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

C. E. Millar[1,2], T. A. A. Sigut[1,4] and J. M. Marlborough[1,3]

ABSTRACT

We have investigated the rates of energy gain and energy loss in the envelopes of Be stars in order to determine the temperature distribution self-consistently. Using our models, we have successfully matched the relative line strengths of Hα for both an early Be star, γ Cas, and a late Be star, 1 Delphini, with the envelope temperature determined via energy balance. In addition, we have estimated the total flux emitted in Hα assuming the central star is the only source of energy input into the circumstellar envelope. We find that an additional source of ionizing photons, as suggested by Apparao (1998), is not necessary to account for the observed emission.

1. Introduction

Ad hoc models have been developed for Be star envelopes by necessity due to the complexity of the equations which describe the structure and dynamics of the circumstellar material. The Poeckert Marlborough model (1978), hereafter PM, is one such model which has been successful in describing some aspects of these disks for a range of Be stars. In the PM model an exponential density distribution perpendicular to the equatorial plane is assumed, and as a result, the gas is dense in and near the equatorial plane but thins rapidly with increasing distance from the plane. Recent direct images of several Be stars (Dougherty & Taylor 1992, Quirrenbach et al. 1993, and Stee et al. 1995) and spectropolarimetry results (Wood et al. 1997) demonstrate that Be star disks are indeed quite thin making the PM model attractive.

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

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

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

[4]asigut@inverse.astro.uwo.ca

For most models of the past, it has been customary to assume either a constant temperature for the entire envelope, or a simple temperature distribution that decreases as a power law with increasing radius from the central star. In contrast to this, we have developed a method to determine the temperature self-consistently, thereby eliminating the need to assume an envelope temperature distribution. We have modified the PM code to calculate the energy gain and loss rates at positions in the gas. If, by chance, the correct temperature were assumed at a particular position, the rate of energy gain would balance the rate of energy loss. If not, we adjust the temperature iteratively and re-calculate the atomic level populations until the energy rates are balanced. The result of this procedure is a self- consistent set of temperatures for various positions throughout the envelope. See Millar & Marlborough (1998 & 1999b) for further details as applied to γ Cas, and Millar & Marlborough (1999a & b), for 1 Del. Figure 1 shows the derived temperatures for γ Cas using the parameters of PM and Millar & Marlborough (1998). Note that due to the exponential density distribution in the vertical direction and the high equatorial densities, there are significant temperature variations both near the star and near the equatorial plane. These temperature variations lead to ionization gradients within the circumstellar envelope which may prove to be a valuable probe into the structure of these envelopes.

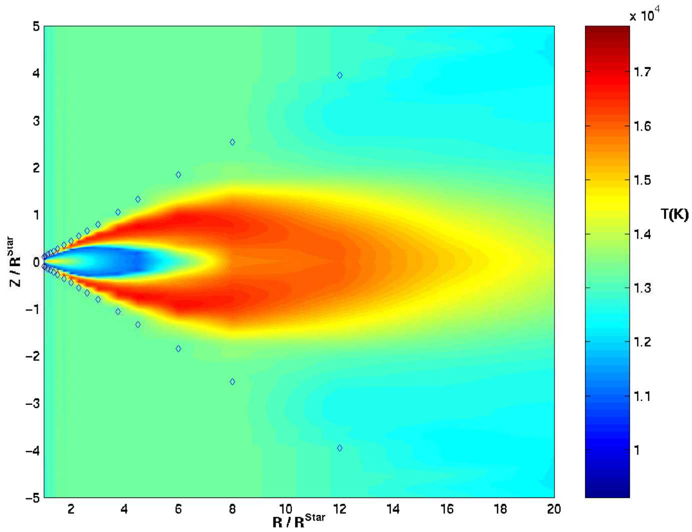

Fig. 1.— The temperature for which the energy gain balances the energy loss for the circumstellar disk of γ Cas as a function of distance from the rotation axis (R) and height above the equatorial plane (Z). The small diamonds indicate the vertical extent of the envelope.

