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The outflowing disks of B[e] supergiants and unclassified B[e] stars

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Abstract. B[e] supergiants are known to possess outflowing cool disks but also some unclassified B[e] stars show clear indications for the presence of a neutral disk. We derive constraints on the disk mass loss rates, temperature distributions and disk opening angles for the Small Magellanic Cloud B[e] supergiant Hen S 18 and the unclassified galactic B[e] star Hen 2-90 by modeling the line luminosities of the [OI] lines arising in their optical spectrum. These lines are supposed to form in a hydrogen neutral disk. We find disk mass fluxes of order $3.4 \times 10^{-4}\,\mathrm{g\,s^{-1}cm^{-2}}$ and $5.5 \times 10^{-1}\,\mathrm{g\,s^{-1}cm^{-2}}$ resulting in disk mass loss rates of $1.0 \times 10^{-4}\,\mathrm{M_{\odot}yr^{-1}}$ and $1.5 \times 10^{-5}\,\mathrm{M_{\odot}yr^{-1}}$ for Hen S 18 and Hen 2-90, respectively.

1. Introduction

The group of stars showing the B[e] phenomenon is heterogeneous and has been divided by Lamers et al. (1998) into subgroups according to their evolutionary phase. These subgroups contain supergiants, Herbig stars, symbiotic objects and compact planetary nebulae. The biggest group, however, are the unclassified B[e] stars whose evolutionary phase is not or not unambiguously known.

The optical spectra[1] of the Small Magellanic Cloud (SMC) B[e] supergiant Hen S 18 and of the galactic unclassified B[e] star Hen 2-90 show both the presence of very strong emission in the [OI] lines which indicates that there must be a huge amount of neutral material close to the star.

In a recent paper, Kraus & Lamers (2003) showed that the disks around B[e] supergiants can indeed become neutral, i.e. hydrogen can recombine, even close to the hot stellar surface, simply due to the high equatorial mass fluxes of these stars that result in effective shielding of the disk material from the ionizing stellar continuum photons.

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[1] Based on observations with the 1.52m telescope at the European Southern Observatory (La Silla, Chile), under the agreement with the Observatório Nacional-MCT (Brasil)

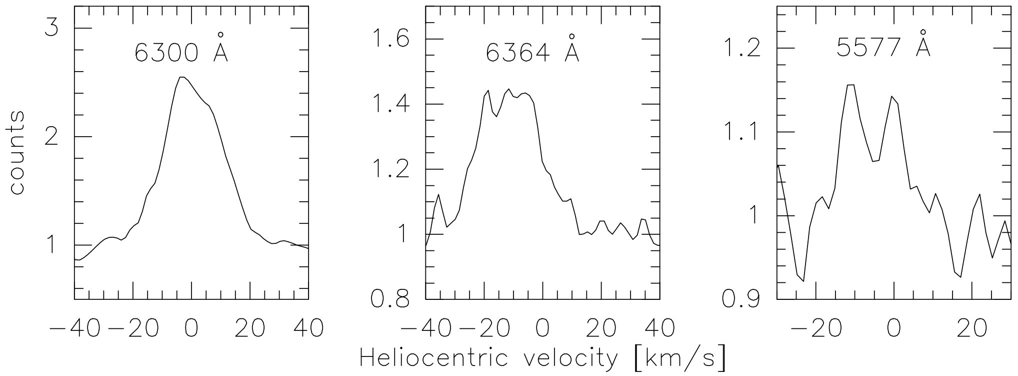

Figure 1. Heliocentric velocities of the three [OI] lines in the FEROS spectrum of Hen S 18. The line wings of about 25 km s^{-1} indicate the disk outflow velocity projected to the line of sight. The real outflow velocity is somewhat higher since Hen S 18 is seen under an intermediate inclination angle.

