Mon. Not. R. Astron. Soc. **352**, 841–846 (2004) doi:10.1111/j.1365-2966.2004.07970.x

Iron line cooling of Be star circumstellar discs

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Accepted 2004 April 28. Received 2004 April 27; in original form 2003 November 13

ABSTRACT

We investigate the effect of line cooling due to iron on the predicted temperature distributions in Be star circumstellar envelopes. This analysis is applied to the early-type Be star, γ Cas, and the late-type Be star, 1 Del, to assess the effect of line cooling due to metals in the circumstellar material over a range of spectral type. We find that iron, and by analogy other abundant metals, can play a role in the energetics of Be star discs by providing both heating from photoionization and cooling by the escape of collisionally excited spectral line radiation. The efficiency of the heating and cooling due to iron varies throughout the circumstellar disc and depends on local physical conditions. Overall, including iron at the solar abundance does not significantly change the volume or density-weighted average temperatures in either γ Cas or 1 Del from that predicted by a pure hydrogen envelope. However, with an increased iron abundance, to simulate the effect of adding other metals, the temperature variations become more pronounced.

Key words: circumstellar matter – stars: early-type – stars: emission-line, Be.

1 INTRODUCTION

Be stars are main-sequence (or slightly evolved) stars which show, or have shown, emission in their Balmer lines. This emission is principally due to radiative recombination in a disc-like envelope of ionized circumstellar gas. Some Be stars can exhibit variations in emission on a wide range of time-scales, whereas others exhibit emission which remains virtually unchanged over periods as long as decades. Stars which are characterized by the Be phenomenon form a diverse group including some stars ranging in spectral type from type O to A (Marlborough 2000; Porter & Rivinius 2003).

There are many unsolved questions pertaining to the Be stars, including the mechanism(s) which create and maintain their discs. There have been many models proposed to explain the formation of these discs: the wind-compressed disc model (Bjorkman & Cassinelli 1993), models based on non-radial pulsations (Vogt & Penrod 1983) or non-spherical, radiatively driven winds (Puls, Petrenz & Owocki 1999), and models which employ rotating magnetic fields (Maheswaran 2003). However, all of these models have various shortcomings; Porter & Rivinius (2003) review recent results and models for classical Be stars.

Due to the lack of a definite model and the complexity of the equations which describe the structure and dynamics of circumstellar discs, many Be star models are ad hoc. The Poeckert & Marlborough (1978, hereafter PM) model is one such model which has been successful in describing some aspects of these discs for a range of Be star parameters. 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 the density decreases rapidly with increasing distance from the equatorial plane. Direct images of several Be stars (Dougherty & Taylor 1992; Quirrenbach et al. 1997) and spectropolarimetric results (Wood, Bjorkman & Bjorkman 1997) demonstrate that Be star discs are indeed quite thin. It is now generally accepted that the discs of Be stars are thin, and thus the PM model fits well with this interpretation.

For most models of the past, the temperature distribution in the circumstellar disc has been simply parametrized either as a constant temperature for the entire envelope or a simple power law decreasing with increasing distance from the central star. In contrast to this approach, Millar & Marlborough (1998, hereafter MM) developed a method to determine the disc temperature self-consistently, thereby eliminating the need to assume an envelope temperature distribution. MM 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 there would equal the rate of energy loss. If not, the temperature was adjusted iteratively and atomic level populations were re-calculated until the energy gain and loss rates were equal. The result of this procedure is a self-consistent set of temperatures for various positions throughout the envelope. See MM and Millar & Marlborough (1999a, hereafter MMa) for further details as applied to γ Cas, an early-type Be star (B0 IVe); Millar & Marlborough (1999a,b, hereafter MMb), for 1 Del, a late-type Be star (B8-9e); and Millar, Sigut & Marlborough (2000) for a more general discussion of the energetics of these discs. This collection of work demonstrates that it is

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possible to reproduce relative line strengths, most notably Hα, with a self-consistent temperature distribution.