2. Energetics of Be Star Envelopes

The initial motivation for this work was to determine whether or not it is possible to reproduce the relative line strengths with a self-consistent temperature distribution. Apparao & Tarafdar, hereafter A&T, in a series of papers (1987, 1997a, 1997b), have argued that there is not sufficient stellar continuum radiation present in late type Be stars to ionize the gas in order to produce the observed emission. Recently, Apparao (1998) has highlighted the results of his work in the previous issue of the Be Star Newsletter. The failure, as emphasized by Apparao, is not one of fundamental energetics as there is in principle more than enough flux in the stellar continuum to account for the observed emission; instead it is one of re-processing efficiency. Apparao claims that the efficiency of Be star disks in converting stellar continuum photons into emission lines is simply not high enough for later spectral types.

In their analysis, A&T (1987) assume that Hα is formed by pure recombination, under case B conditions, in the ionized disk of the Be star. If this assumption is correct, the total flux escaping in Hα is given by

$$\mathrm{F}\,(\mathrm{H}\alpha) = \mathrm{h}\nu\,\alpha_{\mathrm{B}} \int_{\mathrm{Disk}} \mathrm{N_e}^2\,\mathrm{dV} = \mathrm{h}\nu\,\alpha_{\mathrm{B}}\,\mathrm{EM_{Disk}}\,, \tag{1}$$

where h is Planck's constant, ν is the frequency of Hα, α_{B} is the appropriate recombination coefficient, $1.16\,\mathrm{x}\,10^{-13}\mathrm{cm}^3\,\mathrm{s}^{-1}$ for T= 10^4 K (Osterbrock 1989), $\mathrm{N_e}$ is the number density of electrons, $\mathrm{EM_{Disk}}$ is the emission measure of the disk, and the integration is over the volume of the disk. In this view, the Hα flux is controlled only by $\mathrm{EM_{Disk}}$ and thus an accurate estimate of N_e is required throughout the disk. A&T include photoionization from hydrogen levels n= 1 and 2 and approximately account for the thermalization of Lyα, as the latter is well known to increase significantly the n= 2 population, making Balmer photoionizations more important (for example see Kwan & Krolik 1981 in the case of AGN). A&T find that equation (1), given their geometry, a shell 10^{12} cm from the central star with only radially outwardly and inwardly propagating rays considered, cannot reproduce the maximum Hα fluxes of Ashok et al. (1984) for Be stars later than $\sim$ B5. However, their calculation is performed at only one position in the envelope with an assumed constant density. They also *assume* a constant gas temperature of 10^4 K. In order to compare directly to A&T, we have computed the Hα flux using equation (1) for our models of γ Cas and 1 Del. This calculation includes all relevant atomic processes for a 5 level hydrogen atom, enforces radiative equilibrium, and uses the 2D disk geometry of PM. Fluxes from two models for each Be star are presented, one constructed with, and one without, the on-the-spot approximation for the diffuse radiation generated within the envelope (Osterbrock 1989). The diffuse radiation increases the degree of ionization due to increased photoionization from level n = 1. Note that with diffuse radiation included, the density required at the stellar surface to match the observed relative strength of Hα is approximately a factor of 3 lower for both γ Cas and 1 Del. The results are presented in column 5 in Table 1 for γ Cas and 1 Del, both of which have self-consistently determined envelope temperatures. For comparison, typical observed values of Hα luminosities range from approximately 10^{34}erg s^{-1} for early type Be stars to 10^{32}erg s^{-1} for late type Be stars (Ashok et al, 1984).

