The Production of Low Mass Carbon Stars: Carbon-rich Dredge Up or Oxygen-rich Mass Loss?

R.E. Stencel and J.E. Pesce (CASA, Univ. Colorado) and
K.M. MacGregor (High Altitude Observatory/NCAR)

ABSTRACT:

Conventional theory explains the origin of carbon stars as due to dredge up of carbon enriched material from the stellar core during helium flash events late in the life of solar mass AGB stars (e.g. Boothroyd and Sackmann 1988). This relatively efficient process however, seems to produce a larger C/O ratio than observed (Lambert et al. 1987). A secondary effect which could contribute to the appearance of carbon stars, is the selective removal of oxygen from the atmosphere by radiative force expulsion of oxygen rich dust grains (e.g. silicates like $[Mg, Fe_2SiO_4]$). We present calculations for this scenario which evaluate the degree of momentum coupling between the grains and gas under the thermodynamical conditions of AGB star atmospheres.

In their pioneering analysis of the composition of the atmospheres of carbon stars, Lambert et al. (1986) state that there is a surprisingly thin margin separating carbon stars from their oxygen rich progenitors. Moreover, they also determined that ^{13}C, the preferred product of the dredge–up process, is lower than theory predicts. This problem appears to be especially serious for lower mass carbon stars, where large values of mixing length have to be invoked to produce carbon dredge up (Boothroyd and Sackmann 1988). We suggest an additional process: that oxygen in the star's atmosphere could be *selectively removed* by the formation of oxygen–rich dust grains, which are driven off by radiative forces. The importance of this process with respect to dredge–up will depend sensitively on stellar mass.

The advent of the IRAS infrared sky survey and low resolution spectroscopy, enabled Little–Marenin (1986), Willems and deJong (1986) and Nakada, Deguchi and Forster (1988) to discover and analyze carbon stars *with silicate features*, suggestive of oxygen–rich circumstellar envelopes. This juxtaposition of features suggests an evolutionary connection in which the oxygen–rich characteristic of the carbon star progenitor persists in the outflow of material, which left the star on an outflow timescale. Ultimately, it is surmised that such objects will replenish their circumstellar envelopes with carbon–rich material. Hence, it seems established that evidence of the composition history can survive in the dusty stellar wind.

In their analysis of time–dependent models for the expanding atmospheres of carbon rich stars, where the driving force was radiation on grains, Woodrow and Auman (1982) noted that the drift velocity of the carbon–rich grains, with respect to the gas, was large, implying that while the grains shared momentum with the gas, the two species were not positionally coupled. Thus, the carbon was leaving the atmosphere *faster than* the other stellar material and the surface layers were being *differentially depleted of carbon.* They further note that the drift velocities were not so large as to destroy the grains by sputtering. Hence, they noted that the dust–forming process can selectively alter the composition of the stellar atmosphere.

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Composition anomalies have been noticed by several authors. Eaton and Johnson (1988) studied oxygen–rich M stars using ultraviolet spectroscopy, and came to the unsettling conclusion that silicon was somehow depleted in these chromospheres. Judge (1986) did not find silicon underabundance in similar stars, however. Luck and Lambert (1985) performed CNO abundance analysis for Cepheids and non-variable F supergiants and conclude that a significant oxygen underabundance exists which cannot be attributed exclusively to dredge–up of ON cycled material. An analysis of the infrared characteristics of similar stars by Stencel, Pesce and Bauer (1988, 1989) indicates that some of these stars probably have evolved blueward from red supergiant phases where extensive dust production dominated their mass loss history. Snijders et al. (1984) argued that the ejecta in Nova Aql 1982 underwent grain formation which may have led to gas–phase element depletions. Similar arguments have been advanced by Snow et al. (1987) who examined cimcumstellar reddening toward the red supergiant α Sco, using techniques adapted from interstellar work, and concluded that the grains are large and silicon–rich, on the basis of extinction and elemental depletion. Hence, in several instances we find indication that for stars within which dust formation is occuring or has occurred, that composition anomalies occur as well.

The degree of coupling between dust grains and gas atoms in a stellar atmosphere can be evaluated in terms of the ratio of drag forces to radiative acceleration. The drag force per grain is given by (Gilman 1972):

$$f_{drag} = \rho_{gas}\sigma_{gr}v_D^2 \tag{1}$$

where ρ_{gas} is the gas density, σ_{gr} is the grain cross section [cm^2] and v$_D$ is the drift velocity:

$$v_D = |v - v_{gr}| \tag{2}$$

v is the wind velocity, derived from the formalism originally discussed by Parker (1958) where mass and momentum conservation in an isothermal flow require that the wind solution pass through a critical point. For red giants with dust in their outer atmospheres, we add a term for the radiation force. With appropriate values, we were able to reproduce the Parker solutions for the solar wind, and to compute representative wind solutions for red giant winds with non–zero opacity.

The grain terminal velocity can be evaluated in the limit of rarified gas dynamics and constant flow velocity. Gilman (1972) estimated this to be approximately 40 km sec^{-1} for

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red giants. The radiation force is given by:

$$f_{rad} = \rho \sigma L/(4\pi r^2 c) \tag{3}$$

where σ is the atmospheric opacity in $cm^2\ gm^{-1}$.

For three isothermal models, with radii and luminosities comparable to α Ori, and with surface temperatures of 4000K, 5000K and 6000K, $\sigma = 400\ cm^2\ gm^{-1}$, and photospheric densities of $10^8\ cm^{-3}$, we compute that the ratio of drag to radiation forces is much smaller than 0.5, even at the photosphere, where it is largest. Hence, the gas and grains are not coupled positionally and differential depletion of oxygen–rich solids may occur. We assume that a "molecular catastrophe", where the rapid cooling effect of simple molecules like CO and SiO in the upper photosphere, can give rise to grain formation at low altitudes (Muchmore, Nuth and Stencel 1987; Tsuji 1988), and hence, directly affect derived photospheric abundances over evolutionary timescales. For higher photospheric densities, the degree of coupling is larger. Hence the de-oxygenation of stellar photospheres is sensitive to effective gravity and therefore evolutionary state. Low mass stars near the end of their AGB may be the most affected by this process, in addition to dredge–up (if any).

While this low coupling argues for differential depletion, it also raises the question of the role of the grains in the overall dynamical state of the atmosphere. This issue requires further quantitative study with two component wind solutions. We are grateful for support of this research from NASA grants JPL 957632 and NAG5-816 to the University of Colorado.

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