The Correlation between Hα and HeI 6678 Emission Activity in the Be Star γ Cassiopeiae from 1995 to 2021

Ernst Pollmann
Observatory "Vereinigung der Sternfreunde Köln", Germany; ernst-pollmann@t-online.de

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Abstract The Be star γ Cas is among others well known for erratic rapid variations in its HeI emission at 6678 Å. Recently, this emission has become an important diagnostic feature to investigate the regions of disc activity close to the star. It was recognized that several factors—mass loss from the photosphere of the primary star, density variations, and collision excitations of the HeI atoms—force the emissions in HeI (at 6678 Å) to be restricted to about to 2.3 stellar radii from the center of the system. In contrast, the Hα emission may originate from anywhere in the disc. The different loci of these emissions have consequences for any potential correlation between them. Investigating such a phenomenon in this star does not require large telescopes and associated instrumentation, but does need an extended program of monitoring over many years. This is precisely the kind of program that is amenable to an amateur spectroscopic study. Thus, using data sets from long-term observation campaigns by an international consortium of amateurs over 15 years, the study presented here used equivalent width analysis to show that the emission activities of Hα and HeI 6678 are, indeed, strongly correlated.

1. Introduction

γ Cas is the prototype of the group of classical Be stars and shows emission activities in Hα and Helium at 6678 Å, originating in a circumstellar disc. A large number of fundamental and comprehensive studies on the nature of the Be star γ Cas have been carried out over the past few decades (Stee *et al.* 1998; Smith *et al.* 2012; Nemravová *et al.* 2012; Miroshnichenko *et al.* 2002; Borre *et al.* 2020), to name just a few. Therefore, at this point we deliberately refrain from describing these characteristic traits again.

γ Cas has also attracted much amateur attention (Pollmann 1997, 2009). Some prominent objects among the Be stars, such as ζ Tau, 28 Tau, δ Sco, π Aqr (to name just a few), have some certain phenomena in common, such as the quasi-periodic behavior of the equivalent width (EW) of the Hα emission and the HeI 6678 emission or absorption lines. These phenomena have been monitored in the form of long-term observations by entire groups of observers in amateur astronomy; this is especially true for the Be binary star γ Cas.

While the Hα emission of γ Cas originates in the entire volume of the Be star disk around the central star, the HeI 6678 emitting region is located much closer to the surface of the central star. In addition, the HeI 6678 emission is one of the few non-hydrogen lines in the optical spectrum that, at 1–3% of the amplitude of the neighboring continuum, is still strong enough to be analyzed well by using the neighboring continuum. Thanks to the interferometric studies by Stee *et al.* (1995, 1998) we know today (2021) the Hα-emitting regions are limited to within 18 stellar radii and those of the HeI 6678 to 2.3 stellar radii (Figure 1).

Until the 1990s, γ Cas was mainly examined spectroscopically near the Hα line. Around 1994/1995, studies were carried out by Hanuschik (1995) with the aim of finding out more about the kinematics of the circumstellar disks around Be stars. The HeI emission at 6678 Å (Figure 3) became an important diagnostic feature to investigate the regions of activity close to the star (Stee *et al.* 1998; Li *et al.* 2014).

Be stars have rotationally flattened disks (not shells, which are spherical), so matter is expelled by the star to the disk and viscosity causes the local angular momentum exchanges among particles. As a result of these exchanges some particles will gain angular momentum enough to allow them to go into orbit. Those that have lost angular momentum will fall back to the star. Phenomena resulting from these processes are observable by amateur spectrographs. Thus, the author instigated the present study, which has resulted in a very high observation density, and has led to results that are unique in amateur astronomy.

The nonphotospheric component of the HeI line can arise only from matter above the star's surface but still close enough that its HeI atoms can be influenced by the star's UV radiation field—a tighter constraint than is true for the larger region in which Hα can be influenced.

This is an essential difference from the regions of origin of the Hα emission, which is formed over the entire volume of the circumstellar star disk and generally fluctuates much more slowly over time. In the observation season 2019–2021, considerable fluctuations in the Hα EW and HeI 6678 EW were found. A growth of 1.3 Å / year of the Hα EW for the period presented here is a result of the exophotospheric material input into the Be star disk (with the HeI 6678 emission as indicator) and can be calculated from the steady increase of the Hα EW in Figure 5. In addition, both increases' progresses show a synchronous time course, with the special feature that the Hα EW minimum (November 2001) can also be found easily in the course of the HeI 6678 EW.

