THE PLANETARY AND INTERSTELLAR COMPONENTS OF METEORITES: A REVIEW

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ABSTRACT. Recent analyses show that, although most meteorites are collisional debris of asteroids, three meteorites collected on the Antarctic ice sheet were projected to Earth from the highlands of the Moon, and eight meteorites have chemical and isotopic compositions suggestive of derivation from Mars. Although meteorites are primarily of interest to planetary scientists for the abundance of clues they hold to the materials and processes that formed the Solar system, they have begun to engage the attention of astrochemists because of isotopic and mineralogical indications that they contain interstellar components. Although each individual observation to this effect is inconclusive, the body of evidence is becoming ever more persuasive. This paper reviews the main classes of meteorites and their probable sources, with special emphasis on components that appear to be exotic to the Solar system.

1. METEORITE CLASSES

There are five main classes of meteorites: ordinary chondrites, carbonaceous chondrites, achondrites, irons, and stony-irons, each of which includes a number of chemically distinct subclasses. Chondrites, are fragmental aggregates that have never been heated to melting temperatures. Meteorites of other classes are products of complete or partial melting.

1.1 Relative Proportions

We estimate the proportions of meteoritic materials in Earth-crossing orbits on the basis of witnessed falls, of which there have been about 820 in the past 500 years. Of the meteorites collected from these falls, 8% percent are achondrites, which are samples of lavas or of more deeply-seated layered bodies, 3% are iron meteorites, and 1% are stony-irons. Fully 80% of witnessed falls yield ordinary chondrites, and the remaining 7% carbonaceous chondrites. The majority of the cryptic components suggestive of interstellar origin occur in carbonaceous chondrites.

M. S. Vardya and S. P. Tarafdar (eds.), Astrochemistry, 469–484.

1.2. Ordinary Chondrites

These abundant meteorites are aggregates chiefly of ferromagnesian silicate minerals, grains of metallic nickel-iron, and chondrules. Chondrules are spheroidal bodies, up to 3 mm in diameter, that comprise about 70% of the volume of ordinary chondrites. They consist mainly of olivine [$(Mg,Fe)_2SiO_4$] and pyroxene [$(Mg,Fe)SiO_3$)], with or without glass. Most, if not all, chondrules are droplets of silicate melts that congealed before they accumulated into the parent bodies of chondrites. Arguments that chondrules formed on the parent bodies by impact or volcanism were reviewed and dismissed by Taylor, Scott, and Keil (1983), who concluded that most chondrules are melted clots of nebular dust. An alternative view that they are melted aggregates of interstellar dust has been considered by D.D. Clayton (1983) and Wood (1984). Isotopic dating methods show that chondrules of various types all formed about 4,600 million years ago, as did their host chondrites (e.g. Swindle, Caffee, and Hohenberg, 1983).

Ordinary chondrites occur in three distinct chemical classes, indicative of an origin in different parent bodies. As most of them have undergone some degree of thermal alteration, chondrites show a range in metamorphic grade from the so-called unequilibrated ordinary chondrites (UOC), in which the chondrules are sharply delineated and the olivines have differing ratios of Mg/Fe, to highly recrystallized varieties, in which chondrule margins merge with the matrix and constant values of Mg/Fe are found throughout the meteorite. Indications of possible interstellar components are more common in the UOCs than in any other ordinary chondrites.

1.3. Carbonaceous Chondrites

There are three main types of carbonaceous chondrites, designated C1, C2, and C3, with progressively complex mixtures of components. The C1 chondrites are soft, black meteorites consisting almost entirely of layer lattice hydrous silicates, such as clays and serpentine, ranging in grain size from about 5000 angstroms to 10 microns. Grains and spherules of magnetite ($Fe^{++}Fe^{+++}{}_2O_4$) are also present, indicating formation under oxidizing conditions. C1 chondrites contain about 20% H_2O and 4% C, which occurs mainly in macromolecular hydrocarbon compounds (Table I) of types that form and survive only at low temperatures. The structures and stereochemistry of the meteoritic hydrocarbons <u>exclude</u> a biologic origin.[1]

The carbon in C1 chondrites also occurs as amorphous elemental C and in Mg- and Ca-carbonates, which form veinlets in the meteorites. The vein deposits appear to have originated by the action of aqueous

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1. Due to an error in transmission by telex, Abstract R-35 by this author in the volume distributed at the Symposium, states that the structures and stereochemistry "include" a biologic origin. That is not true. No positive evidence of biologic materials, living or fossilized, has been found in any samples from outside the Earth.

