Observations of Hα Line Profiles in Be Stars Using 45 cm Cassegrain Telescope at Arthur C Clarke Institute

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Accepted: 29 December 2008

Abstract. Hα line profiles of 13 Be starts (m_v ≤6.9) were observed using 45 cm Cassegrain telescope at the Arthur C Clarke Institute, Sri Lanka during the period of August 2005 to March 2006. High resolution spectra of these Be stars were obtained using 1200 lines/mm reflective grating in first order with resolution R=λ/Δλ=76800 and linear spectral dispersion 0.31 Å per pixel at 6563 Å in order to find out line parameters such as equivalent width, full width at half-maxima, V/R ratios etc. A study of the correlations between different pairs of parameters was obtained and compared with previous analysis to see the behavior of circumstellar disk. We found a good correlation (0.8) between FWHM and *v sin i* and strong correlation (0.96) between the Ip/Ic and the equivalent width. The drastic changes of the V/R ratio in profiles HR5941 and HR6712 imply the circumstellar disk is more likely an elliptical shape and undergoes slow apsidal motion. The inclination angles (*i*) were estimated for each star using the theoretical *vsin i* values and assuming star rotates in 0.8Vc and are matched with the structure of the line profiles.

Keywords: Be stars, circumstellar disk, line profiles, emission lines, inclination angle

1. Introduction

The Be stars are B – type, luminosity classes III – V stars, that shows emission lines in the Balmer lines (Hα, Hβ,..), singly-ionized metals (FeII, TiII,..), and sometimes neutral helium in their optical spectra. It is proven that Be stars are rapidly rotating stars surrounded by disks or ring like envelopes in the equatorial region, where the emission lines are formed. During the last decades, high resolution, high signal-to-noise ratio observations have been made in various emission lines to study the structure of the circumstellar disk.

The extensive study by Hanuschik [1] classified the Hα emission line profiles in to two parts namely symmetric and asymmetric. The symmetric class which can be explained by Keplerian disk rotation [2] includes the double peak profiles, wine-bottle type profiles [3] or shell profiles with central depression below the continuum. The asymmetric line profiles are timely varying complex structures which are arisen from a rotationally enhance mass ejection of constant rate [3] and elliptical trajectories [4].

Be stars can be classified into three types according to the inclination angle *i:*

a) Pole-on stars (low inclination angle i ≈ 0°): Stars that are characterized by single-peaked narrow emission lines superimposed on the photospheric absorption lines.

b) Be star (Ordinary): Stars showing double-peaked emission-line profiles.

c) Be-shell stars (high inclination angle *i* ≈ 90°): Stars with sharp and deep absorption components in the centers of double-peaked emission lines are called Be-shell stars. These are equator-on Be stars.

Investigation of Hα line reveals important information about stellar and circumstellar disk parameters. We have acquired high resolution Hα profiles for a sample of 13 Be stars in both south and north hemispheres. One of the objectives of this study is to see the correlation between different pairs of parameters which are taken from the line profiles. In addition to this, individual comparisons were done with the previous observations. Anther objective is to compute an approximation for the inclination angle (i) for each star and to see whether the shape of the profile is agreed with it.

2. Observations and Data Reduction

2.1 Observations

Hα line profiles of 13 Be starts (m_v≤6.9) were observed using 45 cm Cassegrain telescope with f/12 at the Arthur C Clarke Institute, Sri Lanka (6° 47' N) during the period of August 2005 to March 2006. The dispersing element of 1200 lines/mm reflective grating was used in the first order with spectral resolution R=λ/Δλ=76800 to obtained high resolution spectra.

The detector was a 765 pixels along the dispersion axis cooled to -6°C. On the CCD image, spectral dispersion of 0.31 Å per pixel at 6563 Å and a spectral coverage of 225 Å were obtained. The exposure time was 10 min in most of the program stars except 15 min for HD142983, HD209409. Fe – Ne emission lamp was used for the wavelength calibration of CCD images. The stars HD149757 and HD138749, close to the spectral type B, were observed to remove the telluric lines from the programmed spectra. Sky images were taken with the same exposure time that of the star images, were used to remove the sky and dark counts.