2. Observations

The spectra for the investigation presented here (with kind permission of the consortium members, see section 7) were obtained with 0.2-m to 0.5-m telescopes and prism spectrographs, Czerney-Turner grating spectrographs, Littrow grating spectrographs, and Echelle spectrographs, with spectral resolutions R = λ / Δλ of 5000–25000. The spectra have been reduced with standard professional procedures (flat-field

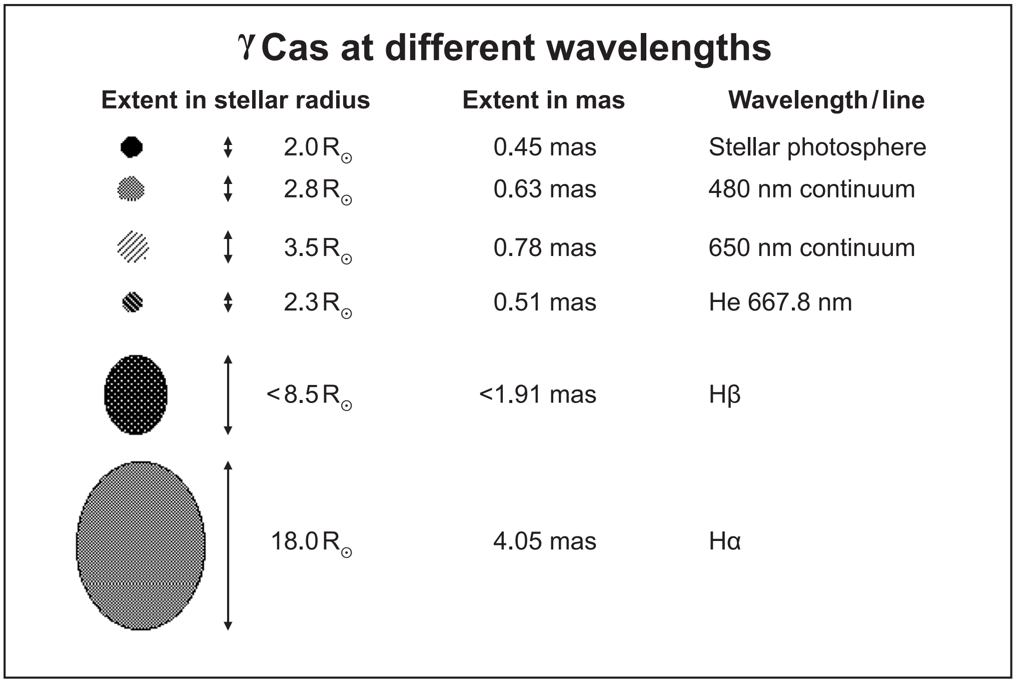

Figure 1. Schematic view of γ Cas as a function of wavelength (used with kind permission of Philippe Stee). These wavelength-dependent shapes are projections onto the sky plane, which were formed under the well founded assumption (justified) functions of envelope symmetry, flattening, and angle of inclination. In this figure the diameters are given as stellar radii. The fact that the modelled size in the HeI-line flux (in in this figure) is not larger than the visible continuum light shows that the observer cannot see HeI emission far from the star (e.g. to inner disk).