Table I. Distribution of Carbon in the Murchison CM2 Meteorite

Species	Abundance
Acid insoluble carbonaceous phase	1.3-1.8%
Carbonate and CO_2	0.1-0.5%
Hydrocarbons	
Aliphatic	12-35 ppm
Aromatic	15-28 ppm
Acids	
Monocarboxylic (C_2-C_8)	~170 ppm
Dicarboxylic (C_2-C_9)	+, not measured
Hydroxy (C_2-C_5)	~6 ppm
Amino Acids	10-20 ppm
Alcohols (C_1-C_4)	~6 ppm
Aldehydes (C_2-C_4)	~6 ppm
Ketones (C_3-C_5)	~10 ppm
Ureas	~20 ppm
Amines (C_1-C_4)	~2 ppm
N-heterocycles	
Pyridines and Quinolines	0.04-0.40 ppm
Purines	~1 ppm
Pyrimidines	~0.05 ppm
Poly-pyrroles	<<1 ppm
Sum:	1.43-2.35%
Total carbon:	2.0-2.5%

(From Wood and Chang, Eds., 1985, page 56) solutions on bulk C1 material in the near-surface portions of the parent bodies (Kerridge and Bunch, 1979).

C1 chondrites contain no chondrules, despite their classification (persisting from the early 19th century) as chondrites. They do, however, contain scattered grains of high-temperature minerals such as olivine, some of which display solar-flare particle tracks acquired in the nebula before they accreted into the carbonaceous matrix (Macdougall, 1977). Although they show evidence of post-accretion processing, C1 chondrites are the most chemically primitive of meteorites. They are, in effect, cosmic sediments with ratios of major and trace elements (except for H, C, N, O, and noble gases) that match so closely those measured in spectra of the Sun that C1 chondrites are used as the standard for judging the departure of all other planetary materials from solar composition.

The C2 chondrites consist of about equal proportions of C1-type matrix material and high temperature components, including chondrules, individual olivine and pyroxene grains, olivine aggregates, fragments of other chondrites, and about 1% inclusions rich in calcium-aluminum silicates. The C3 chondrites, with only about 0.4% C and 1% H_2O, consist of 35-40% matrix, largely made up of Fe-rich olivine averaging 5 microns in grain size, and 60-65% high temperature components. One subgroup of C3 chondrites contains up to 5% by volume of Ca-Al-rich inclusions.

These Ca-Al-rich inclusions (CAIs), have proved to be of extraordinary importance for the indications they give of nebular and interstellar components. They first gained widespread attention after the fall of the Allende meteorite in northern Mexico at 1:05 a.m. on February 8, 1969. More than two tons of fragments were collected and samples distributed to laboratories around the world, just as scientists were preparing to apply new microanalytical techniques to the Apollo 11 samples later the same year. The Allende meteorite proved to be a C3 chondrite with an abundance of pink and white CAIs, both spherical and irregular in shape and ranging in size up to 2 cm. These inclusions are assemblages of anorthite ($CaAl_2Si_2O_8$), Ca-Al-Ti-rich pyroxene, melilites (solid solutions of $Ca_2Al_2SiO_7$ and $Ca_2MgSi_2O_7$), spinel (Mg_2SiO_4), perovskite ($CaTiO_3$) and other highly refractory minerals. Some of them contain "nuggets" of platinum group metals, and all show enhancements in involatile trace elements.

In an early study, Marvin, Wood and Dickey (1970) noted that the constituents of CAIs resemble the series of high temperature minerals predicted by Lord (1965) as condensates from a cooling nebula of solar composition. Subsequently, a vast literature accumulated showing that CAIs are of many varieties, some with igneous textures, others with fluffy textures suggesting nebular condensates (e.g. MacPherson and Grossman, 1984) while still others appear to be refractory residues from which volatile elements have distilled away (e.g. Kornacki, Cohen, and Wood, 1983). Many of the isotopically anomalous involatile elements, suggestive of interstellar origin, have been measured in CAIs.

