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Stable Isotope Measurements of Meteorites and Cosmic Dust Grains [and Discussion]

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Stable isotope measurements of meteorites and cosmic dust grains

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Although it was well known that a high ^{13}C abundance was a common feature of the spectra of evolved stars, it took over 50 years to find evidence of carbonaceous instellar dust, which might have been ejected from such objects, in the Solar System. However, it is now established that dust probably produced in novae and red giants can be located in primitive meteorites and the latest state of knowledge in respect of such components is reviewed herein. Nitrogen isotopic measurements have been helpful in distinguishing another form of dust that is carbonaceous but does not have a distinctive ^{13}C abundance. Likewise they suggest a non-carbonaceous material (possibly a sulphide) present in the meteorite Bencubbin could be a relict of supernovae outbursts. None of the components seen in meteorites can be detected in deep-sea spheres or stratospheric grains to provide a link between interstellar matter and comets. Until now interstellar dust has been the realm of observing astronomers and theoretians; stable isotope measurements are responsible for recognizing a material which it should be possible to isolate and study in the laboratory.

Introduction

Within weeks of the discovery of ^{13}C by optical spectrographic means (King & Birge 1929) astronomical investigations of the relative abundance of carbon isotopes had begun. The spectra of carbon-rich stars were soon found to contain lines corresponding to both ^{12}C–^{13}C (Sandford 1929) and ^{13}C–^{13}C bonding (Menzel 1930); the latter immediately demonstrating the very high ^{13}C abundance in environments beyond the Solar System. In fact, the major carbon components in terrestrial, lunar samples and bulk meteorites all have ^{12}C/^{13}C ratios close to 89 (table 1) whereas, because of nuclear processing via the CNO cycle, values for late-type stars can be as low as 4 although high values (greater than 100) are also possible. Thus it is obvious that interstellar gas and dust ejected from evolved stars ought to contain components of characteristically high ^{13}C abundance. Indeed, in the interstellar medium as a whole, the relative proportions of ^{12}C and ^{13}C are between 60 and 70 to 1 (Wannier 1980; Penzias 1980).

Among the first astronomical objects considered for the presence of ^{13}C was Halley's Comet, the ^{13}C–^{12}C line being found in spectra recorded during the 1910 apparition (Bobrovinikoff 1930). Although no isotopic composition was estimated, the author did suggest the need for similar studies on meteorites to determine any connection between these and comets. Appropriate meteorite data are now available but attempts to obtain well-defined isotopic compositions from comets are few and very imprecise (Vanysek & Rahe 1978); the studies performed seem to point towards an abundance of ^{13}C that is less than the Solar System as a whole (table 1). Measurements made for cosmic dust grains thought to be the terrestrial remains of cometary material (D. Brownlee, this symposium) will be discussed later in this paper.

TABLE 1

(Source: Vanysek (1977) and Vanysek & Rahe (1978).)

object	$^{12}C/^{13}C$
Earth	89^{+10}_{-1}
Moon	89^{+3}_{-2}
bulk meteorites	$89^{+3}_{-0.5}$
comets	
Ikeya 1963 I	70 ± 15
Tayo–Sato–Kosaka 1969 IX	100 ± 20
Kohoutek 1973 XII	115^{+30}_{-20}
	135^{+60}_{-45}
Kobayshi–Berger–Milon 1975	110^{+20}_{-30}

Trofimov (1950) seems to have been the first investigator to consider the possibility of finding variations in the isotopic composition of meteoritic carbon to parallel the known wide-scale distribution in stars. The spread encountered, 89.6–91.8, was even narrower than known for terrestrial samples at the time (89.0 marine carbonate, 92.4 petroleum) thus Trofimov was forced to conclude that terrestrial matter and the 35 meteorites he studied 'belonged to a single system of creation and a single nuclear genesis'. However, once isotopic anomalies† had been discovered for other elements, e.g. oxygen (Clayton *et al.* 1972) and noble gases (Reynolds & Turner 1964; Black & Pepin 1969; Lewis *et al.* 1975) it was inevitable that they would eventually be found for carbon. Nevertheless, it was still another decade before material with $^{13}C/^{12}C$ ratios high enough to be beyond the reach of fractionation mechanisms at realistic temperatures was discovered (Swart *et al.* 1983*a*). These values when considered together with isotopic measurements made for noble gases and nitrogen, thought to be trapped within the host carbon, most strongly imply that dust grains from various stellar sources can be isolated from primitive meteorites to provide an opportunity for laboratory studies as a compliment to astronomical observations.

