# Rates of Energy Gain and Loss in the Circumstellar Envelopes of Be Stars: 1 Delphini

C. E. Millar[1,2] and J. M. Marlborough[1,3]

## ABSTRACT

We have investigated the rates of energy gain and loss in the circumstellar envelope of the cool B8-9e star, 1 Delphini , using the Poeckert-Marlborough model. We determined iteratively the kinetic temperature of the gas as a function of position in the circumstellar envelope by adjusting the temperature at each grid point until the rates of energy gain and loss there were equal. The gas was assumed to gain energy from photoionization, collisional de-excitation of bound levels and free-free absorption, and to lose energy by recombination, collisional excitation and free-free emission. The resultant temperatures are a self-consistent solution of the equation of energy conservation. We were also able to reproduce the gross features of the $H_\alpha$ line with this model and the corresponding temperature grid. Our investigation demonstrates that there is sufficient continuum radiation present to ionize the circumstellar envelope and produce the relative line strength without any additional source of heating in the envelopes of cool Be stars.

*Subject headings:* circumstellar matter—stars: early-type—stars: emission-line, Be

[1]University of Western Ontario, Department of Physics and Astronomy, London, Ontario, Canada N6A 3K7

[2]cmillar@io.astro.uwo.ca

[3]marlboro@titan.astro.uwo.ca

## 1. Introduction

Be stars are rapidly rotating stars on or near the main sequence which have been observed to exhibit emission in one or more Balmer lines, typically H$\alpha$. Generally, the strength of the Balmer emission decreases with decreasing temperature. Emission may also be present in lines of He I and also in lines of singly ionized metals, for example, Fe II. These stars also are observed to have excess continuum radiation both in the infrared and at longer wavelengths. The Be stars, which have sharp deep absorption cores in the spectral lines of hydrogen and singly ionized metals, are commonly called shell stars.

The gas in which the emission lines and excess continuum radiation arise is generally considered to be the denser parts of a disk-like stellar wind, which is concentrated both toward the star and toward the equatorial plane. Spectroscopic data indicate that there is a two component nature to this wind; analysis of UV spectra suggests a low density polar wind with outflow velocities of several thousands km/s, while from optical spectra a high density equatorial wind with very low outflow velocities is inferred. Be stars also have a high intrinsic linear polarization which further implies a non-spherical distribution of gas. See review articles in Slettebak & Snow (1986), Balona et al.(1994), and references therein. Recently, support for a flattened equatorial distribution of gas has come from direct imaging, Dougherty & Taylor (1992), Quirrenbach et al. (1993), and Stee et al. (1995).

It has been suggested that the continuum and line radiation from the central star is not sufficient to ionize the circumstellar envelope and produce the energy emitted in lines and continua in the envelope of all Be stars, but especially for the later types (Ashok et. al. 1984, Apparao & Tarafdar 1987, 1997a, 1997b). In an earlier paper, (Millar & Marlborough 1998, hereafter MM), we determined in a self consistent manner the kinetic temperature of the gas in the circumstellar envelope for the early Be star, $\gamma$ Cas, using the model of Poeckert-Marlborough (1978), hereafter PM. The kinetic temperature was determined from the requirement that the rates of energy gain and loss at each point in the circumstellar envelope be equal. Photoionization, collisional de-excitation of bound levels and free-free absorption were assumed to contribute to the rate of energy gain; radiative recombination, collisional excitation of bound levels and free-free absorption contribute to the rate of energy loss. For additional details see MM.

In this paper we extend our analysis of the PM model to include a cool Be star in order to investigate further the claim of Apparao & Tarafdar (1987, 1997a, 1997b). The energy rate calculations and corresponding temperatures within the circumstellar envelope are given here for the star 1 Delphini. This star has a spectral type in the range B8-9 e-shell (Slettebak 1983); it was previously modeled by Marlborough and Cowley (1974), hereafter MC.

