Grains of Meteorites, Originating in Cool Carbon Stars

Uffe G. Jørgensen
Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark

I. Introduction. The bulk of meteorites consist of material that condensed out of the primitive solar nebula, and their isotopic composition is therefore similar to that of the sun. Unfractionated meteorites (carbonaceous chondrites), nevertheless, contain a small fraction of inclusions that have a distinctly different isotopic composition of carbon, xenon, krypton and other elements (Zinner et al., 1987). These inclusions are therefore believed to be of pre-solar origin, and their composition and mineralogical structure carries information about the place where they were born.

Here I present the theory that inclusions of silicon carbide and diamonds in carbonaceous chondrites have their origin in the upper layers of cool carbon stars. The theory is in agreement with theories of late type stellar evolution, with high resolution stellar spectroscopy, as well as with available laboratory analysis on chemical, isotopic and mineralogical composition of carbonaceous chondrites. The SiC is calculated to be formed primarily in the early phases of carbon star evolution, whereas the diamonds are predicted to come from the later stages of evolution (Fig 2). The excess of heavy and light isotopes of xenon indicate that some of the diamonds have been in contact with a supernova of type I, that could have been triggered by mass flow from the same carbon star that created the diamonds.

II. Grains from carbon stars. Diamonds (C δ) and SiC (C β) with isotopic composition distinctly different from that of the sun, have been isolated from four meteorites (Lewis et al., 1987). Both grain types can form under the chemical and physical conditions that prevail in the upper atmosphere of cool carbon stars. SiC have been identified in the spectrum of several carbon stars.

Isotopic ratios of mainly $^{129}Xe/^{130}Xe$ and $^{12}C/^{13}C$ show that the grains didn't form neither in a supernova of type II nor in a local inhomogeneity of the pre-solar nebula. The atmosphere of a SNII progenitor has C/O < 1, and hence all the carbon bound in CO molecules, so that no carbon is left over for grain formation. The carbon rich interior zone of a SNII has $^{13}C/^{12}C = 0$ (which is not observed in grains from meteorites), and ^{129}I is there produced together with the Xe. If the grains were produced in chemical

https://doi.org/10.1017/S0252921100063326 Published online by Cambridge University Press

equilibrium in such matter, the highly reactive I would be included in the grains together with the Xe, and the ^{129}I would then later decay to ^{129}Xe which is not observed in excess in the meteoritic inclusions.

III. The silicon carbide. The SiC grains in meteorites are observed to have low $^{12}C/^{13}C$ compared to the sun. This is also normal in carbon stars with C/O near to unity (Fig 1). Accepting that the grains come from carbon stars, it is therefore concluded that SiC must come from the early phases of carbon star evolution. The Xe found trapped inside the SiC crystals is pure s-process Xe, which is the isotopic composition found in red giants (including the carbon stars).

IV. The diamonds. The diamonds have approximately solar $^{12}C/^{13}C$ which is usual in evolved carbon stars (higher C/O ratio). The diamonds, nevertheless, have an enhancement of heavy and light (Xe-HL) isotopes of Xe. These isotopes are expected to form only in supernova explosions, and the diamonds must therefore have been in contact with products of a supernova, after they were formed in a carbon star.

V. A binary system. Consider a close binary system, one of the components being a carbon star, the other a white dwarf. In the beginning the carbon star forms SiC grains, its radius is small and the mass flow (onto the white dwarf) is also small. Later the carbon star begins to form diamond grains. At this stage it is bigger and the mass flow onto the white dwarf is increasing. The accumulated mass on the white dwarf therefore grows fast now, and the chance for a supernova explosion increases dramatically. Therefore diamonds and not SiC grains will be contaminated with Xe-HL (as is found in carbonaceous chondrites). Reimers mass loss law predicts that $\dot{M} \propto LRM^{-1}$ (where $\dot{M}$ = mass loss rate, L = luminosity, R = radius and M = mass of the star) for oxygen rich red giants, and there is observational indications that the mass loss increases considerably steeper (with luminosity) for evolved carbon stars.

VI. The model atmosphere prediction. High resolution spectroscopy of nearby carbon stars points at a relation between the $^{12}C/^{13}C$ and the C/O ratios, as do also stellar evolution theory, where pure ^{12}C (from 3α burning) is predicted to be mixed to the surface in AGB stars. Fig 1 shows this relation for the data presented by Lambert et al. (1986) for all of their stars with $^{12}C/^{13}C > 25$. Six stars that have considerably lower $^{12}C/^{13}C$, show no increase in $^{12}C/^{13}C$ with C/O and are assumed to be contaminated with e.g. CNO cycled material. Isotopic analysis of carbonaceous chondrites show that SiC have low $^{12}C/^{13}C$ and diamonds high $^{12}C/^{13}C$ (Lewis & Anders, 1983). Carbon rich model atmospheres (based on the code of Eriksson et al., 1984) predict that the molecular equilibrium favours (molecular progenitors of) diamond and graphite formation if C/O