2.2 Data Reduction and Analysis

The preliminary data reduction of the CCD frames such as dark subtraction was done using the CCDOPS software. The main steps of the data reduction scheme, wavelength calibration, correction for the atmospheric H_2O vapor lines, normalization to continuum and conversion to the heliocentric velocity scale were done by using IRAF (Image Reduction and Analysis Facility). The wavelength calibration was performed by identification of Fe-Ne emission lines in the Hα region in the calibration spectra and fitted with first order spline3 function. Two standard stars HD149757 and HD138749 which are spectral types of O9 and B6 respectively, corrected in the Hα absorption line, were used to divide the program stars to remove telluric lines in the vicinity of Hα. In figure 1, all Hα profiles are plotted on a heliocentric velocity scale. Physical parameters of the emission line profiles, such as equivalent widths W, V/R ratios, FWHM's, peak separations ΔV and I_p/I_c were obtained and tabulated in table 1.

Table 1. Hα profile parameters of observed Be stars

Star HR	Spec. type	v sin*i* (km/s)	Eq. Width W (A°)	FWHM (A°)	V/R	ΔV (km/s)	I_p/I_c
1423	B1.5 Ve	230	-7.514	11.6	0.827	-	1.604
1789[d]	B1 V	315	-9.488	11.76	0.928	262.54	1.814
2284	B1 Vp	200	-19.154	8.919	1.123	125.70	2.761
3858[d]	B6 V	260	-20.927	9.47	1.026	160.42	2.964
4123[d]	B9 Vn	330	-3.088	11.53	1.101	207.78	1.426
5941[d]	B3 III	395	-16.641	9.292	2.12	298.96	2.94
5953	B0 IV	180	-14.129	5.77	-	-	3.378
6118	B2 IV	140	-56.502	4.35	-	-	11.52
6712	B2 Vn	220	-10.908	7.736	1.089	137.13	2.27
6779[a]	B9.5 V	160	6.797	-	-	-	-
HD179343	B9 V	350	-3.837	10.7	0.858	306.41	1.374
8260[d]	B3 II	295	-1.842	-	1.027	466.76	1.229
8402[d]	B6 IV	320	-17.7	9.642	1.117	222.47	2.762

d – double peak a – absorption

- sign indicates the equivalent width of emission lines

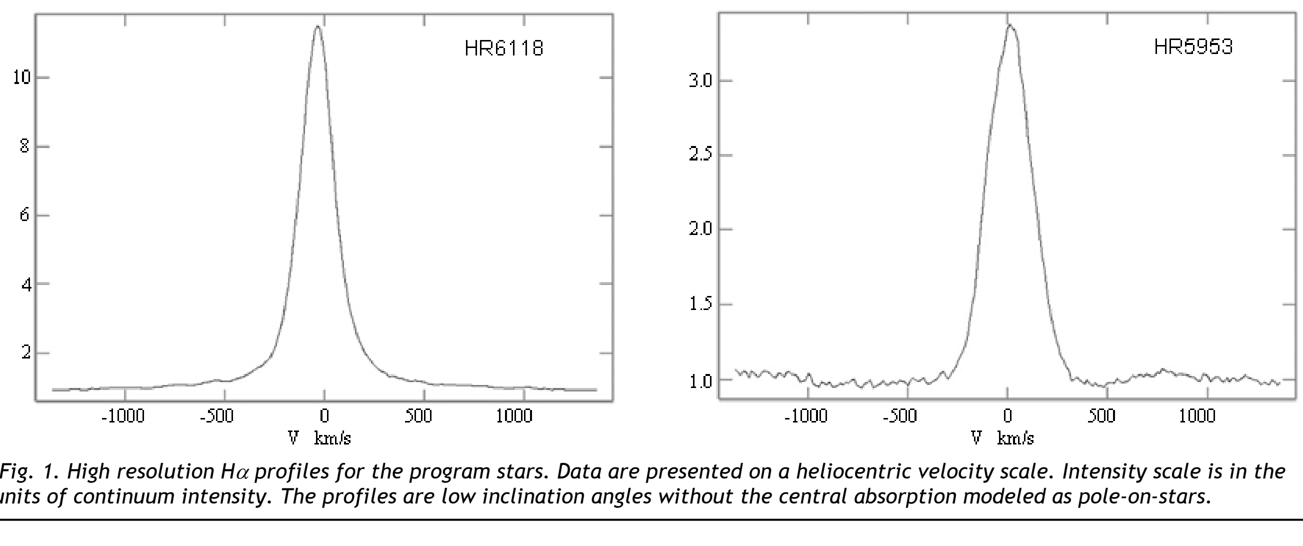

Fig. 1. High resolution Hα profiles for the program stars. Data are presented on a heliocentric velocity scale. Intensity scale is in the units of continuum intensity. The profiles are low inclination angles without the central absorption modeled as pole-on-stars.