## 2. The Model

There are some substantial differences between the models used by MC, PM, and the model of MM used here. The model used by MC was based on the work of Marlborough (1969); the model used here, although based on the same work, was substantially modified by PM. An error in both the model used by MC and the model used by PM was corrected by MM; see MM for details.

The envelope is assumed to be symmetric about both the rotation axis of the star and the equatorial plane. The central star is assumed to be spherically symmetric and rotating at the Keplerian speed. The maximum height of the envelope above the equatorial plane varies from 0.1 stellar radii at the stellar surface to a height of 34.75 stellar radii at a radial distance of 100 stellar radii. Beyond this maximum height of the envelope, the envelope density was assumed to be zero. The specific choice of this maximum height of the envelope does not influence our results in any significant way because of the exponential decrease of density with increasing distance perpendicular to the equatorial plane.

The stellar mass, radius, effective temperature and log g were assumed to have the values 4 $M_{\odot}$, 3.3 $R_{\odot}$, 12,600 K, and 4, respectively, identical to those used by MC. The number density at a position in the equatorial plane and the velocity distribution in the radial direction are assumed; then the equation of continuity is solved for the density distribution in the equatorial plane. We used an assumed number density of $4.19\text{x}10^{13}\,\text{cm}^{-3}$ at a radial distance of 4 stellar radii; MC used a value of $2.35\text{x}10^{12}\ \text{cm}^{-3}$ at this position. The value of the number density was chosen in order to reproduce the gross features of the H$\alpha$ line. It is not surprising that the density used here is quite different from MC. The model used by MC is substantially different from the current model. In particular, the model used by MC had a coding error in one of the subroutines. This error affected the level populations in regions of the envelope where the gas was assumed to be optically thick; this is discussed in MM. In addition, many improvements and additions have been made to this code by PM since it was used by MC.

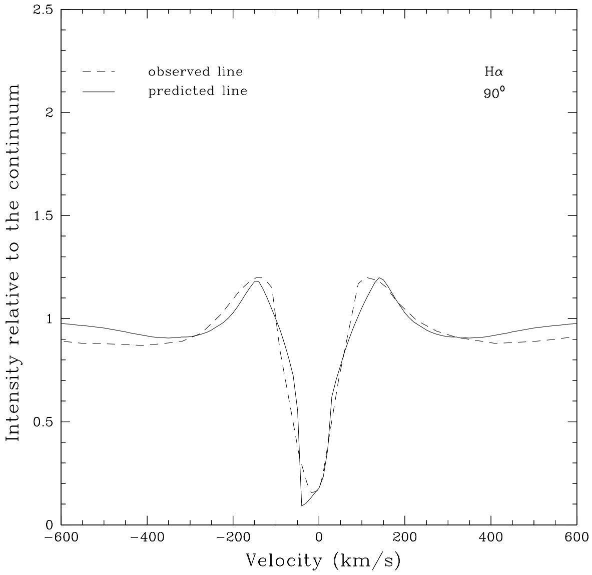


Fig. 1.— Predicted H $\alpha$ line derived from the model calculations compared to the observed line.

At a specified location in the equatorial plane, $\omega'$, the density distribution perpendicular to the equatorial plane is assumed to be hydrostatic; this sets the position and shape of the projection of the density streamlines in a meridional plane. As the value of this parameter increases, the emitting volume of the envelope also increases. We have used the value of $\omega' = 4$, the same as that used by MC. The particular combination of the assumed parameters allowed us to reproduce satisfactorily the gross features of the $H_\alpha$ line; see Figure 1. The predicted line has roughly the correct amount of emission and the widths of the observed and predicted lines are quite similar. However, there are some differences in detail, especially in the shape of the line wings. Nevertheless, since the main objective of this exercise was to check to validity of the temperature previously assumed for the envelope by MC and further to determine a self-consistent temperature profile, we were satisfied to reproduce only the gross features of the H$\alpha$ line. It should also be noted that the observed line in Figure 1 is an average of a series of observations recorded on photographic plates; see Fig. 1 of MC. Uncertainties arising from the conversion of photographic density to relative line strength, together with the fact that Be star spectra are variable, suggests that trying to match observation and model exactly may be futile.

