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Inhalt

	Seite
Ch. Buil: The Very High Resolution Spectrograph VHRES	1
E. Pollmann: Projektkooperation in der Amateur-Astrospektroskopie	10
W. Vollmann	Intermediate Report January 2013
E. Pollmann:	Campaign Photometry and Spectroscopy of P Cyg
	13
S. Zharikov u. a.: Doppler tomography of the circumstellar disk of pi Aqr (erschienen in A&A, 560, A30, 2013)	20

The Very HIgh REsolution Spectrograph VHIRES

(by Christian Buil)

This report describe the conception of a very high spectral resolution spectrograph. The target resolution is around $R=42000$ near H α (i.e. FWHM line shape of $0,16 \text{ \AA}$ or 7 km/s). The definition, construction and adjustment took only 3 hours. No machining, but top performances (and relatively costly) components.

The grating is an échelle Richardson model. Blank size: $220 \times 110 \times 30 \text{ mm}$. The graving density is 110 grooves/mm and the blaze angle of 64.5° . This component is selected because H α is precisely at the center of blaze function for order $k = 25$ ($k = 25.01$ to be precise). Efficiency is maximized. A Takahashi refractor FSQ85ED (a fine apochromatic astrograph) is used in autocollimation mode. The aperture diameter is 85 mm and focal length 450 mm. An Atik Off-Axis Guider is used to inject stellar flux into the refractor coming from a 50 microns optical fiber (from the guiding port).

An excellent Astrodon H α filter (6 \AA pass-band) is mounted just in front of the CCD camera for select order #25 (no cross disperser used, the goal is maximal simplification to observe with some details in immediate vicinity of H α line only - like a fix super Lhires III spectrograph). The camera is an Atik460EX operated in binning 3x3 (equivalent pixels size, 13.62 microns). The spectral covered domain is of 42 \AA (only, but remember the very high resolution). The spectral sampling is $0,0462 \text{ \AA/pixel}$ (bin 3 mode). At the telescope level, the object is guided and the flux injected in the 50 microns fiber by using the eShel interface (Shelyak Instruments). The system is simple, but there is no concession: large aperture elements, high optical quality ...

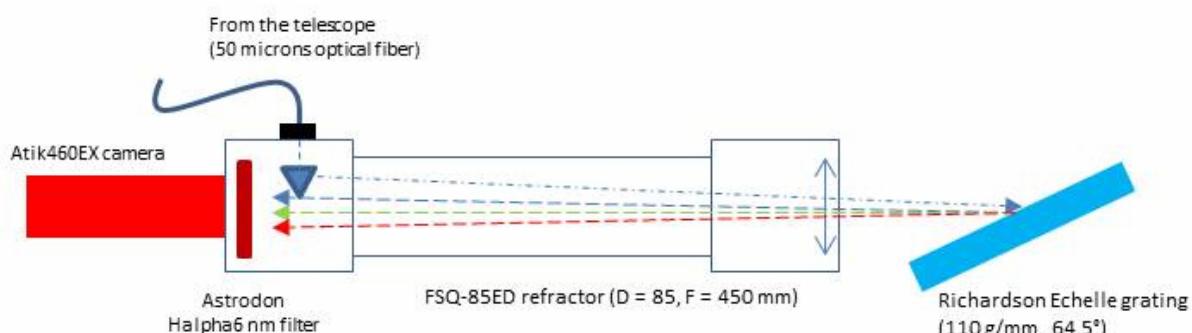


Fig. 1: The optical diagram of VHIRES

The following Fig. 2-6 shows some views of the VERY (!) preliminary setup:



