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Condensation of Carbon in Supernovae: Graphite in Meteorites

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CONDENSATION OF CARBON IN SUPERNOVAE: GRAPHITE IN METEORITES.

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A new model for the carbon condensation chemistry within supernovae has been developed (1) showing that carbon condensates will occur even in gas having abundance ratio O/C >1. The escape from thermochemical bondage of C within CO occurs because the supernova radioactivity dissociates the CO molecule (2). We consider several immediate astrophysical consequences.

1. Numbers of SUNOCONs vs size: We here adopt the "growth model" presented by (1), in which the radiative association rate coefficient for a C atom with a carbon cluster C_n is taken to increase as $k_n = 10^{-10} (n/24)^{2/3}$ cm^{3}s^{-1}. A steady flow develops for the transmutation of C_n to C_{n+1} by C associations occurring at that rate. The steady flow for initial ratio C/O = 1 yields for the abundance $C_n = C_{24} (n/24)^{-2/3}$ per C atom, where from the growth model (1) integration $C_{24} = 10^{-20}$ per C atom. Thus $C_n = 8.33 \times 10^{-20}$ $n^{-2/3}$. Integration of the C-atom fluence from a starting time $t_0 = 10^7$ s using undepleted gaseous atomic C hints that this abundance formula remains valid out to a maximum value of n near $n_{max} = 8.6 \times 10^{15}$. The radius of such a graphite would be about 25μm, since for carbon at density 2.2 gcm^{-3} the radius a $= 1.30 \times 10^{-8}$ $n^{1/3}$ cm. In the numerical integration the free carbon atoms become depleted above $n_{max} = 10^{15}$, restricting the upper grain size for C/O=1.

SUperNOva CONdensate (SUNOCON (4)) graphites up to this size are found in meteorites (3). This suggests that the basic model is correct and that the free C may become depleted above $n=10^{15}$ for C/O = 1. The true associative rate for the large particles is not known, however. If it were 100 times smaller the maximum n_{max} could be a factor 100 less, near $n_{max} = 10^{14}$ or a= 6μm. That remains in the observed size range and would deplete several percent of C. The largest observed grain is about 10μm radius. Abundances at specific values of n can not be compared, but rather those in a range of n (say a decade). The number expected near the maximum particle size can be compared to the number expected near 0.1 of that maximum size. The summed abundance number between n and 10n is $_{10n}C_n = 25.0 \times 10^{-20}[(10n)^{1/3} - n^{1/3}] = 2.89 \times 10^{-19} n^{1/3}$ per C, showing that the total number in a decade of atomic numbers commencing with n increases in proportion to $n^{1/3}$. The next decade in n contains 2.15 times more particles. A factor 10 in radius rather than in atomic number contains the summed abundance number between n and 1000n: $_{1000n}C_n = 2.25 \times 10^{-18}$ $n^{1/3}$. This implies that the number in the size range 0.1-1 micron is less than the number in the size range 1-10 micron by the factor 10, since n must be 1000 times greater for the larger size range. See the table below. Thus if about 100 carbon SUNOCONs in the range 1-10 micron have been documented, only ten in the range 0.1 -1 micron would be expected. We conclude that the chemical model advanced (1) accounts for the preponderance of large carbon SUNOCONs over smaller ones. We also conclude that since those discovered reach only about a= 10μm, the mass fraction can increase only out to near $n=10^{15}$, very close to the expectation of the theory (1).

2. Absolute mass fraction: Comparing theory (1) to the mass fractions in meteorites also agrees reasonably with observation. To see this assume that the mass fraction of meteoritic carbon in the form of SUNOCONs is the same as its mass fraction in the ISM, and that in turn is equal to the mass fractions as ejected from SN, where half of C originates. In meteorites that fraction is 10^{-5}. Fig. 3 of (1) shows that the model gives an ejected mass fraction having sizes near 1μm as 10^{-4}. So the numbers look roughly correct, which is the most one could hope for since the subsequent astrophysical history of these SUNOCONs will modify them destructively by sputtering.

