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## INTERSTELLAR MATERIAL IN THE SOLAR SYSTEM

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All the substance of the earth and other terrestrial planets once existed in the form of interstellar grains and gas. A major aspect of solar system formation (and undoubtedly of star formation generally) is the complex series of processes that converted infalling interstellar grains into planets. A cryptic record of these processes is preserved in certain samples of planetary materials, such as chondritic meteorites, that have been preserved in a relatively unchanged form since the beginning.

It is to be expected that some of these primitive materials might contain or even consist of preserved presolar interstellar grains. The identification and study of such grains, the ancestors of our planetary system, is a matter of intense interest. This Section briefly discusses the types of primitive material accessible to us, or potentially accessible, and its component of or relationship to presolar interstellar grains.

**GRAINS ACCRETING FROM THE INTERSTELLAR MEDIUM TO THE SOLAR SYSTEM IN THE PRESENT EPOCH**

The planets sweep up a certain amount of dust directly from interstellar space as the solar system moves through the galaxy. The solar system is currently surrounded by interstellar material of average density  $0.1 \text{ H atom/cm}^3$ , and temperature 12,000 K. It may be 50% ionized. With respect to the sun this material is moving at 25 km/sec. The velocity vector of the sun suggests that it has been embedded in material of this density for 25 million years.

For a hydrogen-to-dust mass ratio of 100/1 and assuming grain radii of 0.01 microns and densities of  $3 \text{ g/cm}^3$ , the local dust density would be  $10^{-10} \text{ grains/cm}^3$ . If these impinging grains penetrate the heliopause, the solar wind, and the magnetopause without destruction, and have their orbits determined only by the gravitational field of the sun, we might expect the density

at 1 AU to be enhanced by gravitational focusing by factors of 3-10, yielding a maximum grain density near the earth of  $10^{-9} \text{ cm}^{-3}$ . Since the maximum motion of the earth relative to the cloud (when Earth's orbital motion is counter to the particle flux) is 55 km/sec, this would yield a maximum interstellar grain flux at the top of the earth's atmosphere of  $6 \times 10^{-3} \text{ cm}^{-2} \text{ sec}^{-1}$ . This is a substantial flux in terms of numbers, but the increment of mass is very small: it would amount to only 1 mg per  $\text{cm}^2$  of the earth's surface over the age of the solar system in the unlikely event that the earth had always been immersed in its present low density region of interstellar space. (This estimate does not take into account the interaction of the solar wind with charged grains, or the influence of solar radiation pressure. It is possible that these effects would substantially change the rate of accretion of interstellar particles to the earth.) Thus recently-arrived interstellar dust constitutes only a miniscule fraction ( $<10^{-4}$ ) of the extraterrestrial dust swept up by the earth each year ( $>10^4$  tons; McDonnell, 1978).

#### **INTERPLANETARY DUST: PROPERTIES AND PROCESSES**

Information on the interplanetary dust cloud has been obtained from zodiacal light observations, lunar microcrater statistics, dust experiments on spacecraft, meteor observations and laboratory simulation experiments. Here we are talking about particles in the size range 0.01 microns to 1 cm, having masses of  $10^{-18}$  g to 1 g. In the following we review present knowledge of the interplanetary dust cloud and processes governing it. We will show that most of this dust is derived from comets, which constitute a reservoir of relatively unprocessed presolar interstellar grains. After its release from comets, this material may have experienced mutual collisions, and this may have altered the original properties of interstellar grains. In the final paragraph we discuss the possibilities of identifying and analyzing interstellar grains that traverse the solar system.

The flux of interplanetary dust particles at 1 AU has been established from measurements of the lunar microcrater frequency, calibrated by spacecraft particle-impact experiments. For the larger particles, meteor observations provide an important source of information. The cumulative flux of the larger

particles ( $m > 10^{-6}$  g) is an exponential distribution proportional to  $m^{-1.34}$ . The midrange particle flux ( $10^{-12}$  g  $< m < 10^{-8}$  g) is flatter, going as  $m^{-0.36}$ . The small-particle flux steepens up again and is proportional to  $m^{-0.85}$  (for a recent review, see Grün et al., 1985).

The spatial distribution of interplanetary dust grains is obtained from observations of the zodiacal light (most of which is reflected from particles in the size range 10 microns to 1000 microns, i.e.,  $10^{-9}$  g to  $10^{-3}$  g), and from in situ experiments on deep space probes (which encounter particles mostly in the size range 0.1 microns to 10 microns, i.e.,  $10^{-15}$  g to  $10^{-9}$  g). Inside 1 AU the spatial density of interplanetary particles increases proportional to  $r^{-1.3}$ , where  $r$  is the distance to the sun. This increase continues to at least inside 0.1 AU. Outside 1 AU the radial dependence is somewhat steeper ( $r^{-1.5}$ ) to about 3 AU. Outside this distance little is known. The spatial density of small grains ( $m < 10^{-9}$  g) may be constant or only very slowly decreasing out to 20 AU (Pioneer 10).

The major processes presently acting on interplanetary grains are mutual collisions, the Poynting-Robertson effect, and radiation pressure ejection of small meteoroids. These effects act differently on particles of the different size regimes. At 1 AU big meteor particles ( $m > 10^{-5}$  g) are believed to be most affected by mutual collisions. The lifetimes are shortest ( $10^4$  years) for particles of masses  $10^{-3}$  g to 1 g. The Poynting-Robertson lifetimes are at least a factor 100 longer for these particles. These large particles will not change their orbits significantly due to Poynting-Robertson effects before they are involved in a collision and fragmented into smaller particles. Only smaller zodiacal light particles ( $m < 10^{-5}$  g) will have their orbits circularized by Poynting-Robertson drag and will eventually spiral in towards the sun, where they evaporate. Even smaller particles ( $m < 10^{-12}$ ) are affected by radiation pressure, which counteracts gravitational attraction. Such small particles, which are generated by collisions between larger parent meteoroids or which are released from comets, will generally follow unbound trajectories out of the solar system. Because of its short lifetime with respect to collisions ( $10^4$  yr), this meteor-sized particle population needs a steady supply from comets throughout the solar system. Collisions among main belt asteroids do

not seem to play a major role in supplying small meteoroids ( $m < 1$  g) to the Earth and the inner solar system.

The origin of the majority of large particles ( $m > 10^{-5}$  g) is comets. Meteor streams are clearly derived from comets. Even sporadic meteors have somewhat related orbits which indicate a cometary origin. The majority of zodiacal light ( $10^{-10}$  g to  $10^{-5}$  g) particles are fragments from larger meteor-sized particles, the collisions of which are adequate to account for their source. The smallest interplanetary particles ( $m < 10^{-12}$  g) also originate from collisions of meteor-sized particles, for the most part, though in extended cometary tails the small particle population may be dominated by primary particles shed by the nucleus.

The interstellar particles that penetrate the solar system (discussed above) constitute only a small fraction of the small particle population. Orbital information from in situ experiments on Pioneer 8, 9, and Helios indicate that <10% of the observed particles have orbits compatible with an interstellar source. The upcoming International Solar Polar Mission will attempt to measure the interstellar component of particles above the ecliptic plane. With existing technology it is feasible to build a new dedicated experiment that would measure the flux and size distribution of IS grains entering the solar system. When techniques for measuring precise orbital parameters of particles are refined, it will be possible to actually collect particles that can be proven to be extrasolar on the basis of their hyperbolic orbits. Collection will be made with the techniques used on the Long Duration Exposure Facility and developed for the Flyby Comet-Coma-Sample Return mission.

#### **INTERPLANETARY DUST: PARTICLES COLLECTED ON EARTH AND STUDIED INDIVIDUALLY**

Debris from comets and asteroids exists as interplanetary dust for only  $10^4$  yr before being destroyed by collisions and Poynting-Robertson drag. Large numbers of dust particles are swept up by the earth, and their collection and analysis provides a means of investigating a variety of primitive asteroidal and cometary bodies that may not be represented by samples in the existing inventory of conventional meteorites. Of particular importance is



the high probability that many of the collected dust particles are samples of comets, bodies that accreted under very cold conditions and in which presolar IS grains may be preserved.

Interplanetary dust particles (IDP) are collected in the stratosphere by high-altitude aircraft, and particles larger than 100 microns are collected from the ocean floor and from polar ice. All of these particles were strongly heated during stratospheric entry; only those smaller than 10 microns were not heated to more than 600 C. The collected particles probably represent debris from a large number of small parent bodies: they should not be considered to have a common origin. Each particle is an individual meteoritic object with an unknown origin. There is currently no criterion for distinguishing cometary from asteroidal particles. The extraterrestrial origin of the particles is proven by their content of cosmic ray tracks, implanted solar wind atoms, and (in the case of particles >200 microns) cosmogenic  $^{26}\text{Al}$ ,  $^{10}\text{Be}$ , and  $^{53}\text{Mn}$ , primordial noble gases (Rajan et al., 1977; Hudson et al., 1981), and large D/H fractionation ratios (Zinner et al., 1983).

