Chromospheres of cool non-mira giant stars

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Abstract. We review the density and velocity structure of the chromospheres and photospheres of the coolest non-mira M and carbon stars and subject them to the constraints imposed by known mass-loss rates. We note two severe problems. (1) In available chromospheric models, the density falls, within a short distance (< 1 R_*) above the photosphere, to less than the density needed to sustain the observed mass loss with the observed flow velocities. To keep the model chromospheric density above the mass-loss value requires large amounts of turbulent energy. (2) Even with reasonable amounts of turbulent energy, densities in all chromospheric models and some photospheric models become so low that mass flow may become significant. In addition, chromospheres are likely inhomogeneous.

1. Introduction

Chromospheric models for cool giants are still rare. One-dimensional, semi-empirical models for K giants such as Arcturus and Aldebaran and for K supergiants of the ζ Aur class are available. For these K giants, synthetic spectra, including a self-consistent NLTE treatment of excitation, ionization, and line formation, are calculated for several chromospheric models, and the final model is that whose synthetic spectra compares best to observations of the Mg II and Ca II lines (cf. Judge 1989). The ζ Aur stars are eclipsing binaries in which the light of a B-star secondary shines through the chromosphere of a K-supergiant primary, permitting direct deductions of column densities through different lines of sight. A semi-empirical chromosphere for the cool supergiant Betelgeuse (M2 Iab) was obtained from the Mg II and Ca II lines, but it was found that no single-component model was sufficient for both sets of lines (Basri, Linsky, and Eriksson 1981). A more detailed model for the same star has just been reported (Dupree et al. 1990, this meeting).

A semi-empirical chromosphere for the cool carbon star TX Psc was obtained by fitting the Mg II h line (Luttermoser et al. 1989; LJAL). Calculated with plane-parallel geometry and based on a plane-parallel photosphere computed with diatomic molecular opacities (Johnson and Luttermoser 1987), this model includes a temperature minimum of 1240 K, above which the temperature rises very rapidly to 4-6,000 K. The Mg II lines at λ 2800 and the C II] lines at λ 2325 are formed in the height range 0.8-2.7 x 10^6 km above the photosphere. Although the k line and the redward wing of the h line are almost entirely obliterated (Eriksson et al. 1986), the clean blueward wing of the h line is very well fit by the best chromospheric model when correct opacities and partial redistribution are employed.

A semi-empirical chromospheric model for the M6 giant g Her has also been computed in the same way (Luttermoser, Johnson, and Eaton 1990; LJE). This chromospheric model is based on a plane-parallel photospheric model (T_{eff} = 3200 K; g = 1.0 dyne cm^{-2}) that includes an opacity-sampled treatment of the important absorption of H_2O (Brown et al. 1989). Atmospheric extension is unimportant in this star, and the plane-parallel geometry used is probably sufficient. The chromosphere shows the expected rapid temperature rise to values of 4-6,000 K lying about 10^7 km above the level where the Rosseland optical depth is unity.

Generally, ultraviolet observations of emission lines near the star, infrared observations of CS dust at intermediate distances, and radio observations of CS gas far from the star have been handled by different researchers for different purposes. Only rarely has the interaction been emphasized (Pecker, Praderie, and Thomas 1973). Recently, however, Johnson (1990) has pointed out the serious disagreement between the densities in the chromospheric models and that implied by the observed mass-loss rate and the condition of mass continuity. In this paper, we apply that line of reasoning to both carbon stars and M stars.

2. Analysis

Values of mass loss for many cool giant stars have been obtained from IR observations of CS dust or radio observations of thermal CO lines or OH masers. Since most carbon stars have nearly the same mass-loss rate, mass loss must be steady on time scales of 100-1000 years. We make the same assumption for M giants. The mass-loss equation then yields, for any distance, the product of density and velocity. If either is known or can be assumed, the other can be found; we employ the equation in both ways here. Since the observed outflow velocity from the CO radio observations is likely an upper limit to the velocity everywhere, its use leads to minimum values of the density. Consequently, no realistic model can have densities below these values. For normal non-mira carbon stars, typical values of outflow velocity are 10 km s^{-1} and of mass loss are 2×10^{-7} $M_\odot$ y^{-1}. Mass-loss rates for M giant stars span a considerable range. For g Her the rate is also close to 2×10^{-7} $M_\odot$ y^{-1}, while for mira variables, mass-loss rates of 10^{-5} $M_\odot$ y^{-1} are not uncommon.