1.4. Iron Meteorites

Iron meteorites are masses of metallic nickel-iron with minor accessory minerals, chiefly sulfides, carbides, and phosphides. Most irons appear to have crystallized from cores or pods of molten metal within chondritic parent bodies. Cooling rates, ranging from less than 1° to about 110° C per million years, have been calculated from the textures and Ni distributions within iron meteorites (e.g. Scott, 1979). Such rapid rates (by planetary standards) could occur only within small, poorly-insulated bodies. Additional evidence for rapid cooling comes from radiometric age determinations showing that iron meteorites solidified within a few tens of millions of years after the birth of the Solar System. Trace element analyses show that iron meteorites belong to about 60 chemical groups, suggestive of derivation from a large number of different parent bodies. Although, as noted above, most irons originated from melts, some of them show chemical variations over distances of a few centimeters, indicating that the metal never completely melted and homogenized. Indeed, instead of having formed as molten pools within a predominantly silicate-rich planetoid, certain irons may record a history of primary metal-grain condensation and accretion in the cooling solar nebula (Kelly and Larimer, 1977). Isotopic anomalies suggesting the presence of presolar grains in certain irons is reported in Sections 3.1.4. and 3.1.5.

1.5 Stony-Iron Meteorites

These rarest of meteorites contain silicates and metal in roughly equal proportions. They occur in two main varieties: pallasites and mesosiderites. Pallasites consist chiefly of coarse grains of olivine, ranging in size up to about one centimeter, embedded in a meshwork of metallic Ni-Fe. Textural relations suggest that a mush of olivine grains, segregated from a silicate melt, was engulfed by molten metal. Immersion of olivine, of density 3.4 g/cc, in metal of density about 7 g/cc, would be most likely to occur at the core-mantle boundary of a small body with a minimal force of gravity and no convective overturn. Mesosiderites, sometimes called meteoritic "wastebaskets," are admixtures of silicates and nodular masses of Ni-Fe metal, plus minor oxides, phosphates, and sulfides. Many show evidence of metamorphism, brecciation, and even of late-stage partial remelting, ascribed by Floran *et al*., (1978) to meteoritic impacts on their parent bodies. Marked ^{15}N enrichments, of possible interstellar origin, measured in two mesosiderites are discussed in Section 3.2.

1.6. Achondrites

As noted above, 8% of meteorites seen to fall are achondrites--stony meteorites free of chondrules. Achondrites are magmatic rocks, some resembling basaltic lavas while others formed by crystal-settling in cooling melts. Isotopic age determinations indicate that most achondrites crystallized about 4.6 billion years ago, which implies a short period of igneous activity at the birth of the Solar System. The probable source for an early, intense heat pulse was ^{26}Al, a radioactive isotope with a half-life of only about 7.3 x 10^5 years. All achondrites have been brecciated and metamorphosed to some degree, and some show shock-wave effects due to preterrestrial collisions. A few exceptional achondrites, of extraordinary significance in determining the sources of meteorites, are discussed in Sections 2.2 and 2.3.

2. METEORITE SOURCES

Most, if not all, meteorites are collisional debris of planetary bodies. With few exceptions they originated in parent bodies 4.6 billion years old. Indeed, the age of the Earth and of the Solar System was determined by comparing the isotopic ratios of radiogenic to primeval lead in meteorites with those in terrestrial rocks (e.g. Patterson, 1956).