Particles collected from the stratosphere have diverse properties, consistent with their derivation from a number of discrete parent bodies. A common property of most of the particles is that they have chondritic (solar) elemental abundances of the involatile elements. Many of the particles that do not have this composition are single mineral grains with material of chondritic composition adhering to their surfaces, implying that the grains were originally embedded in chondritic material. The chondritic material is black, contains up to 5% carbon, and is often extremely fine grained. It is the only meteoritic material that has a truly chondritic composition on the micron size scale. Most of the chondritic particles are aggregates of grains ranging in size from <100 A to >1 micron, but there is diversity in structure and mineralogy among the aggregates.

Two distinct types are (a) rather nonporous particles composed primarily of hydrated silicates, and (b) extremely porous aggregates (Fig. 1). The latter class (chondritic porous aggregates or CPA's) are the most fragile of meteoritic materials; their physical properties are the most compatible with

those inferred for cometary meteors. The basic subunits of these aggregates are individual rounded grains in the size range 1000-5000 A, which are weakly attached to one another to form a highly porous structure. These constituent grains have widely differing compositions, and obviously did not form in equilibrium with each other.

### IDP Mineralogy

The morphologies of some mineral grains in IDP's suggest that they condensed from a vapor (see below). Some of the rounded submicron grains are single minerals, while others are complex particles composed of tiny crystalline phases embedded in amorphous carbon. This unique material contains grains less than 100 A in size. No IDP (or meteorite) ever examined has been found to contain aggregates of rodlike or rounded core-mantle grains of the types that are commonly discussed as interstellar (IS) grain models. It is possible, however, that the submicron grains composed of tiny crystals embedded in carbon could be either metamorphosed IS grains, or that they might actually be rather well-preserved IS material. Graphite occurs in these materials, but only in trace amounts. Some of the graphite is probably formed by catalysis, because it occurs in association with other forms of carbon that appear to have formed by catalysis. Carbon is as abundant as Silicon (atomic proportions) in IDP's, but the bulk of it is in the form of an amorphous phase that occurs both as coatings on grains and as pure grains several thousand Angstroms in size.

An overriding characteristic of the minerals in IDP's is their very small grain size. Consequently, few of the standard techniques of mineralogical analysis are readily applicable. The best method for the study of individual grains is Analytical Electron Microscopy (AEM) in its various aspects. Details of grain morphology are obtained by imaging, structure by electron diffraction (either selected-area or convergent-beam electron diffraction), and composition by energy-dispersive x-ray emission spectroscopy for elements of atomic number (Z)10 or greater and electron energy-loss spectroscopy for the lighter elements. The AEM thus offers a complete tool for mineralogical characterization on an individual crystal basis (although it does not provide

isotopic, trace element, or spectroscopic data). Major problems arise from sample preparation, radiation damage within the instrument, and the need for critical tilting of the specimen--in some cases beyond the operational capabilities of available instruments. Thus while AEM is in many ways an ideal technique for achieving the goal of understanding IDP mineralogy, it is a difficult technique with distinct limitations.

The carbonaceous material noted above may be present in IDP's as "clumpy masses" (Christofferson and Buseck, 1984; Rietmeijer and Mackinnon, 1985a), as coatings on mineral grains (Bradley et al., 1983a; Mackinnon and Rietmeijer, 1984; Mackinnon et al., 1985), and as filamentary grains. The latter may have been formed by heterogeneous catalysis reactions (Christofferson and Buseck, 1983; Bradley et al., 1984). Some "clumpy masses" may be hydrocarbon compounds (Christofferson and Buseck, 1983). Detailed knowledge of the nature of these hydrocarbon compounds, especially their isotopic signature, will be needed to understand their origin or chemical evolution. The majority of the "clumpy masses" forms stacks of many thin (0.01 micròn) plates. Individual plates are decorated with very finely granular carbonaceous material. The granules sometimes form clusters with an open fluffy texture. The morphology and crystallographic properties of these "clumpy masses" are consistent with those of poorly graphitized carbon (PGC; Rietmeijer and Mackinnon, 1985a). Micro-Raman spectra of individual IDP's show double peaks at 1350 and 1600  $\text{cm}^{-1}$  that are characteristic of "disordered" graphite (Fraundorf et al., 1982). PGC in CPA's constitutes a link with carbonaceous chondrites, as PGC with similar properties has been observed in acid residues of these meteorites (Lumpkin, 1983; Smith and Buseck, 1981, 1982).

Mg-rich olivine and enstatite, which are abundant in chondritic meteorites, are also observed in chondritic IDP's, though in the latter they display a narrower compositional range. Fassaitte (Ca, Al-rich clinopyroxene) has been observed in one IDP (Tomeoka and Buseck, 1985a).

In general, chondritic IDP's are heterogeneous, non-equilibrium mixtures of both high- and low-temperature minerals. The low-temperature minerals may include layer silicates (Brownlee, 1978, Tomeoka and Buseck, 1984, 1985a,

1985b; Rietmeijer and Mackinnon, 1985b). These layer silicates include members of the smectite or mica group (Tomeoka and Buseck, 1984), and possibly also Mg-poor talc and kaolinite (Rietmeijer and Mackinnon, 1985b) and serpentine or chamosite (Brownlee, 1978). The layer silicates in chondritic IDP's are not similar to the principal layer silicates in C2 chondrite matrices, and they are also dissimilar to C1 chondrite phyllosilicates (Rietmeijer and Mackinnon, 1985b). These AEM observations contradict the conclusion of Fraundorf et al. (1981), from their infrared spectroscopy study of chondritic IDP's and C2 chondrite matrices, that layer silicates in both materials are similar. The discrepancy probably results from the difficulty of interpreting the IR spectra of very-fine-grained crystalline aggregates (Rietmeijer et al., 1985).

Most of the minerals in IDP's are similar to terrestrial minerals and/or those found in carbonaceous chondrites. However, IDP's also contain unusual minerals: some that were previously known, though rare, and others that are unknown except in IDP's. It is remarkable that the limited studies performed on IDP's have turned up as many unusual phases as they have. Two minerals have been found to date that are unknown except in IDP's, a carbide and a sulfide.

E-carbide has a composition between  $\text{Fe}_3\text{C}$  and  $\text{Ni}_3\text{C}$  (in approximate proportions of 8:1; Christofferson and Buseck, 1983; Bradley et al., 1984) in two different IDP's. Although it is only a minor constituent of IDP's, this mineral is of special interest because it is a possible residue of the catalytic conversion of  $\text{H}_2$  and CO to hydrocarbons by Fischer-Tropsch (F-T) reactions. Such a catalytic conversion process has been proposed by Anders and colleagues (Studier et al., 1968) as a solution of the long-standing problem of formation of the wide range of hydrocarbons that occur in certain carbonaceous chondrite meteorites. However, there was no evidence in these meteorites that such catalysis occurred, other than the hydrocarbons themselves. E-carbide is known terrestrially to be a product of F-T synthesis, and thus its presence in IDP's lends additional credibility to the proposals of Studier et al.



Sulfides are common constituents of IDP's, but most occurrences are the common minerals troilite (FeS), pyrrhotite ( $\text{Fe}_{1-x}\text{S}$ ), and pentlandite, ( $[\text{Fe},\text{Ni}]_9\text{S}_8$ ). The LOW-CA IDP contains all of these and, in addition, a mineral having the pentlandite structure, but a unique composition (Tomeoka and Buseck, 1984). It differs from normal pentlandite in that it contains less than 3 atomic percent Ni, whereas normal pentlandite contains over 20 atomic percent Ni. This low-Ni pentlandite has been synthesized by deposition from a vapor at  $<200$  C, but is not known from the natural environment (meteoritic or terrestrial).

The presence of carbonates was recently confirmed by electron microscope studies of the CALRISSIAN IDP (Tomeoka and Buseck, 1985b), where it forms in well-developed euhedral crystals having the calcite structure and compositions ranging between  $\text{FeCO}_3$  and  $\text{MgCO}_3$ .

A number of minerals in the IDP's have unusual morphologies that are possibly indicative of vapor-phase formation. The whisker crystals and platelets of enstatite described by Bradley *et al.* (1983b) are strongly suggestive of such an origin. The unusual morphology as well as the anomalous direction of elongation are characteristic of vapor deposition. Platelets of other minerals that are normally more equidimensional have been found in other IDP's. These include flat plates of olivine in U2001E3, and of magnetite and chromite (Christofferson and Buseck, 1984, 1985), and plates of pentlandite and especially low-Ni pentlandite in LOW-CA (Tomeoka and Buseck, 1984). While these unusual morphologies are not proof of vapor deposition, they are expressed in isometric or orthorhombic minerals that normally have very different morphologies. (Platelets of magnetite also occur in the matrices of carbonaceous chondrites, but here the morphology has been ascribed to aqueous alteration rather than vapor deposition.)

### Optical Properties

Detailed infrared absorption measurements in the wavelength region 3 to 20 microns have been made on over two dozen particles. The experimental results and their implications are discussed by Sandford and Walker (1985).

