The Magellanic System: Stars, Gas, and Galaxies
Proceedings IAU Symposium No. 256, 2008
Jacco Th. van Loon & Joana M. Oliveira, eds.

doi:10.1017/S1743921308028822

On the huge mass loss of B[e] supergiants in the Magellanic Clouds

M. Kraus[1], M. Borges Fernandes[2] and F. X. de Araújo[3]

[1] Astronomický ústav, Akademie věd České republiky, Fričova 298, 251 65 Ondřejov,
Czech Republic
email: `kraus@sunstel.asu.cas.cz`

[2] UMR 6525 H. Fizeau, Univ. Nice Sophia Antipolis, CNRS,
Observatoire de la Côte d'Azur, Av. Copernic, 06130 Grasse, France
email: `Marcelo.Borges@obs-azur.fr`

[3] Observatório Nacional, Rua General José Cristino 77, 20921-400 São Cristovão,
Rio de Janeiro, Brazil
email: `araujo@on.br`

Abstract. B[e] supergiants are known to possess circumstellar disks in which molecules and dust can form. The formation mechanism and the resulting structure of these disks is, however, still controversial. Nevertheless, to protect the disk material from the dissociating stellar radiation and to allow for dust formation in the vicinity of a luminous supergiant star, the amount of mass comprised within these disks must be huge. We study the amount of hydrogen neutral material by means of an analysis of the strong [O I] emission lines in our optical high-resolution FEROS spectra of two B[e] supergiants, the edge-on system S 65 in the SMC, and the pole-on system R 126 in the LMC. In addition, we study the possible disk dynamics of S 65, based on a simultaneous line-profile modeling. We find that the [O I] emission lines in S 65 must originate either from an outflowing disk, in which the outflow velocity is slowly decreasing outwards, or from a Keplerian rotating ring, resulting from an ejection event.

Keywords. circumstellar matter, stars: individual (R 126, S 65), stars: mass loss, supergiants, stars: winds, outflows, Magellanic Clouds

1. Introduction

B[e] supergiants in the Magellanic Clouds, even though studied in great detail, are still far from being understood. Their non-spherically symmetric wind is proven by, e.g., polarimetric observations (Magalhães 1992; Magalhães *et al.* 2006; Melgarejo *et al.* 2001), and the presence of a dusty circumstellar disk is confirmed by their strong infrared excess emission (e.g., Zickgraf *et al.* 1986) and the strong CO band emission (McGregor *et al.* 1988a,b, 1989; Morris *et al.* 1996). Based on the analysis of the [O I] lines, it has recently even been suggested that the disks around B[e] supergiants are neutral in hydrogen right from the stellar surface, and that molecules and dust are forming (and can exist) already close to the stellar surface (Kraus *et al.* 2007). In fact, for the LMC B[e] supergiant R 126, Kastner *et al.* (2006) found that the inner edge of the dusty disk is located at about 360 R_*, which is 3 times closer to the star than the value of $\sim 1000\,R_*$ suggested by Zickgraf *et al.* (1985).

To guarantee that the disk material is neutral so that molecules and dust can exist, a huge disk mass must be postulated. Since the disks around supergiants cannot be pre-main sequence in origin, the disk formation must be linked to non-spherical, i.e., predominantly equatorial, high mass loss of the central star, either by continuous steady

Table 1. Parameters of the two B[e] supergiants.

Star	$T_{\rm eff}$ [K]	$R_*[R_\odot]$	$\log L_*/L_\odot$	$v\sin i$[km/s]	inclination	$M_*[M_\odot]$	Reference
S 65	17 000	81	5.7	150	± edge-on	~ 35	Zickgraf *et al.* (1986)
R 126	22 500	72	6.1	?	± pole-on	> 60	Zickgraf *et al.* (1985)

material outflow, or by some violent, ring-shaped mass ejection event(s). In the former scenario, the [O I] emission can be modeled with the so-called outflowing disk scenario, in which the wind material in the equatorial region is streaming out (more or less) radially, forming a disk with constant opening angle. In the ejection scenario, the ring material is disconnected from the star, freely expanding and probably revolving the star on Kepler orbits.