2.1. Asteroids

The overwhelming majority of meteorites are fragments of asteroidal-sized bodies. This is indicated by several lines of evidence: for example, the presence in meteorites of minerals and hydrocarbon compounds stable only at low temperatures and pressures; the ancient ages of meteorites and their rapid cooling rates; and the elliptical orbits of meteorites, calculated from photographed fireballs, which show aphelia in the asteroid belt. A link between meteorites and asteroids is strengthened by infra-red reflectance spectra of asteroidal surfaces, many of which closely match the spectra of crushed meteorites (e.g. Gaffey and McCord, 1979). The asteroid Vesta shows spectra similar to those of basaltic achondrites (Drake, 1979); the spectra of Hebe, Flora, and several other asteroids resemble those of mesosiderites; and numerous asteroids have dark albedos and reflectance spectra matching those of carbonaceous chondrites. There is a surprising dearth of belt asteroids with surface compositions similar to ordinary chondrites. This has led to suggestions that Apollo-Amor asteroids, which follow Earth-crossing orbits, may be a source of ordinary chondrites. Relatively few good spectra have been obtained on Apollo-Amor asteroids, but these bodies appear to be of diverse types. Some of them may be the stony remains of short-period comets that have lost their ices (Shoemaker, et al., 1979). In any case, neither belt nor Apollo-Amor asteroids are likely sources of 11 remarkable achondrites described in the following sections.

2.2. The Moon

On January 18, 1982, the first meteorite from the Moon was discovered by members of a U.S. meteorite-collecting expedition in Antarctica. With large, white clasts in a dark, glassy matrix, the specimen resembled no other meteorite, but it bore an eerie resemblance to rocks collected on the Apollo 16 mission to the lunar highlands. Laboratory studies quickly led to a rare unamimity among meteoriticists and lunar scientists that this meteorite (Allan Hills 81005) is, indeed, a lunar rock (e g. Marvin, 1983, and other authors in Geophys. Res. Lett.) The white clasts are rich in anorthite, a mineral that occurs sparingly in meteorites (mainly in CAIs) but is so abundant on the Moon that it accounts for the light color of the highlands. Clasts of lunar mare basalts are also present, as are glass spherules of types that are common in the lunar soils. The major and trace element abundances, oxygen isotopic signature, solar wind-implanted noble gases, and magnetic properties are all distinctly lunar in character and unlike those of other meteorites. A lack of nuclear particle tracks in lithic fragments, together with an unusually low natural thermoluminescence, suggests a transit time in space of less than 2,500 years--consistent with a rapid flight to Earth of materials blasted off the Moon by a high-energy meteorite impact.

Exceptionally low values of certain trace elements, (notably K, REE, P, U, and Th) in the white clasts, indicate that this specimen came from a highland site not sampled by either the Apollo missions or the unmanned Luna missions of the Soviet Union. Remote sensing analyses of the lunar crust suggest that this meteorite was ejected from an impact crater situated on the easternmost limb, or a little further around on the farside of the Moon. Thus, without leaving the Earth, we have sampled a new area of the Moon.

The discovery of one meteorite from the Moon led to the recognition of two more in Antarctic meteorite collections made by Japanese field parties (Yanai and Kojima, 1984). All of the lunar meteorites are soil breccias with unexpectedly light shock effects. Computer models had predicted that any lunar target materials accelerated to lunar escape velocity (2.4 km/sec) must be excavated from deep in the crust and shocked to glass. New calculations were begun as soon as specimens were found that belied these predictions; and interest was renewed in eight achondrites that had been suspected of coming from Mars.

2.3. Mars

With an escape velocity of 5 km/sec, Mars has always seemed an unlikely planet from which to derive meteorites. Yet 8 enigmatic achondrites have crystallization ages of only about 1.3 billion years (Shih, et al., 1982). Magmatic activity of such recent vintage seems to require a well-insulated parent body significantly larger than the Moon, where the last signs of major volcanic activity ceased more than 3 billion years ago. Furthermore, the petrological and geochemical character of these achondrites (the shergottites, nakhlites, and chassignites, or SNC meteorites) match those of igneous rocks from large, rather than small, parent bodies, an observation that led Walker, Stolper, and Hays (1979) to suggest a Martian origin. Mars has the largest volcanoes in the Solar System, and they are skirted with lava flows that are probably less than 2 billion years old, as shown by the scarcity of impact craters on their surfaces. Nevertheless, the horrendous dynamic problem of blasting specimens off that planet led most scientists to reject the idea of Martian meteorites. We could not, they argued, expect to find meteorites from Mars unless we also found them from our smaller, closer neighbor, the Moon.

