

Strong latitudinal shear in the shallow convection zone of a rapidly rotating A-star^{*}

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Abstract. We have derived the mean broadening profile of the star V 102 in the region of the open cluster IC 4665 from high resolution spectroscopy. At a projected equatorial rotation velocity of $v \sin i = (105 \pm 12) \text{ km s}^{-1}$ we find strong deviation from classical rotation. We discuss several scenarios, the most plausible being strong differential rotation in latitudinal direction. For this scenario we find a difference in angular velocity of $\Delta\Omega = 3.6 \pm 0.8 \text{ rad d}^{-1}$ ($\Delta\Omega/\Omega = 0.42 \pm 0.09$). From the H α line we derive a spectral type of A9 and support photometric measurements classifying IC 4665 V 102 as a non-member of IC 4665. At such early spectral type this is the strongest case of differential rotation observed so far. Together with three similar stars, IC 4665 V 102 seems to form a new class of objects that exhibit extreme latitudinal shear in a very shallow convective envelope.

Key words. stars: rotation – line: profiles – stars: individual: IC 4665 V 102/P35 – clusters: individual: IC 4665

1. Introduction

The substantial difference between photospheres of solar-type stars and A-type stars is the existence of a convective envelope. Late-type stars harbor convective envelopes where turbulent motions of photospheric plasma can occur. In convective envelopes, differential rotation can trigger a magnetic dynamo giving reason for the observed plethora of activity phenomena. The onset of convection may be traced by the onset of coronal X-ray emission around spectral type A7 (Schmitt 1997). Gray & Nagel (1989) searched for the onset of convection analyzing line bisectors of slowly rotating stars. In their targets a bisector reversal was found around spectral type F0. Stronger asymmetries were found in the stars at the hot side of the boundary indicating higher photospheric velocities.

While stellar rotation velocities have been measured for almost a century, differential rotation is more difficult to detect (e.g. Gray 1977, 1998, and references therein). Measurements of differential rotation have been reported in stars rotating faster than $v \sin i > 10 \text{ km s}^{-1}$ and covering all spectral types harboring convective envelopes (Reiners & Schmitt 2003a,b; Reiners & Royer 2004).

2. Data

Our data of V 102 have been taken on April 18th 2003 with the FLAMES multi-object facility at ESO/VLT. Using the UVES spectrograph at a resolution of 38 000 we gained a signal-to-noise ratio of 150 in a one hour exposure. The spectra were reduced using the UVES context embedded in the ESO-MIDAS package. The observed spectral range covers the region from 4800 Å to 6800 Å with a gap at 5800 Å. In a second observation during the same night we collected a spectrum with the FLAMES facility using the GIRAFFE spectrograph which covers the CaII H+K resonance lines. A small region of the UVES spectrum is plotted in Fig. 1 (black spectrum).

3. V102 and its membership to IC 4665

IC 4665 is a young (50–70 Myr; Prosser 1993; Giampapa et al. 1998) open cluster at a distance of roughly 350 pc. The first photometric measurements of V 102 were done by McCarthy & O’Sullivan (1969). Although V 102 fitted onto the main sequence in their color–magnitude diagram, they argued that V 102 is a “less probable” member of IC 4665 due to their proper motion measurements. More than twenty years later, Prosser (1993) carried out a photometric study of IC 4665 and derived more accurate proper motions. From that he derived an 86% membership probability for V 102. However,

^{*} Based on observations carried out at the European Southern Observatory, Paranal, 71.D-0127(A).