EXPERIMENTAL METHODS

Of paramount importance in the discovery of interstellar dust grains in meteorites has been the application of stepped combustion extraction procedures. In this technique, samples are subjected to a sequence of increasing temperatures in the presence of molecular oxygen. There are several early literature references to burning extraterrestrial specimens in two or three stages (Briggs & Ketto 1962; Otting & Zahringer 1967; DesMarais 1978) but Ott *et al.* (1981) were the first authors to increase combustion temperatures systematically as a means of obtaining carbon dioxide for carbon isotopic measurement. Unfortunately, the progressive rise of $\delta^{13}C$‡ from -34.1‰ at 200 °C to -4.1‰ at 1100 °C, during the analysis of an acid residue from the Allende meteorite, was dismissed as kinetic isotope fractionation. Swart *et al.* (1982),

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† An isotopic anomaly is normally defined as a composition that cannot be accredited to mixing or fractionation and thus is attributable to a specific process of nucleosynthesis. The fact that non-mass-dependent isotopic effects occur during photochemical dissociation of oxygen (Thiemens & Heidenreich 1983) is ignored herein, because so far it has not been demonstrated that such reactions have a role in terms of carbon and nitrogen isotopic systematics in meteorites. This may, however, change.

‡ $\delta(‰) = 1000 \dfrac{[(H/L)_{\text{sample}} - (H/L)_{\text{standard}}]}{(H/L)_{\text{standard}}}$, where H represents heavy isotope; L represents light isotope.

however, showed that different carbon phases burned at specific temperatures without an isotopic fractionation of greater than 2‰. A compilation of stepped combustion data for various standard materials is given as figure 1. The temperature at which elemental carbon combusts is dependent upon its crystallinity with amorphous carbon being least stable and diamond most (Swart *et al.* 1983*b*; Grady *et al.* 1985). No systematic investigation into particle size has yet been attempted to establish the effect of surface area, although intuitively this must be important. Organic compounds are particularly unstable in the presence of oxygen, oil source rock kerogens being predominently destroyed at 450 °C (Gilmour & Pillinger 1985) although a continuum exists for samples of increasing maturity, which may be considered as being progressively more graphitized (I. Gilmour, C. T. O'Donnell & C. T. Pillinger, unpublished results). The most stable compounds appear to be carbides: the meteoritic carbide cohenite surviving until at least 1000 °C (Grady *et al.* 1986). More refractory carbides have not been tested but are likely to be even more stable, bearing in mind that SiC is commonly used as a heating element in furnaces designed for use up to 1600 °C.

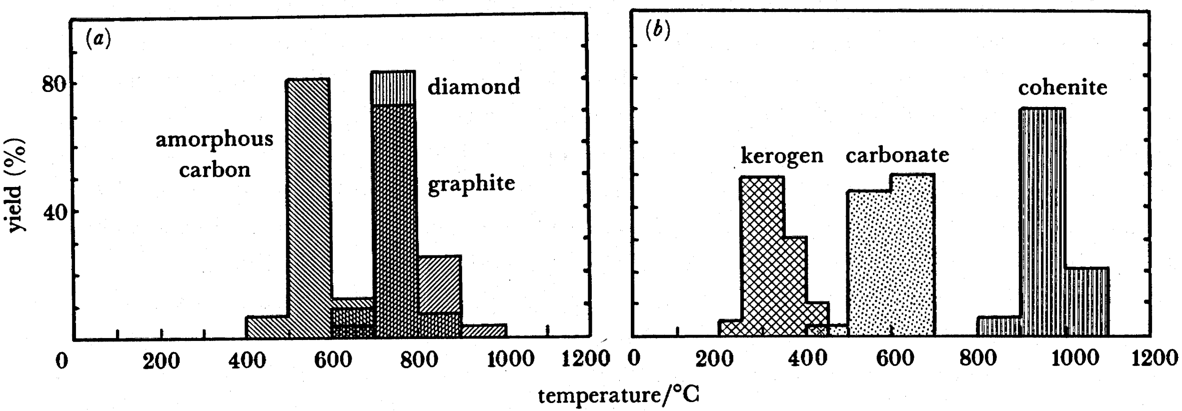

FIGURE 1. Carbon release during combustion. (*a*) Elemental forms of carbon; (*b*) carbon compounds.