Opinions began to change in 1981, partly because of the discovery of lunar meteorites and partly because of the contents of gas-rich pods of glass found in an Antarctic shergottite (Elephant Moraine 79001) collected in the 1979-80 season. The glass contained nitrogen and noble gases with isotopic compositions and relative abundances similar to those measured in the Martian atmosphere by the Viking landers (Bogard and Johnson, 1983). The Viking landers also made x-ray fluorescence analyses of Martian soils, and these show a marked resemblance to those of crushed shergottites (e.g. McSween, 1985; Keil, 1984). The compositions are not identical but would not be expected to be, as Martian soils must derive from several types of bedrock. There remains the unsolved problem of accelerating impact ejecta of appropriate sizes to Martian escape velocities without destroying them altogether. Melosh (1985) and others are testing spallation models but have not yet found a solution.

3. INDICATIONS OF INTERSTELLAR COMPONENTS

Many studies of meteorites have aimed at distinguishing surviving samples of the primeval solar nebula from those processed within planetary bodies. In recent years several lines of research have raised the exciting possibility that meteorites contain interstellar components. The evidence is chiefly isotopic, but some of it is based on mineralogy.

3.1. Isotopic Evidence

Isotopic signatures not positively identified as resulting from solar system processes are found in meteorites among volatile elements, especially H, C, N, O, and the noble gases, and involatile elements (e.g. Mg, Ca, Ag, Nd, Ti, Cr, etc.). Some of the most intriguing evidence is found in carbonaceous chondrites (Kerridge and Chang, 1985).

3.1.1. Deuterium Enrichments in Carbonaceous Chondrites. Insoluble residues of these meteorites consist of extremely fine-grained aromatic and aliphatic species resembling kerogen (Kerridge, 1983). This material shows striking isotopic heterogenieties. Different microsamples of the same residue will vary widely in values of D/H, $^{13}C/^{12}C$, and $^{15}N/^{14}N$. Robert and Epstein (1982) measured enrichments in deuterium (relative to the average galactic value of $2x10^{-5}$) of up to $5.4x10^{-4}$, with even higher values ($7x10^{-4}$) observed during stepwise extractions. In a study of 19 carbonaceous and unequiligrated ordinary chondrites, Yang and Epstein (1983) measured D excesses up to about 2000 per mil in insoluble carbonaceous residues, and an inferred isotopic composition of D equalling 10,000 per mil in acid soluble material.

Such D/H enrichments are attributed not to nuclear processes but to ion-molecular exchange reactions at temperatures below 40^{o} K (Geiss and Reeves, 1981). Yang and Epstein (1983) argued that the D-rich carbonaceous matter must have formed in interstellar clouds where ionizing conditions and low temperatures both existed. McKeegan, Walker, and Zinner (1985) supported this idea, stating that deuterated organic matter in primitive meteorites actually may be a sample of preserved molecular cloud material which has not equilibrated isotopically with average solar system material.

D/H values in individual Brownlee particles (interplanetary dust grains) were measured by Zinner and McKeegan (1984), who found D enhancements associated with carbonaceous matter. Brownlee particles often show extreme isotopic heterogeneity over distances of microns, hence they have escaped mixing and reprocessing in a reservoir of "normal" hydrogen. Most of these particles are presumed to have originated as interstellar grains that were incorporated into comets 4.6 billion years ago and were released to the interplanetary medium less than 10^4 years ago. However, about 0.1% of them may enter the Solar System directly from galactic space.

3.1.2. Anomalous Nitrogen Enrichments. Carbonaceous chondrites often show widely variable values of $^{15}N:^{14}N$. However, the highest enrichments in ^{15}N ever found in any meteorites were recently reported by Prombo and Clayton (1985) in the Bencubbin and Weatherford stony-iron meteorites. They measured enrichments, ranging from ^{15}N +414 to +973 per mil in the silicate fractions, the metal fractions, and bulk samples. Indeed, the bulk meteorites showed a greater enrichment than any of the fractions, implying the presence of a component with extraordinarily high $^{15}N:^{14}N$. Previous whole-rock values measured in meteorites ranged from ^{15}N -90 to +335 per mil, with the great majority lying between -90 and +50 per mil. Prombo and Clayton concluded that the excess ^{15}N may be an unhomogenized product of nova explosions, or else it originated by extreme isotopic fractionation at temperatures below 40° K in a presolar molecular cloud.

