Rates of Energy Gain and Loss in the Circumstellar Envelopes of Be Stars: Diffuse Radiation

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ABSTRACT

We have determined an upper limit to the kinetic temperature of the gas in the circumstellar envelopes of 2 Be stars, a hot star γ Cas, and a cooler star 1 Del, by including in an approximate manner the diffuse radiation produced in the envelope. We computed the temperature as a function of position by balancing at each position the rates of energy gain and energy loss. 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 and free-free emission contribute to the rate of energy loss. The kinetic temperature at a particular location is obtained from the requirement that the rates of energy gain and energy loss there are equal. These results, combined with previous investigations, establish the range of temperatures expected in the circumstellar envelopes of Be stars if the primary source of energy input is the radiation field of the star.

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

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1. Introduction

Be stars are rapidly rotating stars on or near the main sequence which have exhibited emission in a Balmer line, typically H_α, at some time. The emission is thought to arise from radiative recombination in ionized circumstellar material, concentrated toward both the equatorial plane and the star. These stars also have excess continuum radiation in the infrared and at longer wavelengths. In addition, Be stars have a high linear polarization which provides evidence for a non-spherical distribution of material. Recently the circumstellar envelopes of several Be stars have been resolved, providing support for this view of a Be star; Dougherty & Taylor (1992), Quirrenbach et al. (1993), and Stee et al. (1995).

The Poeckert-Marlborough model (1978), hereafter the PM model, is an ad hoc model originally used to model the B0 star γ Cas. Recently, we have used this model to investigate the temperature of the circumstellar envelopes of both γ Cas and 1 Del, see Millar & Marlborough (1998a, 1998b), hereafter MMa, and MMb. We assumed that the gas dynamical terms in the equation for the conservation of energy are sufficiently small so that at each location the rate of radiative energy gain should equal the rate of radiative energy loss if the correct kinetic temperature were known. Photoionization, collisional deexcitation, and free-free absorption were assumed to contribute to the rate of energy gain; radiative recombination, collisional excitation, and free-free emission contribute to the rate of energy loss. We can test the appropriateness of the temperatures assumed in previous investigations by calculating the ratio of the rate of energy gain to the rate of energy loss at various locations within the envelope. If, by chance, the correct temperature were assumed, this ratio would be exactly 1. If not, we adjust the temperature, determine again the ionization-equilibrium and recalculate the ratio of energy gain to loss, until the ratio equals 1 to within some prescribed value.

In our previous investigations, we did not include the diffuse radiation field. Hence the temperature predicted represents a lower limit. An accurate determination of the diffuse radiation requires an integration over 4π at each location in the envelope. Rather than do this we have, instead, chosen to approximate the effect of the diffuse radiation by assuming that every recombination to level $n = 1$ results in a subsequent photoionization locally. This approximation is commonly referred to as the on-the-spot approximation (Osterbrock 1974). The additional ionization adds energy to the gas and contributes to heating of the circumstellar material. This simplification allows an upper limit to the temperature to be calculated. By combining the results of this investigation with earlier temperature calculations, we have determined the range of temperatures self consistently for various locations within the envelopes of Be stars.

2. Results

According to the on-the-spot approximation every recombination to level $n = 1$ produces an ionizing photon which is re-absorbed locally. Since the density in the PM model decreases exponentially with increasing distance perpendicular to the equatorial plane, the uppermost portions of the envelope have very low densities. Although the gas there would be essentially completely ionized, the low density implies a low recombination rate to $n = 1$. Secondly it is doubtful that diffuse