Fig. 2



Fig. 3



Fig. 4

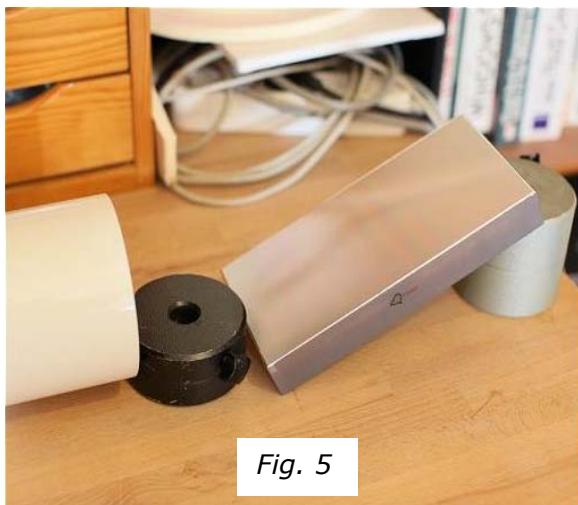


Fig. 5

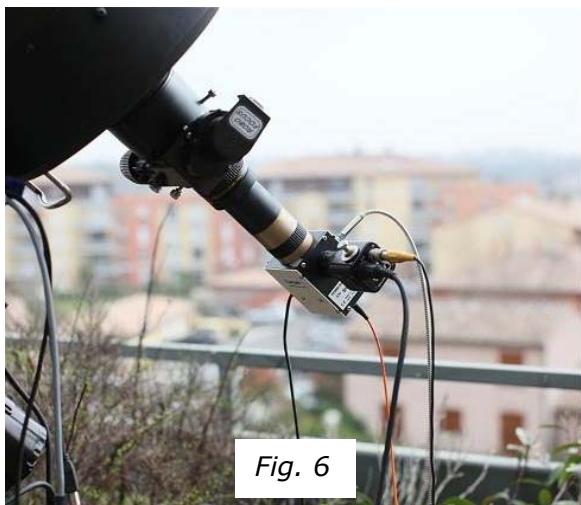


Fig. 6

The manner to maintain the grating is really improvised (prototype phase!)

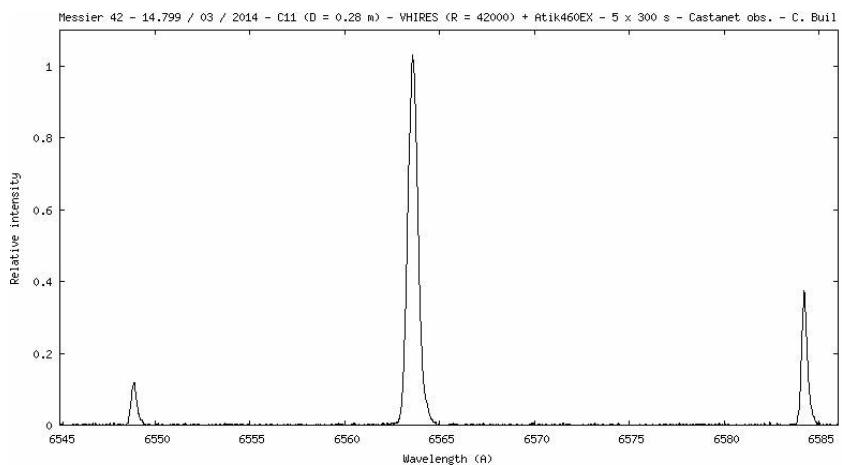


Fig. 7: The spectrum of a part M42 nebulae. Of course, the H α line (HI) is nearly at the center. Note the separation of [NII] lines. The shape of the emission lines is real: asymmetric profile and enlargement are associated to gas velocity field in the nebula.

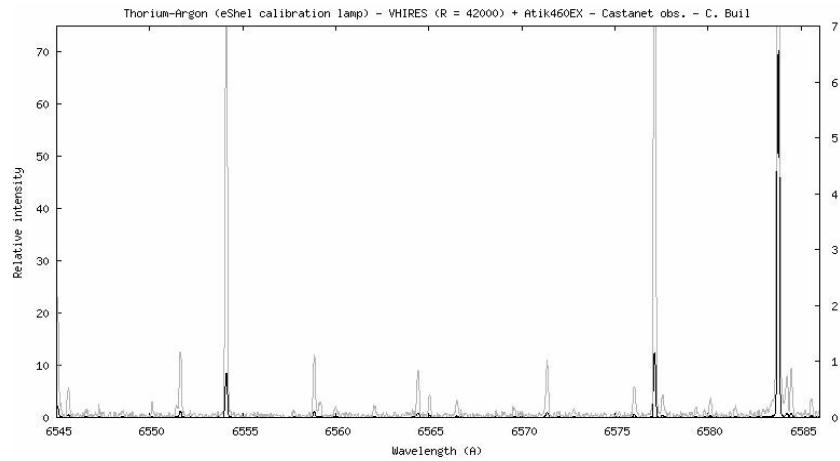


Fig. 8: The proof, look the aspect of pure monochromatic lines from the Thorium-Argon calibration lamp of eShel spectrograph and compare with M42 lines.