3.1.3. Oxygen Isotopic Anomalies. Clayton, Grossman, and Mayeda (1973) reported that oxygen isotopes in carbonaceous chondrites show a pronounced enrichment in ^{16}O, which they ascribed to nuclear processes. They speculated that the ^{16}O-rich component might be presolar dust that escaped homogenization in the nebula. Their observations have been extended to many types of meteoritic samples and the story has become considerably more complex, but the possibility remains that the isotopes, ^{16}O, ^{17}O, and ^{18}O formed in separate astrophysical processes and were sited in different reservoirs of gas and dust (Clayton, et al., 1983). An alternative mode of origin ascribes the ^{16}O enrichments either to differential effects of solar particle bombardment or to non-mass-dependent chemical fractionations within the nebula (Thiemens and Heidenreich, 1983).

3.1.4. Isotopic Anomalies in Noble Gases. All of the noble gases (He, Ne, Ar, Kr, Xe) are found in meteorites, and all display isotopic anomalies suggestive of presolar origin (Lewis et al., 1979). In no case has the carrier of a given anomaly been positively identified, because gas analyses require relatively large samples of crushed or insoluble materials. For an interstellar gas component to survive reprocessing in the nebula and in parent bodies would require it to be implanted in a refractory phase or one encased within an unreactive material. The following are among the more compelling examples of probable interstellar gas isotopes.

^{22}Ne, found in carbonaceous chondrites, was originally described as neon-E by Black (1972), who proposed a presolar origin. The favored mechanism for forming it is condensation in Na-minerals in the vicinity of exploding stars (e.g. Clayton, 1975). Eberhardt, et al. (1979) reported presolar grains in the Orgueil C1 chondrite on the basis of its Ne-E component.

A large excess of ^{40}Ar over that which could be produced by the decay of ^{40}K in the age of the Solar System, was measured in K-rich minerals in CAIs by Jessberger et al. (1980). Could the excess have been carried into the meteorite by presolar dust grains that were previously enriched in ^{40}Ar? We have no answer, but D. D. Clayton (1975) predicted such an effect several years before it was discovered.

Excess ^{129}Xe measured in meteorites is generally interpreted as a daughter product of ^{129}I (half-life 17 my) present in the solar nebula. Other sources have been proposed, however, including a preexisting excess of ^{129}Xe in presolar dust. A component named Xe-X, rich in both the heaviest and lightest of the nine isotopes of xenon, was discovered in carbonaceous chondrites by Manuel, Hennecke, and Sabu (1972). The component is difficult to account for except by r- and p-process synthesis in supernovae, with subsequent siting of carrier grains (of unknown composition) in meteorites. Occurrences in iron meteorites of anomalous isotopes of Xe, indicative of presolar grains, are reported by Goel (this volume).

3.1.5 Anomalous Isotopes of Involatile Elements. Isotopic anomalies of possible presolar origin are of two main types: excess radiogenic daughter nuclides, and FUN anomalies (in which F stands for Fractionation that is mass-dependent; UN for UNknown causes of nonmass-dependent excesses or deficits). FUN anomalies are very rare, but any given inclusion may show either F or UN anomalies or both.

Excess daughter nuclides of possible interstellar origin include ^{26}Mg (from short-lived ^{26}Al), ^{107}Ag (from ^{107}Pd), ^{142}Nd and ^{143}Nd (from ^{146}Sm and ^{147}Sm) (Wasserburg, 1985). Most of these anomalies occur in CAIs but excess ^{107}Ag was reported in iron meteorites by Kaiser, Kelley and Wasserburg (1980). Goel (this volume) reports Hg and Os as well as Xe anomalies in irons, indicating that these igneous-looking metals have not been completely homogenized.