However, a major simplification in the PM model is the assumption of a pure hydrogen disc. Undoubtedly, adding metals to models of the the disc composition will affect the predicted temperature distribution via heating from photoionization and cooling from radiative recombination and spectral line radiation. Our previous results based on pure hydrogen models showed that, generally, Be star discs are approximately isothermal with a temperature of about half the effective temperature of the star. The question we wish to address is whether or not this result remains valid with the inclusion of metals in our disc models. Important implications for interpreting the structure and dynamics of Be star discs hinge on this question. For example, because temperature gradients can fuel gas flows, it is important to determine whether or not these discs are, in fact, approximately isothermal with a more realistic disc composition.

In this paper, we take a first step in evaluating the significance of metal line cooling for the temperature distributions in Be star circumstellar discs by including a single, 'typical' metal in the calculation of the net gas cooling. The astrophysically abundant elements which should contribute to the gas energy balance are CNO, Mg, Si and Fe. Given that typical temperatures in the Be star discs are $\sim 1/2$ the $T_{\rm eff}$ of the underlying B star, dominant ions will be primarily neutrals for CNO and first ions for Mg, Si and Fe. Of particular importance to effective line cooling are low-lying levels which can be easily excited via collisional excitation with electrons. There are many such levels for the Fe-peak elements. Another requirement of the 'typical' element we chose is that its line emission scales approximately linearly with abundance so that the combined effect of the neglected metals can be crudely approximated by a larger abundance of the 'typical' metal. For this reason, Fe-peak elements are again favoured as the line flux is distributed over a large number of transitions. A contrary example is Mg II, with its strong 3s-3p transitions; they certainly cause important line cooling, but they would quickly saturate as the Mg abundance is increased because of the optical thickness in these lines. For these reasons, we have chosen to model Fe II. Fe II is a well known coolant for most astrophysical plasmas from stellar atmospheres to active galaxies (Viotti 1988). The solar abundance of iron is $\sim 4 \times 10^{-5}$, about $\sim 1/40$ the combined abundance of CNO, Mg and Si. We consider Fe abundances in our computed models ranging from solar to 100 times the solar Fe abundance.

2 THEORY

Construction of the disc models follows MM closely; in this section, we discuss only the modifications made to include iron.

The iron ionization balance was determined for the first three iron ionization stages. Photoionization from the ground state of each ion was balanced against an effective recombination rate. Photoionization cross-sections were adopted from the Iron Project **R**-matrix calculations[1] with Fe I taken from Nahar (1995) and Fe II from Nahar & Pradhan (1994). Unified electron–ion recombination rates (which include in a self-consistent manner both radiative and dielectronic recombination) were adopted for Fe II from Nahar, Bautista & Pradhan (1997), and for Fe III from Nahar (1997). The photoionizing radiation field used to compute each photoionization rate was assumed to be that of the central star reduced by the optical depth of the material back along the line of sight to the star; diffuse radiation generated within the circumstellar envelope was not included. Charge exchange ionization of Fe II (by hydrogen) and recombination of Fe III were also included using the rate computed by Neufeld & Dalgarno (1987).

Given the ionization fraction of Fe II, line cooling for a set of Fe II radiative transitions was found in the escape probability approximation. Net cooling (in erg cm^{-3} s^{-1}) in the line $j \rightarrow i$ was taken to be

$$\Phi_{ij} = \frac{h\nu}{4\pi} n_j A_{ji}\, \rho\left(\tau^z_{ij}\right). \tag{1}$$

Here, A_{ji} is the Einstein spontaneous transition probability in s^{-} for the transition, and $\rho(\tau^z_{ij})$ is the probability of escape from the local volume element to the nearest vertical (z) boundary of the disc through an optical depth step of τ^z_{ij}. Assuming the lines are formed in complete redistribution over a Doppler profile, the escape probability can be approximated by

$$\rho\left(\tau^z_{ij}\right) = \frac{1}{2 + \tau^z_{ij}}. \tag{2}$$

The Fe II level populations, n_j, were obtained by solving the statistical equilibrium equations for a 14-level Fe II model atom at each point in the circumstellar disc. The statistical equilibrium equation for level i, which balances the rate of population into level i with that out of level i, was written as

$$\sum_{j \neq i}^{N} n_j \left[A_{ji}\, \rho_{ij}\left(\tau^z_{ij}\right) + C_{ji}\right] = \sum_{j \neq i}^{N} n_i \left[A_{ij}\, \rho_{ij}\left(\tau^z_{ij}\right) + C_{ij}\right]. \tag{3}$$

