Stars with the B[e] Phenomenon
ASP Conference Series, Vol. 355, 2006
Michaela Kraus and Anatoly S. Miroshnichenko

The Compact Planetary Nebula B[e] Star Hen 2–90

Michaela Kraus,[1,2] Marcelo Borges Fernandes,[3] Francisco X. de Araújo,[4] and Henny J. G. L. M. Lamers[2]

[1] *Astronomický ústav, Akademie věd České republiky, Fričova 298, CZ-251 65 Ondřejov, Czech Republic*

[2] *Sterrekundig Instituut, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands*

[3] *Observatório do Valongo (UFRJ), Ladeira do Pedro Antônio 43, 20080-090 Rio de Janeiro, Brazil*

[4] *Observatório Nacional-MCT, Rua General José Cristino 77, 20921-400 São Cristovão, Rio de Janeiro, Brazil*

Abstract. We present a study of the optical spectrum of the fascinating B[e] star Hen 2–90 based on new high-resolution observations taken with FEROS at the ESO 1.52m telescope in La Silla (Chile). The recent HST image of Hen 2–90 (Sahai et al. 2002) reveals a bipolar, highly ionized region, a neutral disk-like structure seen almost perfectly edge-on, and an intermediate region of moderate ionization. The slits of our observations cover the same innermost region of Hen 2–90 as the HST image, which allows us to combine the observations. Our spectra contain a huge amount of permitted and forbidden emission lines of atoms in different stages of ionization. In addition, the line wings deliver velocity information of the emitting region. We find correlation between the different ionization states of the elements and the velocities derived from the line profiles: the highly ionized atoms have the highest outflow velocity, while the neutral lines have the lowest. When combining the velocity information with the HST image of Hen 2–90, it seems that a non-spherical stellar wind model is a good option to explain the ionization and spatial distribution of the circumstellar material. Our modeling of the forbidden emission lines results in strong evidence for Hen 2–90 being a compact planetary nebulae that has undergone a superwind phase of high, non-spherical mass loss, most probably triggered by a central star that was rotating with about 80% of the critical velocity. We find a total mass loss rate during this superwind phase on the order of $3 \times 10^{-5}\,\mathrm{M_\odot yr^{-1}}$.

1. Introduction

The classification of stars with respect to their evolutionary stage is not always straightforward. This is especially true for the southern galactic B[e] star Hen 2–90. It was first classified as a planetary nebula by Webster (1966) and Henize (1967). Later, Costa et al. (1993) and Maciel (1993) classified it as a planetary nebula with low metal abundance and with a central star of low mass and low luminosity. Sahai & Nyman (2000), based on HST images, and Guerrero et al. (2001), using ground-based images, have described the presence of a nebula bisected by a disk and with both a bipolar jet and knots, spaced uniformly. The