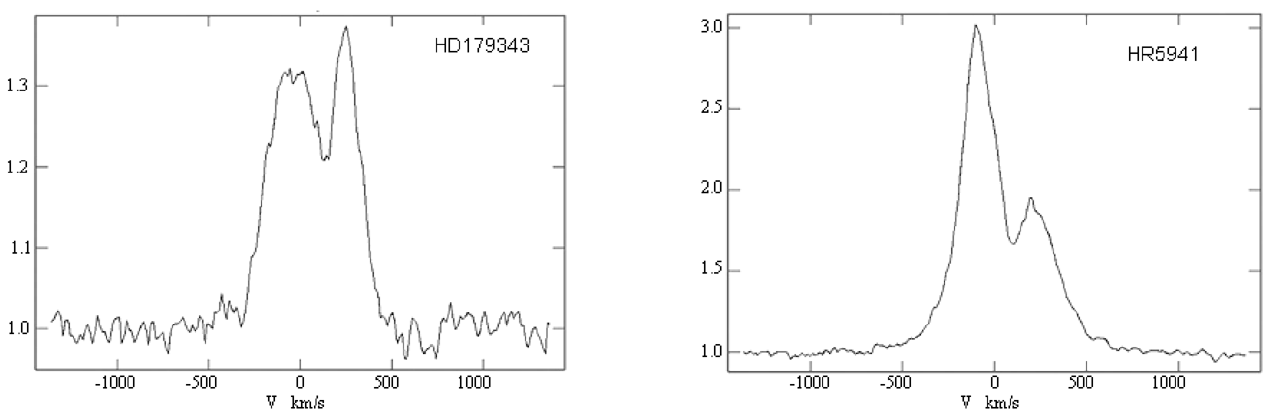

Fig. 2. High inclination angle Hα profiles with high velocity line wings. The radiation of the central star is absorbed by the disk causing the central absorption.

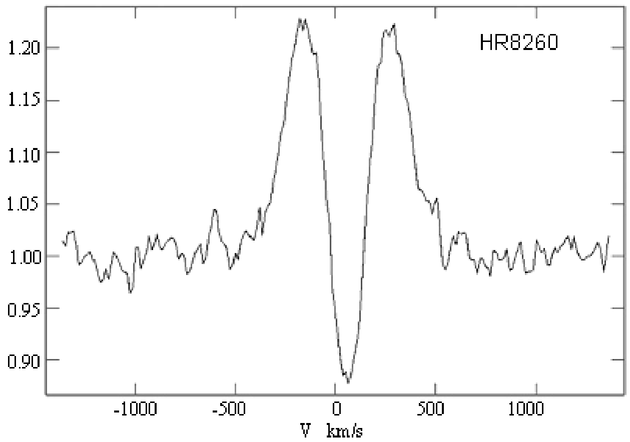

Fig. 3. Shell type Ha profile with absorption trout below the continuum due to stellar obsercusion and shell absorption.

3. Calculations and Results

3.1 Used assumptions and equations

The following assumptions and equations are used to calculate the disk parameters. The computed emission line parameters are listed in Table 2 and table 3.

3.1.1 Rotational velocity law

The rotational velocity law in the disk like envelope is approximated by a power law [2].

$$V_{rot} = V_*(R_d / R_*)^{-j} \tag{1}$$

Where V_* - equatorial rotational velocity of the star, R_d – circumstellar disk radius, R_* - equatorial stellar radius and j - rotational parameter. j = ½ for Keplerian rotation, j = 1 for constant orbital angular momentum and j = -1 for constant angular velocity.

3.1.2 Radius of circumstellar disk (R_d)

$$\frac{R_d}{R_*} = \left(\frac{2V_{rot}\sin i}{\Delta V}\right)^{1/j} \tag{2}$$

Where ΔV is the peak separation of the emission line profile and *i* is the inclination angle of the orbital plane to the line of sight. The ΔV values for the 9 stars were directly calculated since the peak separations were clearly seen in the profile (see Fig. 2). The profiles HR1423, HR5953 and HR6118 are single peaked and ΔV could not be obtained (see Fig. 1). The profiles HR2284 and HR6712 have double peak structure but due to the blunted variation in one of their bumps, peak position cannot be determined. These hidden peak positions are reconstructed from the profile derivative using the points-of-inflection method [5]. The vsin *i* values taken from Catalogue of Bright Stars [9] were used as V_{rot} sin *i* in the equation 2. Due to low S/N ratio in HR8260 and HD179343, the red and blue peaks were found by fitting Gaussian profiles separately for the two components.