Here, $A_{ji} = 0$ if $j < i$, $\rho(\tau^z_{ij})$ is the escape probability as before and the C_{ij} are the rates of collisional transitions. The Fe II model atom is shown in Fig. 1 and includes 14 total LS levels from the septet and quintet spin systems; it includes most of the key odd-parity states near 5 eV which can be easily collisionally excited and thus represent important sources of line cooling. Spontaneous transition probabilities for the 27 UV and optical radiative transitions included were taken either from Fuhr, Martin & Wiese (1988) or Nahar (1995) and Maxwellian-averaged collision strengths were taken from Zhang & Pradhan (1995). Lyman α fluorescence, which can be an important source of excitation to higher levels (Sigut & Pradhan 1998), was not included.

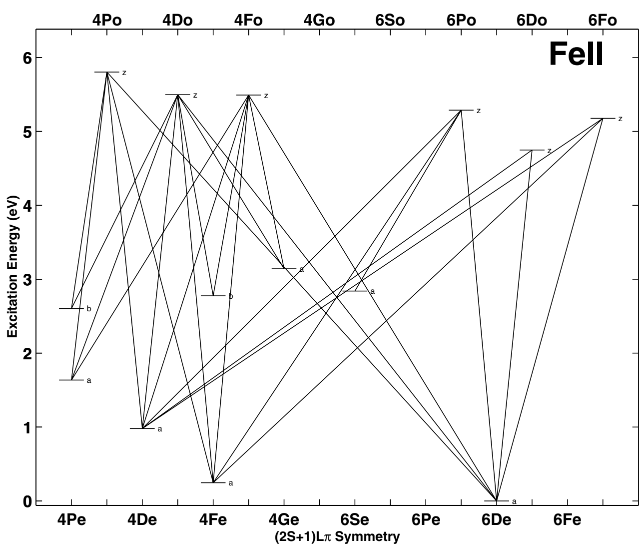

Figure 1. Grotrian diagram of the 14-level LS atom for Fe II with 27 radiative transitions.

[1] http://www.astronomy.ohio-state.edu/∼pradhan/

Table 1. Summary of self-consistent volume-averaged temperatures.

Star	Pure Hydrogen [K][a]	Solar Fe abundance [K]	3 × solar Fe abundance [K]	10 × solar Fe abundance [K]	100 × solar Fe abundance [K]
γ Cas	13000 ± 1700	13000 ± 1600	12900 ± 1500	12300 ± 1700	11500 ± 2200
1 Del	6900 ± 1800	7000 ± 1500	7000 ± 1500	6700 ± 1400	6700 ± 1300

[a]Model of MMa.

Table 2. Summary of self-consistent density averaged temperatures.

Star	Pure hydrogen [K][a]	Solar Fe abundance [K]	3 × solar Fe abundance [K]	10 × solar Fe abundance [K]	100 x Solar Fe abundance [K]
γ Cas	12900 ± 80	12950 ± 90	12900 ± 90	12800 ± 90	12600 ± 90
1 Del	7300 ± 50	7300 ± 50	7300 ± 50	7300 ± 50	7300 ± 50

[a]Model of MMa.

The system of statistical equilibrium equations at each envelope position (r, z) was closed with particle conservation,

$$\sum_{i}^{N} n_i = \epsilon_{\mathrm{Fe}} N_{\mathrm{H}}(r, z)\, f(\mathrm{Fe\,II}), \qquad (4)$$

where ϵ_{Fe} is the iron abundance, relative to hydrogen, N_{H} is the hydrogen number density at position (r, z) and $f(\mathrm{Fe\,II})$ is the Fe II ionization fraction found previously. The level populations obtained were then used to compute the net line-cooling rates (equation 1) for each line which were then added into the net cooling rate already computed in MM. We also included heating from iron photoionization and cooling due to radiative recombination. Expressions for these processes can be found in MM.