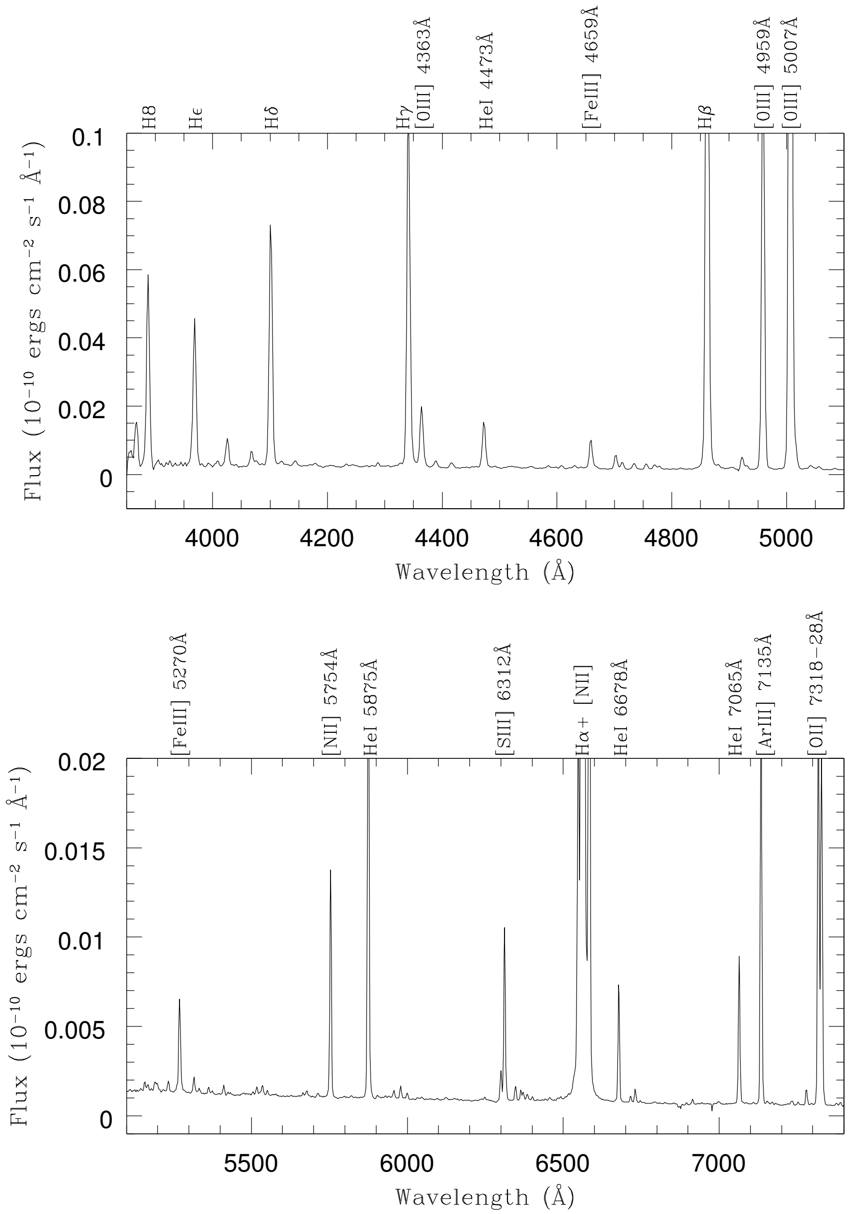

Figure 1. Parts of the low-resolution (B&C) spectrum of Hen 2–90 including the identification of the most prominent lines.

dynamical stability of the jets and knots makes Hen 2–90 even a unique object. These characteristics could point to a compact planetary nebula nature with the jets shaping the spherical AGB wind in a bipolar scenario (Sahai & Trauger 1998; Imai et al. 2002; Vinković et al. 2004) or to a binary nature like e.g. a symbiotic object (Sahai & Nyman 2000; Guerrero et al. 2001). Reason enough for us to take a closer look at this fascinating object by studying its close-by circumstellar material by means of an analysis of its forbidden emission lines arising in the optical spectrum.

2. Observations

High and low resolution observations were obtained with the Fiber-fed Extended Range Optical Spectrograph (FEROS) and with the Boller & Chivens (B&C) spectrograph, respectively, at the ESO 1.52m telescope in La Silla (Chile, under agreement ESO/ON). Parts of the low resolution B&C spectrum are shown in Fig. 1, and a line identification of the most prominent lines is given. Both, the fibre aperture of FEROS and the slit width of B&C were $2''$ which is indicated by the circle overplotted on the HST image (top panel of Fig. 2). An extended description of the observations together with a classification of the line profiles and a complete line list is given in Kraus et al. (2005).

3. The Nature of the Circumstellar Material of Hen 2–90

There exist three major reasons why we think that the circumstellar material can best be approximated by a non-spherical wind scenario:

1. The emission lines: Our spectra contain plenty of emission lines, both permitted and forbidden. Usually, the density considerations for these lines are completely different: while permitted lines need high density regions to be strong, the forbidden lines need a low density environment. The circumstellar medium of Hen 2–90 must therefore consist of at least two (probably more) different density regions.

2. The ionization structure: The HST image clearly shows dominance of high-ionized material (O III) in the polar directions, lower ionized material at intermediate directions (N II), and a dark, probably neutral disk-like structure in the equatorial plane. A zoo of different ionization states is also present in our optical spectra, and we want to stress that we even observed strong emission of [O I], indicative for a huge amount of hydrogen neutral material in the vicinity of the central star and most probably associated with the dark disk-like structure.

3. The velocity structure: From the high-resolution spectra we were able to derive the wing velocities of the individual emission lines. Interestingly, we found that the high-ionized lines have the highest velocities, while the neutral lines (e.g. [O I]) have the lowest velocities.