## 3. Results

The kinetic temperature derived from the criterion of equal rates of energy gain and loss is shown in Fig. 2 as a function of radial distance in the equatorial plane, at a position half way between the equatorial plane and upper edge, and at the upper edge of the envelope. Since there is an exponential decrease in the density distribution perpendicular to the equatorial plane most of the material in a particular column lies below a position half way between the equatorial plane and the upper edge. For example, at a radial distance of 1 stellar radii at J = 10, 0.0474 stellar radii above the equatorial plane, with the point corresponding to J = 1 being in the equatorial plane, 99.8% of the material in a column which extends to the upper edge lies below this position. Similarly, at a radial distance of 34.75 stellar radii at J = 10, 16.46 stellar radii above the equatorial plane, 99.6% of the material in a column which extends to the upper edge lies beneath this position. The global average kinetic temperature for this model is 5800$\pm$1000 K ($1\sigma$); the density weighted average is 5900$\pm$40 K ($1\sigma$). The difference of these two average temperatures reflects the fact that the kinetic temperature is higher in the equatorial plane where the density is higher. The kinetic temperature remains fairly constant with increasing radial distance from the star, and is essentially isothermal. The temperature of the upper edge of the envelope, however, is approximately 1000 K cooler than the mid-section of the disk. Near the equatorial plane, as the density increases collisional processes become increasingly important and tend to populate upper levels. Consequently, even though the envelope is optically thick to Lyman continuum photons, photoionization from upper levels is able to heat the gas.

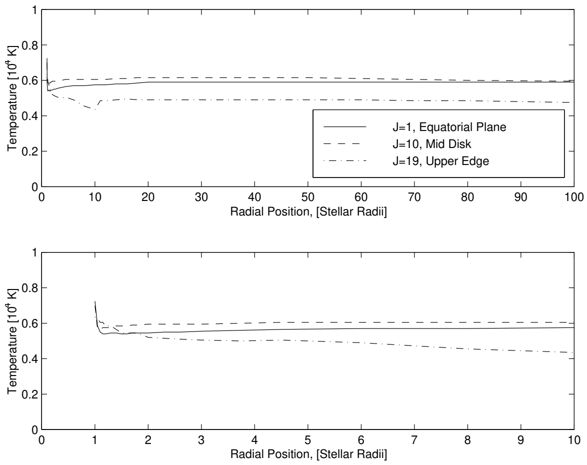


Fig. 2.— The temperature for which the energy gain balances the energy loss as a function of distance from the rotation axis for three locations in the circumstellar envelope: the equatorial plane (J=1), an intermediate location (J=10), and the upper edge (J = 19).

The radial dependence of processes which contribute to energy gains and losses is shown in Fig. 3 and Fig. 4 as a function of distance from the star for the equatorial plane and upper edge, respectively. The dominant source of energy gain and loss at almost all locations in the envelope is photoionization and radiative recombination, respectively. Collisional processes dominate in a very small region in the equatorial plane between the stellar surface and a radial distance of 1.05 stellar radii. Collisional processes are only important where both the density and temperature are large. At radial distances greater than 1.05 stellar radii, energy gain from photoionization has the largest absolute value of all the heating and cooling terms. From the radial distance of 1.05 to 1.80 stellar radii in the equatorial plane, the rate of energy loss due to collisions is larger than the recombination energy rate. However, at all other locations the photionization and radiative recombination terms are the largest. See Fig. 3.