3 RESULTS

Circumstellar disc models for the Be stars γ Cas and 1 Del with self-consistent temperature distributions were created both with and without iron. To simulate the effect of the addition of other metals and to include the possibility of abundance enhancement in some stars (e.g. Porter 1999b), we created a series of models with increasing iron abundance.

We have chosen to use the models of MMa for this investigation. These are the most realistic of the series of models produced by MM, MMa and MMb. The models of MMa have diffuse radiation included by the on-the-spot approximation (Osterbrock 1989).[2] Also, the assumed density distributions produce Hα lines which have the correct shape and relative strength. The models of MMa have envelope density distributions reduced by approximately 13 the original choices of PM and MMb. Quite simply, the effect of including the diffuse radiation field increases the degree of ionization and subsequent strength of emission lines, so these older models which lacked diffuse radiation had assumed densities that were too high.

[2] In this approximation, every recombination to level $n = 1$ of hydrogen produces an ionizing photon which is re-absorbed locally. This is a reasonable approximation for regions in the disc where densities are high and optical depths are large, such as in the equatorial plane and near the star. Near the upper edge of the envelope, and at large distances from the star where the gas density is much lower, the approximation suffers because it is less realistic that photons will be absorbed locally. However, because the greatest contribution to the spectral lines comes from the densest regions, this approximation is adequate for our purposes.

Table 1 lists the various models constructed as well as the final results for the volume-averaged disc temperatures for each of the models. Table 2 is the same as Table 1 except that the density-weighted disc temperatures are presented. The density-weighted temperature emphasizes regions of the disc near the star and in the equatorial plane where densities are high. The density is assumed to decrease exponentially perpendicular to the equatorial plane and at increasing radial distances from the rotation axis of the star, the density decreases via the equation of continuity.

Table 1 shows that, with increasing iron abundance, the global average disc temperature gradually declines for both γ Cas and 1 Del, although γ Cas cools more efficiently than 1 Del. 1 Del is a shell star with a very dense disc and correspondingly large optical depths. Its spectral type is in the range late B or early A. These two properties conspire to make cooling from the inclusion of iron very inefficient for 1 Del. With the solar abundance of iron (column 3 in Table 1 and Table 2), there is virtually no temperature change in γ Cas or 1 Del in the disc temperatures. Any additional iron cooling from lines and radiative recombination is off-set by heating from photoionization. With increasing iron abundance, γ Cas shows a steady decrease in both volume-averaged and density-weighted temperatures. The density-weighted temperatures do not show as much change as the volume-averaged temperatures, and there are two reasons for this: first, the densest regions which are the nearest to the star at the edge of the disc are heated due to photoionization; secondly, between 1 and 2 stellar radii, the envelope is optically thick resulting, in a reduction of photon escape to allow line radiation to cool efficiently. This effect is particularly noticeable in Table 2 for 1 Del, which shows that with increasing iron abundance there is no change in the density-weighted average temperatures.

Figs 2 and 3 show selected temperature slices through the circumstellar envelope for γ Cas and 1 Del with the inclusion of iron at solar abundance. The lower panel of each of these figures has been expanded to illustrate more clearly the temperature variations near to the star. These figures correspond to the models presented in column 3 of Table 1 and Table 2. These figures reveal, to a first approximation, that the temperature is basically constant with increasing radial distance from the star. However, there are some locations in the circumstellar envelope where there are fluctuations in temperature. Both stars have interesting temperature variations near the star which can be attributed to variations in optical

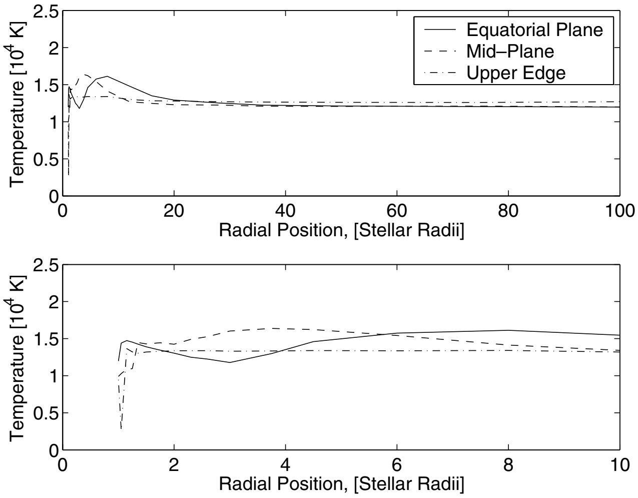

Figure 2. The temperature for which the energy gain balances the energy loss (including iron at solar abundance) as a function of distance from the rotation axis for three locations in the circumstellar envelope of γ Cas: the upper edge, the mid-plane and the equatorial plane. The portion of the envelope nearest to the star has been expanded in the lower panel to resolve temperature variations more easily. The density is set at the same density distribution used by MMa.