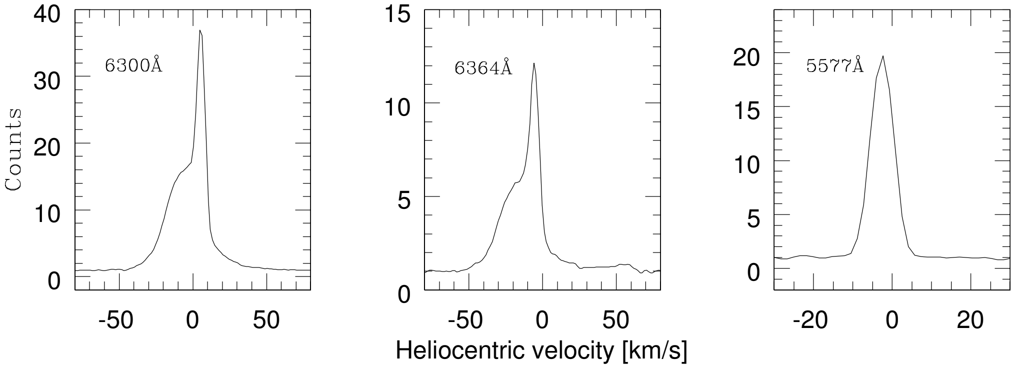

Figure 2. Same as Fig. 1, but for Hen 2-90. This system is seen edge-on. The wings of about 35 km s^{-1} indicate the outflow velocity.

2. The outflowing disk model

Emission of OI is expected to arise from regions in which hydrogen is neutral due to the about equal ionization potentials of H and O. The best location is therefore the outflowing disk. To simplify the model calculations we assume that the outflowing disk is neutral in hydrogen already at the stellar surface. The only free electrons available to collisionally excite the levels in OI result from elements like Fe which have a much lower ionization potential than H. The electron density is therefore of order $N_{\rm e}(r) \simeq 10^{-4} \ldots 5 \times 10^{-4}\, N_{\rm H}(r)$ depending on metallicity and on the internal ionization structure, i.e. temperature distribution, of the disk. The radial hydrogen density distribution is given by the equation of mass continuity. The terminal velocities for each star are derived from the wings of their [OI] lines (see Figs. 1 and 2) assuming that Hen S 18 is seen under an intermediate angle and Hen 2-90 is seen edge-on.

We calculate the level population by solving the statistical equilibrium equations in a 5-level atom. Since the forbidden lines are optically thin, no radiation transfer needs to be calculated which simplifies our analysis. There are three

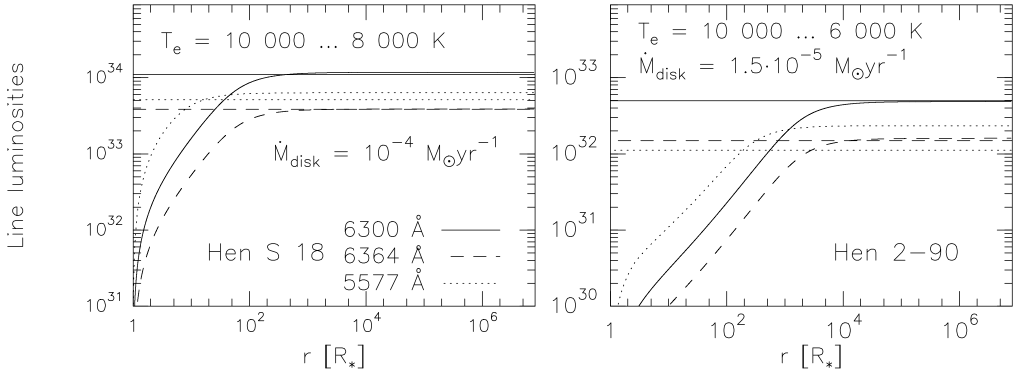

Figure 3. Luminosities of the [OI] lines of the SMC B[e] supergiant Hen S 18 (left) and the unclassified galactic B[e] star Hen 2-90 (right). The straight lines are the observed values, the curved lines represent the modeled luminosities as a function of radial distance from the star. The identification of the lines is the same in both plots.

[OI] lines in our spectra of which we model the luminosities. These lines have laboratory wavelengths of 5577 Å, 6300 Å, and 6364 Å (see Figs. 1 and 2).