Recently, new photospheric models for carbon stars have been computed with spherical geometry and with the opacity of six molecules treated by opacity sampling (Jørgensen, Johnson, and Nordlund 1990; JJN). We also assemble model photospheres for M giants from the literature. To all these we attach hypothetical chromospheres and subject them to the constraint of mass-flow imposed by the IR and radio observations. That is, we attach a hypothetical isothermal chromosphere to the photospheric model at the point where the density is log ρ = -11.50, approximately the density at the temperature minimum in the semi-empirical chromospheres of the carbon star TX Psc (LJAL) or the M6 giant g Her (LJE). At the point of attachment, the temperature in the hypothetical chromosphere rises discontinuously to 6,000 K and remains at that value. We then compute the density profile outward from that point with constant temperature and constant but different turbulent velocities.

Results are shown in Figure 1 for the semi-empirical chromospheres of LJAL and LJE, and photospheric models for M giants (Brown et al. 1989; BJACS), M miras (Bessell et al. 1989; BBSW), and carbon stars with attached hypothetical chromospheres. (The size of the photosphere has been taken from the original publication or estimated, and the absolute scale is less certain than the relative scale.) Labels (A,B) designate density profiles derived from different values of the (assumed constant) scale height, which is $H = [v_{th}^2 + v_b^2]/2g$, where g is the surface gravity, and both thermal and turbulent velocities (labelled "b") are included. The values taken for illustration are as follows: (A) T = 6000 K, no turbulent velocity and g = 1.0 cm s^{-2}; and (B) T = 6000 K, turbulent velocity = sound velocity, and g = 1.0. In all cases, the density drops over a short distance to the "mass-loss" density - that value necessary to supply the observed mass loss at a velocity of 10 km s^{-1}.