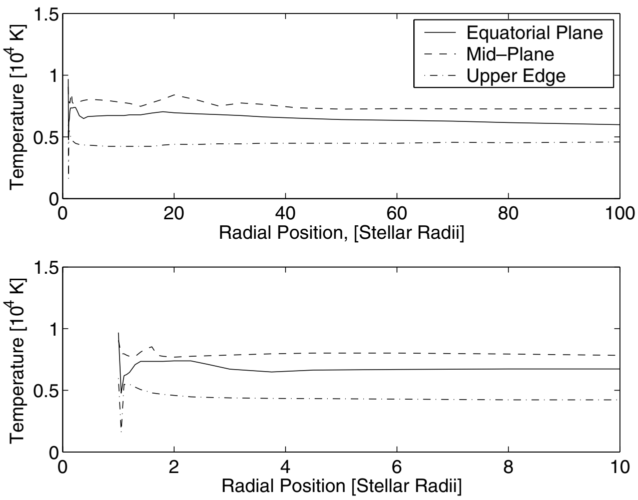

Figure 3. The same as Fig. 2 except for the star 1 Del.

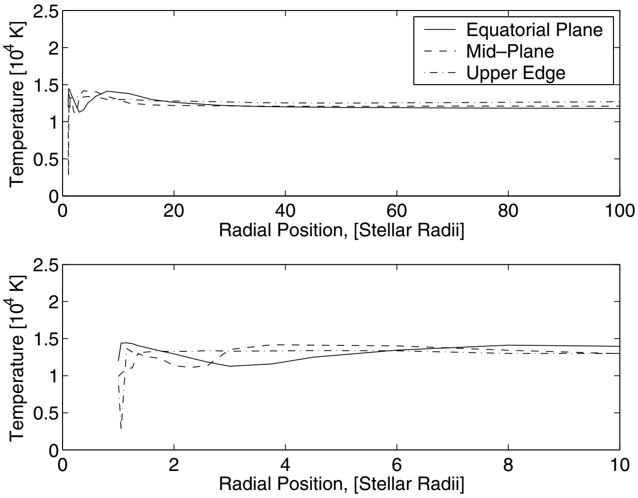

Figure 4. The temperature for which the energy gain balances the energy loss as a function of distance from the rotation axis for three locations in the circumstellar envelope of γ Cas: the upper edge, the mid-plane and the equatorial plane. The portion of the envelope nearest to the star has been expanded in the lower panel to resolve temperature variations more easily. The abundance of iron is 10 times solar abundance.

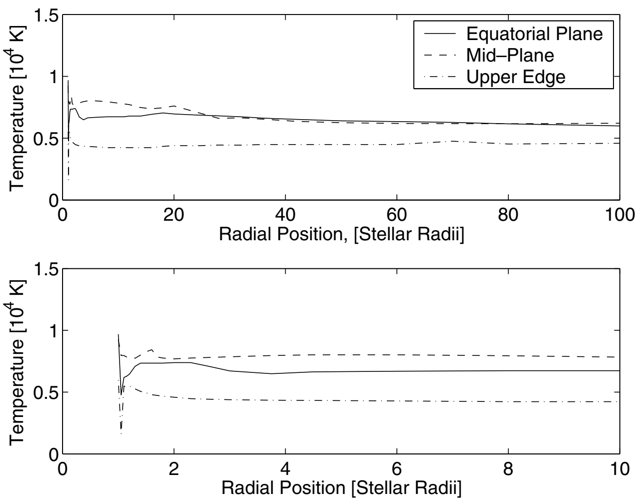

Figure 5. The same as Fig. 4 except for the star 1 Del.