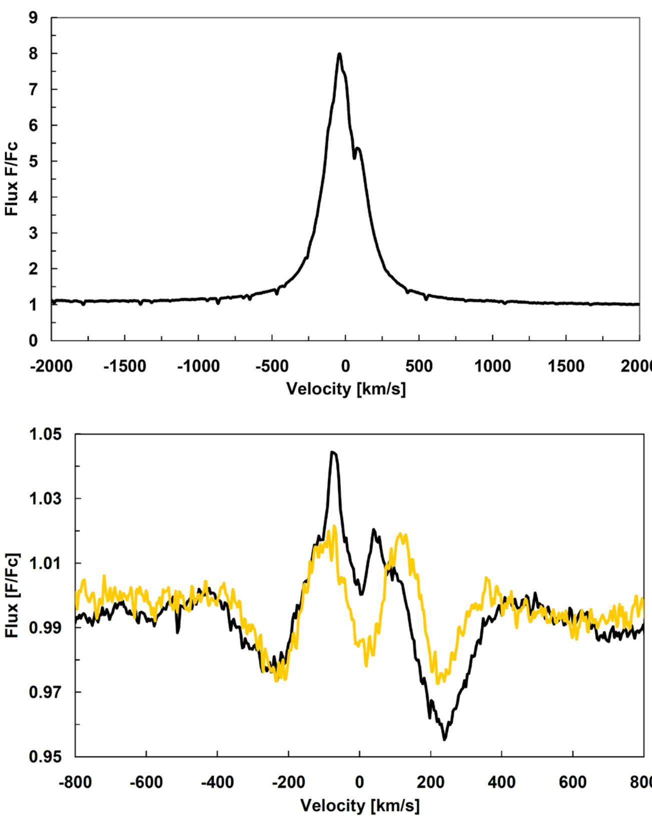

Figure 2. (top) Hα spectrum, S/N ~ 200 (2020/10/29, A. Stiewing, Arizona); (bottom) HeI6678 spectrum, S/N ~ 400 (dark line: 2020/12/10, E. Bryssinck, Belgium; light line: 2020/02/08, A. Stiewing, Arizona).

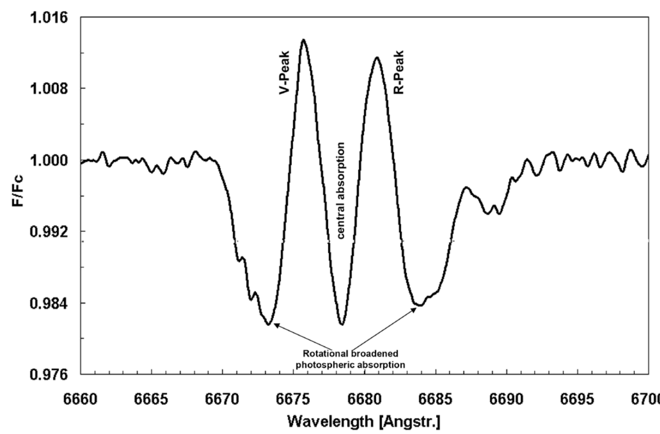

Figure 3. Characteristic features of the HeI double peak emission at 6678 Å in γ Cas.

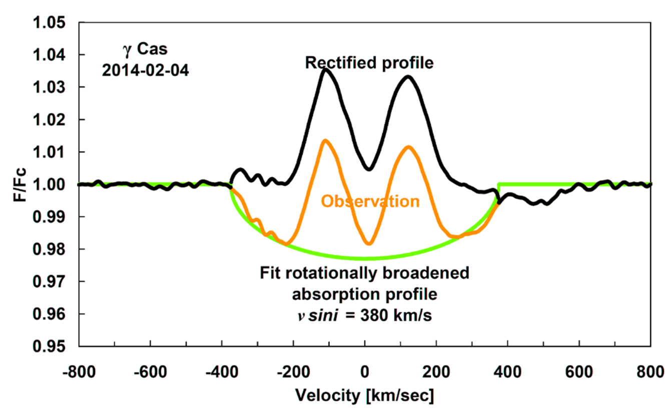

Figure 4. Subtraction of a fitted (lowest line), theoretical photospheric absorption profile with ν * sin i = 380 km/s (Harmanec 2002) of the HeI double peak emission at 6678 Å in γ Cas (2014/02/04).