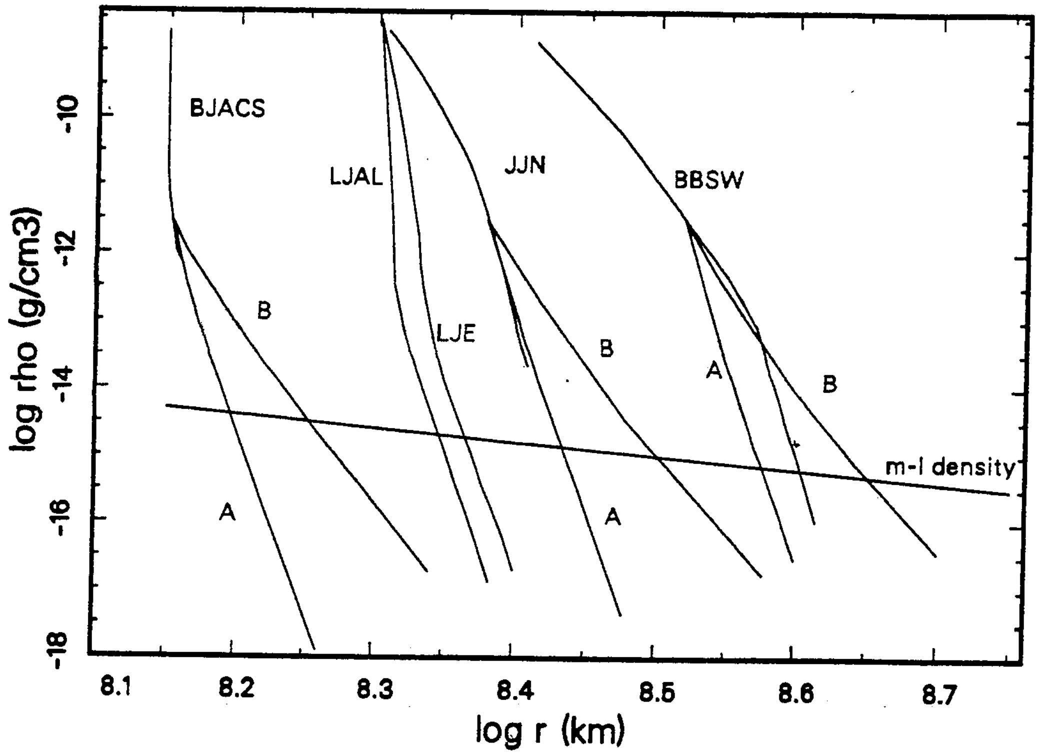

Figure 1. Densities in the photospheres and chromospheres of red-giant stars. Hypothetical chromospheres are marked A (v_b=0) and B ($v_b=v_{sound}$), respectively. The other labels refer to authors initials; see text and references. "m-l density" is the mass-loss density line.

From the figure we draw several conclusions. Clearly the photospheres of the lower gravity and higher opacity models are more extended. But even in these extended photospheres the density in the hypothetical chromospheres falls rapidly to the mass-loss value. Clearly some mechanism for "puffing out" the photosphere-chromosphere is needed. We hasten to point out, of course, that no synthetic spectra have been calculated for these hypothetical chromospheres, and one cannot say to what extent their spectra might match observations of ultraviolet emission lines. However, hypothetical chromospheres lead to useful limits on the dynamical behavior of the gas.

The location of the chromospheric temperature rise, which must be very steep for both carbon stars (LJAL) and M stars (LJE), is fairly well constrained by the appearance of Mg I and Mg II lines. Emission lines of Mg II at λ 2795,2802 are seen in all red giants. In late M stars, the Mg I line at λ 2852 exhibits a distinct emission core (Eaton and Johnson 1988), but emission cores are weak or absent in carbon stars. Clearly, the density at the temperature minimum (base of the chromosphere) must be low enough that the optical depth at the center of the Mg I line is not too great, but still high enough to produce the Mg II line. Such densities confirm the problems shown in Figure 1.

How can the density of the chromosphere be increased, or how can the chromosphere be extended to ameliorate the situation shown? An extended discussion has been given by Johnson (1990). Several ways to increase the "size" or scale of the chromosphere come to mind: (a) add turbulent pressure to "puff up" the atmosphere (Bowen 1988; Cuntz 1990), (b) add molecular levitation, and (c) include spherical geometry. In fact, a model chromosphere calculated with spherical geometry matches slightly better the mass-loss density profile (Luttermoser 1990, private communication), but a serious mismatch still exists.

Some progress has been made in two completely different attacks on the hydrodynamic behavior of the outer stellar atmosphere and CSE. In one, pulsational shocks are mimicked by a piston whose period and amplitude are specified beforehand. These produce long-period acoustic waves, sometimes called hydrodynamic waves. As already pointed out (Johnson 1990), the density decrease in such a shocked atmosphere is close to that of (C) above. Though still exploratory, the method gives interesting results both for a single travelling shock and for periodic shocks. In particular, the latter expecially extend greatly the atmosphere of mira variable stars and lift the matter to the point where grains can form (cf. Bowen 1988). In a second approach, short-period acoustic waves generated stocastically by turbulent convection frequently interact to produce shocks. A time average yields a significant amount of acoustic energy, the amount depending on the effective temperature and surface gravity in such a way that it is very large for red-giant stars. This flux of acoustic energy is a prime candidate for heating the chromospheres of the coolest red giants (cf. Ulmschneider 1989; Gail, Ulmschneider, and Cuntz 1990).

To examine the assumption of hydrostatic equilibrium, on which all these models are based, we accept the densities given in published models and find the outflow velocity which satisfies the mass-loss rate (cf. Johnson 1990). We show in Figure 2 the velocities at different distances obtained in this way for several M and carbon-star model photospheres and chromospheres. (The very high velocities found in the outer atmospheres are of course unrealistic; they simply demonstrate in another way that the densities are unrealistically low.) However crude, these results establish that even in the upper photosphere, outflow velocities (not accounted for in these static models) may be important. This is especially true for miras, with their very low gravities, which may be effectively decreased even more by levitation due to radiation pressure on molecules.