depths where the discs are the densest. γ Cas has a nearly isothermal temperature beyond a radial distance of 20 stellar radii in the equatorial plane and for all heights above the equatorial plane. 1 Del has a temperature distribution which is relatively constant at radial distances greater than approximately 4 stellar radii, but the values of these constant temperatures are different depending on the height above the equatorial plane. These temperature differences are due the significant reduction in optical depth with increasing distance from the equatorial plane. The mid-plane is the hottest; the upper edge, which is able to radiate easily, is coolest; and the equatorial plane, which has the largest optical depths back to the star, resulting in fewer available photons for ionization, has a temperature between these other values.

Figs 4 and 5 show the temperature distributions for γ Cas and 1 Del with the inclusion of iron at 10 times the solar abundance. These models correspond to column 5 of Table 1 and Table 2. Qualitatively, these figures are similar to Figs 2 and 3, with the exception that the increased abundance of iron has resulted in cooler regions of the circumstellar envelopes of both 1 Del and γ Cas. The volume-averaged temperature for γ Cas has decreased by 700 K and the density-weighted temperature which emphasizes the densest regions has also decreased, but only by approximately 100 K. This has resulted in temperature variations which are not as pronounced close to the star as compared with Fig. 2. The large optical depths in 1 Del have not allowed the dense disc to cool nearest the central star. In fact, the density-weighted average temperature is the same as the model with solar Fe abundance. The additional iron, however, has allowed the mid-plane of the envelope to cool. Fig. 5 shows that the mid-plane and equatorial plane have virtually the same temperature beyond a radial distance of 20 stellar radii.

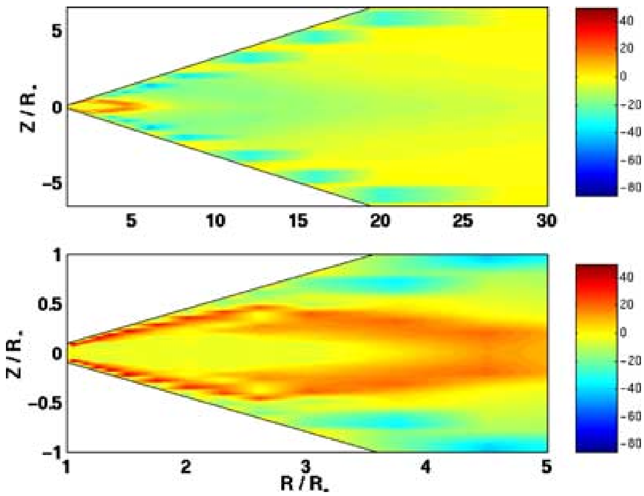

Figure 6. The percentage change in temperature with the inclusion of iron at 10 times the solar abundance for the star, γ Cas, as a function of distance from the rotation axis (R) and height above the equatorial plane (Z). The portion of the envelope nearest to the star has been expanded in the lower panel to resolve the percentage change in temperature more easily.

Because the purpose of this paper is to investigate what change in temperature occurs with the addition of metals, we have constructed two-dimensional plots which show the percentage change in the temperatures throughout the disc relative to that predicted by a pure hydrogen envelope. Fig. 6 shows the percentage change for γ Cas models with 10 times the solar iron abundance. The models used to construct these two-dimensional plots correspond to column 2 and 5, respectively, in Table 1 and Table 2. The light colours (red in the online version of the journal) represent heating and dark colours (blue) represent cooling. Fig. 6 clearly reveals that there are some regions of the disc where the temperature changes are significant. Nearest the star in a small volume in the equatorial plane along a radial distance between the stellar surface and approximately 3 stellar radii, there is a decrease in temperature of 10 per cent. Surrounding this volume, a noticeable temperature increase of 30 per cent occurs out to a radial distance of approximately 6 stellar radii. This volume is, in turn, surrounded by material which is up to 40 per cent cooler. Fig. 7 is the same as Fig. 6 but for 1 Del. 1 Del shows a significant temperature change in the mid-plane volumes. In the mid-plane, at radial distances of approximately 20 stellar radii, there are volumes where the temperature has been reduced by almost 50 per cent due to line cooling. Increases in temperature for 1 Del occur along the upper and lower edge of the disc where the optical depths are very small. However, because the density distribution decreases perpendicular to the equatorial plane, this temperature increase has a minimal effect on spectral line formation because there is very little circumstellar gas here. This increase is due to iron ionization in this optically thin volume.