3.1.3. Critical velocity of the star (V_c)

$$Vc = \sqrt{\frac{GM_*}{R_*}} \tag{3}$$

where M_* is the mass of the star. The MK spectral types and the relative solar masses (M_o) and radii (R_o) are taken from the tables of [7] and interpolated with a fifth order polynomial in order to calculate M_* and R_* for all program stars except for luminosity classes II and IV. The calculated M_* and R_* values relative to solar units and the critical velocities are listed in Table 3.

3.1.4 Estimation of the disk inclination to the line of sight (i)

Based on the assumption that equatorial rotational velocity is 80% of the critical velocity of the star [6], the inclination angles were estimated for the projected rotational velocity (vsin *i*) values taken from Bright Star Catalogue [9].

Assuming $V_{rot} = 0.8V_c$

$$\sin i = \frac{v\sin i}{0.8Vc} \tag{4}$$

Table 2. Outer radii of Hα emitting disk relative the mass and radius of the star

HR	v sin *i* (km/s)	ΔV (km/s)	Disk Radius R/R* (j = 1/2)	Disk Radius R/R* (j = 1)
1423[s]	230	-	-	-
1789	315	262.54	5.76	2.40
2284	200	125.70*	10.13	3.18
3858	260	160.42	10.51	3.24
4123	330	207.78	10.09	3.18
5941	395	298.96	6.98	2.64
5953[s]	180	-	-	-
6118[s]	140	-	-	-
6712	220	137.13*	10.30	3.21
6779	160	-	-	-
HD179343	350	306.41	5.22	2.28
8260	295	466.76	1.60	1.26
8402	320	222.47	8.28	2.88

s – single peak
* - calculated using points-of-inflection method (W. Hummel, et al, 1995)

Table 3. Mass and radius of the star relative to sun and the estimated inclination angles (i)

HR	M*/Mo	R*/Ro	V_c (km/s)	$0.8V_c$	i°
1423	13.28	6.33	630	504	27
1789[d]	13.28	6.33	630	504	39
2284	13.28	6.33	630	504	23
3858[d]	4.84	3.56	510	408	40
4123[d]	3.6	2.73	500	400	56
5941[d]	11	10.32	450	405**	77
5953	-	-	-	-	-
6118	11.3	8.5	500	400	20
6712	10.16	5.48	590	472	28
6779[a]	3.6	2.73	500	400	24
HD179343	3.6	2.73	500	400	61
8260[d]	-	-	-	-	-
8402[d]	-	-	-	-	-

d – double peak a – absorption
** calculated assuming $0.9V_c$

Discussion

The different types of Be stars such as wine bottle-type [3], symmetric double peak, asymmetric double peak and shell type are included in the observation. 10 of the program stars show double peak profiles while HR8260 is a shell type symmetric one. The star HR6779 is more likely to be an absorption star which may be due to the late B spectral type. Future observations should be carried out to explain the peculiar nature of this line profile.

HR5953 and HR6118 are Gaussian profiles with no bumps. The observation made by [1] and [2] showed HR 6118 has a triple peak profile and according to [8] this is a wine – bottle type profile. Present observations, with estimated inclination angle (20°), clearly shows a well define pole-on stars with low vsin *i* (140 km/s).

The profiles HR4123, HR5941 and HD179343 with higher inclinations 56°, 77° and 61° respectively, indicates well resolved double peaks profiles with a central depression. The orientation with higher inclination angles results the lower equivalent widths (here -3.088 for HR4123 and -3.837 for HD179343) as we observe the disk plane parallel to the line of sight. The correlation between the inclination angle and the equivalent width also indicates this fact in Fig. 2.