It must be stressed that the data in figure 1 are for pure substances. Inevitably 'protection' in a mineral matrix could prevent ignition until dissociation of the mineral or diffusion to the surface took place. Equally catalytic effects involving alkali metals (Bergman 1972) or promoted combusion of one phase coexisting with another by exothermic reaction (G. Eglinton, personal communication) cannot be ruled out when dealing with meteorites or other geological materials. Nevertheless high-resolution stepped combustion (less than 100 °C temperature increments) is vital in two respects in distinguishing interstellar dust components. At low temperatures it is capable of removing (i) terrestrial contaminants introduced into meteorites during museum storage and in sample handling procedures and (ii) indigenous macromolecular (kerogen-like) material, which constitutes the vast majority of the carbon budget of primitive meteorites. The improvement of mass-spectrometric measurement techniques (Carr *et al.* 1986*a*) has meant that stepped combustion can be conducted with much smaller steps (frequently 25 °C) to provide better information as to the nature of the carbon involved. The limit of the experiment presently is as much time as sample-availability.

Interstellar dust components in meteorites

Interstellar carbon of high ^{13}C abundance was discovered (Swart *et al.* 1983*a*) as a result of stepped combustion experiments on highly processed residues obtained from the Murchison meteorite for the purpose of identifying exotic noble-gas components (Alaerts *et al.* 1980). Firstly the meteorite was demineralized with HCl and HF to leave only carbonaceous, and probably oxide and minor sulphide, phases and then treated with oxidizing agents to remove the latter and some organics. It was then separated according to size to give three fractions 2C1Oc, 2C1Om and 2C1Of (coarse, 3–10 μm; medium, 1–3 μm; and fine, 1 μm respectively). Only two of these, 2C1Om and 2C1Of, were studied by Swart *et al.* (1983*a*) who observed three peaks in the sequence of isotopic compositions measured for gas extracted from 2C1Om at temperatures greater than 500 °C. Because two anomalous noble-gas components, Ne-E(L) (essentially pure ^{22}Ne, possibly derived from decay of short lived ^{22}Na, residing in a low-density, low-stability phase (Eberhardt 1974; Anders 1981)) and s-Xe (so-named because its isotopic pattern (Srinivasan *et al.* 1978) matches the theoretical pattern calculated by Clayton & Ward (1978) for xenon produced by a slow-neutron-capture process) were known to exist in 2C1Om and have grossly different release temperatures – 600 °C for Ne-E(L) and 1400 °C for s-XE – it was considered plausible that the low- (600 °C) and high- (1200 °C) temperature ^{13}C peaks might correspond to decomposition of the respective host phases. A peak $\delta^{13}C$ value of $+1100$ ‰ ($^{12}C/^{13}C = 42$) measured at 1000 °C in the 2C1Of, known to contain relatively more s-Xe than 2C1Om, supported this interpretation. The view is further endorsed by the circumstantial evidence that the s-process is a feature of red-giant stars characterized by a $^{12}C/^{13}C$ ratio as low as 4 and that novae thought to the direct provenance of ^{22}Ne or its precursor ^{22}Na are ^{13}C-enriched. Thus the carbon phases were dubbed Cα and Cβ according to nomenclature previously introduced by Anders and his co-workers (see Anders 1981).

Swart *et al.* (1983*a*) also obtained isotopic measurements for another carbon phase found in 2C1Of. This is the carbon termed Cδ, which burns from 400–500 °C and is thought to be the host of a noble gas component, originally named carbonaceous chondrite fission (CCF) -Xe by Reynolds & Turner (1964) and suggested to be from an extinct superheavy element (Anders & Heymann 1969). The same component is also referred to as DME-Xe, but its currently accepted nomenclature is Xe(HL) because of the distinctive enrichment in both heavy and light isotopes. The $\delta^{13}C$ values measured for Cδ from Murchison (−38‰) and another meteorite, Allende (−31‰) do nothing to betray that Cδ might be an interstellar dust component. However, nitrogen isotopic compositions obtained on the same samples show $^{14}N/^{15}N$ ratios up to 406 compared to the value of 272 measured for air and suggest that stellar synthesis, possibly in a supernova, is involved. The host carbon and Xe(HL) are likely to be from the same supernova source.