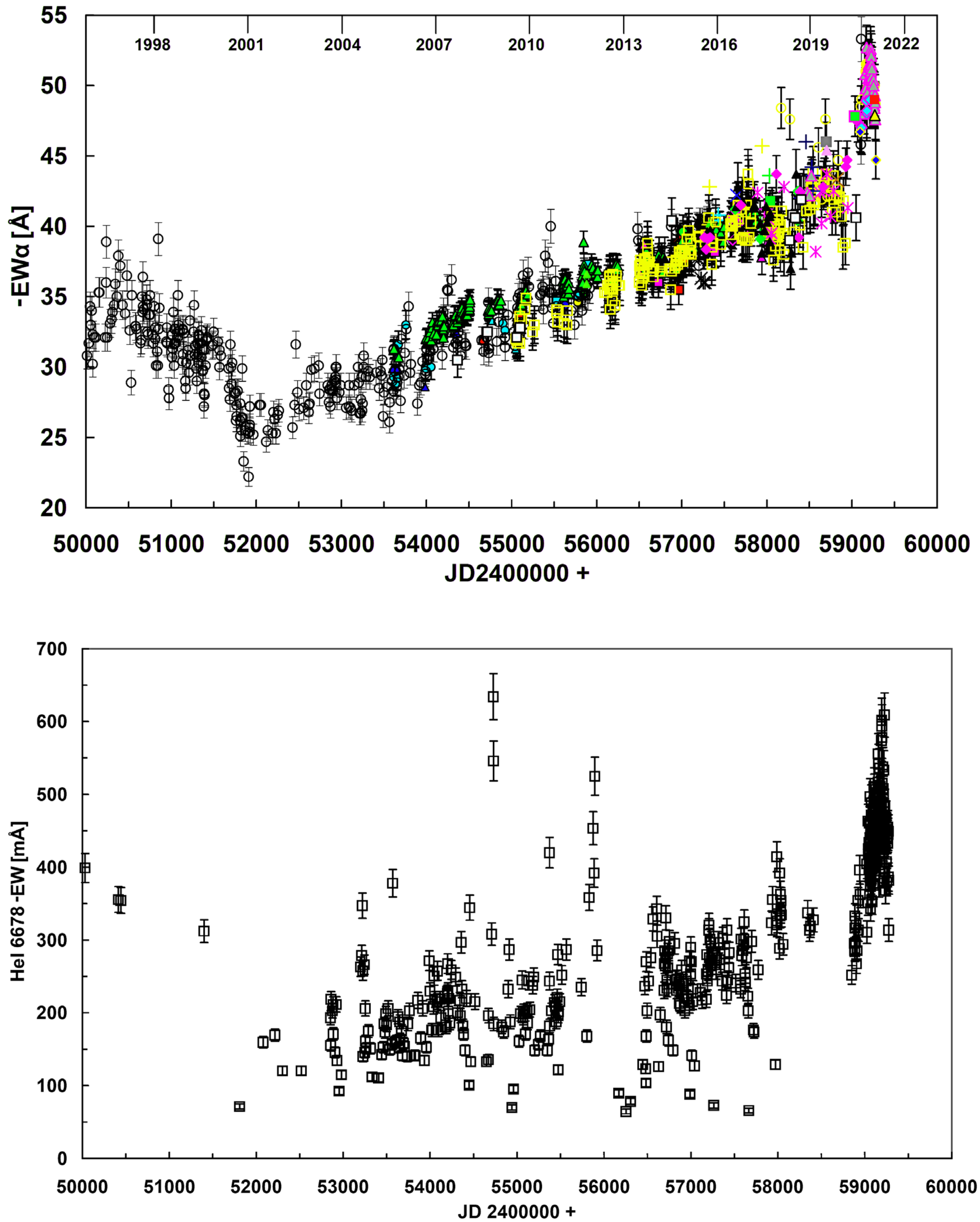

Figure 5. EW long-term monitoring of Hα (top) and HeI 6678 (bottom) by 49 observers (different color symbols) from October 1995 to November 2020.

correction, instrumental response, normalization, wavelength calibration) using the software preferred by individual observers. Typical signal/noise (S/N) of the Hα spectra was at least 100 and for HeI 6678 spectra at least 300 (mostly better). An example spectrum of Hα and HeI 6678 is shown in Figure 2.

A total of 980 spectra have been used from October 1995 to mid-January 2021, with rectification exclusively by the author in order to exclude variation of methodology across observers.

3. Equivalent width of HeI 6678

It was recognized that a time dependent mass loss from the photosphere of the primary star, density variations, and collision excitations of the HeI atoms can produce typical double peak emissions in the HeI 6678 Å line, which are due to the excitations in a range of up to about 2.3 star radii (Stee *et al.* 1998). Based on predictions of precession of disk structures, Okazaki (1991, 2000), and Berio *et al.* (1999) used interferometric modelling techniques with Hα activity to show that there is a single, radial density variation extending

