	0.38	[24]	—	5.3

Table IV

Radiation Ages and Gas-Retention Ages

		Run No.	$^3\text{He}_c$ -age, Myr	$^{21}\text{Ne}_c$ -age, Myr	U,Th-He-age, Gyr	K-Ar age, Gyr	X, ppm
			A	B			
C1	Alais	639	1.5	7.3	a	1.6	380
	Ivuna	645	0.85	2.1	a	1.1	580
	Orgueil	644	0.90	3.7	a	1.5	580
C2	Al Rais	632	4.9	12	a	3.9	270
	Bells	691	>0	0.01	a	b	b
	Boriskino	683	0.05	0.63	a	2.5	300
	Cold Bokkeveld	638	>0	0.22	a	1.2	420
	Cold Bokkeveld	673	>0	0.28	a	1.1	420
	Erakot	681	2.3	2.7	a	3.7	270
	Haripura	635	>0	0.23	a	1.6	580
	Kaba	631	1.5	1.9	a	4.6	100
	Kaba	646	1.7	2.3	a	3.4	100
	Mighei	640	0.25	2.7	a	3.3	420
	Mokoia	633	10	12	a	3.3	330
	Mokoia	641	8.5	17	a	3.7	330
	Mokoia	674	7.0	11	a	3.5	330
	Mokoia	680	11	8.2	a	3.3	330
	Murray	643	0.25	4.3	a	2.7	330
	Nawapall	637	>0	0.19	a	0.63	1300
	Nogoya-light	670	>0	0.26	a	b	b
	Nogoya-dark	671	>0	0.22	a	b	b
	Pollen	647	8.4	1.4	a	b	b
	Pollen	690	1.7	1.7	a	b	b
	Sta. Cruz	636	2.0	5.8	a	c	1000
	Sta. Cruz	650	1.9	6.5	a	2.0	1000

Table IV
Radiation Ages and Gas-Retention Ages

	Run No.	$^3\text{He}_c$ -age, Myr		$^{21}\text{Ne}_c$ -age, Myr	U,Th-He-age, Gyr	K-Ar age, Gyr	K, ppm
		A	B				
C3	Pelix	652	46	48	4.9	4.0	410
	Grossnaja	653	0.60	2.0	4.4	3.2	240
	Lancé	649	3.2	4.7	4.2	2.0	1160
	Ornans	634	19	15	4.9	2.2	1400
	Vigarano	654	3.2	5.6	a	3.7	480
	Warrenton	648	29	24	4.6	4.0	430
C4	Karoonda	630	43	53	4.4	4.1	240
	Karoonda	657	42	48	4.6	4.1	240
H3	Bremervörde	*	10	11	4.8	c	750
	Bremervörde	688	11	10	a	4.1	750
	Prairie Dog Creek	675	22	22	3.8	3.4	(800)
L3	Krynka	*	21	24	4.5	c	580
	Krynka	655	25	30	4.8	4.4	580
	Bishunpur	*	6.6	9.7	4.2	c	830
	Bishunpur	663	7.4	8.4	4.3	3.7	830
	Manyoh	667	7.5	6.3	1.9	2.8	1830
	Khojar	664	8.0	16	2.6	2.6	830
	Mező-Madaras	666	26	29	1.6	1.3	915
	Carraweena	686	3.5	7.9	0.61	1.1	750
	Barratta	687	8.0	7.9	0.48	0.80	915
LL3	Chainpur	*	21	22	4.3	c	1000
	Chainpur	627	24	28	4.5	3.8	1000
	Parnallee	668	4.3	8.4	3.1	3.0	915

References: K contents of C1, C2, C3 were taken from Mason [1], except Warrenton which was taken from Edwards [29].
K contents of the UOC were taken from [8], K of Prairie Dog Creek was assumed 800 ppm.
U and Th contents of Table II were used. In the remaining cases U was assumed to be 0.011 ppm; Th/U = 36.

Notes: A: age calculated with the assumption that ^4He is wholly primordial
B: age calculated with the assumption that ^4He is radiogenic and cosmogenic
a: ^4He definitely or probably primordial
b: no K_2 data available
c: no ^{40}Ar values available.

FIGURE CAPTIONS

Fig 1. ^4He vs $^{20}\text{Ne}_p$ for the meteorites of Table I. Open circles: (C1 + C2) chondrites. Filled-in circles: (C3 + C4) chondrites and UOC. Solid line: $^4\text{He}/^{20}\text{Ne}_p = 250$. Note that all the C1 and C2 chondrites agree closely with this ratio. The points along the left vertical axis represent chondrites with $^{20}\text{Ne}_p < 1.0 \times 10^{-8}$ ccSTP/g.

Fig 2. Radiation ages of carbonaceous chondrites and of UOC. Open symbols: average of $^3\text{He}_c$ and $^{21}\text{Ne}_c$ -ages; filled-in symbols: $^{21}\text{Ne}_c$ -age only. Circles: inert gas data from the present work; triangles: inert gas data from [10], [12], and [34].

Fig 3. U, Th-He ages of carbonaceous chondrites and of UOC. Open symbols: discordant ages; filled-in symbols: concordant ages; starred symbols: no ^{40}Ar data available. Circles: inert gas data from the present work; triangles: inert gas data from [10], [12], and [34].

Fig 4. K-Ar ages of carbonaceous chondrites and of UOC. Circles: inert gas data from the present work; triangles: inert gas data from [10], [12], and [34]. Symbol K refers to Kaba.

Fig 5. U, Th-He ages (from Figure 3) of the UOC versus "percent mean deviation of olivine", taken from [8]. Open circles: H3; filled-in circles: L3; triangles: LL3 chondrites. Lettering: BA = Barratta, BI = Bishunpur, BR = Bremervörde; CA = Carraweena; CH = Chainpur; CL = Clovie; KH = Khohar; KR = Krymka; MA = Manych; MM = Mező-Madaras; PA = Farnallee; PDC = Prairie Dog Creek; TI = Tieschitz.