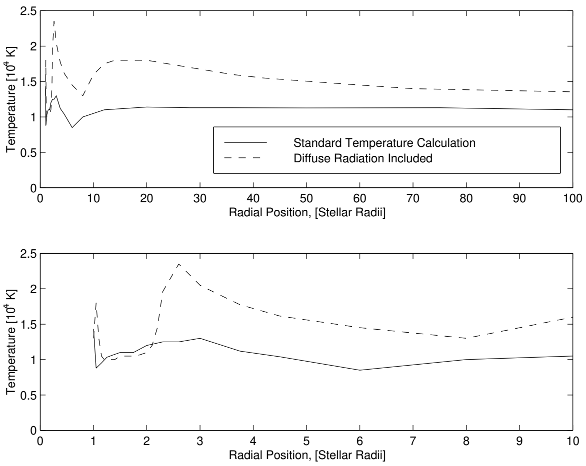

Fig. 1.— The temperature for which the energy gain balances the energy loss as a function of distance from the rotation axis in the equatorial plane for the star γ Cas. The predicted temperature determined by MMa and the predicted temperature with the inclusion of the diffuse radiation field are shown for comparison. The lower portion of the figure is an enlargement of the region between 1 and 10 stellar radii.

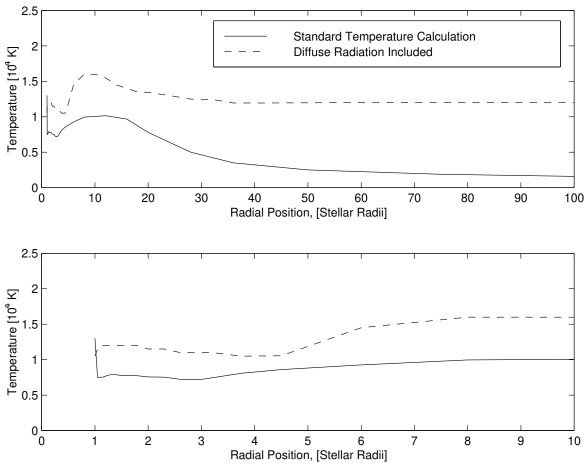

Fig. 2.— The temperature for which the energy gain balances the energy loss as a function of distance from the rotation axis at a location half way between the equatorial plane and the upper edge for the star γ Cas. The predicted temperature determined by MMa and the predicted temperature with the inclusion of the diffuse radiation field are shown for comparison. The lower portion of the figure is an enlargement of the region between 1 and 10 stellar radii.

radiation produced at a particular location in a low density gas would be re-absorbed locally. Hence the on-the-spot approximation may not a reasonable one for the uppermost locations in the envelope. Therefore, we have concentrated our investigation to the regions of the envelope where the density is larger, specifically from the equatorial plane to a distance half way between the equatorial plane and the upper edge. This volume comprises approximately 99% of the circumstellar gas.

The variation of temperature with radial position in the equatorial plane, and at a distance half way between the equatorial plane and the upper edge, respectively, for the star γ Cas is shown in Figures 1 and 2. For comparison, these Figures show both the temperature of MMa, and the temperature determined by the inclusion of the diffuse radiation field. Figures 3 and 4 are the equivalent plots for the star 1 Del. The temperature grid for 1 Del was determined previously by MMb. The stellar parameters used for γ Cas and 1 Del are the same as those used by MMa and MMb, respectively.

Generally, the inclusion of the diffuse radiation field increases the temperature locally due to the energy gain by additional photoionization from level n = 1. The largest temperature increases occur in regions where the degrees of ionization are the greatest; the more ionizations, the larger the number of re-

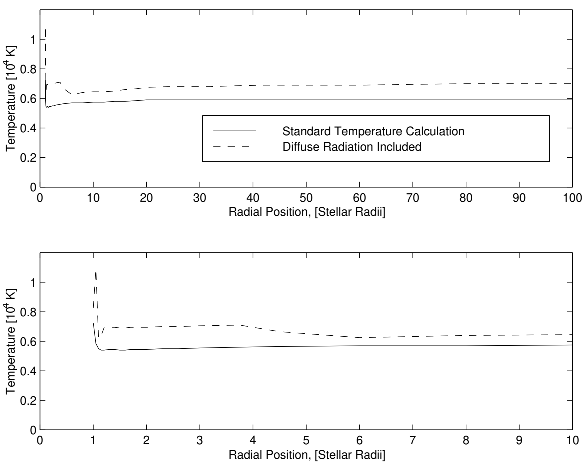

Fig. 3.— The same as Fig. 1 for the star 1 Del.