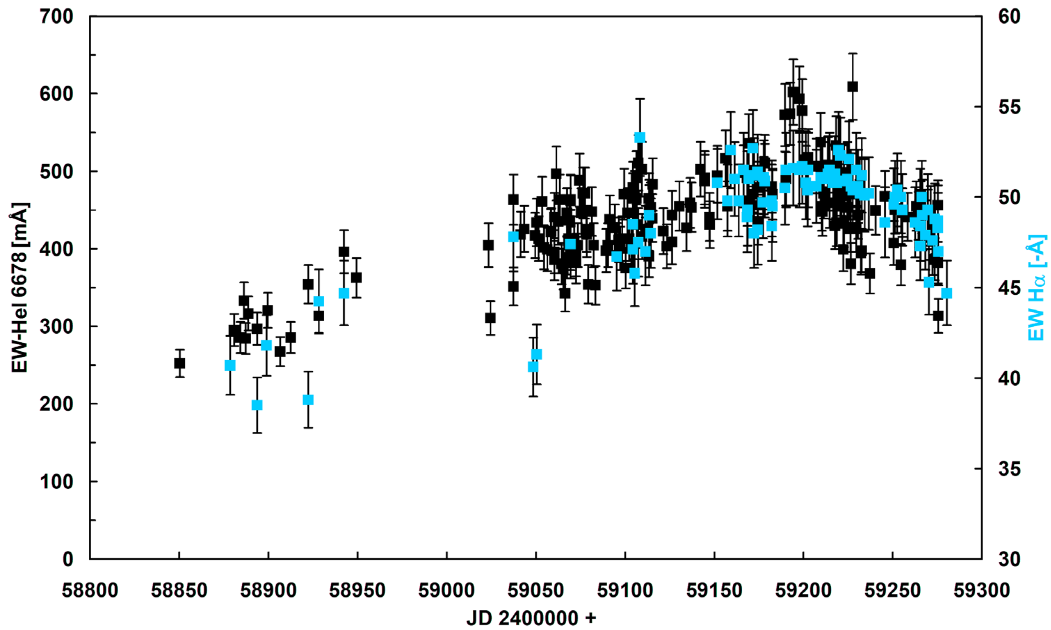

Figure 6. Particularly strong emission activity of Hα EW and HeI 6678 EW of the period after start of the intensified monitoring JD 2458850 to JD 2459321; error bars correspond to those in the text.

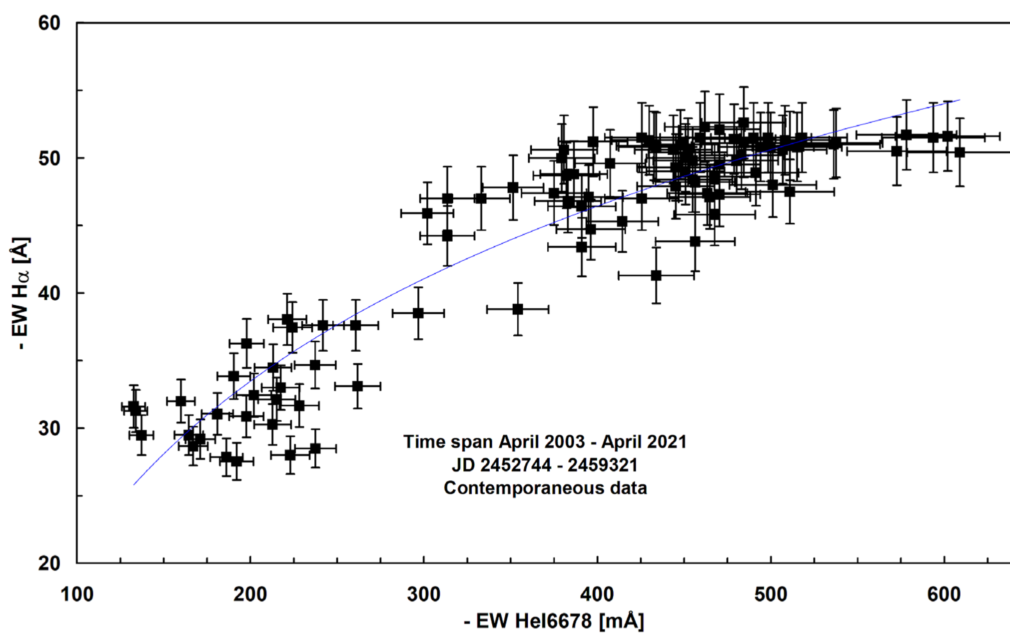

Figure 7. Clarification of the correlation of Hα EW and HeI 6678 EW; contemporaneous data of the monitoring in Figure 5. Error bars correspond to those in the text. The best-fit line is the polynomial order 2 performed with EXCEL; correlation coefficient R = 0.94! All data from Figure 7 is shown in Table 1, and will be web-archived and made available through the AAVSO ftp site at *ftp://ftp.aavso.org/public/datasets/491-Pollmann-ewdata.txt* .

outwards from the center of the disc (a so-called "one-armed" perturbation).