The existence of heavy carbon in carbonaceous chondrites has been confirmed by several other groups using stepped combustion (Kerridge 1983; Yang & Epstein 1984; Halbout *et al.* 1986). Only the latter authors, however, have succeeded in obtaining data to suggest that more than one component exists. Ion-probe studies (Niederer *et al.* 1985; Zinner & Epstein 1986; E. Zinner personal communication) have raised the maximum $\delta^{13}C$ value obtained to *ca.* 7000‰. Work with ion probes is only just beginning and it is too early to know whether this technique will be able to distinguish between different forms of interstellar carbon (see below). So far there is no independent confirmation concerning Cδ probably because no other conjoint carbon, nitrogen, noble gas studies have been made.

Carbon alpha

Work by my group in collaboration with the University of Chicago has continued and we are now able to refine the interpretation made by Swart *et al.* (1983*a*). An important facet in confirming that low temperature, heavy carbon is indeed Cα the host of NeE(L) has been the stepped combustion of 2C1Oc a residue not studied by Swart *et al.* (1983*a*). The major heavy carbon component in this sample is combustible over the well defined temperature interval 600–700 °C with a maximum $\delta^{13}C$ of +338‰ and no $\delta^{13}C$ values greater than +78‰ at higher temperatures (Carr *et al.* 1983). Residue 2C1Oc is known to contain neon with a high $^{22}Ne/^{20}Ne$ and it is considered that Ne-E is present in rather pure form (Alaerts *et al.* 1980) albeit as both Ne-E(L) and Ne-E(H). S-process xenon is only found in 2C1Oc in minor amounts.

It was possible to resolve Cα in 2C1Oc only because the sample was relatively free of isotopically normal polymer or amorphous carbon that could be burnt off below 600 °C. Residue 2C1Oc was in fact only 2% C (by mass); the majority of the sample being spinel, chromite and hibonite. The same material was used for the ion probe study of Niederer *et al.* (1985) who noted that single aluminium and oxygen-rich grains had the highest ^{13}C ($\delta^{13}C \approx$ 2000–4000‰) abundance; carbon-rich grains were of normal terrestrial isotopic composition. Similarly Zinner & Epstein (1986) only found high $\delta^{13}C$ values (up to 2400‰) by ion probe in a spinel–hibonite–chromite fraction after they had removed isotopically normal carbon using an RF discharge. The isotopic composition measured by gas-source mass spectroscopy for 2C1Oc is clearly only a minimum value for Cα. It is perhaps more appropriate to estimate its $^{12}C/^{13}C$ as less than 11 based on the most recent unpublished ion-probe data (E. Zinner personal communication) even though this is subject to comparatively large errors.

From the combustion temperature Cα is likely to be some form of disordered graphite that burns at temperatures 100 °C below the spectrographically pure sample used as a standard material. It is not amorphous carbon because 2C1Oc is a coarse fraction although its coarseness could be dictated by the oxide minerals. However, Eberhardt *et al.* (1981), using non-chemical separation techniques, established convincingly that Ne-E in Orgueil does not reside in colloidal material. Given than Ne-E(H) is thought to be trapped in spinel (Lewis *et al.* 1979), it is tempting to postulate that the real carrier of this is Cα enclosed within the oxide mineral, i.e. not available to oxygen during combustion.