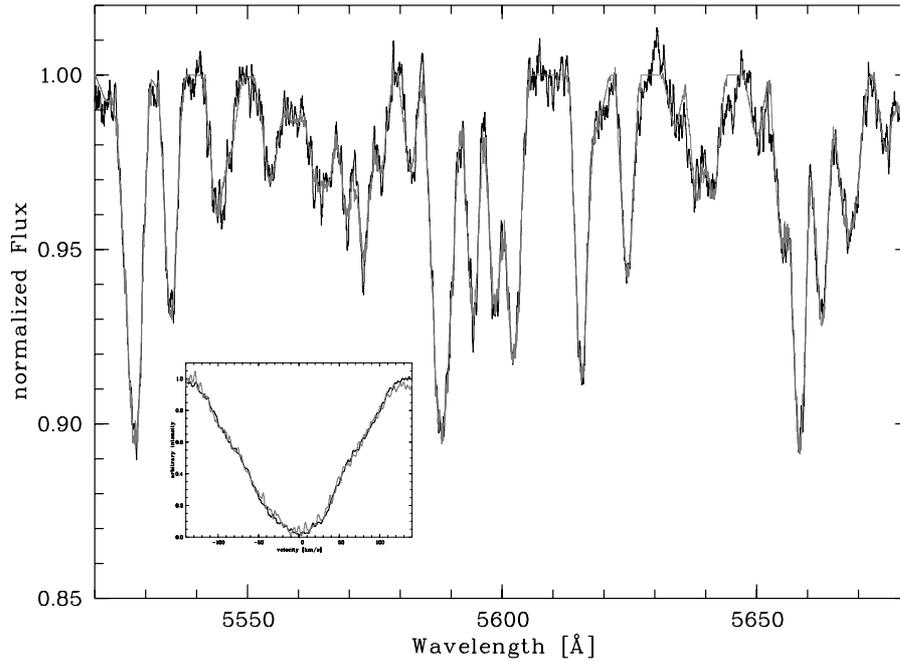


Fig. 1. Data (black) and fit (grey) in a small part of the used wavelength region. In the inset the two broadening functions derived from the spectral regions 4950 Å–5550 Å (grey) and 5440 Å–5745 Å (black) are shown. Both broadening functions perfectly match one another.

he also carried out CCD-photometry and found V 102 not to fit onto the cluster main sequence according to its brightness in V . The results from photometric measurements in V 102 are given in Table 1. The V -magnitudes derived by McCarthy & O’Sullivan (1969) and by Prosser (1993) are significantly different while B -magnitudes are identical and are also reproduced by the value measured by Kislyuk et al. (1999). Since magnitudes in the B -filter are identical in all three references we suspect that one of the magnitudes in V is incorrect, giving rise to the different values of $B - V$.

The spectral types according to the $B - V$ measurements are either A9 or F5. In this spectral range the $H\alpha$ -line is very sensitive to temperature and we can deduce the spectral type from our data. The $H\alpha$ -line of V 102 is plotted in Fig. 2 together with spectra of HD 115 810¹ ($B - V = 0.27$, $v \sin i = 100 \text{ km s}^{-1}$, light grey) and HD 120 987² ($B - V = 0.44$, $v \sin i = 8.5 \text{ km s}^{-1}$, dark grey) spun up to $v \sin i \approx 100 \text{ km s}^{-1}$. From the excellent fit to the $H\alpha$ -line of HD 115 810, we conclude that the color of V 102 must be similar to HD 115 810. We thus adopt the value of $B - V = 0.26$ given in Prosser (1993), i.e., from photometry V 102 is likely to be a background star and not a member of IC 4665 (Prosser 1993).

4. Broadening function

From our observations we derived the mean line broadening profile following the strategy outlined in Reiners & Schmitt (2002a). Normalization of the spectrum was done by eye, even at rapid rotation the continuum is still visible. Using absorption line wavelengths from the Vienna Atomic Line Database (Kupka et al. 1999) as a reference, we iteratively determine

Table 1. Photometric data of IC 4665 V 102.

| V | B | $B - V$ | $V - I$ | $B - R$ | Designation |
|-------|--------------------|---------|---------|---------|----------------------|
| 11.65 | 12.09 | 0.44 | | | V 102 ^a |
| 11.82 | 12.08 ¹ | 0.26 | 0.41 | | P 35 ^b |
| | 12.06 | | | 0.69 | 354 699 ^c |

¹ Calculated from V and $B - V$, not given in the catalog.