The earliest work (Fraundorf et al., 1980) showed that the spectrum of an ensemble of three particles was dominated by a strong absorption at 10 microns. Subsequent work has shown that almost all particles fall into three major categories, labelled "olivine", "pyroxene", and "layer-lattice silicate," based on their spectral similarities to terrestrial mineral standards. Detailed transmission electron microscope investigations of several selected particles have confirmed that the actual mineral assemblages are, indeed, dominated by the minerals identified by the infrared absorptions.

Comparison with the dust spectrum of comet Kohoutek determined by Merrill indicates both similarities and differences with the particle data; a reasonable fit to the comet spectrum is obtained by combining the spectra obtained from the pyroxene and layer-lattice silicate classes. However, the fit is much worse when particles of the olivine class are included. It would appear that the infrared properties of the particles can be made to fit the comet data, but only at the expense of including particles with very different mineralogies (pyroxenes and layer lattice silicate classes) and excluding particles that are known to be extraterrestrial (the olivine class). Thus the optical data are not straightforwardly consistent with a cometary origin of interplanetary dust.

Comparison of the dust spectra with astronomical observations of protostars show some interesting similarities and raise some questions to be answered by future research. In addition to the dominant 10 micron feature in their spectra (commonly ascribed to absorption by amorphous Mg,Fe silicate dust), both protostars and particles in the hydrated silicate class exhibit a ubiquitous feature at 6.8 microns. In one IDP, CALRISSIAN, the 6.8 micron band is actually stronger than the 10 micron band. The presence in this particle of a substantially weaker band at 11.3 microns indicates that the 6.8 micron band is due to a carbonate mineral. As noted above, detailed electron diffraction measurements and imaging of this particle (Tomeoka and Buseck, 1985b) confirm that it contains abundant Fe and Mg carbonates. It is possible, but not proven, that the 6.8 micron band seen in other particles of the same spectral class are also due to the presence of carbonates. Although the carbonate identification is virtually certain in the case of this one IDP, it

remains an open and interesting question whether the band seen in protostars has, at least in part, a similar explanation.

### Isotopic Compositions

Although the small size of interplanetary dust particles makes measurement a distinct challenge, isotopic measurements on major elements have been made. The first results were reported by Esat et al. (1979). Individual particles were studied in a thermal ionization source mass spectrometer, using a direct loading technique. Data were obtained on both Mg and Ca isotopes for 13 samples. The Mg isotopic composition of one particle was found to be highly mass fractionated (1.1% per amu). The measured Ca isotopic composition was the same as terrestrial Ca to within 2 percent.

In 1983 Zinner et al. showed that the D/H ratios in several particles were very much higher than in terrestrial samples. Values up to  $\delta D + 2000$  o/oo\* were found. These data were obtained with an ion microprobe, an instrument capable of measuring isotopes on sub-fragments of an IDP several microns in size. Subsequent work by Zinner and McKeegan (1984) demonstrated that the D/H signature was highly variable from one part of a given particle to the next. The excess deuterium was also found to be correlated with the concentration of C, but not OH, indicating that the carrier was probably a carbonaceous phase.

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$$\delta D = \left[ \frac{(D/H)_{\text{sample}}}{(D/H)_{\text{standard}}} - 1 \right] \times 1000;$$

typical range of terrestrial samples is  $\delta D = \pm 200$  per mil (o/oo)

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Carbon isotopic data were also obtained for several particles. Differences between particles of up to 40 ‰ were noted. This is a small effect, but outside the expected errors in the measurement. In contrast to the deuterium results, the carbon isotopic ratios were found to be constant from one fragment to the next of a given particle. As is the case with meteorites, the hydrogen and carbon isotopic effects appear to be decoupled.

Measurements of Mg and Si isotopes in three particles by Zinner et al. (1984) showed no deviation from terrestrial values.

Earlier measurements of the isotopic and elemental composition of the noble gases Ne and Ar in an ensemble of 13 particles by Hudson et al. (1981) indicate the presence of a solar-like component, presumably solar wind ions implanted into the particles during their recent sojourn in space as small particles. However, the presence of an indigenous trapped noble gas component of distinctive isotopic composition is also possible. Limited data on Xe isotopes indeed suggest the presence of a sizable trapped component.

Particles that fall into distinctive infrared spectral categories are currently being measured for their isotopic signatures. The data are as yet fragmentary, and no general conclusions can be drawn. Some particles falling in the layer-lattice silicate and pyroxene infrared classes have large  $d_{\text{D}}$  values; however this is not true of all particles in these spectral categories, some of which have  $d_{\text{D}}$  values which fall in the range of terrestrial values. At least one particle in the olivine spectral class, which is demonstrably extraterrestrial because it contains solar flare nuclear particle tracks, has a D/H ratio that is terrestrial.

The excess deuterium signature is thus highly variable in IDPs. This is similar to the situation in meteorites. Most carbonaceous meteorites do not give D/H anomalies when bulk samples are measured, but some do. In addition, acid residues of carbonaceous chondrites generally exhibit large, but variable, D excesses (e.g., Yang and Epstein (1983)). Thus in both IDP's and meteorites there appears to be a trace carrier which is highly enriched in deuterium and is present in highly variable amounts. Since the measured D

values give only lower limits on the deuterium concentration in the trace carrier phase, the D/H ratio in the carrier will be very large. A commonly held view is that these deuterium enrichments were probably caused by ion-molecule reactions in interstellar clouds.

### The Collection of Interplanetary Dust by Orbiting Spacecraft

A new way to study interplanetary dust became possible with the return to Earth of parts of the Solar Maximum satellite in April 1984. The Solar Maximum parts had been exposed to the space environment for about 50 months. Impact craters on these parts are being examined by scanning electron microscopy in conjunction with energy dispersive x-ray spectroscopy; this provides an excellent means of determining the compositions of impacted particles (Kessler et al., 1985). The results show that some of the impacted materials include residues of chondritic and iron-sulfide micrometeoroids (Schramm et al., 1985).

Several dust experiments are included in the payload of the Long Duration Exposure Facility (LDEF I), whose return to Earth, originally scheduled for March 1985, has been delayed. The experiments are designed to measure the elemental and isotopic composition of dust particles. The high impact velocity of the dust makes it unlikely that unaltered material will be studied. Instead, atoms from dust impacts will be collected and analyzed. This mission is a precursor to Flyby-Comet-Coma-Sample-Return missions, and to future experiments in which the orbital parameters of individual dust particles will be determined prior to their analysis.

## **COMETS**

### Dust Particles

Our knowledge of the physical properties of cometary grains derives mostly from measurements of their thermal emission and optical scattering in comets observed within 2 AU of the sun. From these data we can make only very general statements about the grain size and composition.



The scattered light is different in color for different comets, ranging from neutral to somewhat red in the wavelength range 0.25 - 2 microns. The lack of Rayleigh scattering tells us that the optically important grains have size  $\geq 1$  micron (A'Hearn, 1982). Thermal emission spectra indicate temperatures up to 25% higher than a theoretical black body in equilibrium, indicating that the grains contain absorbing material and are mostly  $\leq 10$  microns in size. A size distribution for the flux of grains released from the nucleus that peaks at radii of 0.35-0.6 microns and decreases proportional to  $r^{-4.2}$  for larger particle sizes is compatible with both the photometric data and analyses of the grain dynamics (Hanner, 1983, 1985).

The ratio of the scattered/thermal radiation indicates that the grains are very dark, with a geometric albedo typically 0.03-0.04 at wavelengths of 1-2 microns. The grains shed by Comet Cromelin at 1 AU were even blacker, with geometric albedo 0.015 at 1.2 microns and 0.022 at 2.2 microns (Hanner et al., 1985).

Cometary emission features near 10 microns and 18 microns are generally interpreted as signifying the presence of small ( $< 10$  microns) silicate grains. The only spectral scan that has been made of the 10 micron feature (comet Kohoutek at 0.3 AU; Merrill, 1974) shows a broad structureless feature, suggesting amorphous, rather than crystalline grains.

### Volatiles

Much of the icy material in comets may have arrived there from the interstellar medium as mantles on refractory grains, and therefore should be considered in this Section. Nearly all species directly measurable in comets are products of photodissociation or other processing (gas phase chemistry, ionization, etc.). In a few cases the parent molecule is reliably known, but in most cases it is not.

The dominant volatile species in the nucleus is  $H_2O$ . It was detected directly (via a radio emission line) in comet IRAS-Araki-Alcock 1983d (Altenhoff et al., 1983), and probably detected in comet Bradfield 1974B

(Jackson et al., 1976). It is reliably inferred in other comets from the relative abundances of O, H, OH, and  $\text{H}_2\text{O}^+$  (Weaver et al., 1981). In most comets  $\text{H}_2\text{O}$  represents more than 95% of the volatiles, although in a few comets (e.g., comet West 1976 VI) there may be roughly 30% CO or possibly  $\text{CO}_2$  (Delsemme, 1982). CO has been detected directly in comet West by its ultraviolet emission bands (Feldman, 1982).

