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On the inner envelope of the Be star γ Cassiopeiae

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Abstract. We report the first spectrally-resolved observations of the Be star γ Cas in the He I λ6678 and Hβ emission lines using the Grand Interféromètre à 2 Télescopes in the southern France. Milliarcsecond angular resolution measurements were carried in both lines and their neighbouring continuum during October and November 1993. The He I λ6678 and Hβ maximum emissions correspond respectively to 1.05 and 1.5 of the local continuum level. The interferometric baselines ranged from 15m to 51m on the sky which correspond to angular resolutions of 9 to 3 mas at He I λ6678 and 6.5 to 2 mas at Hβ wavelengths. We compare these values to predicted extents of Hβ and He I λ6678 components of the circumstellar gas from models of radiative transfer in these lines. We conclude that the emitting region must be smaller than 8.5 stellar radius in Hβ and close to 2.3 stellar radius in He I λ6678 which is, for He I λ6678, smaller than the nearby continuum extent. These results confirm γ Cas basic parameters for this star obtained by Stee et al. on 1993 from their model constrained by GI2T observations in Hα line.

Key words: stars: individual: γ Cas – circumstellar matter – stars: emission-line, Be – stars: mass-loss – techniques: interferometric

1. Introduction

Be stars like γ Cas are often observed in the Balmer series (Slettebak et al. 1992) although more recent studies have emphasized the diagnosis value of He and Fe lines for understanding the occurence of Be episodes (Smith 1995) as well as the kinematics of the circumstellar envelope (Hanuschik 1994). Thanks to optical long baseline interferometry (Quirrenbach et al. 1993, Quirrenbach et al. 1994, Stee et al. 1995, S95 hereafter and Rousselet-Perraut et al. 1997, RP97 hereafter) the controversy on the oblateness of the envelope is now well clarified. High angular resolution observations ruled out spherical or spheroidal structures and, even if other Be stars may have more oblate envelopes than those of γ Cas, the observations are not in favour of a highly flattened structure, as it would be expected for circumstellar gas distribution with a disk-like shape. The next step in understanding the Be phenomenon will be the direct mapping of local structures of the envelope pending on the operation of aperture synthesis arrays operated in the visible and IR wavelengths. Meanwhile, the variations of the envelope geometry, most likely related to the variability of the underlying star (Marlborough 1997), should be accurately followed to understand the mechanisms which govern the dynamical behaviour of the circumstellar matter. From this point of view the GI2T has the unique property to provide spectrally-resolved interferometric data which enable to sound the stratified structure of Be stars wind through the simultaneous observations of different spectral lines and regions (Vakili et al. 1997) . In the following we describe the first high angular observations of γ Cas in He I λ6678 and Hβ emission lines by the GI2T optical interferometer widely described in the litterature (Mourard et al. 1994a and 1994b, and references therein). In the first section we briefly present the instrumentation of the GI2T and the data analysis used to estimate the angular diameter of γ Cas in He I λ6678 and Hβ. Next we investigate the formation of helium and hydrogen emission using a radiation transfer model with chemical abundances and stellar parameters as in S95. We used this model to interpret our interferometric measurements and to bring new constraints on the envelope temperature distribution.

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2. Observations and data reduction

The present study follows the same observational strategies as reported by S95 and RP97. We recall that the data collected by the GI2T correspond to spectrally dispersed interferograms which contain spatial informations depending on the chromatic morphology of the object under study. These interferograms are short 20 ms exposures recorded on the CP40 photon-counting camera (Blazit 1987). For the present work based on the high spectral dispersing mode of the GI2T we could record either the Hα and He I λ6678 fringes or the Hβ and their neighbouring continua by simply matching the adequate grating's angle