The combination of these three facts led us to the conclusion that the circumstellar medium of Hen 2–90 might best be modeled with a non-spherical wind scenario with latitude dependent temperature (ionization structure), density distribution, and outflow velocity. Such a scenario, as shown in the bottom panel of Fig. 2, is the basis for our model calculations.

4. The Non-Spherical Wind Model for Hen 2–90

The stellar parameters of Hen 2–90 are not well known. For example,a its effective temperature ranges between 50 000 K (Kaler & Jacoby 1991; Costa et al.

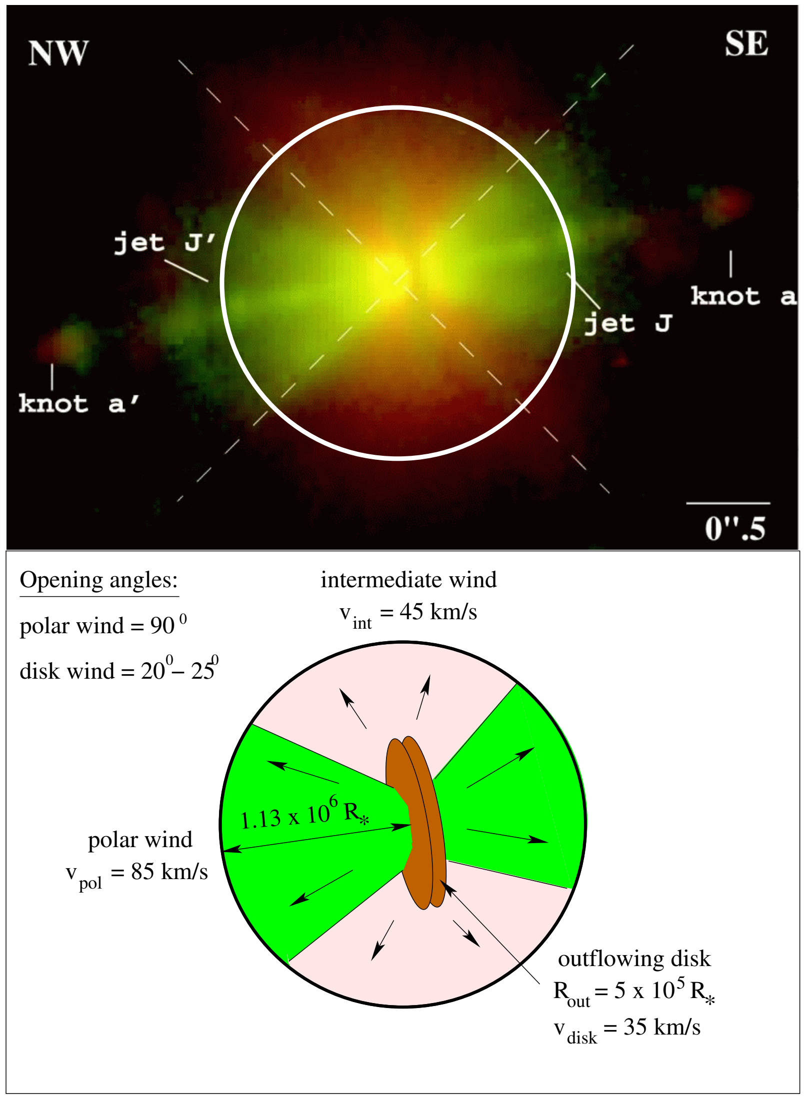

Figure 2. Top: HST image of Hen 2–90 from Sahai et al. (2002) indicating the bipolar wind separated by the equatorial edge-on seen disk-like structure. The big white circle indicates the aperture/slit width of our observations. Bottom: Sketch of the non-spherical wind model divided up into the polar wind, outflowing disk, and intermediate wind. Also given are the corresponding wind terminal velocities, derived from the wings of the emission lines in the different wind parts.

1993) and 32 000 K (Cidale et al. 2001), depending on the method used[1]. During the modeling it turned out that the real surface temperature in the polar wind is not really relevant, because the forbidden lines are produced further away from

[1]Note, that classification as a B star is based on the emission spectrum, but it does not reflect the effective temperature of the star.

the star where the wind temperature dropped already to its final value. Equally poorly known is the distance to Hen 2–90, which ranges between 1.5 kpc (Costa et al. 1993) and 2.5 kpc (Sahai & Nyman 2000), and we use a mean value of 2.0 kpc.