Other species which may reside in the nucleus and which have been directly detected include:  $\text{NH}_3$ , a trace species seen only in comet IRAS-Araki-Alcock (Altenhoff et al., 1983); HCN and  $\text{CH}_3\text{CN}$ , trace species detected in comet Kohoutek 1973f and comet 1983d, and inferred in many other comets from the presence of CN;  $\text{S}_2$ , measured in comet 1983d (A'Hearn et al., 1983), whose spatial distribution suggests that it comes from the nucleus despite the unlikely chemical situation necessary. Modeling of the chemistry in cometary comae has shown that the ices of the nucleus can not produce the observed radicals in the coma in the right amounts if the ices are equilibrium condensates, but can produce them all in the right amounts if the ices contain the complete suite of molecules seen in interstellar clouds (Mitchell et al., 1981).

The inventory of atoms in the cometary volatiles is not complete, but it seems clear that C is depleted by a factor of 2-4 relative to its cosmic abundance (normalizing to N, O, S, and Si); the abundance of H is no more than twice O (Delsemme, 1982).

Several arguments suggest that the volatiles are directly associated with the grains in the coma, and therefore presumably with the grains while they were in the nucleus. First, the reflection spectrum of the grains has shown an absorption at 3 microns in two comets: Bowell 1980b (Campins et al., 1983), and Cernis 19831 (Hanner, 1984). Both of these comets were observed far from the sun (more than 3 AU), and a suitable spectrum resolving the absorption has not yet been obtained for any comet, but the data are strongly suggestive of water ice on the grains. A second, closely related point is that comet Bowell also exhibited a remarkably high production of OH at 4 AU from the sun (A'Hearn et al., 1984), a production that cannot be explained by

vaporization directly from the nucleus, and which therefore implies that the ice is spread over the surface of all the grains in the coma. Third, a number of authors have argued that the spatial profiles of the reflected continuum in cometary spectra can only be explained if the grains decrease in size as they move away from the nucleus; this reduction in size is more easily understood if icy mantles are vaporizing. Unfortunately these observations are very difficult, and some investigators find the evidence less than convincing. Although the observations provide no evidence for a present-day connection between volatile ices and refractory grains, A'Hearn and Feldman (1985) have argued that the presence of S<sub>2</sub> in comets can only be explained if it was formed by the irradiation of icy mantles of interstellar grains which were incorporated in comets without significant warming. This conclusion has often been reached using less direct arguments by Greenberg (1982).

Isotopic ratios have been measured for only two volatile species in comets, both spectroscopically. <sup>12</sup>C/<sup>13</sup>C in C<sub>2</sub> is >100 (average of 5 comets); but the errors are so large that this is not significantly different from the terrestrial value (see reference in A'Hearn, 1982). Upper limits for D/H in OH have been determined for several comets. In the best determined cases, the upper limit is D/H <2x10<sup>-3</sup> (A'Hearn et al., 1985). The models for chemical fractionation between HDO and H<sub>2</sub>O during condensation on grains are not yet reliable enough to determine whether these upper limits are more consistent with interstellar or presolar conditions.

#### CHONDRITIC METEORITES

The most primitive surviving samples of nonvolatile planetary material are the subset of meteorites called chondrites. The bulk compositions of chondrites (except for a few highly volatile elements) differ only minimally from our best estimates of the solar elemental abundances. Chondrites are aggregations of small objects (chondrules; Ca,Al-rich inclusions, or CAI's; dust particles, aggregations of which are referred to as matrix and which are discussed below) that are widely understood to have been dispersed in the protosolar nebula at the time when the solar system was formed. These objects have not been perfectly preserved since the nebular era, however. Their min-

eralogy and petrography reveal that they have actually experienced significant thermal processing, in the case of carbonaceous chondrites in a watery environment, while they resided in asteroid-sized parent bodies (Dodd, 1981; Kerridge and Bunch, 1979; McSween, 1979). Truly pristine material is rare.

The least-altered classes of chondrites are the "unequilibrated ordinary chondrites" (UOC's; evidence of slight anhydrous metamorphism; Dodd et al., 1967), C3 carbonaceous chondrites (Allende is a prominent example; possible slight anhydrous metamorphism; Clarke et al., 1970), and C2 carbonaceous chondrites (hydrous metamorphism; Fuchs et al., 1973).

Several events in the early history of chondritic material have been reliably dated radiometrically. Thus, the crystallization of several lithic components in carbonaceous chondrites, including some produced by aqueous activity on the parent body, occurred  $4.55 \times 10^9$  years ago (e.g., Tatsumoto et al., 1976; Macdougall et al., 1984), and final compaction of the particulate components apparently took place during the interval from 4.5 to  $4.2 \times 10^9$  years ago (Macdougall and Kothari, 1976).

#### Components of chondritic meteorites: chondrules

Chondrules (Fig. 2) are mm-size, more or less spheroidal igneous objects that are very abundant (up to 70%) in chondrites. It seems clear that they were once molten droplets dispersed in the nebula. Some early high-energy process melted a previous generation of dispersed solid material, which may (Wood, 1984) or may not (Grossman and Wasson, 1983) have been presolar interstellar dust. If the precursor was interstellar dust, its properties have been almost completely obliterated by the melting event that created the chondrules. Isotopic anomalies which may be a memory of presolar conditions are largely lacking--only oxygen isotope anomalies have been documented (Clayton et al., 1983).

### Ca,Al-rich inclusions

This class of mm- to cm-size objects (Fig. 3) attracted scientific attention initially because they match closely in chemical and mineralogical composition the thermodynamically predicted composition of high-temperature condensates from a cooling gas of solar composition. They have been regarded by many as the most primitive objects in the solar system, and hence are thought to contain the best preserved record of early solar system processes and raw materials. However, recent studies of isotopic fractionation of moderately refractory elements in CAI's (silicon, magnesium and calcium) show that the enrichment of non-volatile elements in the inclusions is due predominantly to extensive evaporation of volatile elements from pre-existing solids, rather than to condensation of refractory elements from a gas. Furthermore, the complicated interrelationships among these elements indicate multiple events of evaporation and condensation. These events must have taken place while  $^{26}\text{Al}$  ( $t_{1/2}$ ,  $0.7 \times 10^6$  yr) was still alive in the solar system, as the abundance of its daughter,  $^{26}\text{Mg}$ , has been found to correlate with the abundance of the stable isotope of aluminum ( $^{27}\text{Al}$ ) among the minerals of some CAI's. In some cases, this extensive chemical processing may have obliterated earlier isotopic heterogeneities. In other cases, such as the FUN inclusions, they may reveal heterogeneities that previously existed in different chemical forms. The CAI's provide some remarkable information about the nucleosynthetic history of matter in one part of the solar system, but they should not be regarded as typical or especially primitive in comparison to other meteoritic material.

CAI's are abundant in the C3 carbonaceous chondrites, are less abundant in C2 carbonaceous chondrites, and are present, but rare, in unequilibrated ordinary chondrites. In all cases they are less abundant than chondrules. Because of the ready availability of large quantities of the Allende (CV3) meteorite, most chemical and isotopic studies of CAI's have been done in this meteorite.



## Matrix

Chondritic matrix is an aggregation of dust particles of roughly micron dimension. The mineralogy and state of oxidation of matrix indicate a lower temperature of formation than that of chondrules and CAI's. If presolar interstellar grains are preserved in chondrites at all, they are located in the matrix. To date no particular class of matrix particles has been identified as presolar grains, though as will be seen, acid residues--the products of extensive laboratory processing and dissolution of bulk matrix samples--have isotopic signatures that appear to have been preserved from presolar times. The great bulk of chondritic matrix grains differ in significant ways from interstellar dust particles (Brownlee et al., 1977).

The matrices of UOC (Huss et al., 1981) and CV3 (Peck, 1983) chondrites are largely anhydrous, and in many cases consist of autonomous mineral grains (Fig. 4) that appear not to have been seriously disturbed by metamorphism. It is likely that most of these grains are condensates from the solar nebula. Some are undoubtedly the debris of comminuted chondrules and CAI's; and as noted, some may be presolar interstellar grains. C2 matrices consist largely of hydrous magnesium silicate minerals. In some cases there is unequivocal textural evidence that the hydrated minerals were produced in situ, by post-accretional hydrous metamorphism (Kerridge et al., 1979; Bunch and Chang, 1980). Elsewhere this cannot be established: the hydrous minerals may have existed as dispersed grains in the nebula or even in interstellar space, pre-dating the accretion of parent chondrite planetesimals.

Of particular interest are the matrices of a few UOC's, which consist of submicron graphite and magnetite grains (Scott et al., 1981a); and some chondritic regolith breccias (samples of the impact-comminuted surface layers of chondritic planetesimals, subsequently relithified) containing aggregates of the same graphite-magnetite material, which clearly were mixed into the regolith from some external source (Fig. 5; Scott et al., 1981b). Magnetite and especially graphite are uncommon meteoritic minerals, but they have figured prominently in interstellar grain models. However, no evidence has been found as yet that these grains had an interstellar origin.