Carbon beta

A repeat analysis of 2C1Of that uses a greater number of temperature steps (Carr *et al.* 1983) showed that there were two peaks in the pattern of $\delta^{13}C$ values obtained above 600 °C. The first occurs at 850 °C (+624‰) and the second 100 K higher (+950‰). The presence of the lower-temperature peak has been confirmed by even higher-resolution studies (D. W. McGarvie *et al.*, unpublished results) and data from Orgeuil (M. M. Grady *et al.*, unpublished results) and the enstatite chondrites Qingzhen and Indarch (Carr *et al.* 1984). D. W. McGarvie (unpublished results) further resolved the high-temperature peak in $\delta^{13}C$ values measured for 2C1Of into a doublet, which has subsequently been seen for high density fractions from acid residues of the Murray carbonaceous chondrite (Ming *et al.*, unpublished results). Cβ is clearly not a simple component. It is possible that the peak values in the carbon isotopic composition at different temperatures reflect a single carbon phase being released from separate sites (trapped inside minerals ?). Alternatively there could be several components that have different combustion temperatures because of variation in particle size, degree of crystallinity, etc. If the latter is true, deciding which is the authentic Cβ, host of s-Xe, will require considerable effort, possibly involving physical separation of three markedly similar carbon phases. It will be interesting to establish whether each of the carbon components has a separate noble gas isotopic signature.

A major problem concerning the identity of Cβ is that much of the carbon combusts at temperatures which are higher than those found with standard materials such as graphite or diamond. This would seem to favour the hypothesis that the carbon is shielded by a mineral phase and combustion temperature is a site-dependent phenomenon. There are forms of elemental carbon that have not yet been the subject of high resolution stepped combustion experiments. Londsdaleite (hexagonal carbon), which is observed in iron meteorites (Frondel & Marvin, 1967), where it is thought to have been shock produced, is one possibility, especially because this has more recently been recognized in stratospheric dust grains (Reitmeijer & MacKinnon 1985). Carbyne, once thought to be implicated as an anomalous noble gas host phase (Whittaker *et al.* 1980) could stand reinvestigation and the recently discovered C60 (Kroto *et al.* 1985) is worthy of consideration. It cannot be discounted that graphite made from a very high proportion of ^{13}C atoms ($^{12}C/^{13}C \approx 4$) is thermodynamically more stable than terrestrial graphite ($^{12}C/^{13}C \approx 89$).

Carbon delta

Xenon(HL), the anomalous gas associated with Cδ is ubiquitous in primitive meteorites having been identified in CI, CM2, CV3, CO3, H, L, LL and E chondrites (Anders 1981). Because Cδ is very fine-grained and known to undergo combustion in the temperature range 400–600 °C, it is instructive to consider $\delta^{13}C$ values measured for various samples in that interval (see figure 2). Isotopic data (M. M. Grady *et al.*, unpublished results) for an acid residue from the CI meterorite Orgeuil (Lewis *et al.* 1983) and a bulk sample of the enstatite chondrite South Oman (Grady *et al.* 1986) are indicative that Cδ is isotopically lighter than at first believed (Swart *et al.* 1983*a*). The $\delta^{15}N$ of $-72‰$ found for nitrogen released from South Oman in the 400–600 °C temperature interval suggests that Cδ is involved. Thus it may be easier to separate Cδ from enstatite chondrites, where the bulk of the normal carbon is graphite, than it was in the case of Allende, where the major phase was amorphous carbon of $\delta^{13}C = -17‰$ (Swart *et al.* 1982).

Isotope studies on the Bencubbin meteorite

It is possible that not all the interstellar dust trapped in meteorites is carbonaceous in nature. Recently, interest in the Bencubbin meteorite was aroused by measurements made on gram-sized specimens, which suggested that the bulk sample is enriched in the heavy isotope of nitrogen by a factor of two (Prombo & Clayton 1985). This was the first recognition of an isotopic anomaly involving a light element in a meteorite that was not a primitive chondrite (Bencubbin is a polymict breccia consisting of recrystallized kamacite and silicates together with a variety of chondritic xenoliths welded in a shock melted metal–silicate matrix (Newsom & Drake 1979)). Almost all the nitrogen is uniformly enriched in ^{15}N; it is not confined to the matrix or the xenoliths. In fact, the latter have the lowest $\delta^{15}N$ values and may have acquired their nitrogen in a secondary event. Stepped combustion experiments performed on material separated from a sample of metal clasts and matrix (Franchi *et al.* 1986) suggest that the heavy