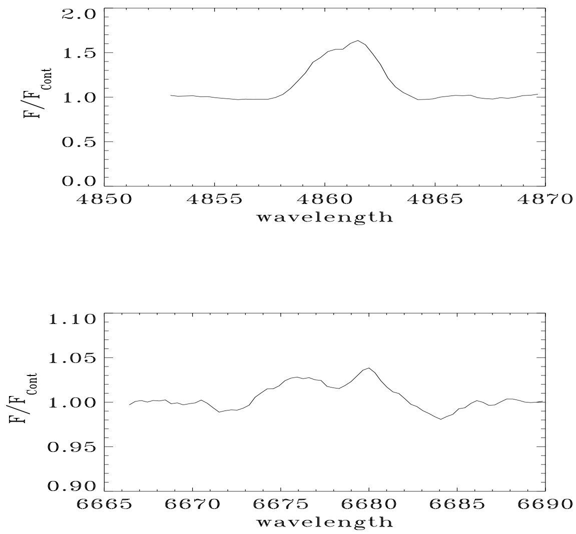

Fig. 1. Typical flat fielded Hβ and He I λ6678 spectra for γ Cas. Top:Hβ profile on 93/11/25, bottom:He I λ6678 profile on 93/11/25. The wavelength scale is given in Angstrom.

in the GI2T spectrometer. The results from the Hα reduction were reported in the previous paper S95 and hereafter we will give a few more details specific to Hβ and He I λ6678 observations. The spectral resolution of the GI2T spectrometer was calibrated at red wavelengths thanks to a neon source at 0.17nm but could not be done for the Hβ region. If chromatic aberrations are neglected, a linear extrapolation would give a 0.23 resolving power at 486.1nm which corresponds to an average Hβ spectral extent of 0.7nm during our run. Fig. 1 displays typical flat fielded Hβ and He I λ6678 spectra corresponding to the 93/11/25 night in γ Cas. For both He I λ6678 and Hβ we decided to set the channel bandwidths to the extent of those lines from the violet wing to the red one. The same bandwidths were used for estimating the visibility in the continuum in order to avoid spectral decorrelation of the fringe signal (Berio et al. 1997). Table 1 gives the journal of observations during October and November 1993 and the visibilities of He I λ6678 and Hβ lines normalized on their local continua visibilities. He I λ6678, and very probably Hβ, can exhibit variable emission features on the scale of a few minutes or hours on γ Cas (Smith 1995). This has been neglected for the present study and high angular resolution measurements obtained for γ Cas correspond to mean angular diameters during one month. We must emphasize that our spectral data reduction processes were checked using a high resolution spectra of γ Cas in the He I λ6678 line recorded on a classical spectrometer during the same period (Smith 1995).

3. A model for the inner envelope of γ Cassiopeiae

3.1. The He I λ6678 emitting region

We have introduced an helium contribution of 10% (Osterbrock, 1974) in the model for γ Cas presented in S95. We have solved the ionization-excitation equation as described in Stee & Araújo

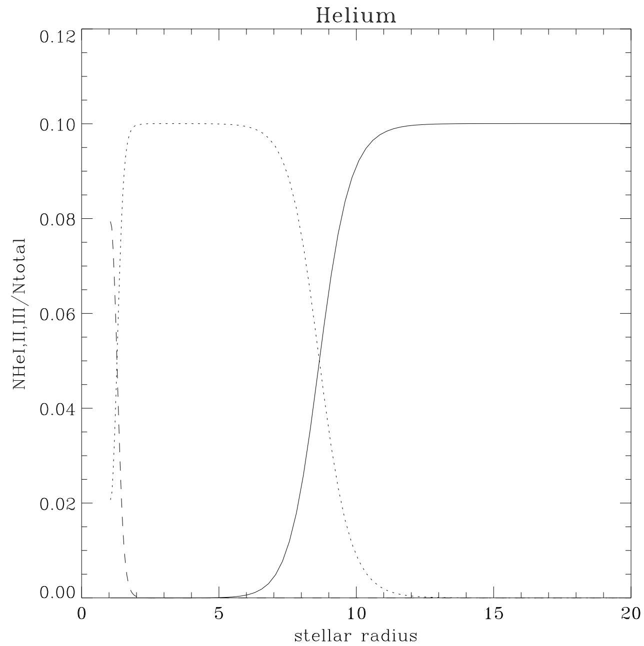

Fig. 2. Ionization structure of the He region. Solid line: He I, dotted: He II, dashed: He III. Ntotal= NHe I+NHe II+NHe III+NH I+NH II