Here, we study the [O I] line emission from two B[e] supergiants, the SMC star S 65 and the LMC star R 126, whose stellar parameters are summarised in Table 1. For both stars we obtained high-resolution spectra in 1999 with FEROS attached to the *ESO* 1.52-m telescope (agreement *ESO*/ON-MCT) in La Silla (Chile). In addition, in order to flux calibrate the line emission, low-resolution spectra were obtained with the Boller & Chivens spectrograph, also at the *ESO* 1.52-m telescope (agreement *ESO*/ON-MCT).

2. Modeling of the [O I] lines

Oxygen has about the same ionization potential as hydrogen. The detection of emission lines from O I thus means, that these lines must be generated within a region, in which hydrogen is predominantly neutral as well. Since free electrons are (besides the less efficient, but nevertheless important, neutral hydrogen atoms) the main collision partners to excite the lowest energy levels in O I, from which the forbidden emission lines arise, we introduce the parameter $q_{\rm e}$ as the ionization fraction, defined by $n_{\rm e} = q_{\rm e} n_{\rm H}$, with $q_{\rm e} = q_{\rm metals} + q_{\rm H^+}$. Assuming that all elements with ionization potential lower than that of hydrogen and oxygen are fully ionized, delivers an upper limit of $q_{\rm metals} < 5\times 10^{-5}$ for SMC metallicity, and $q_{\rm metals} < 1.6\times 10^{-4}$ for LMC metallicity. This means, that if hydrogen is ionized by only 1%, it will still deliver the dominant amount of free electrons. Since we do not know the amounts of ionized hydrogen and ionized metals within the disk, $q_{\rm e}$ is a free parameter at first. The hydrogen density distribution in the disk, $n_{\rm H}(r)$, follows from the equation of mass continuity, i.e. $n_{\rm H}(r) \sim F_{\rm m,Disk}/(r^2 v_{\rm out})$, where the parameters $F_{\rm m,Disk}$ and $v_{\rm out}$ represent the disk mass flux and outflow velocity, respectively.

The SMC B[e] supergiant S 65. We start our investigation with the star S 65, which is assumed to be oriented more or less edge-on (see Table 1). The disk opening angle is set to ∼ 20°, and we first adopt the outflowing disk scenario.

Our optical spectra display 3 [O I] lines, of which two originate from the same upper level (see left panel of Fig. 1). This means that their line ratio is determined by pure quantum mechanics. Only line ratios with the $\lambda\,5577$ Å line are thus sensitive to temperature and density. To constrain these two parameters, we use in the following the $\lambda\,6300/\lambda\,5577$ line ratio. The observed value of this ratio is plotted as the dotted line in the top right panel of Fig. 1. For the computation of the line ratios, we use different (but constant) electron temperatures and calculate for each input value of $q_{\rm e}$ the [O I] line luminosities. For this, the density parameter, $F_{\rm m,Disk}/v_{\rm out}$ is varied until the $\lambda\,6300$ line luminosity can be fitted, delivering a certain value for the line ratio with the $\lambda\,5577$ line.