Table 1. Best fit model parameters for the polar, intermediate, and disk wind. The mass fluxes are assumed to be constant within the indicated θ-ranges and have an error on the order of 20 %.

Wind	T_0 [10^3 K]	T_∞ [10^3 K]	$\theta_{\rm min}$ [°]	$\theta_{\rm max}$ [°]	v_∞ [km s^{-1}]	$F_{\rm m}(\theta)$ [g s^{-1}cm^{-2}]
polar	30–50	10	0	45	85	7.2×10^{-2}
intermediate	30–50	10	45	78	45	1.5×10^{-1}
disk	10	6	78	90	35	5.5×10^{-1}

We concentrate our detailed analysis on the forbidden lines[2], which are excellent indicators of the circumstellar material for two reasons:

- They are excited collisionally and are therefore sensitive to temperature and density;
- The circumstellar nebula is optically thin for these lines, simplifying the analysis.

Available forbidden lines in our spectrum are from O I, O II, O III, N II, Cl II, Cl III, Ar III, S II, and S III. We do not model lines from Fe II because iron cannot be treated in such a simple way as the other elements.

The different ionization states mirror the different emission regions in the non-spherical wind scenario and we could model the individual lines self-consistently. The resulting parameters describing the non-spherical wind are given in Table 1. We find the following latitude dependences from pole to equator:

- A decrease in surface temperature by a factor 3–5;
- A decrease in terminal velocity by about a factor 2.5;
- An increase in mass flux by about a factor 8.

Such a variation of the different parameters with latitude strongly reminds of the scenario of a rapidly rotating star. We used the decrease in terminal velocity to derive a rotation speed of $\sim 80\%$ of the critical velocity (see Fig. 6 of Kraus & Lamers, this volume), which is on the same order as the values typically found e.g. for classical Be stars (Porter & Rivinius 2003).

The total mass loss rate[3] was found to be on the order of $3 \times 10^{-5}\, M_\odot {\rm yr}^{-1}$, which coincides nicely with those found for proto-planetary nebulae with axially

[2]For a detailed description of the line luminosity calculation see Kraus et al. (2005).

[3]Note, that this is the past mass loss rate during the superwind phase, not the present one.

symmetric dust shells resulting from a superwind phase (see e.g., Meixner et al. 1997).

Finally, we would like to mention that during the fitting of the observed line luminosities we had to reduce the abundances of C, N, and O to values of < 0.6, 0.5, and 0.3 solar, respectively, while Ar, S, and Cl could be modeled with standard solar abundances. The depletions of C and O follow from stellar evolution, but we have no explanation for the depletion in N. There exist some B-type post AGB stars of similar behaviour in the halo of our galaxy (Moehler & Heber 1998), and recently Lennon et al. (2005) reported on a Be star with an unexpected low N abundance. The origin of those anomalies is, however, still poorly understood.

5. The Nature of Hen 2–90

In the literature, Hen 2–90 has been classified either as a (compact) planetary nebula (e.g., Costa et al. 1993; Maciel 1993; Lamers et al. 1998), or as a symbiotic object (Sahai & Nyman 2000; Guerrero et al. 2001). One goal of our study was also to clarify this open question. The major characteristics of a symbiotic object are:

- Emission of HeII lines from the hot component;
- Presence of TiO bands from the cool component.

The absence of both features in our optical spectra clearly speaks against the classification of Hen 2–90 as a symbiotic object. In addition, the lack of any emission line from ions with ionization potential higher than ~ 40 eV even indicates that the effective temperature of Hen 2–90 is more on the order of 30 000 K as suggested by Cidale et al. (2001) than 50 000 K as stated by Kaler & Jacoby (1991).

On the other hand, the derived mass loss rate of $\sim 3 \times 10^{-5}\, M_{\odot}\mathrm{yr}^{-1}$ and the strength of the [OIII] 5007Å line (when taking into account the depletion in O) are consistent with what is known for (compact) planetary nebulae, and even the jet-like structure and regular blob ejection could be modeled perfectly with a planetary nebula scenario and under the assumption of a solar-like magnetic cycle (García-Segura et al. 2001).