1994 and S95 for the hydrogen part of the envelope, and assuming LTE degree of excitation and ionization for the helium part of the gas. Since He I λ6678 is formed by recombination processes, we have used the emission coefficient j_{6678} for recombination lines given by Pottasch (1984):

$$j_{6678}(T) = \frac{5.64 \times 10^{-27}}{T^{0.12}} n_e n_{He} \quad (1)$$

where T is the envelope temperature distribution (see Sect. 4 for a complete discussion on the effect of T(r)).

Fig. 2 shows the ionization structure of the He region as a function of the stellar radius in the equatorial plane of γ Cas. He is singly ionized between 1 and 7 stellar radii. After 9 stellar radii it is essentialy neutral. We found that half of the He I λ6678 flux is radiated within a region of 2.3 stellar radii. This gives an extent of the He I λ6678 emission region of 0.51 mas assuming a diameter of 0.45 mas for the photosphere of γ Cas (see S95). Note that conversions from linear extents to angular ones are in agreement with γ Cas parallax obtained by HIPPARCOS.

3.2. The Hα and Hβ emitting regions

We have computed, for the same parameters used in S95, the amount of energy $E_{H\alpha,\beta}$ radiated in the Hα and Hβ lines as a function of the stellar radius. Thus we calculate:

$$E_{H\alpha,\beta} = \int_0^{\pi} \int_0^{2\pi} I_{H\alpha,\beta}(r,\theta,\phi)(\frac{r}{R})^2 sin\theta d\theta d\phi. \quad (2)$$

with

$$I_{H\alpha,\beta}(r,\theta,\phi) = \frac{\eta(r,\theta,\phi)}{\kappa(r,\theta,\phi)}(1 - e^{-\tau(r,\theta,\phi)}) \quad (3)$$

Table 1. Journal of observations and interferometric data on γ Cassiopeiae in GI2T. First column: gregorian dates, second: mean UT for each observation, third: corresponding julian date, fourth: the projected baseline on the sky in meter, fifth: the spectral lines for which fringes were recorded, sixth: the spatial frequency f in $cycle.arcs^{-1}$ for the line at the corresponding baseline, seventh: the ratio M_a of the raw visibility in the line to the raw visibility in the neighbouring continuum and the corresponding errors.

Date	UT	JD(2449000+)	B	Spectral Line	f	M_a
93/10/29	21:57	290	15.40	He I λ6678	112	0.99 ± 0.10
93/11/07	21:22	299	15.40	He I λ6678	112	0.99 ± 0.16
				Hβ	154	1.00 ± 0.23
93/11/08	21:18	300	20.70	He I λ6678	150	1.04 ± 0.08
93/11/11	21:18	303	20.70	Hβ	206	0.93 ± 0.40
93/11/16	20:47	308	28.00	He I λ6678	203	1.23 ± 0.15
			28.00	Hβ	279	0.87 ± 0.36
93/11/24	20:11	317	37.80	He I λ6678	274	1.01 ± 0.10
				Hβ	377	1.07 ± 0.47
93/11/25	20:07	318	51.04	He I λ6678	371	1.04 ± 0.10
				Hβ	509	0.94 ± 0.33
93/11/28	19:55	321	29.60	He I λ6678	215	1.21 ± 0.13

