INTERSTELLAR DIAMONDS IN METEORITES

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Primitive meteorites contain up to 400 ppm of a very fine-grained (-20 Å) carbon component, noncommitally called C₆ (1). It is presolar, as it carries highly anomalous Xe ("Xe-HL" or "CCFXe," enriched -2-fold in the lightest and heaviest isotopes) and anomalous N (δ¹⁶N = -330 ‰; 2). We now report evidence that part or all of C₆ is diamond—not shock-produced but primary, formed by stellar condensation.

Procedure. C₆ is isolated from meteorites such as the Allende C₃V chondrite by dissolving the major minerals in HF-HCl (3), and generating a colloid from the remaining, 0.5% residue to separate carbon from coarse-grained spinel and chromite (4). The major, gas-poor part of the colloidal carbon (= Cᵧ) is removed by cautious oxidation with HClO₄ (4,5) or K₂Cr₂O₇ (6), leaving a residue enriched in Xe-HL and C₆. On the hunch that C₆ might be a C₆ cluster (7), we prepared a new residue (Allende CH, 109 ppm) by a similar oxidative treatment, first with HNO₃ and red fuming HNO₃ for 16 hr at 70°C and then with HClO₄ for 2 hr at 140°C. Surprisingly, the sample was light tan when wet and light grey when dry. To remove any possible silicates, it was reprocessed with HCl and HF, yielding Allende CJ (89 ppm).

Identification of Diamond. On the SEM, Allende CH and CJ showed no elements above oxygen (Mg, Al, and Si <2.5 wt% if evenly dispersed or <1% if in grains of >0.5 µm). X-ray diffraction of CJ showed only 3 very broad, diffuse lines, matching the 3 principal lines of diamond. On the TEM, the grains turned out to be typically 50 Å in size. Electron diffraction confirmed that most grains were diamond, as shown by the agreement of the observed spacings with ASTM values (parenthesized): 2.06 (2.06), 1.26 (1.26), 1.07 (1.075) Å. Elemental analysis by AEM showed a small amount of Cl (contamination or surface-bound Cl from HCl?) as well as Cr and Fe (submicron-sized ferrichromite; 5,8). Examination by HRMS at 70-550°C showed only small amounts of volatile material, probably contamination. Peaks appeared up to at least m/e = 733, but the most abundant ones did not correspond to C₆ or other C ions.

Other Meteorites. To check whether such diamonds are present in other meteorites containing Xe-HL, we isolated similar residues from Murchison (C₂) and Indarch (EO₄), using HClO₄ at higher T (190°-206°C) to remove the more reactive forms of carbon. Residues Murchison GL1 (white, 225 ppm) and Indarch CF (dark grey, 36 ppm) both showed diamond by electron diffraction. Murray A2C (white, 150 ppm) was not checked by ED but showed only traces of Al and Si on the SEM.

Noble Gases. The noble-gas content of Allende CH agrees closely with the previous most enriched samples, suggesting that Xe-HL and other gases belong to the diamond (Ne²⁰ = 8,700 x 10⁻⁸ cc/g, Xe¹³² = 24 x 10⁻⁸ cc/g, Xe¹³⁶/Xe¹³² = 0.649). Allende CJ, Indarch CF, and Murray A2C also had high concentrations of Xe-HL. However, the past history of the field has shown that one can't safely assign a noble-gas component to the dominant phase in a sample; the true carrier is the last of a series of minor phases receding into infinity like the innermost of a set of Russian dolls. Thus we cannot yet conclusively prove that diamond is the carrier of Xe-HL; this will require careful, quantitative measurements establishing a 1:1 correlation between diamond and Xe-HL. As it is hard to avoid mechanical loss of 50 Å particles, such
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experiments will be difficult.

*Origin of Diamonds.* All previously known meteoritic diamonds (ureilites, irons) have formed by shock, in terrestrial or asteroidal impacts. However, it seems unlikely that the C6 diamonds originated in this way. Though all 3 meteorites in which these diamonds have been found are somewhat brecciated (Allende least so), none show the strong shock effects and/or high post-shock temperatures that characterize other diamond-bearing meteorites. Moreover, all these meteorites also contain graphitic or amorphous carbon that has no Xe-HL or anomalous N and is isotopically heavier ($^{13}C = -15\% - 38\%$ for C6; 1,14). If the C6 diamonds were made by shock, why did the shock--in 3 different parent bodies--singlemindedly transform only the Xe-HL-bearing grains, while ignoring the more abundant, gas-poor carbon grains? Moreover, all 4 meteorites have essentially similar C6, with comparable gas contents and isotopic compositions. If the diamonds were shock-produced, one would expect greater variations, depending on the proportions of the two types of carbon converted to diamond and on post-shock diffusion losses. Ureilites for example, show a -100 fold variation in gas concentration (9).

By default, it seems necessary to invoke a presolar origin for the diamonds. Xe-HL apparently formed in a supernova (10) and was trapped in carbon grains by ion implantation (11); the high relative velocities required for the latter process imply that the grains predate the supernova, and presumably formed in the dust shell ejected by the presupernova during its red giant or planetary nebula stage (12). Diamonds could presumably form during condensation in such a shell, as the metastable formation of diamond from the vapor phase has been amply demonstrated in the laboratory (13). The processes studied thus far involve decomposition of CH$_4$ or organic compounds in the presence of large amounts of hydrogen, either by ordinary pyrolysis or by plasma reactions. The mechanism is not yet known, but seems to involve CH radicals and H atoms. Though CH$_3$ is not an abundant radical in red giants, other radicals or molecules (CH, C$_2$H, C$_2$H$_2$, etc.) presumably can serve in its place. Whatever the mechanism, it now seems necessary to add diamond to the list of interstellar grain constituents.

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