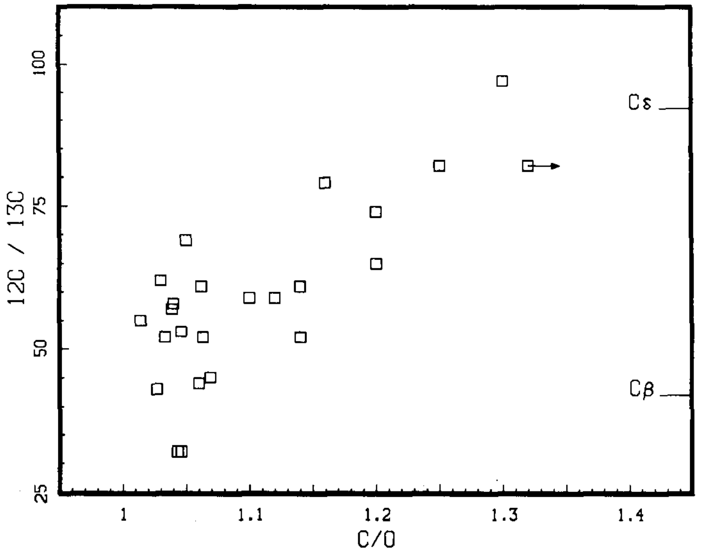

Fig 1. The $^{12}C/^{13}C$ and the C/O ratio of 24 of the brightest C stars in the sky. Also shown is the measured $^{12}C/^{13}C$ ratio of $C\beta$ and $C\delta$ grains in carbonaceous chondrites.

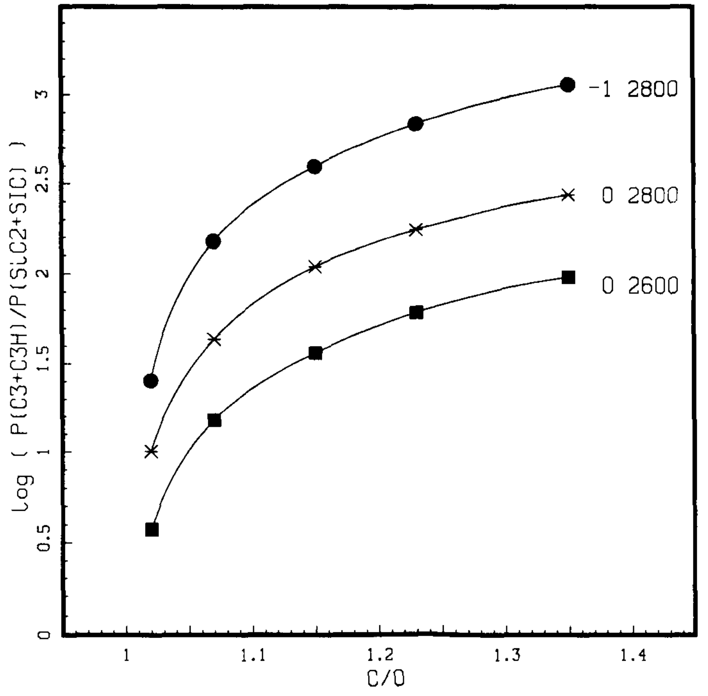

Fig 2. The ratio of expected molecular progenitors of diamonds and SiC, calculated as function of C/O in model atmospheres with (log(g),T_{eff}) = (-1,2800), (0,2800), (0,2600), respectively.

https://doi.org/10.1017/S0252921100063326 Published online by Cambridge University Press

(and hence $^{12}C/^{13}C$) is high, whereas SiC formation is favoured when C/O is close to unity (Fig 2). Model atmospheres combined with evolutionary theory (or high resolution spectroscopy) therefore predict diamonds with high $^{12}C/^{13}C$ and SiC with low $^{12}C/^{13}C$. This is also what is observed in carbonaceous chondrites.

VII. Carbon stars in the time of the solar system formation. Today the ratio of the number of red giants to the number of carbon stars, in our Galaxy, exceeds 100. Nevertheless, this ratio is strongly dependent on metallicity (Richer & Westerlund, 1983). The metallicity of the Galaxy was lower prior to the solar system formation, and carbon stars were therefore more common. The total amount of material transferred to the white dwarf SNI progenitors from carbon stars, is estimated to have been 9 times bigger than that transferred from oxygen AGB stars, at the time of the solar system formation (Jørgensen, 1988). Recent calculations (Gallino et al., 1988), furthermore, shows that the Kr isotopes found in the SiC grains can be predicted only from stars with metallicity lower than solar.

VIII. Conclusions. In conclusions it is found that the mineralogical, as well as the isotopic, composition that is found in small inclusions of carbonaceous chondrites, is in agreement with production of these grains in cool carbon star atmospheres, and that the diamonds enriched in Xe-HL were formed in a close binary system when a carbon star near its end of evolution were in the process of transferring material onto a companion white dwarf. This project has been supported by the Danish Natural Science Research Council.

Eriksson, K., Gustafsson, B., Jørgensen, U.G., Nordlund, Å. 1984, *Astron. Astrophys.* **132**, 37.
Gallino, R. et al. 1988, to be submitted to *Nature*.
Jørgensen, U.G. 1988, *Nature*, **332**, 702.
Lambert, D.L., Eriksson, K., Gustafsson, B., Hinkel, K. 1986, *Ap. J. Suppl.*, **62**, 373.
Lewis, R.S., Anders, E. 1983, *Scient. Am.*, **249**, 54.
Lewis, R.S., Ming, T., Wacker, J.F., Anders, E., Steel, E. 1987, *Nature*, **326**, 160.
Richer, H.B., Westerlund, B.E. 1983, *Ap. J.*, **264**, 114.
Zinner, E., Ming, T., Anders, E. 1987, *Nature*, **330**, 730.