Access to the shell structures in Be stars is obtained by investigating the kinematic line broadening. Stellar absorption lines in Be stars are rotationally broadened. The dimension of the half-widths (FWHM) is on the average the projected rotation velocity (v* sin i) of the Be star, where v* is the equatorial rotation velocity and (i) is the inclination of the axis in the direction of the observer (Dachs *et al.* 1986).

The total width of an emission line depends (among others) on the definition of the line wing profile and is affected by the underlying photospheric profile. In the case of a well-defined emission line, the equivalent width has to be corrected by the determination of this photospheric absorption.

The HeI 6678 profile shown in Figure 4 is a superposition of the emission line profile (produced in the star's gas disk) and the effect of the rotationally broadened photospheric absorption profile. A way to determine the effect of the rotational broadened absorption has been comprehensive described by Gray (1992) in Chapter 17. Following Dachs *et al.* (1986) and Burbidge and Burbidge (1953), we subtracted a fitted, theoretical noise-free absorption profile with v* sin i = 380 km/s (Harmanec 2002), in order to isolate the contribution of the pure emission from the constant rotationally broadened absorption. Therefore, the corrected EW is defined as the area, normalized to the continuum intensity, between the emission line profile and that of the photospheric absorption line.

According to Chalabaev and Maillard (1983), the uncertainty of the EW determination is essentially determined by the S/N of the neighboring continuum and the flux in the spectral line. In addition, the definition of the line wings and the underlying photosphere absorption line profile (Figure 3) are important. With the equation given in Chalabaev and Maillard (1983, page 263) this results in an average error of the order of (+/–) 4–5% in practical measurements of a single observation on a given night. In this respect, this order of magnitude of the error applies to the results presented here, which were obtained with very different spectrographs (prism spectrographs, Czerney-Turner grating spectrographs, Littrow- and Echelle-spectrographs).

4. EW-results 1995–2020

The long-term monitoring presented in Figure 5 describes the period from October 1995 (JD 2450000) to January 2021 (JD 2459230). The determination of the equivalent width was carried out according the equation:

$$EW_\lambda = \int_{\lambda_1}^{\lambda_2} \frac{F_c - F_\lambda}{F_c} \, d\lambda \qquad (1)$$

with F_λ the flux at wavelength λ and F_c the continuum flux.

The EW for Hα and HeI 6678 was determined in each case in the spectral sections between 6525–6610 Å and 6670–6685 Å, with an estimated uncertainty of a single measurement in one night as mentioned above. In Figure 5 it is easy to see the steady increase in both emission contributions, although the increase in HeI 6678 shows superposed by some strong short-term fluctuations. Such fluctuations, as observed at JD 2454847–2454928 and JD 2455874–2455896, are generally associated in the HeI line spectra of active Be stars with a photospheric outburst of the Be star (e.g. Peters 1986; Smith 1989, 1995; Smith *et al.* 1997).

The rapid Hα emission increase from ~JD 2452200 onwards and the spikes in JD 2454456, JD 2455373, and JD 2455384–2455428 coincide with V brightness measurements of the APT telescope (Smith *et al.* 2012).

The apparently obvious correlation of the time courses of Hα and HeI6678 in Figures 5 and 6 is emphasized more clearly in Figure 7. This plot shows only contemporaneous EW data of Hα and HeI 6678 from spectra of the total period April 2003–April 2021 (JD 2452744–2459321).

5. Interpretation and discussion

The obvious correlation in Figures 5, 6, and 7 between the EW's of Hα and HeI 6678, generated by mass ejection from the surface of the primary star into the circumstellar disk is, however, subject to rapid fluctuations in HeI 6678, which are not directly recognizable in Hα. This is due to the fact that such a mass input is relatively small compared to the already existing massive disk and therefore may not be immediately visible. In addition, in close, interactive binaries the companion can have a strong influence on the behavior of the primary, whereas in wide systems it may be negligible. This has to be taken into account in interpretation of the behavior of the circumstellar disk. So, in that sense a question might be whether the appearance of a minimum in Hα around JD 2452000 (Figure 5, top) is related to the passage of the binary companion.

Correlation model calculations of Hα EW and UBV photometry for Be stars with increasing disk sizes of Sigut and Patel (2013) are able to explain positive and negative correlations between long-term variations in Hα EW and V brightness as observed for well known Be stars (Harmanec 1983). The very first investigation of this kind was conducted by Doazan *et al.* (1983). Their investigation shows that during and after the spectacular episode of the Be phase from 1932 to 1942, the Balmer lines and the brightness followed the same trend of variations. Pollmann *et al.* (2014) show that an increase of the Hα EW of γ Cas of ca. 10 Å observed during 15 years was accompanied by a slight magnitude increase of 0.06 mag.