### Presolar Isotopic Signatures Preserved in Meteorites: H, C, N

A major fraction of the organic matter in carbonaceous chondrites is an insoluble macromolecular material which resembles terrestrial kerogen. It consists of a highly condensed aromatic backbone with minor aliphatic bridges and side-chains. This material is not isotopically homogeneous; different moieties within it are apparently characterized by significantly different  $^{13}\text{C}/^{12}\text{C}$  and  $^{15}\text{N}/^{14}\text{N}$  values and by very pronounced differences in D/H. Bulk samples of the insoluble fraction yield D/H values up to  $5.4 \times 10^{-4}$ , with values up to  $7 \times 10^{-4}$  being observed during stepwise extraction (Robert and Epstein, 1982). However, it is not known whether this represents the maximum D-enrichment preserved in meteoritic material, or whether even more highly enriched moieties exist within the organic matter. In either case, the meteoritic D-enrichments relative to the galactic value,  $2 \times 10^{-5}$ , require fractionation of a magnitude apparently only achievable by ion-molecule reactions at very low temperatures. Such low temperatures, and even greater D-enrichments, are observed in molecular clouds, suggesting that part of the meteoritic organic matter is of interstellar origin (Geiss and Reeves, 1981; Kerridge, 1983). Whether the kerogen-like material itself was formed in an interstellar cloud or whether it was produced by "diagenesis" in the early solar system of simpler molecules synthesized in interstellar clouds, is not known.

### Presolar Isotopic Signatures Preserved in Meteorites: Oxygen

On earth, natural processes lead to fractionation of the three stable isotopes of oxygen due to differences in their masses. These mass-dependent processes produce a well-understood relationship between  $^{17}\text{O}/^{16}\text{O}$  ratios and  $^{18}\text{O}/^{16}\text{O}$  ratios. The observed isotopic patterns in meteorites do not conform to this simple relationship, and therefore require another major source of isotopic variability (Clayton, 1978). The simplest interpretation of the observations is that the solar nebula was isotopically heterogeneous, and consisted of two or more reservoirs differing in their  $^{16}\text{O}$  abundances. A likely possibility is that this heterogeneity could be established and maintained if the two or more reservoirs were in chemically and physically different states, such as gas and solids. The observed meteoritic variability

could then be accounted for by various degrees of interaction and exchange between those reservoirs.

Oxygen isotopic heterogeneity is observed on every scale yet analyzed: from micrometers to planetary size. The range of excess or depletion in  $^{16}\text{O}$  is at least 6%. The oxygen of the earth is not an end-member in the compositional variation, so that we have no "normal" solar system composition against which to measure absolute amounts of excess  $^{16}\text{O}$ . Oxygen isotopic anomalies differ from isotopic anomalies in other elements in two principal ways: (1) they are present in all solar system bodies, (2) they involve very large numbers of atoms. These effects may result from the unique cosmochemistry of oxygen which allows it to form physically distinct reservoirs, and thus avoid the isotopic homogenization that has occurred for other elements.

There are no oxygen isotopic data on stratospherically collected interplanetary dust particles, since they are too small to be analyzed by existing techniques. Measurements on composite samples of deep-sea spherules suggest a relationship to C2 carbonaceous chondrites.

The ultimate origin of oxygen isotopic heterogeneities in the early solar system remains unknown. One possibility is the inheritance of presolar differences due to incomplete homogenization of the products of nucleosynthesis. The three stable isotopes of oxygen are produced in different astrophysical processes, and may be injected into the interstellar medium chemically bound in refractory solid phases. An alternative possibility is the generation of the heterogeneities within an initially homogenized solar system, either by nuclear reactions involving energetic particles from the sun or by isotope effects involving chemical reactions that do not follow the usual dependence of fractionation on isotopic mass. The latter possibility is suggested by the laboratory experiments of Thiemens and Heidenreich (1983), which showed that the conversion of  $\text{O}_2$  to  $\text{O}_3$  favors the molecules containing  $^{17}\text{O}$  and  $^{18}\text{O}$  and produce a fractionation pattern very similar to that observed in carbonaceous chondrites. The mechanism of the reaction has not yet been established.

## Presolar Isotopic Signatures Preserved in Meteorites: Noble Gases

Anomalous isotopic patterns in noble gases (He, Ne, Ar, Kr, Xe) are found primarily in meteorite samples, in lunar dust, in putative Mars meteorites, and in planetary atmospheres. They have not been measurable in IDP's because the particles collected to date are not large enough or numerous enough. So as far as dust studies are concerned, one is limited primarily to samples from meteorites.

The meteoritic samples studied are not grains. Grains are too small to contain enough noble gas (perhaps  $10^{-12}$  to  $10^{-8}$  cm<sup>3</sup> STP/gm) for individual study. The materials studied are either samples (perhaps a milligram) of bulk meteorite, or other small bulk samples that are separated out of a whole meteorite. Selection techniques are, for example, hand-picking of a chondrule or inclusion, grinding and sieving into size fractions, gravimetric sorting into density fractions, or partial dissolution by various solvents. But in any case one gathers enough material, say a milligram, to have enough noble gas to measure. The wide ranges of details and sensitivities can be found only by referring to the literature (e.g., Podosek, 1978). Because of this need for a relatively large sample, it is not generally known what particular type of grain or chemical structure the gas analyzed resides in. Only by repeated careful inferences can the nature of the carrier of a noble gas anomaly within the meteorite be identified.

As an example of this situation, the dissolution of bulk Allende meteorite in acid has been shown to leave insoluble residues that are very rich in noble gases (Lewis et al., 1975). Because carbon and hydrocarbon polymers are not generally soluble in acid, it can be inferred that the carriers in these cases are either the carbonaceous matter of the carbonaceous meteorite or they are mineral carriers that are themselves insoluble in acid or are contained within and protected by carbonaceous matter. Further studies on the residues are also possible and yield useful information.

Another technique that has been found essential for noble gas studies is partial release of the gases as a function of temperature. For example, a

bulk sample is heated in a crucible for enough time to effectively outgas it at that temperature. The gas is collected and analyzed isotopically. Then the temperature is increased (typically by an increment of 100K) and the procedure repeated. In general, the isotopic composition of the gas released differs from one temperature fraction to the next. It is then possible to seek the minimum number of distinct components (i.e., basis vectors) that can describe the entire set of compositions of the different temperature fractions. The so-called three isotope diagram [ $N(i)/N(k)$  vs.  $N(j)/N(k)$ , where  $i$ ,  $j$ ,  $k$  are isotopes of the element in question] is useful because it identifies mixtures of components.

Several physical mechanisms have been observed in space and in the laboratory that lead to isotopic fractionation of noble gases. One such effect is the strong fractionation of helium isotopes that occurs in the solar wind, which is presumably caused by hydromagnetic acceleration or deceleration processes, such as critical velocity ionization, in the solar atmosphere. Condensation, e.g., of nickel-iron from an argon plasma, has been observed to lead to mass fractionation in the occluded noble gas component (Arrhenius, 1972). The distribution of noble gas isotopes in meteorites suggests that such processes are also likely to affect condensing matter in space. Methods are needed to distinguish this type of effect from those due to cosmic ray interaction and nucleosynthetic contributions. Isotopic fractionation in noble gases under space excitation conditions has been only superficially explored experimentally, and further investigations would seem important for understanding the cosmic record.

With these general remarks one can detail the major patterns found in meteoritic noble gases that have been argued to have presolar memory.

Helium. Because it has only two isotopes, the rare one,  $^3\text{He}$ , is useful primarily as an indicator of cosmic-ray irradiation. Perhaps the major question in that regard is whether the spallation reactions that produced  $^3\text{He}$  (and also  $^{21}\text{Ne}$ , another major indicator) occurred entirely within the assembled meteorite, or whether some earlier (possible presolar) irradiation is also



recorded. This is unsettled. Ray and Völk (1983) have discussed the nuclear reaction kinematics and the retention of recoiling nuclei.

Neon. Using temperature release fractions on bulk meteorites, Black (1972) identified five discrete components of neon, which he called Ne-A, -B, -C, -D, -E. Of these the most interesting is Ne-E, which is now known to be essentially pure  $^{22}\text{Ne}$  (Eberhardt *et al.*, 1979). Black even went so far as to suggest that Ne-E was a preserved presolar component, a view that is almost universally accepted today. The condensation of  $^{22}\text{Ne}$  in sodium minerals outside exploding stars (Clayton, 1975a) is the favored model for creating it (see the Section on Interrelationships). However, the nature and history of the Ne-E carrier from condensation to meteorite is yet to be specified, a problem that is shared by all noble gas connections to some degree.

Argon. With only three isotopes (36, 38, 40), one of which is a decay product of  $^{40}\text{K}$ , it is not easy to seek very many meaningful connections to the presolar ISM. Overwhelmingly the most significant use of Ar has been the K-Ar dating method, which locates meteorite ages at  $4.5 \times 10^9$  yr in undisturbed cases. One great surprise, still controversial, has emerged--the discovery of some samples that contain more  $^{40}\text{Ar}$  than can have been produced by  $^{40}\text{K}$  decay over  $4.5 \times 10^9$  years (Jessberger *et al.*, 1980). A possible connection to presolar dust is indicated, because decay in interstellar grains could carry excess  $^{40}\text{Ar}$  into the early solar system. This effect was predicted before discovery as a general astrophysical clue to be sought (Clayton, 1975a, 1977). Jessberger's samples are K-rich minerals removed from Allende inclusions, and it must be remembered that the origin of these inclusions and their minerals is still not understood.