3. The SMC B[e] supergiant Hen S 18

Hen S 18 is a supergiant with effective temperature $T_{\rm eff} \simeq 25\,000$ K, a luminosity of $\log(L/L_\odot) \simeq 5.3$ and a radius of about $R_* \simeq 39\,\mathrm{R}_\odot$ (Lamers et al. 1998). Its distance is roughly 60 kpc. The oxygen abundance is set to $0.25 \times$ solar, which is a mean SMC value. In Fig. 3 we show results for the line luminosity calculations for the [OI] lines indicated. We need a disk mass flux of $3.4 \times 10^{-4}\mathrm{g\,s^{-1}cm^{-2}}$ which results into a disk mass loss rate of $\dot{M}_{\rm disk} = 1.0 \cdot 10^{-4}\mathrm{M_\odot yr^{-1}}$ if we assume that the disk covers a fraction of about 0.2 of the total volume.

We want to strengthen that this is a lower limit to the disk (and therefore the total) mass loss rate of the star because we used the typical SMC abundance in our calculations. Since supergiants are normally in an evolved phase, the surface oxygen abundance might be much lower due to several dredge-ups. An underabundance in O would then result in a much higher mass flux needed to explain the observed line luminosities.

4. The unclassified B[e] star Hen 2-90

Hen 2-90 has been classified either as a symbiotic object or as a compact planetary nebula. Its HST image (Sahai et al. 2002) reveals a bipolar high-ionized wind, a low-ionized wind at intermediate latitudes as well as a high-density circumstellar disk. In addition, a bipolar jet has been found with several knots extending up to $\sim 10''$ on both sides of the star. The clearly distinct regions of different ionization degrees leads us to the assumption that Hen 2-90 has either a latitude dependent surface temperature being hotter on the poles, or a latitude dependent mass flux being strongest at the equator, or both.

The star is at a distance of about 2 kpc and the following stellar parameters are known: $T_{\rm eff} \simeq 50\,000\,{\rm K}$, $R_{*} \simeq 0.38\,{\rm R}_{\odot}$ and $\log(L/L_{\odot}) \simeq 3$ (Costa et al. 1993). In Fig. 3 we show the modeled line luminosities. The disk mass flux is found to be of order $5.5 \times 10^{-1}{\rm g\,s^{-1}cm^{-2}}$. From the HST image we find that the disk covers about 0.2 of the wind volume leading to a disk mass loss rate of about $1.5 \cdot 10^{-5}{\rm M}_{\odot}{\rm yr}^{-1}$.

For this star we did not only model the [OI] lines but almost all available forbidden lines arising in the optical spectrum (Kraus et al. 2004). These lines come from all the different ionization regions in the non-spherical wind seen in the HST image. From a self-consistent modeling we find that the star must be underabundant in C, N, and also in O with an O abundance of only $0.3 \times$ solar. We could explain the different ionization regions indeed in terms of a latitude dependent mass flux as well as a latitude dependent surface temperature which might be explained in terms of a rapidly rotating underlying star. In addition, we could fix the total mass loss rate of Hen 2-90 to about $3 \times 10^{-5}\,{\rm M}_{\odot}{\rm yr}^{-1}$.

5. Discussion and Conclusions

It is obvious that our model predicts for both stars a [OI] 5577 Å luminosity which is higher than the observed value. This line corresponds to the transition $5 \longrightarrow 4$ in our adopted 5-level atom. There exists one single permitted transition between its upper level and an energetically much higher lying level with wavelength $\lambda = 1217.6$ Å which falls into the wavelength range covered by a broadened Ly α line ($\lambda_{{\rm Ly}\,\alpha} = 1215.6$ Å). The fifth level might therefore be depopulated radiatively into this higher state from which several permitted lines arise. Consequently, the observable 5577 Å line luminosity will decrease. This depopulation mechanism might also explain why the 5577 Å line is much narrower than the other two [OI] lines in our sample.

Nevertheless, the presence of [OI] lines proofs the existence of cool and neutral material close to hot B[e] stars. From modeling the line luminosities we could (i) fix a temperature distribution within the disk and (ii) determine the disk mass fluxes resulting in disk mass loss rates which are lower limits to the total mass loss rates for the two studied stars.

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