Table 1

Star	Spectral Type	Luminosity [erg s^{-1}]	Diffuse Radiation	Hα Flux Equation (1) [erg s^{-1}]	Hα Flux Equation (2) [erg s^{-1}]	Hα Flux Equation (3) [erg s^{-1}]
γ Cas	B0IVe	1.3x10^{38}	yes	8.3x10^{35}	2.1x10^{32}	5.9x10^{33}
			no	2.3x10^{36}	6.3x10^{31}	6.9x10^{33}
1 Del	B8-9e shell	9.5x10^{35}	yes	2.4x10^{34}	7.5x10^{28}	1.3x10^{32}
			no	3.1x10^{33}	4.9x10^{29}	2.3x10^{32}

It is assumed in Equation (1) and by A&T (1987) that all Hα photons generated by recombination escape. We have found, however, that there are portions of the envelope both near the star and the equatorial plane that are optically thick in Hα. Clearly then, the Hα flux cannot be given by Equation (1) as not all the Hα photons can escape. As a crude correction for this effect, we have computed the Hα flux using

$$\mathrm{F}\,(\mathrm{H}\alpha) = \mathrm{h}\nu\, \alpha_{\mathrm{B}} \int_{\mathrm{Disk}} \mathrm{P_{esc}}\, \mathrm{N_e}^2\, \mathrm{dV}\,, \qquad (2)$$

where $\mathrm{P_{esc}}$ is the fraction of Hα photons which escape from the volume element. $\mathrm{P_{esc}}$ is estimated based on the line center optical depth along a path perpendicular to the equatorial plane from the volume element to the upper edge of the envelope. See Millar & Marlborough (1998) or Marlborough (1969) for additional details; $\mathrm{P_{esc}}$ corresponds to the cases to which these papers refer. Column 6 of Table 1 contains results based on equation (2). Large changes in the Hα fluxes are apparent with reductions to levels far below observation. Two conclusions follow: (i) it is imperative to account for the optical depths in Hα and (ii) case B recombination is clearly not an accurate approximation.

Equation (2) is still not correct, however, as the hydrogen ionization balance is not correctly given by case B due to the optical depth effects previously mentioned. A proper estimate of the Hα flux includes both collisional excitation of Hα and optical depth effects, and can be obtained by using the standard escape probability approximation for the flux divergence,

$$\mathrm{F\,(H\alpha) = h\nu\, A_{32} \int_{Disk} N_3\, P_{esc}\, dV}\,, \tag{3}$$

where $\mathrm{N_3}$ is the number density of level n = 3 and $\mathrm{A_{32}}$ is the Hα spontaneous radiative transition probability, $4.41\mathrm{x}10^7\,\mathrm{s^{-1}}$. The results of this calculation are displayed in column 7 of Table 1. Note the large increase over Equation (2), even with the $\mathrm{P_{esc}}$ factor, to values which roughly agree with the observations of Ashok et al (1984).

3. Discussion

As previously noted, typical observed values of Hα luminosities range from approximately $10^{34}\mathrm{erg\,s^{-1}}$ for early type Be stars to $10^{32}\mathrm{erg\,s^{-1}}$ for late type Be stars (Ashok et al. 1984), with the caveat that there can be considerable uncertainty in the absolute value of these fluxes due uncertainties in distances of these stars. Stee et al. (1998) and Kastner & Mazzali (1989) give values of the Hα luminosity for γ Cas of 6.36 x 10^{34} and 3.24 x 10^{34} $\mathrm{erg\,s^{-1}}$, respectively with the difference in the values discussed by Stee et al. Comparing our results in Table 1 with these observations, we see that there is no clear case for an additional source of ionizing radiation in order to produce the observed Hα emission for our particular choice of model parameters for either γ Cas or 1 Del. The discrepancies between the Apparao's work and our calculations are due to mainly to our realistic 2D geometry, and the inclusion of collisional excitation and optical depths in Hα. The importance of optical depths for line emission in Be stars is also discussed by van Kerkwijk et al. (1995). The results of our work will be described in greater detail in a paper currently being prepared.

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