The Variable Line Width of Achernar

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Abstract. Spectroscopic observations of Achernar over the past decades, have shown the photospheric line width, as measured by the rotational parameter $v \sin i$, to vary in correlation with the emission activity. Here we present new observations, covering the most recent activity phase, and further archival data collected from the archives. The $v \sin i$ variation is confirmed. On the basis of the available data it cannot be decided with certainty whether the increased line width precedes the emission activity, i.e. is a signature of the ejection mechanism, or postdates it, which would make it a signature of re-accretion of some of the disk-material. However, the observed evidence leans towards the re-accretion hypothesis. Two further stars showing the effect of variable line width in correlation with emission activity, namely 66 Oph and π Aqr, are presented as well.

1. Introduction

Recently, the bright southern Be star Achernar ($\alpha$ Eri, HD 10144, B4 IV) has been found to show variations in the width of its photospheric lines, as measured by the rotational parameter $v \sin i$ (Rivinius et al. 2013). The amplitude of this variation is about 15% of the value of $v \sin i$ of 250 km s$^{-1}$. This was interpreted by Rivinius et al. with the help of preliminary modeling in the sense that at least the photospheric layers of Achernar (more specific, at least the equatorial layers, which contribute most strongly to the line shape and width) can change their rotational velocity on a relatively short time scale.

This variation is correlated with the circumstellar emission activity in the sense that during such activity the line is wider. However, the precise sense of this correlation could not be determined. The first possibility is that the speed-up of the photosphere precedes the activity, and this way could be understood as a trigger and possibly physical origin of the outburst. Also possible, however, is that the speed-up of the photosphere develops only when parts of the newly formed disk re-accrete onto the star (which is an unavoidable feature of a disk controlled by viscosity), and in this way is not cause, but consequence of the circumstellar activity.
New observational data, as well as more data from observing runs predating the public archive era, were collected to shed light on this question. Available data for other stars were scanned for similar signatures as seen in Achernar as well.

2. Achernar

2.1. Archival Data and New Observations

Additionally to the spectra already shown by Rivinius et al. (2013), further data could be acquired. Prior to 2002, FEROS spectra were not routinely injected into the ESO archive. The star was observed, however, during the Brazilian time, and these data could be recovered and included in the dataset (Vinicius et al. 2006). Additional data for the late 2000’s and early 2010’s were taken from Domiciano de Souza et al. (2014, see their Table 3 and Fig. 4). As mentioned by Rivinius et al. (2013), a new circumstellar activity episode started in January 2013, and Achernar was observed as a target of opportunity with FEROS mounted at the 2.2m-MPG telescope at La Silla. A detailed description of the newly acquired data, archival and recent observations, will be published elsewhere together with a more complete modeling of the variations.

This additional data were subjected to the same analysis as the previous ones, outlined in Rivinius et al. (2013). In particular, we refer to Fig. 2 of that work for a description of the residual spectra and the signatures seen in them. The resulting parameters, excess wing indentation and equivalent width, are plotted jointly with the previous data in Fig. 1.

2.2. Correlations Between Activity and Rotation

The most important question is whether the amended data set allows a clearer view on the causal link behind the observed correlation between emission activity and the stellar surface rotation. The data now shows two full emission cycles (2000 to 2004 and 2004
to 2010, cycles 2 and 3), the end of the previous (cycle 1), and the beginning of the most recent ones (cycle 4).

**Cycle 1:** The disk emission dissipates fully. The rotational width also goes back to the base value during quiescence, although it seems it reaches the base level only slightly after the emission has disappeared.

**Cycle 2:** Around MJD 51 900 the star does not show any emission, but enhanced $v \sin i$. The latest at MJD 52 200 a disk starts to develop. The disk remains weak and then decays until MJD 53 400. However, the rotational width does not fully decay back to its quiescence level.

**Cycle 3:** Instead, almost immediately after MJD 53 400 a new activity cycle starts (seen best in the photometric amplitude data by Goss et al. (2011). The disk evolves to a stronger emission than in cycle 2, and then decays back to zero by about MJD 55 200. At this time, the rotational enhancement is still marginally present. Note the pulsation amplitude has returned to its base level already around MJD 54 000, which may indicate that disk feeding has as well ended already then.