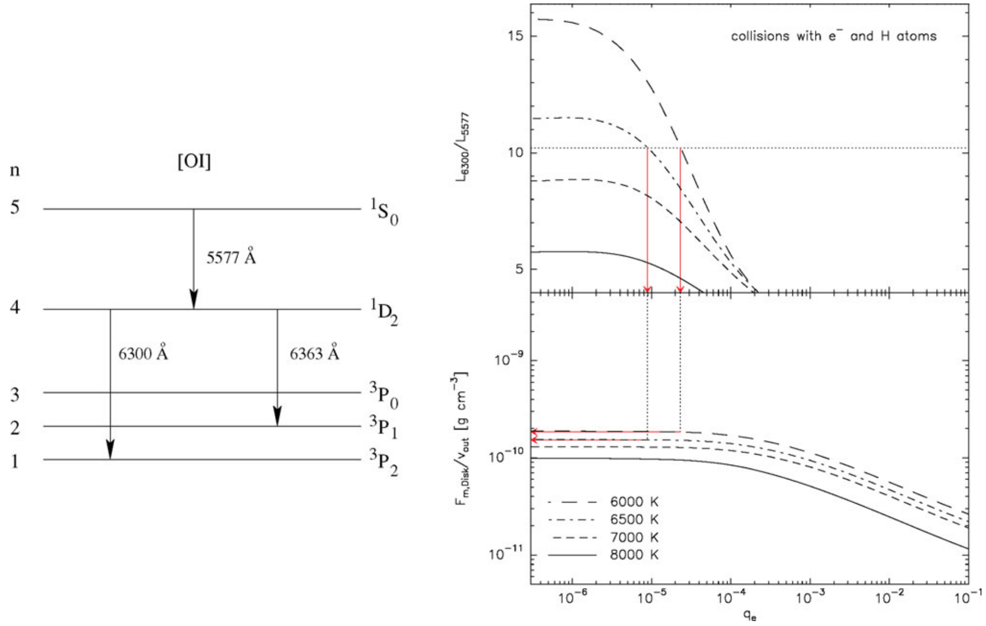

Figure 1. Left: The 5-level atom with the observed transitions indicated. Right: Determination of the possible ranges in disk electron temperature and ionization fraction, q_e, based on the observed [O I] line ratio (top panel), and the disk density parameter (bottom panel).

These line ratio values for different temperatures and as a function of q_e are included in the top right panel of Fig. 1.

Comparison with the observed value shows, that the ranges within the possible parameter space are quite narrow, restricting the temperature to $T_e \simeq 6000$–6500 K, and the ionization fraction to $q_e \simeq 9 \times 10^{-6} - 2.5 \times 10^{-5}$. This low value of q_e confirms indeed that the disk must be predominantly neutral ($q_{H^+} < 2 \times 10^{-5}$). In addition, the small ranges in q_e and T_e confine the density parameter, $F_{m,Disk}/v_{out}$, to a value of $\sim 1.8 \times 10^{-10}$ g cm^{-3} (bottom right panel of Fig. 1).

The increase in line luminosity with distance from the star is shown in the top left panel of Fig. 2 for all three [O I] lines. Saturation of the lines happens at a distance of roughly $500\,R_*$, with the $\lambda\,5577$ line saturating even much closer to the star. The arrows to the right indicate the observed line luminosity values.

Inspection of the observed [O I] line profiles (lower panels of Fig. 2) shows that the lines are double-peaked, with the $\lambda\,5577$ line showing the widest peak separation. With the knowledge that S 65 is seen edge-on, a double-peak structure alone does not give any hint on the underlying kinematics, because both, an outflowing disk with constant outflow velocity, as well as a narrow Keplerian rotating ring, result in the identical, double-peaked line profile (left panel of Fig. 3). To test the outflowing disk scenario, we calculate the line profiles for a constant outflow velocity of $v_{out} \simeq 22$ km s^{-1} as can be derived from the peak separation of the $\lambda\,5577$ line. In addition, to account for the broader wings of the line, some Gaussian shaped turbulent velocity of $v_{turb} \simeq 8$ km s^{-1} needs to be included. The resulting fit to the $\lambda\,5577$ line is shown by the dashed line in the bottom left panel of Fig. 2. Using the same model parameters, delivers identical line profiles for the other two [O I] lines (dotted lines), which do, however, not agree with the observed ones. Instead, to fit these two lines, which are formed further away from the star, we need to assume that the outflow velocity has slowed down to $v_{out} \simeq 16$ km s^{-1}, while the turbulence has