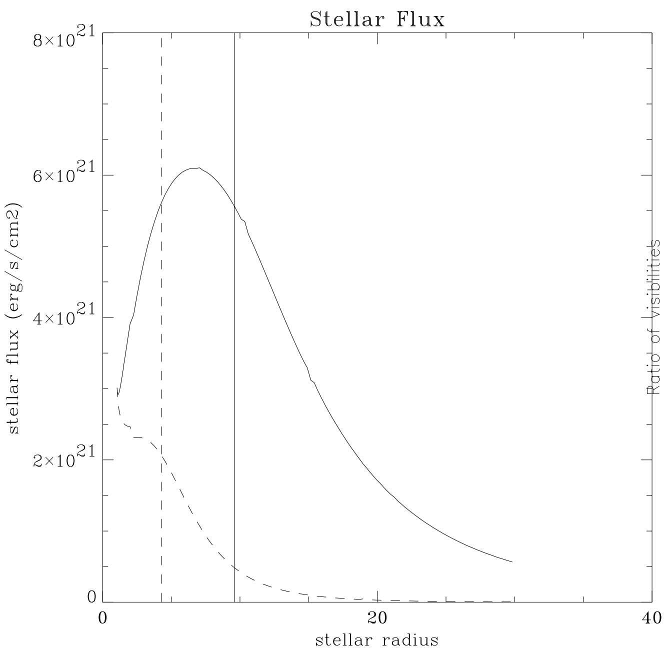

Fig. 3. Hα and Hβ emitted energy depending on the distance from the star (respectively solid and dashed lines). The corresponding verticale lines are the radii where half of the flux is radiated. The total extent of the emitting region is twice the corresponding radius, i.e 8.5 stellar radii for Hβ and 18 stellar radii for Hα.

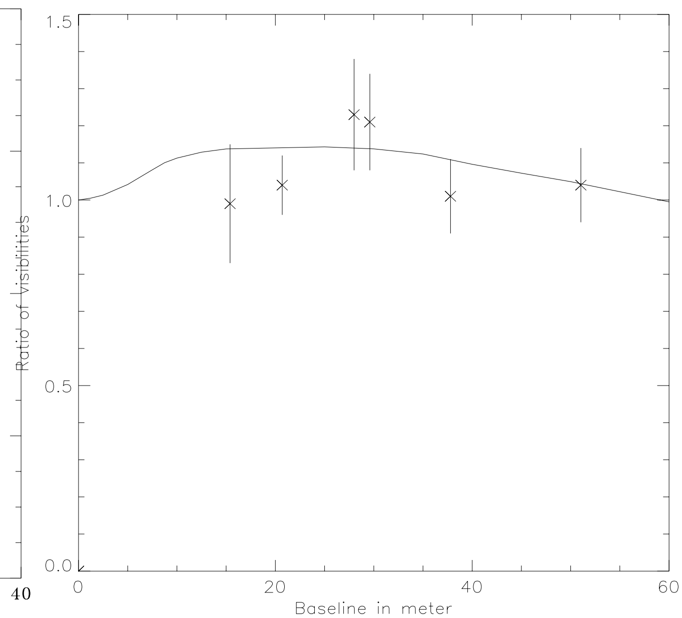

Fig. 4. Ratio of the visibilities in the He I λ6678 line and in the nearby continuum (crosses). The solid line is the visibility in the He I λ6678 line referenced to the continuum visibility obtained from the model by S95.

where $\eta(r, \theta, \phi)$ and $\kappa(r, \theta, \phi)$ are respectively the emission and absorption coefficients for Hα and Hβ and R the stellar radius (see Stee & Araùjo, 1994 for more details). We see in Fig. 3 that the Hβ emission originates closer to the star than Hα. We obtained that half of the energy in Hβ is radiated within a region of 8.5 stellar radii, i.e. 1.91 mas whereas half of the Hα energy is emitted within 18 stellar radii, i.e. 4.05 mas. This last value of 4.05 mas obtained for Hα agrees well with the extent of 4 mas obtained from the direct mapping of the Hα emitting region computed from S95. The luminosities obtained are respectively 1.0810^{34} erg s^{-1} for Hβ and 6.3610^{34} erg s^{-1} for Hα. This last value can be compared to 3.2410^{34} erg s^{-1} obtained by Kastner & Mazzali (1989). They have used the mean Hα equivalent widths listed by Coté and Waters (1987) which are converted into line luminosities assuming an equivalent black-body stellar continuum. They used the tables in Straizys and Kuriliene (1981) which list stellar radius and temperature vs. spectral type in order to compute the Planck function. Their underestimation is most probably due to the omission of the continuum flux excess produced by the circumstellar envelope, which is at least of

Table 2. Basic parameters of γ Cassiopeiae from S95 and confirmed by the present study.