Krypton. The largest isotopic anomalies are found in acid-insoluble residues of Allende and other carbonaceous chondrites. But for various reasons the situation is not as clear or favorable to study as is xenon (below).

Xenon. This noble gas is blessed with nine stable isotopes, so it has rich possibilities for identifying specific processes. It is also fortunate

that meteorites are quite retentive of Xe, even though it is a noble gas. This means that surprisingly large quantities of Xe are available for study (perhaps  $10^{-8}$  to  $10^{-2}$  in comparison to abundances of neighboring refractory heavy elements). The largest literature exists on the special excess at  $^{129}\text{Xe}$  resulting from the decay of  $^{129}\text{I}$ , with half-life 17 million years. The major effort has been to try to fix a relative age scheme for meteorites by assuming that all excess  $^{129}\text{Xe}$  has resulted from in situ  $^{129}\text{I}$  decay in the meteorite. Clayton (1975b) questioned this on astrophysical grounds. The dating scheme has since been found to have some problems (Jordan, et al., 1980; Crabb et al., 1982), but the interpretation remains controversial. A portion of the excess  $^{129}\text{Xe}$  may have been trapped from the beginning in interstellar grains that were never totally degassed, somewhat like the excess  $^{40}\text{Ar}$  problem noted earlier.

Much more exciting are the clear presolar isotopic patterns that have been found in the elements generally. One of these corresponds to the s-process isotopes of Xe, and it has been found in acid-resistant carbonaceous residues (Srinivasan and Anders, 1978; Lewis et al., 1979). This discovery has proven that the theoretical division of heavy-element nucleosynthesis into s and r components is more than just an intellectual convenience for mankind. Nature has done it first. The question is where and when. The occurrence of these nuclides in acid-insoluble residues (and only in the high-temperature fraction of those) suggests carbonaceous dust. Carbon-rich red giants (carbon stars) have observed excesses of s-process elements, so the condensation of carbon dust there seems to be implicated.

Xe-X, also called Xe-HL. Manuel et al., (1972) discovered that concentrations of the heaviest ( $^{136}\text{Xe}$ ,  $^{134}\text{Xe}$ ) and lightest ( $^{124}\text{Xe}$ ,  $^{126}\text{Xe}$ ) isotopes of xenon are greatly enhanced in a single cryptic component in carbonaceous chondrites; they named this component "Xe-X". Lewis et al., (1975) subsequently found that spinel and carbon in acid-insoluble residues serve as carriers for Xe-X. R- and p- process synthesis in supernovae most plausibly rationalizes this Xe component (see Interrelationship Section). As in the case of other presolar noble gas components, the carrier grains must have

survived intact during the nebular phase of solar system history in order for us still to be able to see the effect today.

Xe derived from  $^{244}\text{Pu}$ . The existence of live  $^{244}\text{Pu}$  ( $t_{1/2}$ , 82 myr) in some system of solid particles at some early time is attested to by the positive identification of  $^{244}\text{Pu}$  spontaneous fission fragments in the Xe isotopes of meteorites (Alexander et al., 1971). There are possible implications for presolar (Clayton, 1975b) as well as meteoritic history (Podosek, 1978).

### Presolar Isotopic Signatures Preserved in Meteorites: Involatile Elements

Most isotopic anomalies have been found only in very special samples and/or special phases. These samples (CAI's) are characterized by their refractory nature, and range in size from <1 mm to several cm (Fig. 3). So-called FUN inclusions have attracted most of the attention so far: most of the isotopic anomalies of involatile elements have been found in these objects. It should be pointed out, however, that small individual mineral grains which are not portions of larger inclusions could very well also be carriers of isotopic anomalies; they simply have not been studied yet to any extent. Three types of isotopic effects are observed in meteorites:

1. Radiogenic effects seen as enrichment of the daughter nuclide. Examples are  $^{26}\text{Mg}$  excesses from  $^{26}\text{Al}$ ,  $^{107}\text{Ag}$  from  $^{107}\text{Pd}$ , and  $^{142}\text{Nd}$  and  $^{143}\text{Nd}$  from  $^{146}\text{Sm}$  and  $^{147}\text{Sm}$ . Radiogenic effects can be large for large parent/daughter concentration ratios (e.g.,  $^{26}\text{Mg}$  excesses of >100% in Dhajala hibonite for  $^{27}\text{Al}/^{24}\text{Mg}$  of 17,000: Hinton and Bischoff, 1984).
2. Mass-dependent fractionation (the F in FUN). Usually up to 1-2%/amu.
3. Non-mass-dependent excesses or deficits of certain nuclides, of unknown origin (the UN in FUN).

Both F and UN anomalies are present in FUN inclusions. These samples are exceedingly rare; only a few have been found so far, but most of the experimental work has been concentrated on them.

The topic of isotopic anomalies is too complex to be covered adequately in the brief survey that follows. For more details the reader is referred to reviews by Clayton (1978), Begemann (1980), Lee (1979), and Wasserburg and Papanastassiou (1982). Isotopic anomalies have been found in the following elements:

Mg--FUN anomalies in FUN inclusions; in Murchison hibonite, only F with no accompanying UN effects (Hutcheon et al., 1983), and an excess of  $^{26}\text{Mg}$  from the decay of  $^{26}\text{Al}$ .

Si--FUN anomalies in FUN inclusions. F effects in Mg and Si are related to fractionation effects in O isotopes.

Ca--FUN anomalies in FUN inclusions; also  $^{48}\text{Ca}$  excess, fairly common but small in non-FUN CAI's (Jungck et al., 1984).

Ti--FUN anomalies in FUN inclusions (Niederer et al., 1985), but also the ubiquitous presence of complicated UN anomalies in many carbonaceous chondrites;  $^{50}\text{Ti}$  excess of up to 10% in C2 hibonites (Fahey et al., 1985).

Cr-- $^{54}\text{Cr}$  excess in Allende CAI's (Birk and Allegre, 1984); probably related to  $^{50}\text{Ti}$ .

Sr, Ba, Nd, Sm--UN anomalies in FUN inclusions.

Ag-- $^{107}\text{Ag}$  excess from the decay of  $^{107}\text{Pd}$ .

These isotopic anomalies are mainly restricted to carbonaceous chondrites. Exceptions are radiogenic  $^{107}\text{Ag}$  in iron meteorites (Kaiser et al., 1980), and  $^{26}\text{Mg}$  anomalies in ordinary chondrites (Hinton and Bischoff, 1984).

Isotopic anomalies in meteorites have been taken by many to be signatures of presolar material which survived the homogenization process of the formation of the solar system. What evidence is there that any IS dust material survived? It is clear that some isotopic anomalies must have been produced outside of the solar system, and prior to its formation. There is strong evidence that live  $^{26}\text{Al}$  was present at the time of the formation of the minerals in which  $^{26}\text{Mg}$  excesses are now found. Fractionation effects could be the result of solar system processes. Indeed, some F effects are correlated with the thermal histories of the specimens. For example, fine-grained (Group II) condensates are consistently enriched in lighter Mg and Si isotopes, while coarse-grained (Group I) evaporative residues are enriched in the heavy isotopes. Recent laboratory experiments which produced non-linear mass fractionation effects in Mg by thermal evaporation (Esat et al., 1985) make it appear possible that the small Mg and Si UN anomalies seen in FUN inclusions are the result of solar system processes.

However, there is no doubt that a variety of isotopic anomalies must be of nucleosynthetic origin. This is the case for most Ti anomalies, especially the very large  $^{50}\text{Ti}$  excesses; also for  $^{48}\text{Ca}$  and  $^{54}\text{Cr}$  anomalies, which probably have the same source. It is also the case for the elements Ba, Nd, and Sm, where definite r-process or s-process patterns have been observed.

It is not generally understood why many of these nucleosynthetic anomalies are seen in FUN samples, i.e., why they are associated with mass-dependent fractionation effects. There are notable exceptions to this association of F with UN:

1. Titanium isotope anomalies, which were originally found in FUN samples, are also ubiquitous in other samples which do not show any mass fractionation nor any isotopic anomalies in other elements. Most prominent is the 10%  $^{50}\text{Ti}$  excess in Murray hibonite (Fahey et al., 1985) which does not show a Mg anomaly. The anomalous Ti has a homogeneous distribution in this 40 micron mineral grain.



2. Very large F effects, without other anomalies, have been found in a Murchison hibonite by Hutcheon et al. (1983). The mean Mg fractionation is +10%/amu, but the anomalous Mg is heterogeneously distributed in tiny patches, among which the fractionation ranges up to >35%/amu.

The Hutcheon et al. (1983) ion microprobe study is the only one that points to small carrier grains, and thus possibly to preserved IS dust. The only problem is that, unlike a clear nucleosynthetic signature, a manifestation of mass-dependent fractionation is no definite proof of a presolar origin. Most techniques of isotopic analysis do not allow the determination of the spatial distribution of isotopic anomalies in individual mineral grains. Normally, the large sample size and the chemical processing necessary for analysis destroys this information. In cases where the spatial distribution can be measured (by ion probe), no heterogeneous distribution of isotopic anomalies on a micron size scale has been found except for the above example.