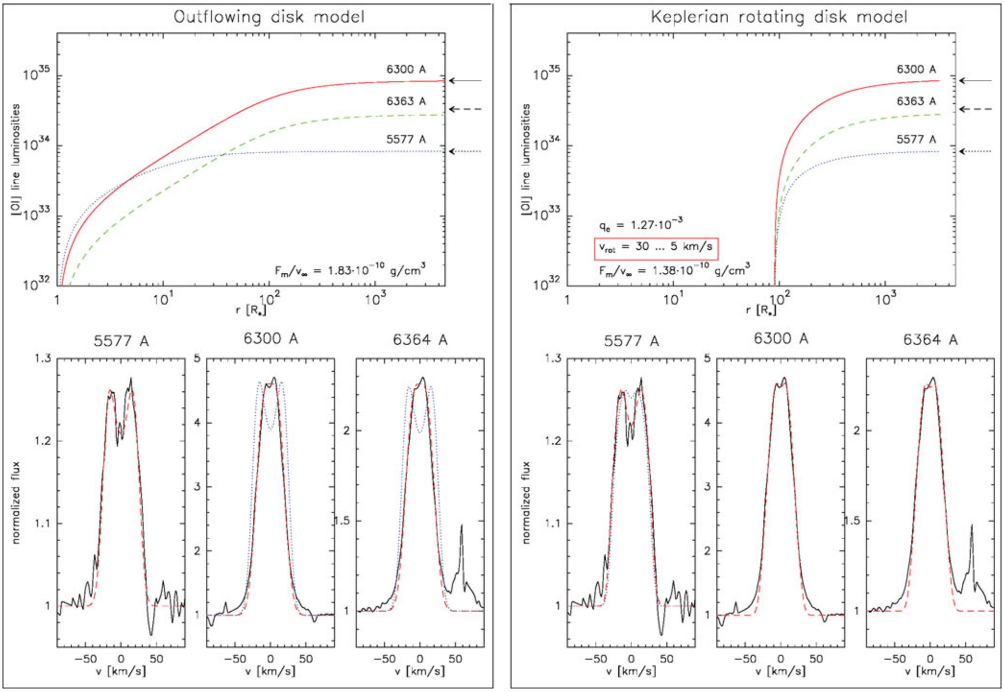

Figure 2. Results for the [O I] line luminosities (top panels) and line profile fits (bottom panels) for the two competing scenarios. For details see text.

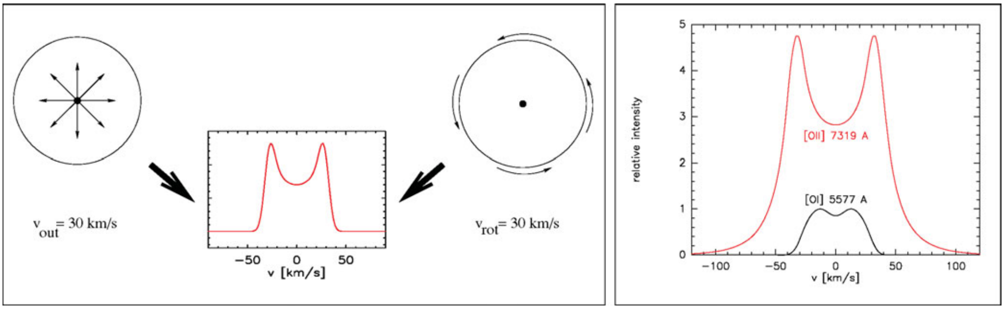

Figure 3. Left: Both scenarios, an edge-on seen outflowing disk or ring, and a narrow Keplerian rotating ring, result in the identical, double-peaked line profile. Right: Expected strength and shape of the [O II] λ7319 line in the Keplerian rotating disk scenario.

slightly increased to $v_{\rm turb} \simeq 11$ km s^{-1} (dashed lines). Such a scenario is, however, quite reasonable and does not contradict or discard the outflowing disk scenario.