Parameters	
Spectral type	B0.5IVe
Effective temperature	25000 K
Mass	16 $M_\odot$
Radius	10 $R_\odot$
Stellar angular diameter	0.45 mas
Luminosity	$3.510^4 L_\odot$
Vsin i	230 km^{-1}
Inclination angle i	45°
Photospheric density	$\rho_0 = 2.0 \cdot 10^{-11}$ g.cm^{-3}

Table 3. Extent of the He I λ6678 envelope region of γ Cas for different temperature laws.

β law	Extent in stellar radius (model)	Model in mas
0.25	3.7	0.83
0.5	2.3	0.51
1.0	2.1	0.47

the order of $10^{-0.4\Delta V}$; ΔV = V − V$_*$, where V is the observed apparent visual magnitude of the system star+envelope and V$_*$ is the apparent visual magnitude corresponding to the underlying photospheric radiation, as the star would be without circumstellar envelope (ΔV $<$ 0 when the emission phenomenon is present). This flux excess is widely discussed in Ballereau et al. (1995). Moreover, their smaller value can also be due to their estimated luminosity which is proportional to the squared stellar radius, whereas we found that the Hα emission extends over 18 stellar radii. In fact, it is uncorrect to reduce the extended Hα emission produced by non LTE processes to a black-body stellar continuum of a given radius.

Since our interferometric measurement is the ratio between the visibilities in the line and in the continuum (see S95 and Sect. 2) we have also computed the continuum emission close to Hα, He I λ6678 and Hβ lines. We find that the continuum emission near Hα and He I λ6678 wavelengths is produced within 3.5 stellar radii, whereas for Hβ it originates within 2.8 stellar radius. The corresponding computed visibilities are for He I λ6678 constant and close to unity between 10 and 60 meters whereas for Hβ it is also constant after 15 meters but close to 0.65.

4. Discussion

We recall that the measured quantity in GI2T is (S95):

$$M_a = \frac{V_l}{V_c}, \tag{4}$$

where V_l and V_c denote raw line and continuum visibilities respectively. This quantity is independent of seeing and instrumental noise.

From the error bars on Hβ in Table 1 it can be checked that M_a is not accurate enough to put direct constraints on the model of γ Cas. However, the Hβ angular upper limit 1.91 mas agrees well with the general picture of this star obtained from Hα observations in S95.

Fig. 4 displays the observed values of M_a for the He I λ6678 line. From this figure it is clear that the data points M_a are close to or larger than unity which means that the He I λ6678 visibility should be slightly larger than the visibility in the nearby continuum. In other words, the He I λ6678 emitting region appears **smaller** than the overall continuum source. This result is also consistent with our physical modeling where we obtained that the extent of the He I λ6678 region is 2.3 stellar radii whereas the neighbouring continuum extends to 3.5 stellar radii (see Table 4). We have also computed the theoretical visibility in the He I λ6678 line referenced to the continuum obtained by S95. The result shown in Fig. 4 predicts also that the ratio of computed visibilities is larger than unity and follows the same trend as the measured visibility ratios. These results confirm the basic parameters for γ Cas obtained by S95 from the model based on GI2T observations in Hα line. Table 2 summarizes these parameters confirming that our treatement of the He I λ6678 emission is realistic. This is not surprising since, in our model, the helium emission line is formed very close to the star, where the photospheric density is high (i.e. $2.0 \cdot 10^{-11}$ g.cm^{-3}). Therefore, collisional processes may cause the relative numbers of helium atoms in successive stages of ionization to follow the classical Saha-Boltzmann equation. A strong point that comes up with our results is that a lemniscat-shaped circumstellar envelope (axisymmetric thin envelopes at the inner edge and thick at the outher rim) is completely inappropriate for γ Cas. This kind of circumstellar envelopes was however frequently invoked in the literature to interprete observations of Be stars as in the case of hydrostatic disks with a concave-shape models proposed by Hanuschik (1996) which are in contradiction with our high angular resolution observations.