Most meteoritic matter is considerably coarser-grained than IS dust, and has undergone thermal processing  $4.5 \times 10^9$  years ago. Thus it is likely that most properties of the IS dust precursor to meteorites have been erased. No direct, unequivocal experimental evidence exists for the existence of IS dust grains in meteoritic material. Consequently, any isotopic anomalies of presolar (nucleosynthetic) origin that were brought into the solar system were incorporated into larger objects (individual larger mineral grains, whole CAI's) from IS dust grains during the early stages of the solar system, and at this point the dust grains lost their identity; or possibly these larger objects themselves were of presolar origin. While this is unlikely (e.g., why would extreme  $^{50}\text{Ti}$  effects be found in a hibonite with normal Mg isotopic composition?) and probably is not the case for whole CAI's, it cannot be strictly ruled out for some individual mineral grains. Only improved measurements probing the isotopic composition on a small spatial scale will be able to settle this question.

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## Figure Captions

**Figure 1.** An interplanetary dust particle (IDP) collected in the earth's stratosphere; note 1 micron scale bar. This particular object is a chondritic porous aggregate (CPA), consisting of relatively large grains of crystalline Mg,Fe silicates and smaller (0.1 micron) anhydrous grains of variable composition. Figure from Bradley et al. (1983b).

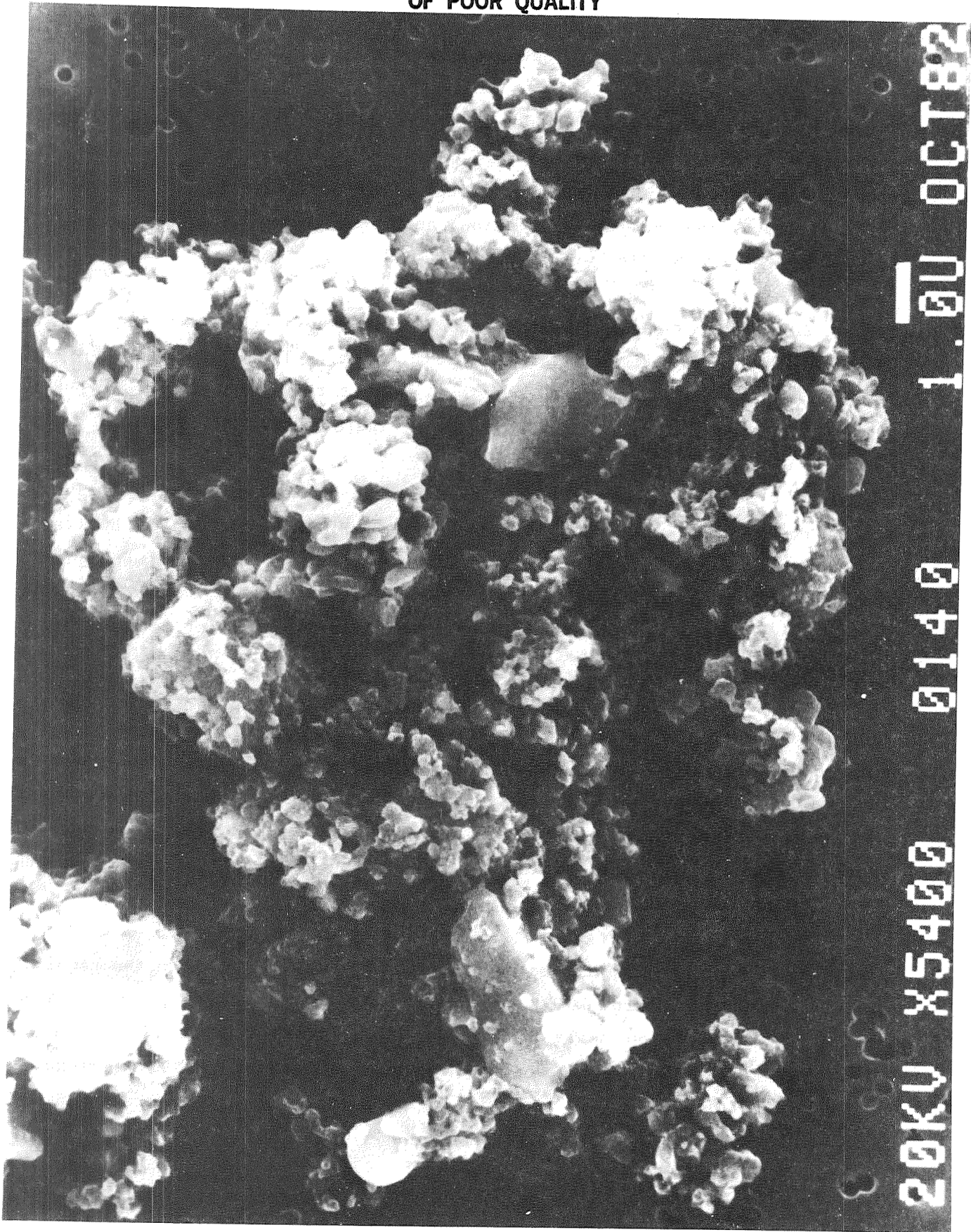
**Figure 2.** Chondrules in the Tieschitz UOC chondrite (thin section, illuminated by transmitted light; width of field, 4 mm). These consist largely of the Mg,Fe silicates olivine and pyroxene. Their textures (crystal morphologies) are characteristic of igneous rocks. Figure from Wood (1985).

**Figure 3.** A large (diameter, 2.4 cm), coarse-grained Ca,Al-rich inclusion (CAI) from the CV3 chondrite Allende. Thin section, illuminated by transmitted light. The minerals are melilite, anorthite, fassaite, and spinel, compounds enriched in the most involatile elements (such as Ca and Al). The igneous texture and spheroidal shape make it clear that this object was once a molten globule. Figure from Clarke et al. (1970).

**Figure 4.** Matrix in the CV3 chondrite Allende (SEM backscattered-electron image of a polished section; width of field, 110 microns). This consists of a loose aggregation of, mostly, plates of ferrous olivine which appear as rods where cut by the section. Also visible are minor amounts of metal and sulfide minerals (white) and pyroxene (darker gray, irregular). Pore space appears black. Figure courtesy of J. A. Peck.

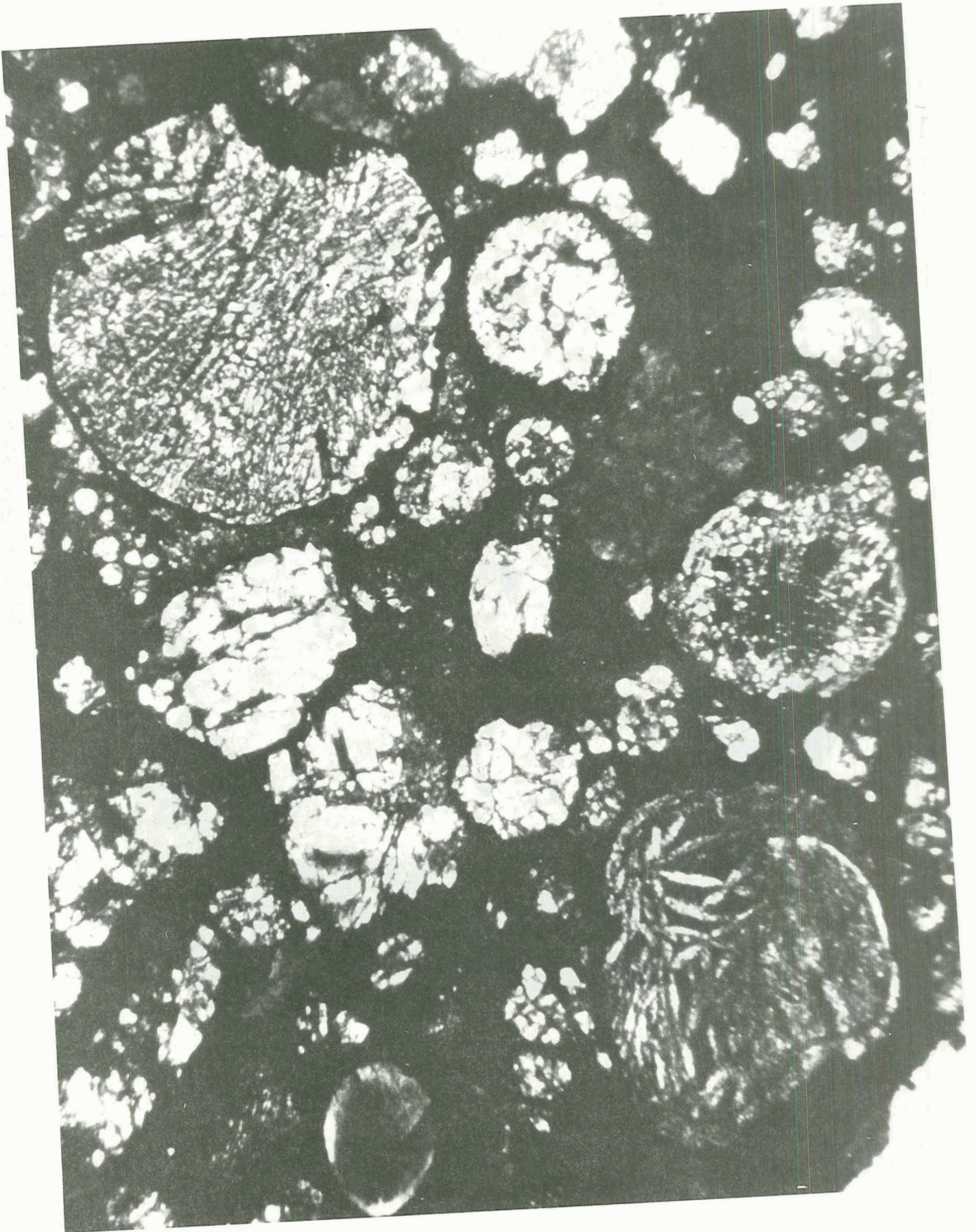
**Figure 5.** Submicron graphite-magnetite aggregate in a clast from the regolith breccia chondrite Sharps (SEM backscattered-electron image of a polished section; note 5 micron scale bar). The finest-grained areas of the image, which are poorly resolved, are graphite and magnetite. White, irregular grains are metal and sulfide minerals. Figure courtesy of S. Recca and E. R. D. Scott.