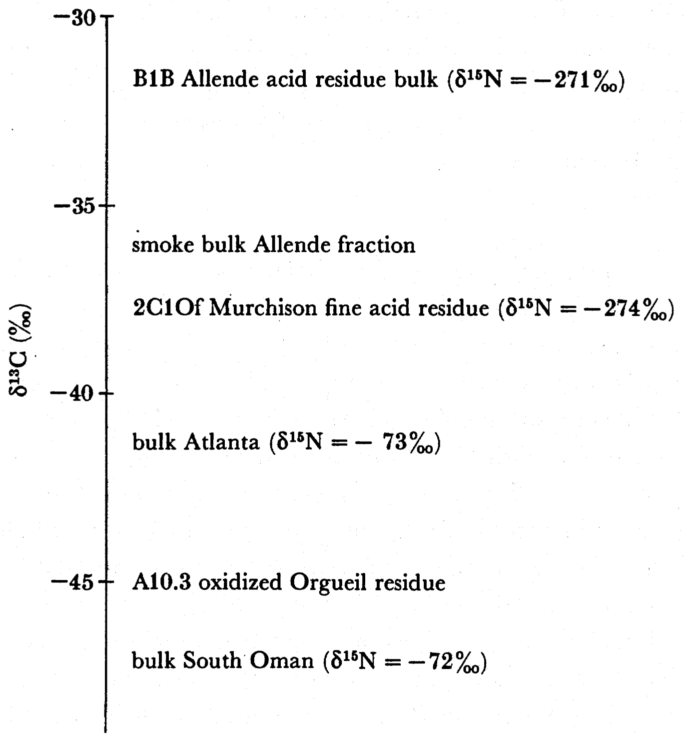

Figure 2. Isotopic composition of the combustion of carbon in the temperature range 400–600 °C.

nitrogen (max. $\delta^{15}N = +1033‰$) is located in two components both of which are insoluble in 6 M HCl but only one of which survives treatment with 12 M HCl or 28 M HF. It is very unlikely that the component degraded by strong acid is carbonaceous. Carbon analyses suggest that if the more stable one is carbonaceous then its C:N ratio is unusually low (less than 4). Furthermore, the carbon is not distinguished by an unduly anomalous isotopic composition ($\delta^{13}C \approx +25‰$). A novel chromium-rich sulphide recognized during petrological examination (Newsom & Drake 1979) cannot be ruled out as a possible nitrogen host; the 6 M HCl residue contains 1.7% sulphur (by mass). If sulphides are implicated they could have been produced in a supernova evolved to the silicon-burning state (Clayton & Ramadurai 1977).

Studies of cosmic dust grains

The high $\delta^{13}C$ values measured at combustion temperatures above 600 °C for fractions isolated from various primitive meteorites provide compelling evidence for the survival of interstellar grains in the Solar System. With the benefit of hindsight it has proven possible to detect heavy carbon in bulk samples (Halbout *et al.* 1986) or those subject to a minimum of processing (McGarvie *et al.* 1985, 1987). It would be of great significance for our understanding of comets to recognize similar isotopic signatures for materials thought to have derived from cometary sources. Although all micrometeorites are heated to some extent during deceleration in the Earth's atmosphere, such a process should only serve to remove low-temperature organic matter (analogous to organic contamination or meteorite polymer). If any carbon survives, it ought to be the carbon that combusts at high temperature, therefore, stepped combustion experiments of materials of possible cometary origin could be highly informative. A significant fraction of deep-sea spherules may be melted cometary material although a large proportion are more likely to be meteorite ablation debris (Murray & Renard 1883), however, there seems to be unanimity that grains collected in the stratosphere (Brownlee particles) are from cometary sources (D. Brownlee, this symposium). Both types of material have been the subject of carbon isotope measurements.

Deep-sea spherules

A total of six individual deep-sea spherules have been analysed by stepped combustion (Carr *et al.* 1984; Carr 1985). Four of these had clearly been heated to temperatures high enough to cause some melting but two were chondritic in nature and unmelted. Although both the unmelted grains had higher $\delta^{13}C$ values (-16 and -21‰) than the melted samples, fractions between 600 and 1200 °C were isotopically lighter (-30 to -34‰). None of the particles can be said to exhibit evidence of a high ^{13}C abundance, which might betray the existence of an interstellar dust component. In all cases the majority of the carbon burned at temperatures below 600 °C with up to a maximum of 6% (by mass) for one of the unmelted samples. The $\delta^{13}C$ value (-18‰) for the low-temperature carbon is uncommonly high for terrestrial contamination, in our experience between -25 and -35‰. It could be contamination by marine organisms that have high $\delta^{13}C$ values but, studies of volcanic glasses of deep sea origin (Mattey *et al.* 1984; Exley *et al.* 1986) have revealed only isotopically light organics at low temperature. Thus, there is a strong possibility that unmelted deep-sea spherules have some indigenous carbon which needs to be further explored. It is noteworthy that the isotopic value of -18‰ is close to that measured for macromolecular material in carbonaceous chondrites (Smith & Kaplan 1970).