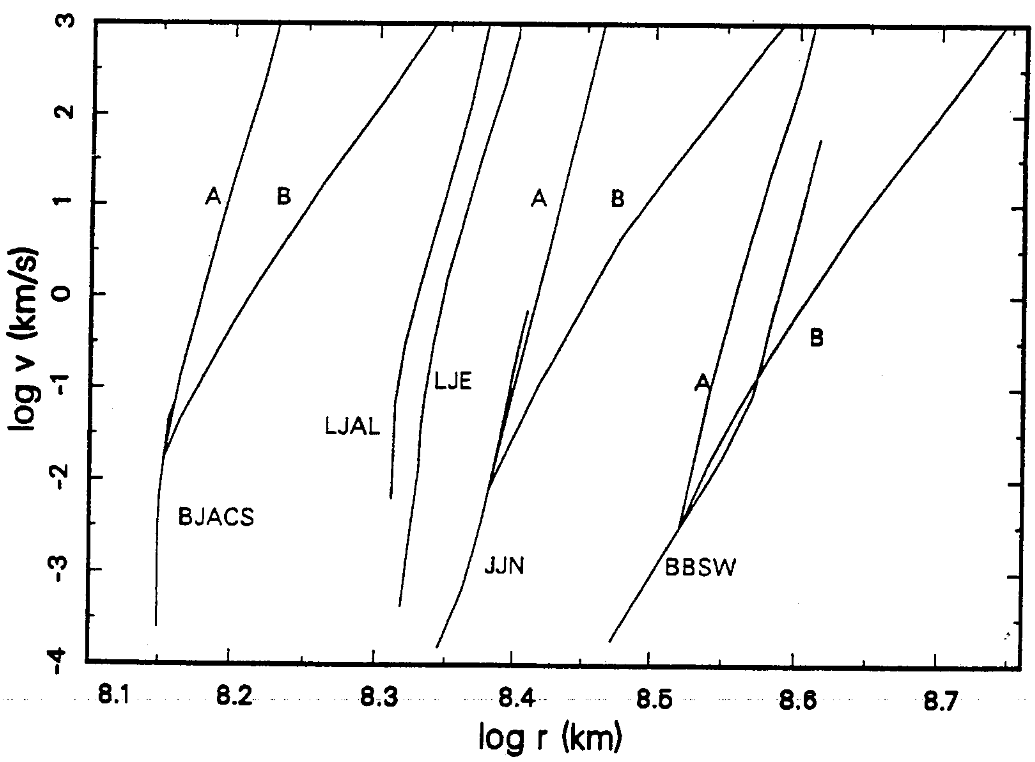

Figure 2. Velocities in the photospheres and chromospheres of red-giant stars. Labels as in Fig. 1

Taken together, these results allow us to make certain general statements about the heating mechanisms and mass-loss mechanisms in late-type giants. Whatever mechanism is primarily responsible for mass loss, it must operate close to the star. Radiation pressure on dust grains is a popular choice, but our results clearly require these grains to form within a fraction of a stellar radius from the star, while present calculations place the region of grain formation at 2-5 R_*. Apparently, some other mechanism must initiate the flow, and the grains form in the stellar wind. For the JJN models such low temperatures are never reached before the chromospheric temperature rise sets in, and we therefore conclude that the grains must form after the acceleration of the material to the wind has taken place. But the grains are then clearly not the primary mechanism for acceleration of the wind.

Finally, we note that recent research shows that, while band intensities of most molecules are relatively unaffected by the addition of a chromosphere, the lines of CO develop emission cores if they are formed, as normally assumed, by pure absorption. No such emission is ever observed. Thus the chromospheric region must contain a large amount of cool matter to produce the CO absorption. This seems to require at least a two-component chromosphere, with a small filling factor for the warm component (Jørgensen and Johnson 1990).

3. Conclusions and Discussion

In spite of numerous uncertainties regarding the chromospheres of the coolest non-mira red giants, several rather important conclusions can already be stated.