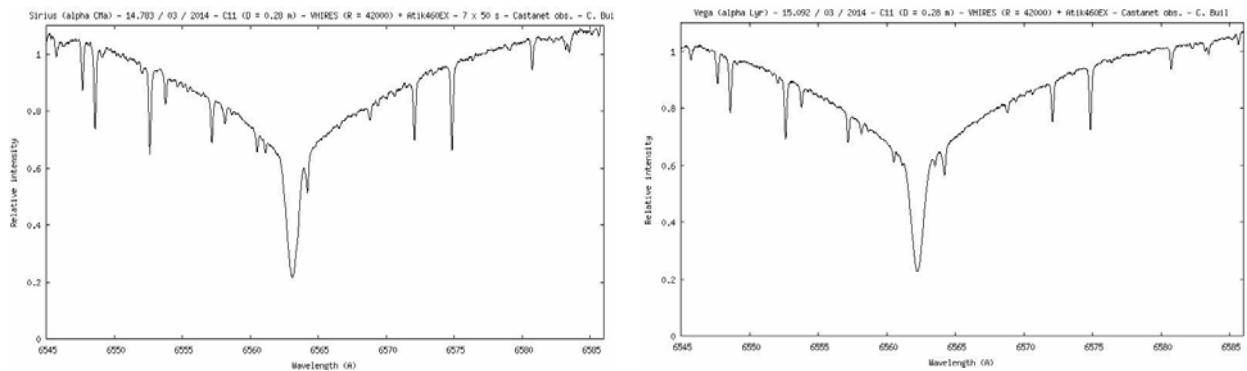


Fig.9: Two example of A type star spectra with a well marked Voigt profile [Sirius (left) and Vega (right)]. The H α wing line extend out of CCD field (a more largest detector format can be selected). Note the difference of HI line position relative to H₂O telluric lines.

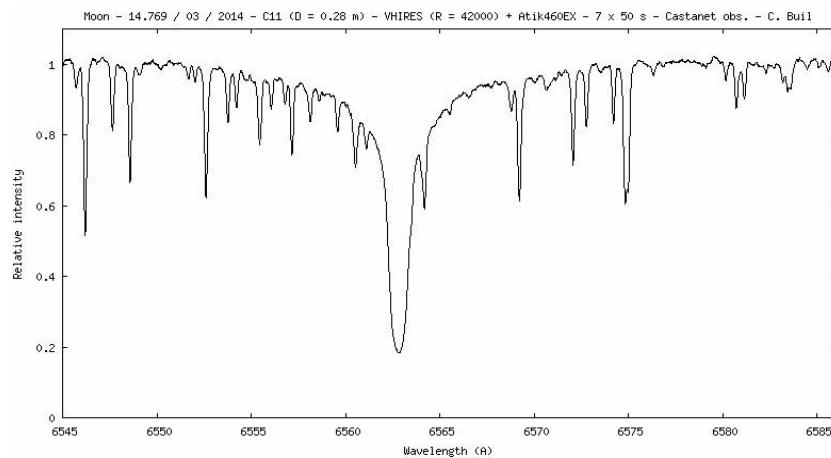
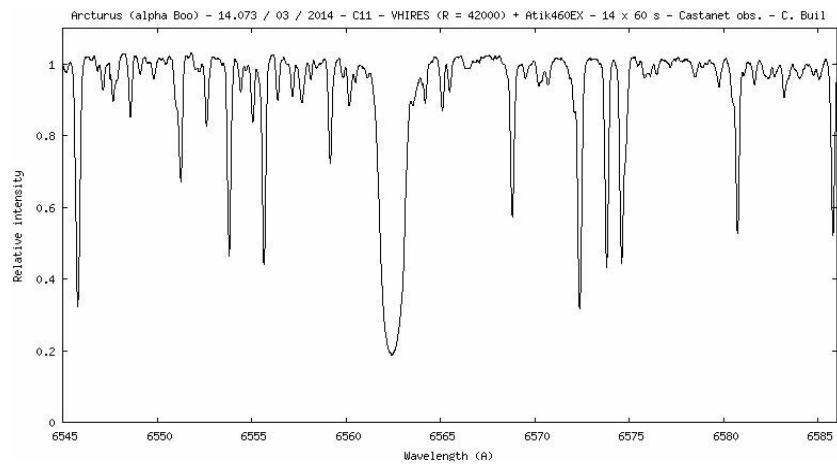