Stratospheric particles

Because of their size and friable nature, stratospheric particles present experimental difficulties not encountered with deep-sea spherules. Procedures involving silicone oil are used to ensure that a stratospheric grain adheres to a suitable carrier (platinum foil) for transfer to the combustion system. Unfortunately the silicone oil burns over a wider temperature range than normal laboratory contamination but nevertheless its distinctive light isotopic signature (*ca.* -40‰) would allow it to be distinguished from heavy carbon of interstellar origin. Isotopic measurements on refractory components in carbonaceous chondrites show that anomalous (high $\delta^{13}C$) compositions may be detected successfully on samples as small as 150 pg. However, when five stratospheric grains, *ca.* 10 μm in diameter with a calculated carbon content of 2 ng, were subjected to stepped combustion, there was no indication of a $\delta^{13}C$ in excess of -30‰ at temperatures above 600 °C (Carr *et al.* 1986*b*). The bulk isotopic value measured for the grains (plus the silicone oil on platinum foil) was -37.57‰, marginally heavier than a blank analysis performed in duplicate (-39.15‰, -39.20‰). Thus, within the limits of detection of the experiment, it was impossible to recognize the existence of isotopically heavy carbon in stratospheric particles. The results are in keeping with ion-probe measurements reported by McKeegan *et al.* (1985) whose carbon isotopic data for fragments from three individual particles are given in table 2. Although ion-probe studies for carbon have not been refined to a high level of precision, the extreme difference between the particles named Skywalker and Mosquito is believed to be real. None of the values obtained is remotely near the high ^{13}C determined by ion probe for meteorite residues (Niederer *et al.* 1985; Zinner & Epstein 1986).

TABLE 2. δ^{13}C AND δD MEASUREMENTS FOR STRATOSPHERIC PARTICLES FROM MCKEEGAN *ET AL.* (1985)

(Average errors on an individual measurement: δ^{13}C ± 17.0‰, δD ± 125 to 520‰.)

particle	δ^{13}C (‰) (number of measurements)	δD (‰) (number of measurements)
Mosquito	−0.2 (5)	+125 to +2534 (8)
Skywalker	−38.9 (9)	+51 to +696 (26)
Calrissian	−14.1 (5)	+373 to +2196 (7)

In summary, isotopic measurements made on material that could derive from comets seem to agree with the spectroscopic data rather than match values obtained for refractory components from primitive meteorites.

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Discussion

SIR WILLIAM MCCREA, F.R.S. (*Astronomy Centre, University of Sussex, Brighton, U.K.*). Dr Pillinger speaks of material of extra-Solar System composition, which apparently he finds in very small inclusions in the meteoritic matter he has described. One asks (*a*) how might the material have reached the sites where it is found, (*b*) whether any particles have been found that are composed entirely of such material and that are not inclusions within bodies having otherwise Solar-System composition.

C. T. PILLINGER. Our interpretation of the heavy carbon we find in primitive meteorites is that it is intersteller dust condensed from the expanding shells of evolved stars. However, we have yet to isolate a pure sample; all the material we study is contaminated by phases which were produced in the solar nebula. We could therefore conceive that the interstellar grains are acting and 'seed' crystals. The only source of the isotopically heavy carbon known at present is meteorites but obviously a very logical place to look would be comets, where it could easily be present in greater abundance and variety.

M. ARNOULD (*Institut d'Astronomie, Université Libre de Bruxelles, Brussels, Belgium*). The differential irradiation of portions of the pristine Solar System matter by an intense flux of energetic particles from the young Sun has sometimes been advocated to account for at least some of the observed anomalies. An interesting test of that model would be provided by the search for lithium isotopic anomalies in meterorites. Could such a search be conducted again with the very powerful experimental techniques available today?

C. T. PILLINGER. It should be possible to search for lithium isotopes with an ion probe.