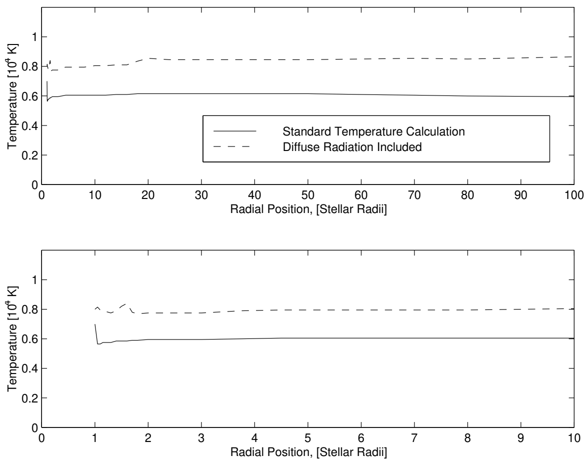

Fig. 4.— The same as Fig. 2 for the star 1 Del

combinations, so that more ionizing photons are produced. Therefore, the differences between the temperatures predicted by MMa and MMb, and the temperatures obtained by inclusion of the diffuse radiation field increase with increasing distance perpendicular to the equatorial plane as the degree of ionization increases. In contrast, in the equatorial plane differences between the predicted temperatures by MMa, MMb and those obtained by inclusion of the diffuse field are not as large. In and near the equatorial plane where densities are the highest, the column densities in the ground state are large and the degree of ionization corresponding low. Consequently, the diffuse radiation field has essentially no significant effect for distances between 1 and 2 stellar radii for the star γ Cas since the numbers of recombinations to level n = 1 are very low. This can readily be observed in Figure 1. In these locations the density of the gas is high, column densities are very large, and only a very few recombinations to level n = 1 occur. Therefore, inclusion of the diffuse radiation field has little effect because of the small number of recombinations to level n = 1. The average temperature of the envelope with the diffuse radiation included is compared with the previous investigations of MMa and MMb in Table 1; the uncertainties are 1σ values.

3. Discussion and Conclusion

Table 1 clearly demonstrates that the inclusion of the diffuse radiation field increases the average envelope temperature. The diffuse radiation field provides additional heating due to the increase in photoionization from level n = 1. This increases the ionization fraction which subsequently increases the number of recombinations, with the result that the emission lines also increase in strength. The increase in strength of the H_α line with the inclusion of the diffuse field is quite dramatic for both γ Cas and 1 Del. For example, in order to reproduce the observed line with the diffuse field included for 1 Del, the number density must be reduced by a factor of approximately 3, that is, from $4.2\text{x}10^{13}\,\text{cm}^{-3}$ to $1.3\text{x}10^{13}\,\text{cm}^{-3}$ at 4 stellar radii. The H_α line for 1Del from MMb, with the diffuse field included, is shown in Figure 5. Since the diffuse radiation field increases the ionization fraction and subsequently increases the number of recombinations, the density must be reduced when the diffuse field is included in order to match the observed line. The reduction of assumed ρ_o also changes the derived temperatures; optical depths become smaller so that the stellar radiation can heat the gas more effectively. For 1 Del, there is a modest increase of the density weighted temperature average and a reduction in the simple global temperature average corresponding to the decrease in ρ_o. The reduction in ρ_o reduces the optical depths and allows more stellar radiation to penetrate the envelope and heat the gas. This effect is most important in the densest regions of the envelope near the equatorial plane. The gas in the envelope of 1 Del is neutral in and near the equatorial plane and the effect of lowering the density increases the ionization fraction. Therefore, the density weighted average temperature increases slightly. In the upper regions of the envelope the gas is ionized; lowering the density in these regions simply reduces the amount of material that can be photoionized. This is the reason why the global average temperature decreases slightly for 1 Del with a reduction in ρ_o. The changes in temperature for 1 Del with the reduction in assumed ρ_o are modest and are, in fact, less than the estimated errors. The H_α line from MMb and that for the line predicted with lower ρ_o and inclusion of the diffuse radiation field is shown in Figure 6. In order to reproduce the approximate amount of emission in the H_α line with the observed profile for γ Cas, (see PM), with the diffuse radiation field included, the assumed density at the surface of the star in the equatorial plane must be reduced by a factor of approximately 2.5. This reduction of ρ_o results in a modest decrease in the derived temperature of approximately 1000 K for both the density weighted temperature average and the simple global temperature for γ Cas. The global average is 13000 K $\pm$ 1700 K and the density weighted average is 12900 K $\pm$ 80 K. The envelope of γ Cas at the original density is almost completely ionized with the diffuse field included. The reduction in the density by decreasing the assumed value of ρ_o simply reduces the amount of gas that can be ionized and heated.