^a McCarthy & O’Sullivan (1969).

^b Prosser (1993).

^c Kislyuk et al. (1999).

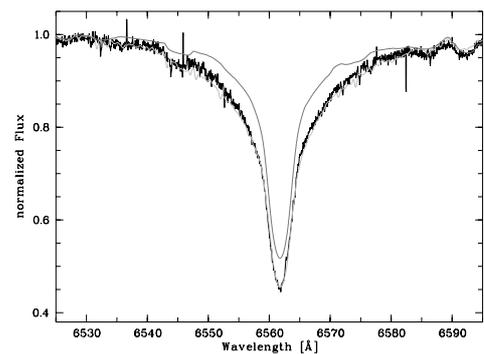


Fig. 2. $H\alpha$ -line of V 102 (black). Overplotted are spectra of HD 115 810 ($B - V = 0.27$; light grey) and HD 120 987 ($B - V = 0.44$ spun up to $v \sin i \approx 100 \text{ km s}^{-1}$; dark grey). The spectrum of HD 115 810 resembles the one of V 102 much better than the spectrum of HD 120 987 does.

the shape of the broadening function and equivalent widths of all incorporated lines. To check against systematic errors we performed the fit in two overlapping wavelength regions. The wavelength region at 4950 Å–5550 Å incorporates 185 lines, the second region at 5440 Å–5745 Å 137 lines.

¹ Taken with the FOCES spectrograph, DSAZ, Calar Alto.

² Taken with the FEROS spectrograph, ESO, La Silla.

Table 2. Results derived from the broadening function.

| $v \sin i$ | $\frac{q_2}{q_1}$ | $\alpha = \Delta\Omega/\Omega$ | $\Delta\Omega$ |
|----------------------------------|-------------------|--------------------------------|----------------------------------|
| $(105 \pm 12) \text{ km s}^{-1}$ | 1.39 ± 0.01 | 0.42 ± 0.09 | $3.6 \pm 0.8 \text{ rad d}^{-1}$ |

We calculate the variances of the broadening function by taking into account the uncertainties of the two nearest neighbors of each pixel. We overplot in Fig. 1 our final fit to the data in grey. The line shapes of all lines are well resembled within data quality. In the inset of Fig. 1 we compare the two broadening functions independently derived from the two overlapping wavelength regions mentioned above. Both broadening functions resemble each other indicating independence on the wavelength region; the broadening function with its errors is plotted in black in the left panel of Fig. 3. Although every pixel was a free parameter during the fit, the broadening profile is symmetric within the uncertainties.

Quantitative conclusions can be drawn from the Fourier transform of the broadening profile which is shown with its errors in the right panel of Fig. 3. In Fig. 3, we also plot the broadening profile of HD 46 273, a star of similar spectral type and $v \sin i$ (F2V, $v \sin i = 107 \text{ km s}^{-1}$). This profile was achieved applying the same procedure to data obtained with the FEROS spectrograph at ESO/La Silla (Reiners & Schmitt 2003b), it has a shape as expected from classical solid body rotation.

5. Interpretation

The broadening function of V 102 shows significant differences to classical rotation broadening. Within the error bars a difference is clearly visible between the profiles of V 102 and HD 46 273. At a projected equatorial rotation velocity of $v \sin i = 105 \text{ km s}^{-1}$, the broadening functions are clearly rotation dominated. Since the derived broadening functions are symmetric, it is unlikely that they are dominated by starspots and we argue that the profiles are due to the rotation law of the stellar surface. In the following, we will discuss the amount of differential rotation we derive for V 102 and the consequences for the surface shear. However, we will also discuss several other scenarios that could be reason for such a profile.