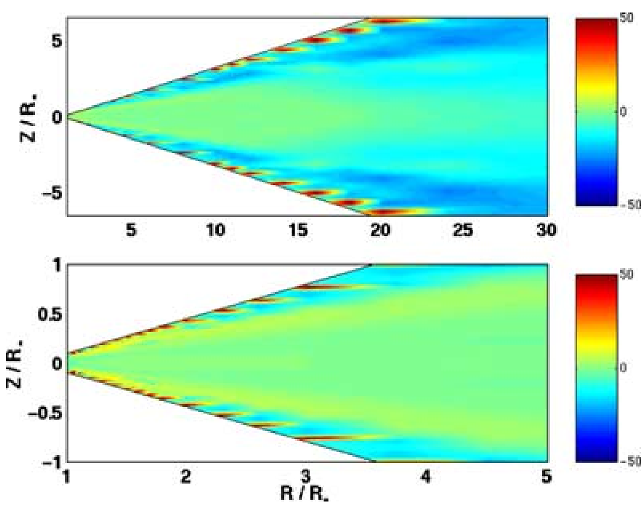

Figure 7. The same as Fig. 6 except for the star 1Del.

4 CONCLUSIONS

The models presented in this paper for γ Cas and 1 Del show that the inclusion of iron with increasing abundance results in temperature distributions which are cooler than those calculated for a pure hydrogen envelope. However, to a first approximation, the average temperature distribution in Be star discs is still nearly constant and is approximately half the effective temperature of the central star, as in earlier papers by MM, MMa and MMb. Depending on both the density of the circumstellar gas and the availability of ionizing radiation, the addition of metals can alter the temperature distribution in circumstellar envelopes. We found that the effect of increasing abundances of iron and, by analogy, other metals, was very different for 1 Del compared with γ Cas. γ Cas has more regions of low density and hence more photon escape, allowing even the densest part of the envelope to cool. These dense regions contribute significantly to the lines which are formed within the envelope. On the other hand, the disc of 1 Del was not able to cool efficiently in its densest regions; the greatest cooling was in the mid-plane regions of the disc. Also, where ionizing radiation is available, and where optical depths back to the star are not too large, additional heating from photoionization can increase the temperature. This effect also occurred in different regions of the disc, depending on the physical parameters of the envelope and the availability of ionizing photons. For γ Cas, the most significant heating occurred in a shell, centred about 3 stellar radii from the central star and up to approximately 0.5 stellar radii above and below the equatorial plane. On the other hand, the envelope of 1 Del had the most significant heating along the upper and lower edges of the envelope.

Although this investigation included only iron, we have simulated the effect of other metals by constructing a series of models with increased iron abundance. The effect of these abundance changes varied depending on the physical parameters within the disc and characteristics of the central star. The effect on temperature of other metals, such as CNO and Mg, should be investigated in models when characteristics which are sensitive to temperature need to be determined accurately. Because spectral lines are produced in various locations within the envelope, temperature variations throughout the disc must be accurately modelled so that observations can be better matched by predicted theoretical lines. Accurate, self-consistent temperatures are necessary to probe the physical conditions within these discs.

In the future, we plan to construct models of axisymmetric, circumstellar envelopes for Be star discs which incorporate a more realistic chemical composition in order to further investigate Be disc energetics in a quantitative manner. The predicted temperatures, combined with other model parameters such as the disc density and velocity distribution, will be used to investigate the stability of the outflowing viscous disc models for Be stars of Porter (1999a).

ACKNOWLEDGMENTS

We thank an anonymous referee whose comments and suggestions helped to improve the paper. This research was supported in part by NSERC, the Natural Sciences and Engineering Research Council of Canada. CEJ acknowledges financial support from an NSERC postdoctoral fellowship. TAAS and JMM also acknowledge support from NSERC.

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