From our observations, modeling and this discussion, we conclude that Hen 2–90 is at least an evolved object, and the classification as a compact planetary nebula seems favourable. Whether it is indeed part of a binary could not yet been proven (see also Kraus et al. 2006) and needs some further investigation.

6. Conclusions

We studied the non-spherical mass loss history of the enigmatic B[e] star Hen 2–90 by means of a detailed analysis of the optical forbidden emisison lines. The wind geometry used is based on the HST image, which reveals a non-spherical wind structure consisting of a high-ionized polar wind, a neutral outflowing disk, and a low-ionized intermediate wind. Such a latitude dependent ionization structure could be confirmed by the zoo of emission lines of different ions in our spectra. In addition, we found a decrease in velocity and an increase in mass flux from pole to equator, which might be interpreted in terms of a rapidly rotating (80% critical) underlying star. Such rapid rotation might have caused the massive non-spherical wind structure during a superwind phase with total mass loss of about $3 \times 10^{-5}\,M_{\odot}\mathrm{yr}^{-1}$, as it is often observed during the formation of a (proto) planetary nebula. From our observations and modeling results we conclude that Hen 2–90 must be an evolved object, and we favour the interpretation of a compact planetary nebula. Whether it is part of a binary system, is still an unsolved question.

Acknowledgments. M.K. acknowledges financial support from GA ČR grant number 205/04/1267 and from the Nederlandse Organisatie voor Wetenschappelijk Onderzoek grant No. 614.000.310. M.B.F. acknowledges financial support from FAPERJ (E-26/170.371/2005), CNPq (Post-doc position - 150170/2004-1), Utrecht University, LKBF and NOVA foundations.

References

Cidale, L., Zorec, J., & Tringaniello, L. 2001, A&A, 368, 160
Costa, R. D. D., de Freitas Pacheco, J. A., & Maciel, W. J. 1993, A&A, 276, 184
García-Segura, G., López, J. A., & Franco, J. 2001, ApJ, 560, 928
Guerrero, M. A., Miranda, L. F., Chu, Y. H., Rodriguez, M., & Williams, R. M. 2001, ApJ, 563, 883
Henize, K. G. 1967, ApJS, 14, 125
Imai, H., Obara, K., Diamond, P. J., Omodaka, T., & Sasao, T. 2002, Nat, 417, 829
Kaler, J. B., & Jacoby, G. H. 1991, ApJ, 372, 215
Kraus, M., Borges Fernandes, M., & de Araújo, F. X. 2006, in ASP Conf. Ser., Massive Stars in Interacting Binaries, ed. A. Moffat, & N. St-Louis (San Francisco: ASP), in press [astro-ph/0410196]
Kraus, M., Borges Fernandes, M., de Araújo, F. X., & Lamers, H. J. G. L. M. 2005, A&A, 441, 289
Lamers, H. J. G. L. M., Zickgraf, F.-J., de Winter, D., Houziaux, L., & Zorec, J. 1998, A&A, 340, 117
Lennon, D. J., Lee, J.-K., Dufton, P. L., & Ryans, R. S. I. 2005, A&A, 438, 265
Maciel, W. J. 1993, Ap&SS, 209, 65
Meixner, M., Skinner, C. J., Graham, J. R., Keto, E., Jernigan, J. G., & Arens, J. F. 1997, ApJ, 482, 897
Moehler, S., & Heber, U. 1998, A&A 335, 985
Porter, J. M., & Rivinius, Th. 2003, PASP, 115, 1153
Sahai, R., & Nyman, L.-A. 2000, ApJ, 537, L 145
Sahai, R., & Trauger, J. T. 1998, AJ, 116, 1357
Sahai, R., Brillant, S., Livio, M., Grebel, E. K., Brandner, W., Tingay, S., & Nyman, L.-A. 2002, ApJ, 573, L 123
Vinković, D., Hofmann, K.-H., Elitzur, M., & Weigelt, G. 2004, in ASP Conf. Ser. Vol. 313, Asymmetric Planetary Nebulae III: Winds, Structure and the Thunderbird, ed. M. Meixner, J. H. Kastner, B. Balick, & N. Soker (San Francisco: ASP), 321
Webster, L. B. 1966, PASP, 78, 136