Nevertheless, the $\lambda\,6300$ and $\lambda\,6364$ lines, which are produced at larger distances from the star, show a much narrower peak-separation than the $\lambda\,5577$ line, which is produced much closer to the star. This might be a clear indication for Keplerian rotation. In a second attempt we, therefore, calculate the [O I] line luminosities and the profiles with a Keplerian rotating disk model. The peak separation of the $\lambda\,6300$ and $\lambda\,6364$ lines delivers a minimum rotation velocity of about 5 km s^{-1}, which sets the outer edge of the [O I] line emission region to about 3000 R_*. The width of the $\lambda\,5577$ line defines a maximum rotation velocity of about 30 km s^{-1}, placing the inner edge of the disk to about 90 R_*.

The line luminosity calculations (top right panel of Fig. 2) indicate that in this case, the disk ionization fraction, q_e, must be higher by about a factor of 100. This trend is clear, since the line formation is now forced to happen at much larger distances from the star, where the O I density is generally much lower. Therefore, a higher number of collision partners (i.e., free electrons) is necessary to produce the same luminosity. Nevertheless, even with this much higher ionization fraction, the disk can still be considered as neutral in hydrogen ($q_{\mathrm{H}^+} < 1.3 \times 10^{-3}$).

Calculating the shapes of the line profiles, it turns out that the $\lambda\,6300$ and $\lambda\,6364$ lines can be excellently fitted (dashed lines in the bottom right panel of Fig. 2), while the same model fails to reproduce the $\lambda\,5577$ line profile (dotted line). Instead, to fit the $\lambda\,5577$ line profile we need to request that at the inner edge of the Keplerian rotating disk the material is still slowly expanding, with $v_{\mathrm{out}} \simeq 9$ km s^{-1}. Also this scenario seems to be reasonable, since the disk material originates from some mass loss or material ejection.

If the [O I] lines result from a Keplerian rotating disk, the question arises whether this disk extends down to the stellar surface, or whether the material is detached from the stellar surface. In the case that the disk extends down to (or close to) the stellar surface, the disk parts within $90\,R_*$, which do not contribute to the [O I] emission, must consequently be ionized. Since O II is also known to have forbidden emission lines in the optical spectral range, we calculate the line luminosity and profile of the [O II] $\lambda\,7319$ line from the inner disk parts, extending from the stellar surface to $90\,R_*$. The line profile and intensity is then compared to the weakest of our [O I] lines, i.e., the $\lambda\,5577$ line (right panel of Fig. 3). The [O II] line turns out to be much broader (due to the higher rotation velocities closer to the star) and about 5 times more intense than the $\lambda\,5577$ line. It should, therefore, be clearly detectable. However, our spectra do not show indications for any [O II] line. This might indeed indicate that, if the Keplerian rotating disk scenario is the correct one, the material must be detached from the star, speaking in favour of a (single or multiple) mass ejection event rather than a steady outflow. The best-fit parameters of both scenarios for S 65 are summarised in Table 2. Also included are the resulting amounts of gas mass enclosed within the [O I] line forming regions.

Table 2. Best fit parameters of the two competing scenarios for S 65.

	Outflowing Disk	**Detached Keplerian Ring**
Extend of line forming region	$1\,R_* - 500\,R_*$	$90\,R_* - 3000\,R_*$
v_{out}	$22\ldots16$ km/s	$9\ldots0$ km/s
v_{rot}	—	$30\ldots5$ km/s
v_{turb}	$8\ldots11$ km/s	—
Total M_{gas} in [O I] forming regions	$\sim 3.3 \times 10^{-3}\,\mathrm{M}_\odot$	$\sim 1.5 \times 10^{-2}\,\mathrm{M}_\odot$

The LMC B[e] supergiant R 126. The modeling of the [OI] lines from R 126 has been discussed in detail by Kraus *et al.* (2007). Therefore, we give here only a short summary of the main results and conclusions.