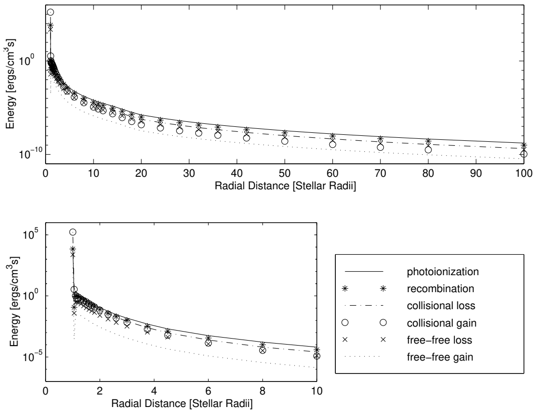


Fig. 3.— The sources of energy gain and loss along the equatorial plane (J=1).

Nevertheless, near the star and in the equatorial plane where densities are the greatest, collisions are important in increasing the populations above the ground level from which atoms may then be photoionized. Along the upper edge where densities are low, collisional energy terms are orders of magnitude smaller than photoionization and recombination energy terms; see Fig. 4.

Energy transfer to the gas in the equatorial plane is dominated by photoionization from levels 2p and 2s. In the equatorial plane

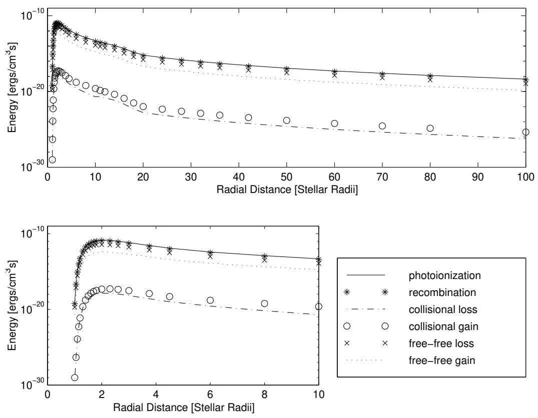


Fig. 4.— The same as Fig. 3 for the upper envelope (J=19).

the gas is optically thick in Lyman continuum radiation; consequently photoionization from level 1 by stellar radiation is not important. In contrast, the upper edge of the envelope is dominated by photoionization from levels 1 and 2s. The heating due to photoionization from level 2s is important here due to the relative increase in the population of this metastable level. The number density is low along the upper edge and collisions are not important; consequently the population in level 2s becomes substantially greater than the population in 2p. When collisions are dominant the population in level 2p is expected to be approximately 3 times the population in level 2s. See Fig. 5 and Fig 6 for graphs of the source of photoionization energy as a function of radial distance from the star for the equatorial plane and upper edge, respectively.

The portion of the envelope nearest the equatorial plane is neutral. The greatest degree of ionization in the equatorial plane is 1.3% near the star, at all other radial distances in the equatorial plane, the degree of ionization is less than this value. There is simply not enough ionizing radiation from the

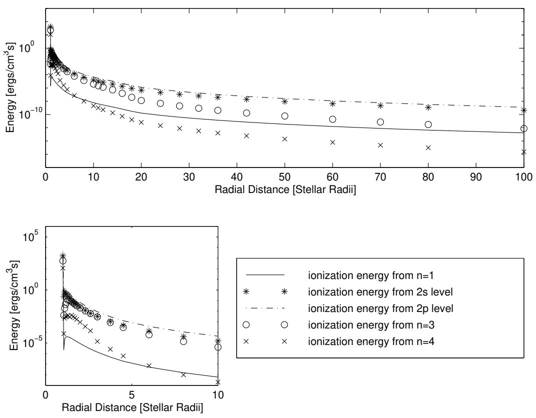


Fig. 5.— The contribution of ionization energy from levels n = 1, 2s, 2p, 3, and 4 for the equatorial plane (J=1).