We compared our H alpha line profiles with the past research work done by several authors. The profile HR5941 is previously observed by [1], [2] and [8] and the corresponding V/R ratios are 0.47, 0.61 and 0.65 respectively. All these observation showed the V/R < 1 but the present study shows V/R > 1 (2.12), a drastic change in V/R ratio, i.e. the violet and red peak intensities are reversed. The profile HR6712 is also showed V/R < 1 for previous observations but present it is 1.089. This is a cyclic variation which is described by [4], as the elliptical ring model for circumstellar disk, in which peak asymmetries are supposed to result from variations of orbital velocity and of gas density due to Keplerian motion in an eccentric gas ring, where observed cyclic V/R variations are described to slow apsidal motion of the ring. We suggest that it is important to include these stars in the future observation schedules to investigate the periodic changes.

Observed HR2284 profile is a wine bottle-type profile [3] which caused by the non-coherent scattering broadening (NSB) [3] of the optical thickness of H-alpha line radiation. It is difficult to identify the blue and red peak positions of these profiles since the peaks are hidden. We used peak reconstruction line profile derivative method described by [5]. For the profile derivation we developed Visual Basic program which shows the hidden peaks on the line profile. This method was applied to the spectra HR 2284, HR 6712 to obtain the peak separations.

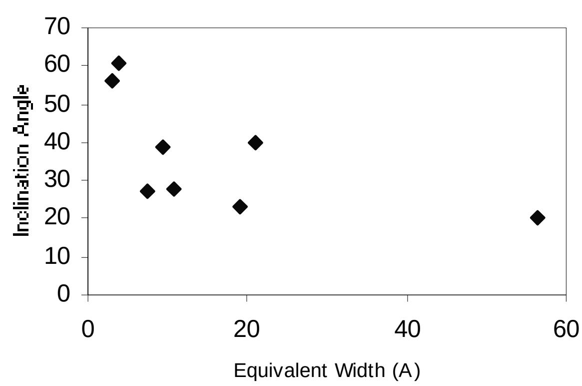

Fig. 4. Plot of the estimated inclination angles versus equivalent widths.

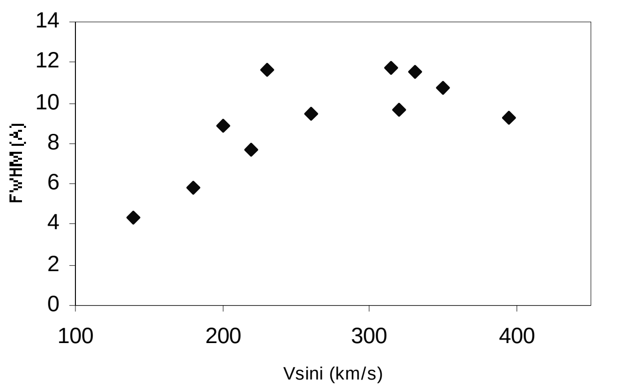

Fig. 5. Plot of full width at half maxima versus vsin i.

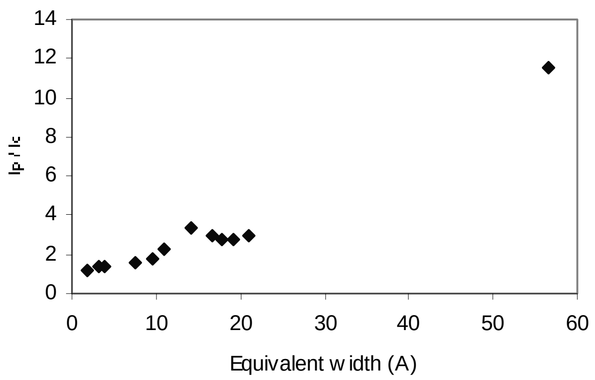

Fig. 6. Plot of Ip/Ic versus equivalent width.

We also found a good correlation (0.8) between FWHM and vsin *i* which is also observed [8]. This can be explained by the Keplerian motion of the gas in the ring and the kinematic broadening is the major factor to the profile width. Projected velocity vsin *i* and the Keplerian velocity of the disk increases with the stellar rotation velocity v. Thereby increase the width of the profile. The strong correlation (0.96) between the Ip/Ic and the equivalent width of the profile clearly aggress with the definition of the equivalent width.

Conclusions

Among the several parameters estimated which were used to explain the different shapes of Ha line profiles, the inclination angle (i) is a major factor to differentiate the line profiles. The timely varying V/R ratio is due to the precession of non circular plane of the disk whose density distribution is also non uniform. The broadening of the line profile is mainly due to the kinetic broadening and the gas disk rotates under Keplerian motion.

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