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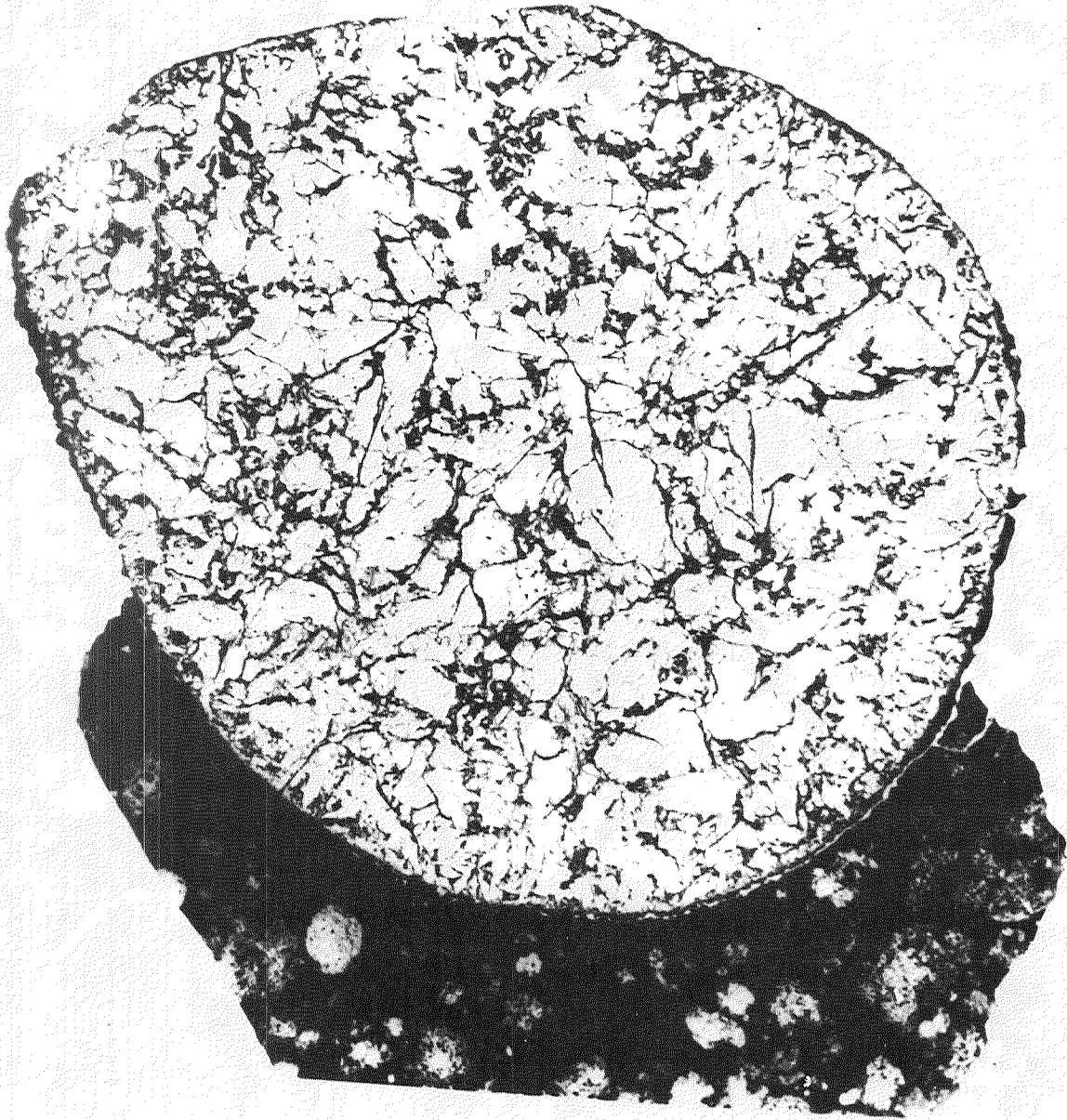


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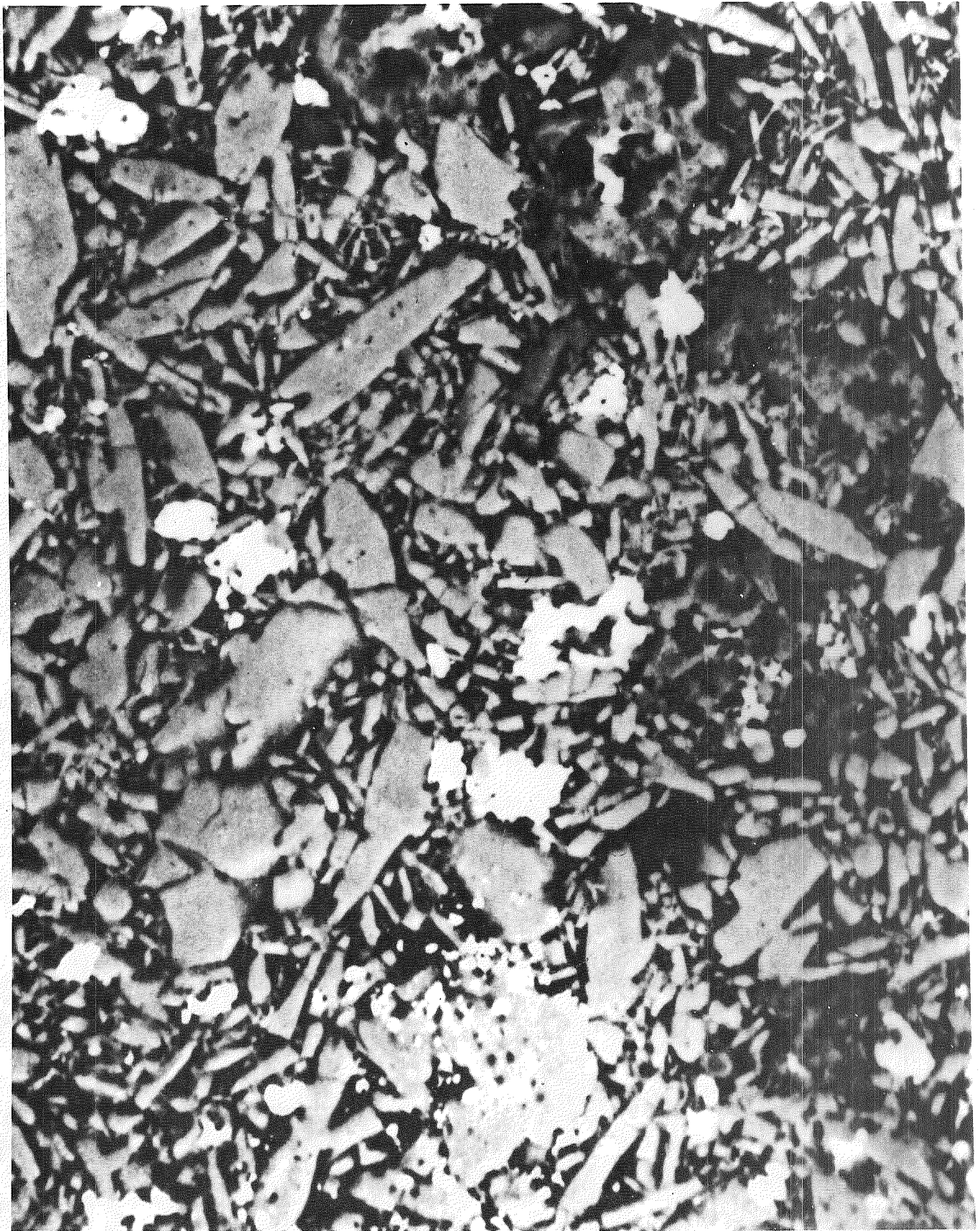
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