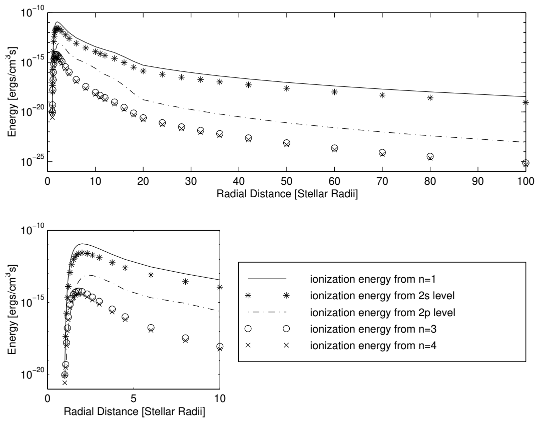


Fig. 6.— The same as Fig. 5 for the upper envelope (J=19).

star able to reach the dense areas to keep the gas ionized. With increasing height above the equatorial plane, the ionization fraction increases gradually as the gas becomes optically thin due to the exponential decrease in density. However, only the uppermost 25% of the envelope is more than 80 % ionized.

## 4. Discussion

We have derived a self consistent temperature grid for the envelope of 1 Del; see Fig. 1. The average global temperature for this model is 5800±700 K ($1\sigma$); the density weighted is 5900±40 K ($1\sigma$). The difference between these 2 averages simply means that the temperature is slightly greater near the equatorial plane where the density is higher. These calculated values of temperature are considerably smaller than the isothermal temperature of 10,000 K assumed by MC.

Diffuse radiation produced within the envelope is not considered in this model; all of the ionizing radiation comes from the central star. Therefore, these calculated envelope temperatures based on equal energy gain and loss rates represent a lower limit. Since we were able to reproduce the gross features of the $H_\alpha$ line using the envelope temperatures calculated by this model, it is clear that there is sufficient stellar radiation present to ionize the circumstellar envelope and produce the relative line strength without any additional source of heating. Apparao & Tarafdar (1987, 1997a, 1997b) have reached an opposite conclusion. Their 1D model assumes the physical conditions at just one position in the circumstellar gas, and that the gas is completely ionized and ionization bound. No optical depth effects are included in $H_\alpha$ and they assume a kinetic temperature of $10^4$ K. The model calculations of the current investigation of 1 Delphini include both optical depth effects in the hydrogen lines and enforce radiative equilibrium, a critical ingredient for modeling such strong lines. These effects are also discussed by van Kerwijk, Waters & Marlborough (1995). Finally, we note that observed fluxes that Apparao & Tarafdar fail to reproduce are the *highest values* observed for each Be spectral type.

The parameter $\omega'$ greatly affects the distribution of gas perpendicular to the equatorial plane. This, in turn, results in changes to the temperature distribution. In particular, larger values of $\omega'$ result in a much slower decrease in density perpendicular to the equatorial plane. As a consequence collisional terms are more effective in increasing the populations of upper levels from which photoionization can occur. Hence, the temperature does not drop off for regions near the uppermost edge of the envelope for larger values of $\omega'$. Also, for larger values of $\omega'$ the surface density assumed must be reduced in order to reproduce the gross features of the H$\alpha$ line. In addition, for larger values of $\omega'$ more of the line is formed further from the star where rotational velocities are reduced. This is evident from the shape of the line; with increasing values of $\omega'$ the width of the absorption component decreases. Therefore, the line width can be used as a tool to investigate at what radial distance from the star the line is formed.

In order to reproduce the gross features of the H$\alpha$ line we had to assume that the envelope rotation was completely Keplerian so that the velocity did not decrease too fast with increasing distance from the star. Only then was the predicted model line sufficiently wide.

The temperature along the upper edge of the envelope is quite sensitive to to minor changes in the model. The energy terms are all very small in magnitude because of the exponential decrease in density. Any small change in model parameters, which influences the level populations, affects the relative value of energy terms. This, in turn, modifies the temperature since it is calculated from the assumption of equal energy gain and loss rates. For example, changing the spacing of the grid locations in the radial direction has no significant effect on the calculated temperatures in the envelope except along the uppermost edge. Therefore, along the uppermost edge the quoted temperatures must be viewed as estimates. However, since these regions have relatively small densities and since generally the emission goes as the number density squared, the uppermost region does not contribute to the observed emission lines in the optical portion of the spectrum.

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