The pole-on orientation of R 126 (see Table 1) does not allow for a detailed line profile calculation as in the case of S 65. For the line-luminosity calculations, we followed the same procedure as described above, assuming an outflowing disk scenario that is predominantly neutral in hydrogen right from the stellar surface. With this model, we derive a disk electron temperature of $T_{\mathrm{e}} \simeq 8000$ K, an ionization fraction of $q_{\mathrm{e}} \simeq 4 \times 10^{-4}$, and a density parameter of $F_{\mathrm{m,Disk}}/v_{\mathrm{out}} \simeq 2.2 \times 10^{-11}$ g cm^{-3}. As in the case of S 65, the [O I] line luminosities clearly saturate within about 500 R_*.

Interestingly, observations with the *Spitzer Space Telescope* performed by Kastner *et al.* (2006) revealed that the inner edge of the dusty disk must be located at about 360 R_*, which is even closer to the stellar surface than the [O I] saturation region found from our analysis. In addition, for dust to exist, the disk temperatures must have dropped below the dust sublimation temperature of about 1500 K. This means that our model assumptions were even too conservative, and that the disk mass loss rate must be even (much) higher than our assumed value, confirming the high-mass character of the B[e] supergiant stars' disks.

3. Conclusions

Based on the modeling of both, the observed line luminosities of the [O I] lines and their line profiles, we found that the two B[e] supergiants studied must have high-density disks, which are predominantly neutral in hydrogen. The total amount of ionized hydrogen is found to be less than $\sim 0.1\%$. While for the LMC star R 126 an outflowing disk scenario seems to be the most plausible one, our analysis of the SMC star S 65 showed that for this star both models, i.e., either an outflowing disk, or a detached Keplerian rotating ring, delivered reasonably good fits to the line profiles. For this star, further investigations, which help to distinguish between the two scenarios, are thus necessary.

Acknowledgements

M.K. acknowledges financial support from GA AV ČR grant number KJB300030701, and M.B.F. from the Centre National de la Recherche Scientifique (CNRS). M.K. and M.B.F. are further grateful to the IAU and the organizers for their financial support to attend this IAU Symposium.

References

Kastner, J. H., Buchanan, C. L., Sargent, B., & Forrest, W. J. 2006, *ApJ*, 638, L 29

Kraus, M., Borges Fernandes, M., & de Araújo, F. X. 2007, *A&A*, 463, 627

Magalhães, A. M. 1992, *ApJ*, 398, 286

Magalhães, A. M., Melgarejo, R., Pereyra, A., & Carciofi, A. C. 2006, in M. Kraus & A. S. Miroshnichenko (eds.), *Stars with the B[e] Phenomenon* (San Francisco: ASP), p. 147

McGregor, P. J., Hillier, D. J., & Hyland, A. R. 1988a, *ApJ*, 334, 639

McGregor, P. J., Hyland, A. R., & Hillier, D. J. 1988b, *ApJ*, 324, 1071

McGregor, P. J., Hyland, A. R., & McGinn, M. T. 1989, *A&A*, 223, 237

Melgarejo, R., Magalhães, A. M., Carciofi, A. C., & Rodrigues, C. V. 2001, *A&A*, 377, 581

Morris, P. W., Eenens, P. R. J., Hanson, M. M., Conti, P. S., & Blum, R. D. 1996, *ApJ*, 470, 597

Zickgraf, F. -J., Wolf, B., Stahl, O., Leitherer, C., & Klare, G. 1985, *A&A*, 143, 421

Zickgraf, F. -J., Wolf, B., Stahl, O., Leitherer, C., & Appenzeller, I. 1986, *A&A*, 163, 119