**Cycle 4:** Achernar remained inactive for several years until MJD 56 600. During this time, also no enhancement of $v \sin i$ was observed. Since the beginning of disk formation after MJD 56 600 both emission and rotational enhancement are strong.

The above produces a puzzling picture: Cycles 1, 3, and 4 support one picture in which the rotational enhancement is fully in parallel with the presence of a disk, which, as will be discussed below, points to the enhancement as a consequence of the presence of a disk. Cycle 2, however, supports view that the rotational enhancement precedes the presence of the disk, which in the most simple picture would link it to the cause of disk formation, rather than to disk dissipation. Before discussing this possible contradiction below, further possible cases of rotational variability will be presented in the next section.

### 3. Other Stars

#### 3.1. Disk Decay of 66 Oph

Between about 1993 and 2011 the Hα emission of the Be star 66 Oph continuously decayed to the level of zero emission (Miroshnichenko et al. 2012). For the final few years of this phase archival high quality spectra are available, which were originally taken for the MiMeS program on Magnetism in Massive Stars (see Wade et al., this volume) with NARVAL at the TBL (2007, 2008, and 2009) and ESPaDOnS at the CFHT (2011). For each observation multiple frames were taken in short succession for polarimetric purposes, for this work all spectra taken during these short epochs were co-added. The upper panel of Fig. 2 shows this decay. Although brief phases of injection of fresh material into the circumstellar environment are seen in these data, the general downward trend is hardly disturbed.

Analogous to the case of Achernar, residuals were constructed, in which the state with low emission was taken as a reference. Unfortunately, the continuum normalization is not fully consistent between the NARVAL and the ESPaDOnS data. Therefore,
Figure 2. Top: The decay of the H$\alpha$ emission of 66 Oph, observed from 2007 (largest emission, but already far away from its maximum several years before) to 2011 (no emission). Bottom: Residual spectra of 66 Oph 2007 and 2008 vs. the low emission state of 2009. A typical Achernar residual spectrum for active vs. inactive state is shown above for comparison. For a more in-depth discussion of the construction of such residual spectra and their interpretation see Rivinius et al. (2013).

the construction of residuals is constrained to the NARVAL data to eliminate the effect, and the 2009 NARVAL spectrum is taken as reference.

The lower panel of Fig. 2 shows the residual spectra constructed this way, together with a typical residual spectrum of Achernar. The signatures are very similar, for both the decrease of circumstellar emission seen in the Balmer lines as well as the change of line width signature in the He I and Ca II lines. In fact, the most obvious difference between Achernar and 66 Oph is the lack of broad emission wings in the Balmer lines and the shell signature in Ca II 3933. The latter is simply a consequence of 66 Oph being seen at a more polar inclination angle, the former possibly due to the fact that the disk in 66 Oph has been in quasi-steady decay since many years, while in Achernar the disk density profile, and hence the scattering close to the star, is more dynamic.

3.2. Disk Formation of $\pi$ Aqr

$\pi$ Aqr was observed in a phase of disk build-up. The disk decayed to almost emissionless state in the mid 1990’s, but did never actually reach zero emission. Rather, emission remained at a minimum for several years and $\pi$ Aqr started to re-build a more massive disk in the mid 2000’s (Wisniewski et al. 2010). Two high-quality spectra, covering the low state in 1999 and the active state in 2008, are available in the public archives.
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Figure 3. Top: The increase of the Hα emission of π Aqr in 2008 vs. 1999. Middle: Residual spectra region of He i 4471, He ii 4542, and the Si iii triplet at 4553/68/75, each having a distinct residual signature. Bottom: Residual spectra of the blue wavelength region similar as shown in Fig. 2, with blending of signatures from various effects in individual lines.

(Fig. 3, upper panel). Both were taken with FEROS, which 1999 was mounted at the 1.52m-ESO and 2008 at the 2.2m-MPG telescopes at La Silla.