5.1. Differential rotation

Convenient quantities characterizing stellar rotational broadening are the first two zeros q_1 and q_2 of the broadening profile's Fourier transform (cf. Reiners & Schmitt 2002a). The value of $v \sin i$ can be derived from q_1 . Furthermore, in a rigid rotator, the ratio q_2/q_1 always is larger than 1.72. For V 102 we derive a ratio $q_2/q_1 = (1.39 \pm 0.01) < 1.72$. This small ratio is visible in the narrow first side-lobe of the Fourier transform compared to the profile of HD 46 273 in the right panel of Fig. 3. To quantify differential rotation we assume a rotation law parameterized in analogy to the solar case:

$$\Omega(l) = \Omega_{\text{Equator}}(1 - \alpha \sin^2 l), \quad (1)$$

with l heliographic latitude and Ω_{Equator} angular rotation speed at the equator. Differential rotation can be described by the parameter α , which is the difference of the equatorial and polar rotation velocities relative to the equatorial velocity.

As shown in Reiners & Schmitt (2003a), this parameter α can be calculated from the observed ratio q_2/q_1 , specifically $q_2/q_1 \propto \alpha/\sqrt{\sin i}$, with i the inclination angle. For the case of V 102 we derive $\alpha = 0.42 \pm 0.09$, and with a radius of $R = 1.5 R_{\odot}$ the difference between polar and equatorial angular velocities is $\Delta = 3.6 \pm 0.8 \text{ rad d}^{-1}$.

Such strong a shear in a fast rotator is expected to maintain a strong magnetic dynamo and we would expect significant X-ray flux from V 102. Giampapa et al. (1998) carried out X-ray observations of IC 4665 with no detection of X-ray flux from V 102. However, for a distance of $d = 350 \text{ pc}$, we estimate an upper limit of X-ray luminosity $L_X \lesssim 3.4 \times 10^{29} \text{ erg s}^{-1}$. This is about the typical X-ray luminosity detected in that spectral range (Pallavicini et al. 1981). Since V 102 is likely to be a background object, the X-ray observations do not contradict the picture of a strong magnetic dynamo being driven by rapid differential rotation.

5.2. Alternative scenarios

Although we believe that differential rotation is the most probable interpretation of the derived broadening profile, other mechanisms can be potential reasons for the deviations from classical rotational broadening as well. We discuss three alternative scenarios.

5.2.1. Low inclination

Very rapidly rotating stars become gravity darkened, i.e., they become cooler at the equator. At (unprojected) rotational velocities larger than 150 km s^{-1} , the shape of the broadening profile, and especially the ratio q_2/q_1 , is affected by gravity darkening (cf. Reiners 2003). From the models given in Reiners (2003) we can calculate the equatorial velocity needed for our observed ratio of $q_2/q_1 = 1.39$; we get a value of $v_{\text{rot}} = 800 \text{ km s}^{-1}$, which is far beyond breakup velocity. Thus we can rule out gravity darkening as the main reason for the observed profile.

5.2.2. Bright polar spot

The surface of V 102 may be covered with spots. If the star were magnetically active, one would expect cool spots covering the star. Cool spots generate characteristic signatures in absorption profiles. Since the derived broadening profile is symmetric, the surface coverage of spots must also be symmetric to a high degree. One configuration that would satisfy these requirements is a polar spot. We examined the influence of spots on the broadening profile (cf. Reiners & Schmitt 2002b) and found that cool polar spots do change the profile shape and the ratio q_2/q_1 but in the opposite direction; q_2/q_1 becomes larger. A profile shape as the one observed could only be due to a hot polar spot. From our models we estimate that a polar cap with a radius larger than 30° at a temperature about 1000 K hotter than the rest of the star is needed to produce such a profile shape. This could be similar to what is observed in T Tauri stars accreting material at the poles, and one obvious sign of such accretion would be H α emission. In V 102, no sign of H α emission can be found (cf. Fig. 2).

We emphasize that this may nevertheless be a scenario alternative to differential rotation, but we see no physical connection to any phenomenon observed on other stars.