In order to check the influence of the envelope temperature distribution we used the following law:

$$T(r) \propto T_{eff} \left(\frac{R}{r}\right)^{\beta}. \tag{5}$$

with β = 0.25 and β = 1.0 (we recall that in S95 and for this study we have used β = 0.5). From Table 3 it seems that the temperature in the envelope must drop faster then β = 0.25 in order to obtain an He I λ6678 region smaller than the overall continuum source. On the other hand a β = 1.0 law produces a 2.1 stellar radii He I λ6678 region which agrees well with our measurements but it also produces a too faint continuum emission of the envelope and an $H\alpha$ line profile which does not agree with the observed one. Therefore, a temperature law with 0.5<β<1.0 is a good compromise and seems to rule out classical models with constant envelope temperature distribution of T_{env}=0.8 T_{eff} (see for instance Waters et al. 1987).

Finally our main results on the first spectrally-resolved observations of γ Cas in the He I λ6678 and Hβ emission lines are summarized in Table 4 in addition to previous results obtained

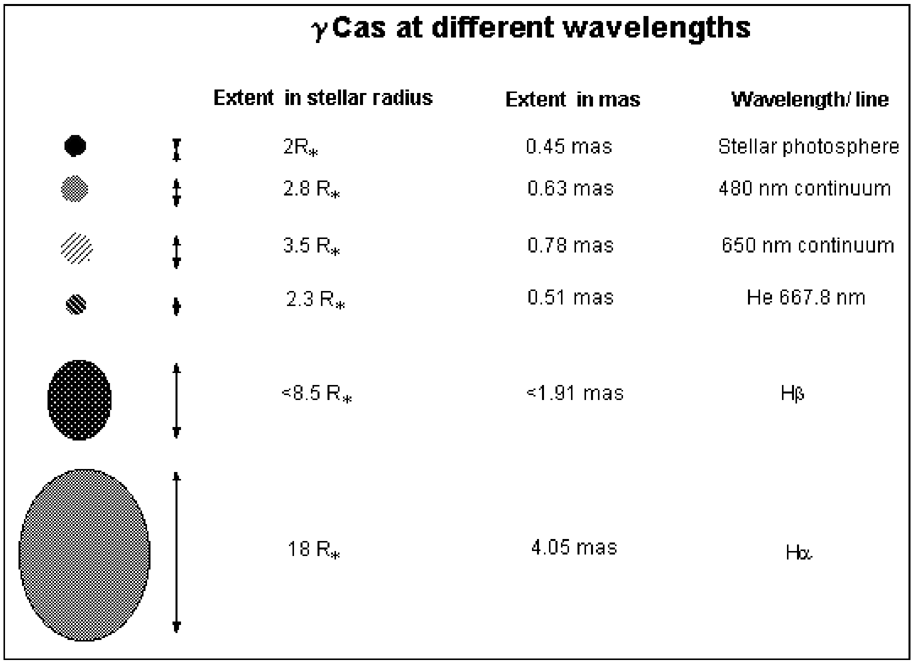

Fig. 5. A schematic view of γ Cas as a function of wavelength from the S95 model constraint by the GI2T observations. These envelope wavelength dependent shapes are projections onto the sky plane which are function of our assumptions made on the envelope symmetry, oblateness and inclination angle. Note that conversions from linear extents to angular ones are in agreement with γ Cas parallax obtained by HIPPARCOS.

Table 4. Extent of the envelope regions of γ Cas from our modeling constraint by the GI2T observations.

Region	Extent in stellar radius (model)	Model in mas
He I λ6678	2.3	0.51
Hα	18.0	4.05
Hβ	<8.5	<1.91
Continuum at 650 nm	3.5	0.78
Continuum at 480 nm	2.8	0.63

by S95 for Hα and the continuum. A schematic view of γ Cas as a function of wavelength is shown in Fig. 5.

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