6. Conclusion

The high quality of the HeI 6678 versus Hα correlation in Figures 5, 6, and 7 of better than 90% confirms among others the accuracy and practicability of the subtraction method described in section 3 of the evaluation of the HeI 6678 emission. All data from Figure 7 is shown in Table 1, and will be web-archived and made available through the AAVSO ftp site at:

ftp://ftp.aavso.org/public/datasets/491-Pollmann-ewdata.txt .

The intuitive explanation of the presented correlation is that the HeI 6678 line-forming region is contained in a much smaller volume that the region in which Hα is formed, but coincide in the inner region (Figure 1). Percentage-wise this would imply that an increase of line-emitting material within the described 2.3 stellar radii should have a much larger effect on the HeI 6678 emission as compared to the Hα emission. This is consistent with the difference in amplitude. Also, a time delay between the changes in HeI 6678 and Hα is conceivable, depending on whether the particles first emitting HeI 6678 will move outward to a larger volume. The international efforts presented here will now also be continued for other bright Be stars. In particular, projects of this kind have been initiated by Be star researchers from the University of São Paulo in collaboration with the amateur astronomical community.

7. Observer consortium

(contact address: ernst-pollmann@t-online.de)

R. Bücke, P. Fossanelli, Th. Garrel, J. Guaro, Th. Blank, P. Debreuil, St. Charbonnel, H. Kalbermatten, Ch. Netzel, E. Pollmann, Ch. Kreider, A. Wilson, E. Bertrand, O. Thizy, F. Masviel, N. Montigiani/Mannucci, M. Schwarz, B. Stober, P. Berardi, T. Lester, M. Pujol, J. Montier, J. N. Terry, L. Schanne, M. Büchner, B. Hanisch, G. Winkler, J. Guarro, P. Fosanelli, O. Garde, Th. Garrel, C. Sawicki, Th. Lemoult, Ch. Buil, P. Somogyi, J. J. Broussat, M. Keiser, S. Hess, E. Bryssinck, J. Martin, A. Stiewing, A. Maetz, Th. Daiber, Ch. Quandt, K. Alich, U. Zurmühl, D. Doctor, K. Gurney.

Table 1. Data for HeI 6678 EW and Hα EW.

HeI 6678 EW (mÅ)	Hα EW (Å)	JD	HeI 6678 EW (mÅ)	Hα EW (Å)	JD
223	28.0	52818.667	480	49.8	59182.199
238	28.5	53100.333	470	49.5	59182.633
192	27.5	53242.200	573	50.5	59189.598
137	29.5	53337.000	490	51.5	59190.193
167	28.7	53496.222	602	51.6	59194.198
171	29.2	53198.884	594	51.5	59197.604
165	29.5	53198.884	578	51.7	59199.221
181	31.1	53307.748	515	50.8	59201.285
186	27.9	53300.435	518	51.5	59202.630
198	30.9	53272.713	507	50.6	59207.192
213	30.3	53269.945	538	51.1	59209.655
262	33.1	53281.031	448	51.0	59210.590
217	33.0	54206.000	508	51.3	59213.633
202	32.4	53585.659	459	51.5	59214.584
215	32.1	53690.897	500	50.8	59216.588
160	32.0	53690.897	430	51.3	59217.617
134	31.3	53655.817	434	50.8	59218.598
228	31.7	53679.203	484	52.6	59219.603
133	31.6	53660.495	462	52.3	59220.594
213	34.5	53675.462	433	50.9	59222.608
198	36.3	53662.633	470	52.1	59225.584
237	34.7	53669.448	381	50.6	59226.592
190	33.9	53667.009	609	50.4	59227.609
242	37.6	53645.730	426	51.5	59229.624
261	37.6	53664.056	444	50.6	59230.599
224	37.5	53661.561	483	50.2	59231.609
221	38.0	56919.750	398	51.2	59232.599
297	38.5	58893.692	468	48.6	59245.597
354	38.8	58922.301	407	49.6	59250.621
314	44.2	58928.291	451	50.0	59251.274
396	44.7	58942.358	452	50.4	59252.602
351	47.8	59037.438	379	50.0	59254.640
434	41.3	59050.407	447	49.3	59255.294
463	47.4	59069.358	470	47.3	59265.375
465	47.1	59104.364	455	48.4	59265.645
468	45.8	59105.351	445	47.9	59268.307
511	47.5	59107.408	445	49.3	59269.610
426	47.0	59111.374	414	45.3	59270.315
451	49.0	59113.429	386	48.8	59273.597
494	50.8	59151.625	456	43.8	59275.336
455	49.8	59157.442	382	48.7	59275.340
498	51.5	59166.426	314	47.0	59275.594
491	48.9	59168.373	395	47.1	59292.609
536	51.0	59169.258	383	46.8	59293.289
501	48.0	59172.221	391	43.4	59298.286
456	48.2	59174.218	375	47.4	59299.361
479	51.4	59174.294	391	46.4	59303.292
484	51.1	59177.678	333	47.0	59303.298
511	50.9	59178.259	302	45.9	59321.314

