CONSTRAINTS ON GRAIN FORMATION AROUND CARBON STARS FROM LABORATORY STUDIES OF PRESOLAR GRAPHITE. T. J. Bernatowicz, O. W. Akande, T. K. Croat, and R. Cowsik, Laboratory for Space Sciences and Department of Physics, CB 1105, Washington University, 1 Brookings Drive, St. Louis, MO 63130-4899, USA (tom@wustl.edu).

We report the results of an investigation into the physical conditions in the mass outflows of asymptotic giant branch (AGB) carbon stars that are required for the formation of micron-sized presolar graphite grains, either with or without internal crystals of titanium carbide (TiC).

In addition to providing detailed information about stellar nucleosynthesis, the structure and composition of presolar grains give unique information about the conditions of grain formation. In the present work we use laboratory observations of presolar graphite to gain insight into the physical conditions in circumstellar outflows from carbon AGB stars. The periodic pulsation of AGB stars enhances the gas density through shocks in the stellar atmosphere above the photosphere, promoting the condensation of dust grains [1]. Copious mass outflow occurs largely because grains are coupled to the radiation field of the star, which accelerates them by radiation pressure; momentum is in turn transferred to gas molecules by collisions with grains. The dust/gas mixture is effectively a two-component fluid whose motion depends on atmospheric structure and which, in turn, influences that structure. In particular, the radiation pressure on the grains determines the velocity field of the outflow and thus the density distribution, while the density distribution itself determines the conditions of radiative transfer within the outflow and thus the effective radiation pressure [2-5].

Our analytical strategy is as follows: First, we derive a lower mass limit of 1.1 M_O for stars that might contribute presolar grains to the solar nebula, from an upper limit on stellar lifetimes imposed by the ages of the Galaxy and Solar System, along with the main sequence mass-luminosity relationship. This mass limit is used, in conjunction with a mass-luminosity relation for carbon stars [6], to identify the region of the HR diagram relevant to the production of presolar graphite. We investigated stellar masses from $M = 1.1 - 5$ M_O, and temperatures $T = 2240$ K – 3350 K. The mass range translates into luminosities $L = 4700$ L_O – 11,700 L_O, for variable carbon (CV) stars with radii $R = 200$ R_O – 700 R_O.

Parameterizations of results from detailed dynamical models of density and radiative transfer in AGB outflows [7] were used to find mass loss rates dM/dt as a function of M, T, and L. We then used the observed astronomical relationship between terminal outflow velocity v_e and dM/dt [2], along with parameterized results of dynamical calculations [4], to characterize the outflow velocity field v(R) from the radius at which grain condensation first occurs and beyond, as a function of dust optical depth. The velocity field v(R) is given approximately by

$$v(R) \approx v_e \left(1 - \frac{R_{cond}}{R}\right)^{1/k} \tag{1}$$

where R_{cond} is the condensation radius and the power index k ranges from $k = 1.5$ in optically thin outflows to $k = 2.5$ in optically thick ones [4]. For radiative equilibrium, the radial distance R from the stellar center is related to the local temperature T in the outflow by

$$\frac{R}{R_O} = 23.6 \left(\frac{L}{L_O}\right)^{\frac{1}{2}} \left(\frac{1000K}{T}\right)^2 \tag{2}$$

We used results of equilibrium thermodynamics [8, 9] and kinetics calculations to infer a plausible temperature range over which TiC and graphite grains could form ($\Delta T = 1800$ K – 1000 K). This temperature range leads to inferred condensation radii of 2.3 A.U. to 3.7 A.U. for stars in the 1.1 M_O – 5 M_O range. We integrated dR/v(R) over the range ΔR corresponding to ΔT [eq. (2)], to obtain the grain growth time intervals Δt shown in Figure 1, which are on the order of a few years. These results, which assume an optically thick ($k = 2.5$) outflow, are independent of any considerations of grain size or the assumption of spherical outflow symmetry.
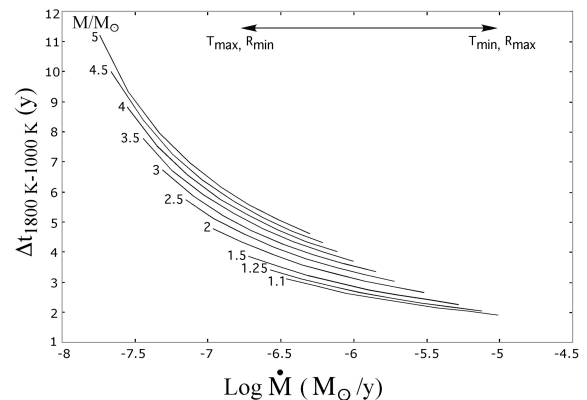

Figure 1. Maximum graphite growth intervals in AGB carbon star atmospheres in the temperature range T = 1800 K to 1000 K, as a function of stellar mass, effective temperature, and mass loss rate.

In an optically thin ($k = 1.5$) outflow, Δt is increased by a factor of 1.26. In either case, the grain growth interval Δt, operationally defined as the time required for the temperature of a parcel of gas in the outflow to cool from a condensation temperature of 1800 K to 1000 K, increases systematically with stellar mass. For the entire stellar mass range considered (1.1 − 5 M_O), Δt varies by about an order of magnitude, roughly from 2 to 10 years. The growth intervals Δt are minimal for the smallest possible stellar mass (1.1 M_O) that could contribute circumstellar graphite to the solar nebula. Overall, the growth of circumstellar graphite grains is predicted to occur in the relatively short time interval of a few years, as opposed to far longer time intervals that might have been expected on the basis of simple considerations of grain size and growth kinetics.

Using optimal growth assumptions (perfect sticking efficiency, no evaporation, no depletion of gas species contributing to grain growth), we also calculated a strict upper limit on grain sizes for graphite and TiC in spherically symmetric AGB outflows. Grain radii are found from

$$r = r_o + \frac{\mu_s}{\mu} \frac{dM}{dt} \frac{f_i}{16\pi\rho} \int_{R_{1800K}}^{R_{1000K}} \frac{v}{R^2 [v(R)]^2} \, dR \qquad (3)$$

where f_i is the fraction of the gas number density of the gas species contributing to grain growth, μ_s is the molecular weight of the condensate, μ is the molecular weight of the outflowing gas, ρ is the density of the condensate, $v(R)$ is the outflow velocity at radius R, and v is the impact speed of gas molecules on grain surfaces given by

$$v = \left[(\overline{v}_i)^2 + (v_{drift})^2 \right]^{1/2}. \qquad (4)$$

In equation (4) $\overline{v}_i$ is the average kinetic molecular speed and v_{drift} is the drift speed of grains relative to gas in the stellar mass outflow.

In spite of the optimal assumptions used, the calculated grain sizes generally fall short of the mean grain sizes for both presolar graphite and TiC (1.2 μm and 22 nm, respectively) observed in the laboratory by at least an order of magnitude. These results, as well as pressure constraints from TiC condensation prior to graphite condensation that are derived from equilibrium thermodynamics [8, 9] considerations, force us to conclude that presolar graphite and TiC must form in small regions of enhanced density (clumps, jets) in AGB outflows that have length scales much less than the local condensation radius.

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