1. Chromospheres for M giants, M supergiants, and carbon stars can be constructed, in plane-parallel geometry and with full NLTE treatments of ionization and excitation, so that synthetic spectra, including partial redistribution in the line source function, match well the observed line profiles of the Mg II emission lines (when CS absorption is accounted for), whose presence indicates the existence of warm gas ($T > T_{eff}$).

2. Synthetic spectra from such chromospheres match moderately well the profiles and fluxes in the Ca II lines and other chromospheric lines.

3. The chromospheric temperature rise (the base of the chromosphere) must occur at sufficiently shallow layers that the stronger lines of neutral metals, particularly Mg I, have reached reasonably low optical depths; otherwise these develop strong emission cores, contrary to observation.

4. The chromospheric temperature rise must be very steep in all models, so that such elements as C, Mg, Al, Si, Ca, and Fe can become ionized while the density is still sufficiently high to produce the observed emission lines.

5. The addition of a chromospheric temperature rise does not affect the molecular dissociative equilibrium and has insignificant effect upon the spectra of molecules formed in the photosphere except for CO, the strongest lines of which develop emission cores if, as usually assumed, they are formed in pure absorption. Apparently, then, there must be cool regions as well as warm (chromospheric) regions - the outer atmosphere is not homogeneous. Furthermore, the filling factor of the warm regions must be small.

6. Semi-empirical chromospheres, computed for plane-parallel geometry and based on plane-parallel photospheres, tend to be quite shallow, their depths being only a small fraction of the stellar radius. Model chromospheres with spherical geometry and the same photospheres are only slightly more extended. Adding opacity to the photosphere significantly extends it.

7. In available chromospheric models, the density falls, within a short distance compared to the stellar radius, to less than that required by the observed mass-loss rate with the observed velocities. To keep the chromospheric density above the mass-loss density (to puff out the chromosphere) would require very large amounts of additional acoustic or hydrodynamic energy.

8. Even with additional turbulent pressure from both short-period (acoustic) and long-period (hydrodynamic) waves, all available models for chromospheres of red-giant stars of all types have sufficiently low densities that significant mass flow must begin in the chromosphere. In some cases, the outflow may be substantial even in the photosphere.

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Discussion

A. Dupree: The most recent observations of mira variables indicate that dust/grain formation occurs not in the chromosphere but at several (say 5) stellar radii distant. Thus, similar to the carbon stars, a mechanism is still needed to move material from the photosphere to a distance where radiation pressure on dust can become important.

Answer: Finding a mechanism to and initiate the flow is the central problem for all cool red-giant stars. In a poster here, Fleischer et al. put the region of grain formation in M miras at about 2.5 R_*. Some other mechanism must therefore initiate the wind. Short-period acoustic waves may heat the chromosphere, and long-period waves (pulsations) may be responsible for puffing out the atmosphere. Whether these actually drive mass loss is still an open question.

R.N. Thomas: You also should thank Andrea Dupree for showing the Hα profiles. They are the type found in a variety of stars showing low-ionization emission lines like Hα, but which are produced in post-chromospheric/coronal regions. So I would urge you to rethink some of your "cool" components as post chromospheric instead of only considering the hot-cool column-structured chromosphere, since you argue persuasively that you indeed need hot-chromosphere regions ("hot" relative to the effective temperature of these stars, not the sun).

Answer: Yes, I thank Andrea again, even though it is a fact that the non-mira carbon stars do not show Balmer α at all. Cool gas ($T < T_{eff}$) is everywhere - both in the photosphere and in the CSE or "post chromospheric" region. Strong absorption lines of both atoms and molecules often show extra (unusual or wavelength-shifted or asymmetric) components that are most readily explained by circumstellar absorption. Ultraviolet emission lines of Mg II in the coolest M and carbon stars are very badly reabsorbed by neutral metal lines in overlying cool gas. However, the strong CO lines are generally photospheric, and they demonstrate that the cool component extends out past the temperature minimum. Thus we have both a two-component outer atmosphere and a cool layer overlying the chromosphere.