Note: All data in Table 1 will be web-archived and made available through the AAVSO ftp site at: ftp://ftp.aavso.org/public/datasets/491-Pollmann-ewdata.txt .

8. Acknowledgements

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References

Berio, P., *et al.* 1999, *Astron. Astrophys.*, **345**, 203.
Borre, C. C., *et al.* 2020, *Astron. Astrophys.*, **635A**, 140.
Burbidge, G. R., and Burbidge, E. M. 1953, *Astrophys. J.*, **117**, 407.
Chalaaev, A, and Maillard J. P. 1983, *Astron. Astrophys.*, **127**, 297.
Dachs, J., *et al.* 1986, *Astron. Astrophys., Suppl. Ser.*, **63**, 87.
Doazan, V., Franco, M., Rusconi, L., Sedmark, G., and Stalio, R. 1983, *Astron. Astrophys.*, **128**, 171.
Gray D. F. 1992, *The Observation and Analysis of Stellar Photospheres*, Cambridge Univ. Press, Cambridge.
Hanuschik, R. W. 1995, private communication.
Harmanec, P. 1983, *Hvar Obs. Bull.*, **7**, 55.
Harmanec, P. 2002, in *Exotic Stars as Challenges to Evolution*, ASP Conference Proceedings, eds. C. A. Tout, W. Van Hamme, ASP Confer. Series, 279, Astronomical Society of the Pacific, San Francisco, 221.
Li, H., Yan, J., Zhou, J., and Liu, Q. 2014, *Astron. J.*,**148**, 113.
Miroshnichenko, A. S., Bjorkman, K. S., and Krugov, V. D. 2002, *Publ. Astron. Soc. Pacific*, **114**, 1226.
Nemravová, J., *et al.* 2012, *Astron. Astrophys.*, **537A**, 59.
Okazaki, A. T. 1991, Publ. Astron. Soc. Japan, 43, 75.
Okazaki, A.T. 2000, in *The Be Phenomenon in Early-Type Stars*, eds. M. A. Smith, H. F. Henrichs, ASP Conf. Ser. 214, Astronomical Society of the Pacific, San Francisco, 409.
Peters, G. J. 1986, *Astrophys. J., Lett.*, **301**, L61.
Pollmann, E. 1997, *Be Star Newsl.*, **32**, 11.
Pollmann, E. 2009, *Be Star Newsl.*, **39**, 32.
Pollmann, E., Vollmann, W., and Henry, G. W. 2014, *Inf. Bull. Var. Stars*, No. 6109, 1.
Sigut, T. A. A., and Patel, P. 2013, *Astrophys. J.*, **765**, 41.
Smith, M. A. 1989, *Astrophys. J., Suppl. Ser.*, **71**, 357.
Smith, M. A. 1995, *Astrophys. J.*, **442**, 812.
Smith, M.A., Murakami, T., Ezuka, H., Anandarao, B. G., Chakraborty, A., Corcoran, M. F., and Hirata, R. 1997, *Astrophys. J.*, **481**, 467. [ADS says ApJ 481, 479]
Smith, M. A., *et al.*, 2012, *Astron. Astrophys.*, **540A**, 53.
Stee, P., de Araujo, F. X., Vakili, F., Mourard, D., Arnold, L., Bonneau, D., Morand, F., and Tallon-Bosc, I. 1995, *Astron. Astrophys.*, **300**, 219.
Stee, P., Vakili, F., Bonneau, D., and Mourard, D. 1998, *Astron. Astrophys.*, **332**, 268.