FUN anomalies, believed to be of nucleosynthetic rather than nebular origin, have been measured in Mg, Si, Ca, Ti, Cr, Sr, Ba, Nd, and Sm (e.g. Lee, 1979; Begeman, 1980). A striking example of an F (mass-dependent fractionation) was reported by Hutcheon et al. (1983), who located minute patches of anomalous Mg scattered through a grain of hibonite ($CaAl_{12}O_{18}$) in the Murchison C2 chondrite. Was the anomalous Mg carried by interstellar grains that were captured and preserved within the hibonite? It is an intriguing possibility, but F effects are not uniquely interstellar.

3.2. Mineralogical Indications of Presolar Grains

3.2.1. Graphite-Magnetite Aggregates. Small quantities of graphite and magnetite, in aggregates of submicron grain size, occur in the matrixes of some unequilibrated ordinary chondrites and in veinlets in brecciated chondrites (Scott et al., 1981). Graphite and magnetite are relatively uncommon minerals in meteorites, and it is difficult to attribute the fine-grained aggregates to any familiar meteoritic process. The mode of occurrence indicates that the aggregates were mixed into the fragmental surface materials of parent bodies by a succession of impacts. Could the magnetite-graphite component itself, which occurs in some models of interstellar grains, have been plastered onto the parent asteroid from the interstellar medium?

3.2.2. Luminescent Olivine. Recent studies have revealed certain types of olivine that glow blue and red when exposed to cathode luminescence (e.g. Steele Smith and Skirius, 1985). Typically, olivine with blue luminescence occurs as cores, up to 0.5 mm across, rimmed with red-luminescing olivine. The blue variety is essentially pure forsterite (Mg_2SiO_4), but, unlike any familiar olivine, it contains up to 0.6% CaO, 3000 ppm Al_2O_3, 2000 ppm Cr_2O_3, 800 ppm TiO_2, and traces of V. The forsterite is highly refractory and so clear and inclusion-free that it looks like a condensate from a vapor. The red-luminescing phase rimming the blue is Fe-rich, cloudy with minute inclusions of glass and metal, and clearly a later melt product.

Isolated grains of the forsterite are embedded in the matrixes of C2 and C3 chondrites and of some unequilibrated ordinary chondrites. Well-formed crystals of it also occur in chondrules, where they are clearly an earlier component, showing only marginal traces of reaction with the surrounding melt. Similar-appearing grains of forsterite (too small for trace element analyses) have been found in Brownlee particles (Steele, Smith, and Brownlee, 1985).

An interstellar origin has been suggested for this refractory olivine partly because some grains of it are older than chondrules. The distinctive trace element content is not expected in melted nebular dust, or in nebular condensates, as the Al should enter spinel or anorthite at temperatures of 1300-1400^{o} K when olivine is condensing. However, an origin by condensation in interstellar clouds is scarcely easier to envision. Both the coarse grain size and the abundance of the blue-luminescing olivine grains argue against an interstellar origin. We expect presolar components to be tiny, elusive, and impossible to isolate. No particles above the micron size range have been detected in interstellar space, but, if they occur there we could not observe them with the sensing techniques avaliable to us.

4. METEORITE SOURCES ON THE EARTH: THE ANTARCTIC CONCENTRATIONS

Except for a minor preponderance of falls within the tropics (because most interplanetary material orbits within the plane of the ecliptic) meteorites fall at random on the Earth, at an estimated rate of two to

https://doi.org/10.1017/S007418090015449X Published online by Cambridge University Press

three each day. Meteorite discoveries could never be anticipated, however, until 1973 when Japanese scientists learned that specimens from many different falls are sometimes frozen within the Antarctic ice sheet and concentrated on "stranding surfaces" behind mountain barriers. Since that year Japanese and American-led teams have searched for meteorites at several widely separated sites in Antarctica and have recovered approximately 7000 fragments--most of them weighing only about 5 grams but with a significant number over 10 kilograms (e.g. Marvin and Mason, 1984). The numbers are not so important, however, as the fact that the Antarctic collections include new species of stony meteorites, the first lunar meteorites, the second known diamond-bearing iron meteorite, a gas-rich shergottite bearing earmarks of possible Martian origin, and meteorites from the oldest falls ever dated. Measurements of cosmic ray-produced isotopes show that certain Antarctic meteorites fell to the ice 700,000 years ago, and many of them fell between 100,000 and 400,000 years ago, whereas most specimens collected elsewhere in the world fell within the past 200 years.