Other than 66 Oph and Achernar, which are mid-type Be stars, π Aqr is an early type Be star. The photospheric spectrum exhibits lines of He ii, and when in active state, the spectrum shows He i lines in emission. It is further a non-radial β Cephei type pulsator (Peters & Gies 2005). These properties seriously complicate the detection of subtle signatures in the residual spectra, in particular since the signatures are most obvious in He i lines.

The middle panel of Fig. 3 attempts to disentangle the different signatures. While the residual profile of He i 4471 is clearly dominated by the change of the emission activity, the residuals of the Si iii triplet are hallmarking the non-radial pulsation signature. The residual signature of He ii 4542, however, shows something different. It has
no emission contribution, and as well the variability with the pulsation period, seen in dynamical spectra similar to the ones shown in Fig. 2 of Peters & Gies (2005), is very weak and restricted to the line center. Yet, the outer wings of the line show the similar “dents” as the ones indicating the $v \sin i$ variations in Achernar.

The lower panel illustrates how these three signatures can get blended in spectral lines. The two Balmer lines have emission contribution only, while the metallic lines show only pulsational residuals. The He I lines at 4009, 4021, and 4144 show signatures blended. In He I 4009 no emission signature is seen, but a small pseudo-absorption close to the line center is due to the pulsation. The overall residual signature of this line, however, is dominated by the supposed $v \sin i$ variation signature. In He I 4144 $v \sin i$ variation and pulsation signature are about equally strong. The residual signature of He I 4021 is dominated by the line emission, but both the pulsation signature close to the line center as well as the outer wing indentations due to rotational variability can be detected on a close look.

Although the case for $\pi$ Aqr is certainly weaker than that for Achernar or 66 Oph, the star should still be considered a strong candidate for rotational variability connected to the disk activity state.

4. Discussion and Conclusion

The interpretation of the observed correlations between disk activity and rotational enhancement is not straightforward. Among the most simple possibilities is that the rotational enhancement is due to an acceleration of equatorial surface material by disk material re-accreting onto the star with slightly sub-Keplerian velocity. The enhanced velocity of the surface layers then dissipates by transferring the excess angular momentum back into the star and maybe as well sideways into the non-equatorial surface layers as well. Observations in favour of this scenario are the presence of rotational enhancement up to the late phases of disk emission, i.e. at times by when the disk feeding should have stopped already long ago (cycle 1 and cycle 3 of Achernar, 66 Oph). We note that such a re-accretion inevitably has to occur for a disk that is governed by viscosity, because there is no other way to transfer angular momentum outwards than to take it away from particles that subsequently fall back onto the star. This process starts as soon as the disk exists and only ends when the disk is fully dissipated. The presence of rotational enhancement without a disk, such as in cycle 2, is an argument against this simple process, unless one speculates about a brief (and not observed) emission episode just before the observations.

A second simple possibility is that angular momentum is transported towards the surface by processes from inside the star, e.g. the pulsation, until the surface nears the critical limit, at which point this angular momentum is shed by the formation of a disk. Then the rotational enhancement should be out of phase with the disk presence, by about 1/4 of a cycle. While cycle 2 does point to such a phase difference, the absence of any rotational enhancement in the quiescent period before cycle 4 speaks against it. Just as in the above hypothesis cycle 2 could be speculated to be due to a brief activity period, the same could be speculated for the rotational enhancements seen in the late phases of a cycle, namely to be due to brief, but otherwise undetected, activity phases.

Summing up the evidence for the above two possibilities, the first seems to require fewer additional assumptions (just one unseen brief activity phase), while the sec-
ond not only demands several of those in several stars, but still leaves the quiescence before the activity onset in cycle 4 unexplained.

Adding an additional trigger process, that keeps the rotational enhancement due to pulsation at bay during the inactive phases, and speeds up the surface only just before the outburst does only move the problem one layer down: It is exactly the appeal of the angular-momentum-spillover hypothesis to remove the need for such a trigger. Although not entirely conclusive, the sum of evidence seems to weigh towards the re-accretion hypothesis.

In any case, the discovery of the same type of signature in 66 Oph, and likely as well in π Aqr, makes it worthwhile testing the hypothesis that the rotational variability as seen in Achernar as a property of all Be stars.

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