3. Surface area per C atom and supernova optical depth: Grain area of particle n is $A_n = a_n^2 = 5.28 \times 10^{-16}$ $n^{2/3}$ cm^2 with abundance $C_n = 8.33 \times 10^{-20}$ $n^{-2/3}$. So the product $C_n A_n = 4.40 \times 10^{-35}$ cm^2 per C atom, independent of size n. Each size makes the same contribution to the optical depth if the optical cross section is taken to be given by the area (ignoring for the moment the quantum efficiencies). If n_{max} is 10^{15}, for example, with each value of n contributing equal area, the sum of areas $\sum A_n = 4.40 \times10^{-20}$ cm^2 per C atom. This area for carbon grains suffices to make the supernova optically thick, redistributing the radiation. If the ejecta includes 0.2M_{sun} of C (2 x 10^{55} C atoms) filling uniformly a sphere of radius R $= (10^9$ cms$^{-1})$t, the column depth of C atoms is $n_C R = 4.77 \times 10^{36}$ t^{-2} C atoms cm^{-2}. At t $=10^7$s this is $n_C R = 4.47 \times 10^{22}$ cm^{-2}. Giving to each C atom (assumed undepleted) an accompanying grain area $\sum A_n = 4.40 \times 10^{-20}$ cm^2 per C atom yields optical

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depth $= n_C R$ $A_n = 2100$, which is optically thick. For early times   is proportional to $(t/10^7)^{-2}$. Because some mass shells contain C and some do not, the supernova remnant will have opaque regions where the C abundance is high, but perhaps transparent ones elsewhere. This structure must be taken into account for its redistribution of radiant energy.

4. <u>Infrared emission</u>: The particles will have a temperature of order 500K -1000K for a year or two and will thus provide continuum infrared emission from young supernovae. Each particle C_n will radiate (if taken to be as efficient as a blackbody) the infrared power $l_n = 1.2 \times 10^{-7}(T/1000K)^4 n^{2/3}$ erg/s. Because the optical depth is large, however, the escaping emission will come from an effective blackbody surface surrounding the grains. Estimating that radius as $R = 3 \times 10^{15}$ cm gives a total expected infrared luminosity $L_{IR} = 6.4 \times 10^{39}(T/1000K)^4$ erg/s, comparable to observations near 500d. Much of the early IR luminosity is the result of these carbon grains.

5. <u>Isotopic and chemical fractionation</u>: These carbon particles afford an example of what has been called "cosmic chemical memory" (4) in the analysis of bulk fractionations. One aspect involves surface correlated accretion of trace elements (5). The following table compares two size ranges:

	0.1 - 1 μm	1 - 10 μm
		(arbitrary units)
Size	1	10
Range of n	10^3	10^6
abundance	10	100
Mass	1	10^4
Area	1	10^3
Area/Mass	10	1

Trace elements in the gas will accrete to grains in proportion to their surface areas. Consider an element unable to associate with the grains until after much of their growth, as could happen if cooler grains are required. Although the larger decade has 10^3 more surface area, it has 10^4 more mass; therefore the Area/Mass ratio is ten times larger in the smaller decade. The consequence is that elements condensing later than C (most elements, save perhaps Ti, Si and Al) will accrete preferentially onto the smallest C grains. Considering Ca as an example, the Ca/C ratio will be larger in the smaller decade.

However, if the C growth instead continues *after* prior depletion of a compatible refractory element (e.g. Ti), as might occur if that element associates with C molecules and small C grains with a higher rate factor than does C itself, elevated trace concentrations near the centers of the final particles result. Ti is a suggestive example because TiC crystals are found within, even central to, large grains of C (3). Larger Ti/C ratio in cores suggests that the TiC crystallizes there after accretion, perhaps annealed by electron bombardment. Such phenomena, rather than thermal condensation sequences, account for the structure in SUNOCONs. A caveat is that subsequent annealing owing to energetic impulses may not only cause the crystallization of TiC in high-Ti cores but may effectively homogenize the trace elements that cannot crystallize into favorable forms.

6. <u>Effects of the O/C ratio</u>:   At values of O/C larger than unity, the seed molecule C_{24} is less abundant (1). Although large C grains will then be less abundant, they may, curiously, be larger! This reversal occurs if the grains ultimately deplete all C to stop further growth. For example, (1) showed that if $C_{24} = 10^{-20}$ per C atom, the growth of C grains will stop near $n=10^{15}$ because of C depletion (not because of oxidation). For an O/C ratio twice as large (O/C=2), (1) showed that $C_{24} = 10^{-24}$, so that large graphites must also be 10^4 less abundant than for O/C = 1. Owing to their smaller abundance, they could grow to $n = 10^{19}$ before depleting the C. Eventual discovery of 100μm graphite SUNOCONs might be expected to reveal isotopes that require a more oxidizing environment rather than the other way round, as might have been naively supposed. This might be expected to carry smaller $^{18}O/^{16}O$ isotopic ratio, for instance. On the other hand, C condensation within the He-burning shell, where C/O = 4-5, may produce such a large abundance of C_{24} that gaseous C becomes exhausted before macroscopic graphites can be achieved.

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