Expeditions to Antarctica are an elegant means of enriching the world's collections with research material while we await future planetary missions. In 1985 a third nation joined the effort. That nation was India. We congratulate our Indian colleagues, and wish them all success.

5. ACKNOWLEDGEMENTS. This work was supported by NASA Grant NAG 9-29 and Smithsonian Institution Research Opportunities Fund 1240F617.

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DISCUSSION

D'HENDECOURT: In what form does carbon occur in Cl chondrites? What is kerogen?
MARVIN: The elemental carbon in Cl chondrites is amorphous. Kerogen is a very general term for insoluble organic matter in terrestrial sediments.

D'HENDECOURT: Olivine grains are believed to be formed in M super-giants, but their structure is amorphous (as inferred from IR spectra of interstellar dust. The olivine, even in Cl chondrites, seems to be crystalline, which implies a degree of processing (heating) to go from amorphous to crystalline material. What is the precise structure of olivine in Cl chondrities and what can be inferred from this structure?
MARVIN: The olivine grains in Cl chondrites are indeed crystalline and are generally regarded as high temperature nebular components. The blue luminescing olivines in C2 and C3 chondrites are crystalline but their refractory composition, clarity, and pre-chondrule date of formation led to suggestions of an origin by gas-solid condensation. It is not clear that later, high temperature recrystallization would be necessary. But an origin by direct condensation in either the nebular or interstellar clouds is by no means established.

SHAPIRO: Could the excess ^{15}N in the stony-irons be due to bombardment of oxygen by cosmic rays?

https://doi.org/10.1017/S007418090015449X Published online by Cambridge University Press

MARVIN: That mechanism was not among those discussed by Prombo and Clayton who reported the excess. Such an origin is unlikely because the isotopic effects of cosmic ray bombardment die out quickly from the surfaces to the interiors of meteorites, and the excess ^{15}N was measured in all fractions of the two stony-irons.

GOEL: (i) I would like to answer the question raised by Dr. Shapiro regarding the cosmic ray production of N isotopes from O in meteorites. These rates are too low to cause appreciable isotopic changes. Moreover, most stones are exposed to cosmic rays and the huge N isotopic excesses are seen, on the contrary, only in a few. (ii) My second comment is in defence of the suggestion that I have presented in my contributed paper advocating that iron meteorites are produced by a non-magmatic process, perhaps by particle-particle accretion. Leaving aside the isotopic anomalies that we have reported in irons, there are a number of peculiar observations about these objects that force us to abandon the magmatic origin. For example, (a) how do we get angular inclusions in irons; (b) how is it that the chemical composition of some of the inclusions is like those of C-1 chondrites? The constraints due to slow cooling rates have now been removed since in a recent publication in Geochimica Acta, these have been revised by two orders of magnitude, from a few degrees per million years to a few hundred or few thousand degrees per million year.

SAHAI: Since SiC is thought to be a consistent of circumstellar grains of carbon-rich giants, has anyone looked for SiC in meteorites and with what result?
MARVIN: Early in this century SiC was found in the Canyon Diablo iron meteorite and named moissanite, for Henri Moissan who discovered it. Subsequent investigators found that the Canyon Diablo material matched the crystal structure of Type II SiC, the main component of Carborundum, an abrasive commonly used in polishing iron meteorites. Moissanite was not found again in any meteorite where it could be confirmed as a valid component, and so, in the 1960s, it was removed from lists of meteoritic minerals. Perhaps we should make a special search for SiC in fine-grained aggregates in carbonaceous meteorites.

GUELIN: I thought that the agreement between carbonaceous chondrite and solar abundance was much better for C and N than what you showed. There was a large difference specially for C and N abundance. Can you comment on that.
MARVIN: I don't quite understand it but I don't think, that I can assert that there isn't any better than what was shown from a recent compilation.