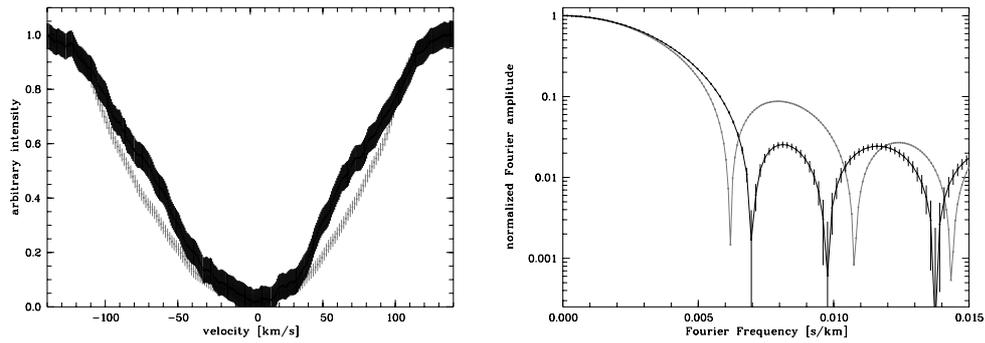


Fig. 3. Broadening functions of IC 4665 V 102 (black) and HD 46 273 (grey) in velocity (*left panel*) and Fourier space (*right panel*). The profile of HD 46 273 is resembles classical rotation broadening. Significant differences are visible to the profile of IC 4665 V 102. Note especially the narrowed first sidelobe in the Fourier transform – a typical signature for differential rotation with the equator rotating faster than the pole.

5.2.3. Composite spectrum

The derived broadening profile could tentatively also be a composition of two spectra from rigidly rotating stars. Especially the curvature at around $\pm 70 \text{ km s}^{-1}$ could be interpreted as an indication for that scenario (although it can also be explained by differential rotation). The profile could then be interpreted by a spectrum of the first star rotating at $v \sin i \approx 110 \text{ km s}^{-1}$, superimposed by a spectrum of a second object rotating at $v \sin i \approx 70 \text{ km s}^{-1}$. Thus both stars would have either significantly different rotation velocities or were seen under different angles of inclination, i.e., a hypothetical double system could not be corotating. Since we derived identical profiles from two different wavelength regions covering several hundred Ångströms, both stars had to be of similar spectral type, otherwise the line profile would change at different wavelengths. In order to resemble the derived profile, both stars must also contribute approximately the same amount of flux. Given similar spectral types of the components, that implies that both stars are at the same distance and are probably physically bound. The double system would then emit roughly twice the flux a single star would, i.e., the real magnitude of each member would be 0.75 mag higher than the measured ones putting V 102 even further away from the main sequence in the color–magnitude diagram.

In this scenario, V 102 would be a physically bound system consisting of two stars of similar spectral type and different rotation velocities located far outside the cluster but comoving with the cluster. We would expect such a spectrum to be variable. Although we consider this scenario very unlikely, we aim to reobserve the star to check the profile for variability.

6. Conclusions

We derived the mean line broadening profile of V 102, a background star of spectral type A9 in the region of the young open cluster IC 4665. From the broadening profile we determined a projected rotation velocity of $v \sin i = 105 \pm 12 \text{ km s}^{-1}$. The broadening profile significantly differs from classical rotation broadening and we discuss several scenarios for such a profile. The most plausible scenario is that V 102 does not rotate

as a solid body but that its equator rotates at a higher velocity than the pole. For that case we derive a difference in polar and equatorial angular velocities of $\Delta\Omega = 3.6 \pm 0.8 \text{ rad d}^{-1}$, or $\Delta\Omega/\Omega = 0.42 \pm 0.09$.

This is so far the strongest observed case of differential rotation. The equator of V 102 laps the polar region once every 40 h, compared to roughly 120 days on the Sun. Three other stars with strong differential rotation of the order of $\Delta\Omega/\Omega = 0.3$ have been reported in Reiners & Royer (2004), they have colors of $B - V = 0.29$ or 0.30 . Our result supports evidence for differential rotation being strongest in a class of rapidly rotating objects with very shallow convection zones.

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