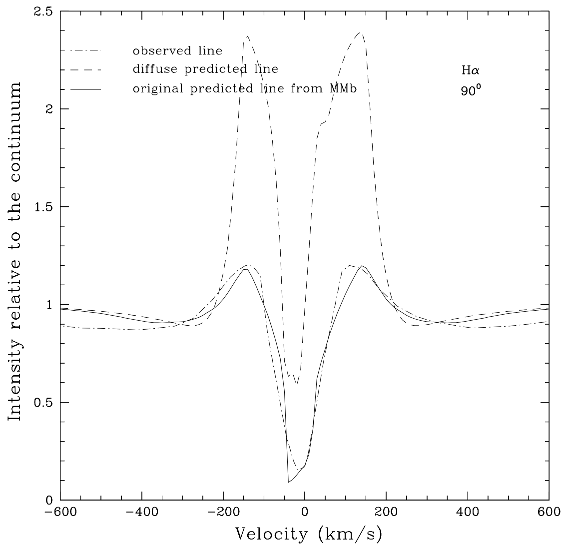

Fig. 5.— The predicted H_α line from MMb and the predicted line with the diffuse radiation field included for the star 1 Del. The observed line is also shown for comparison.

Our investigation has demonstrated that the inclusion of the diffuse radiation field is necessary in order to predict accurate kinetic temperatures for the circumstellar envelopes of Be stars. The on-the-spot approximation is a reasonable one to use to investigate the effect of the diffuse radiation field. It is not, however, a reasonable approximation for locations in the envelope where densities are very low since it is unlikely that diffuse radiation would be re-absorbed locally. In regions of low density, it is more likely that any ionizing radiation produced would be re-absorbed somewhere else in the envelope. However, since recombination line strengths are proportional to the electron density squared, regions of low density do not contribute greatly to the observed lines.

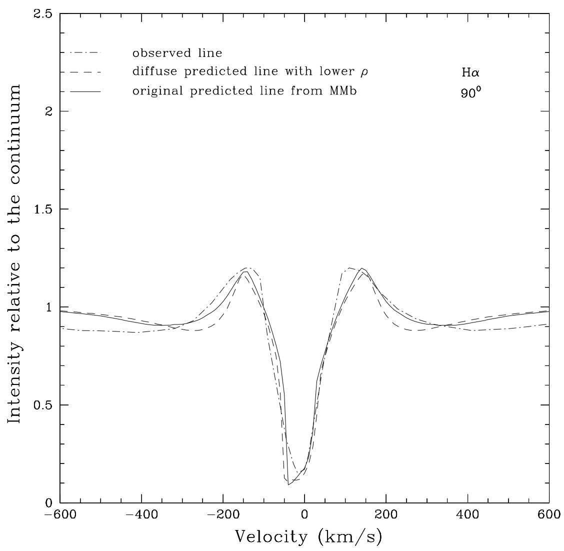

Fig. 6.— The predicted H_α line from MMb and the predicted line with the diffuse radiation field included with a lower ρ_o for the star 1 Del. The observed line is also shown for comparison.

4. Acknowledgments

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Table 1: Envelope Temperatures

	global average [K]	global average including diffuse radiation [K]	density weighted average [K]	density weighted average including diffuse radiation [K]
γ Cas	12000±4000	14000±3000	10700±90	14500±80
1 Del	5800±1000	6900±1700	5900±40	7200±50