Fig. 10: the spectrum of the moon surface (i.e. Solar spectrum, a G2V star). The H α profile is well detailed. The H₂O telluric lines begin to be also resolved:



*Fig. 11: A coolest star, Arcturus (a Boo) - type K1.5III.
Note symmetry of H α and sharp Fe lines:*

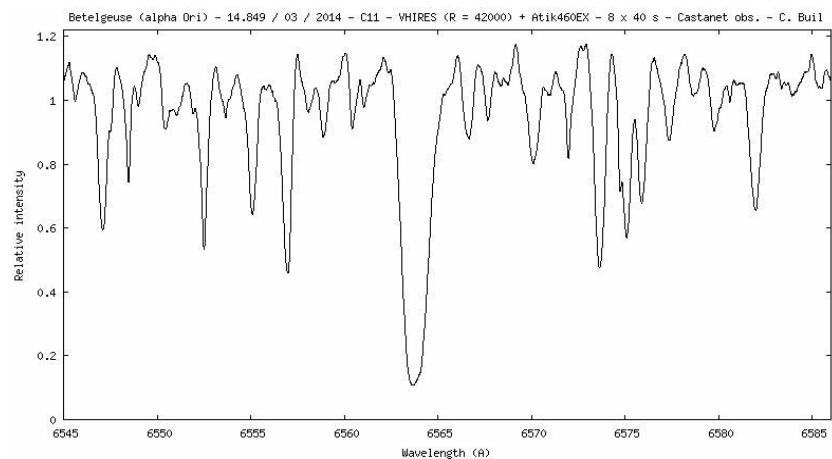


Fig. 12: More largest metallic lines are noted on Betelgeuse spectrum (M2Iab):

Some Be stars:

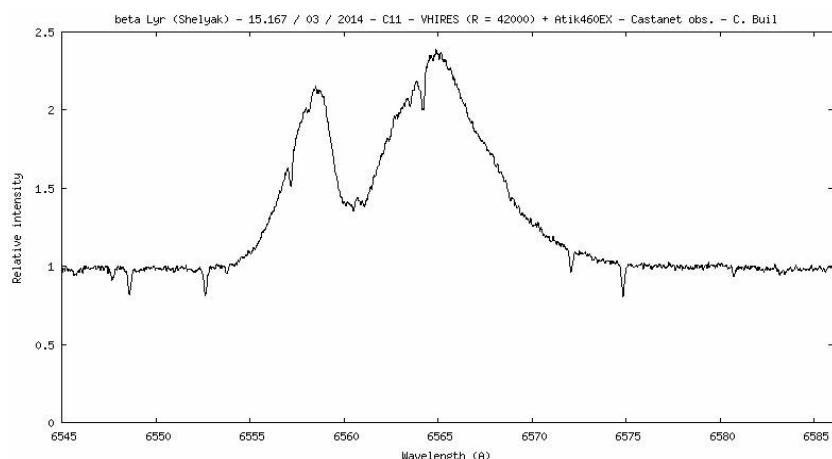


Fig. 13: β Lyrae

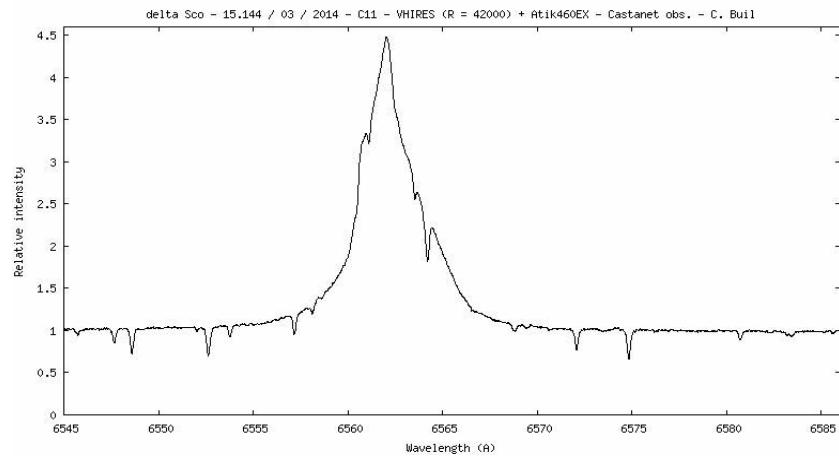


Fig. 14: δ Scorpii

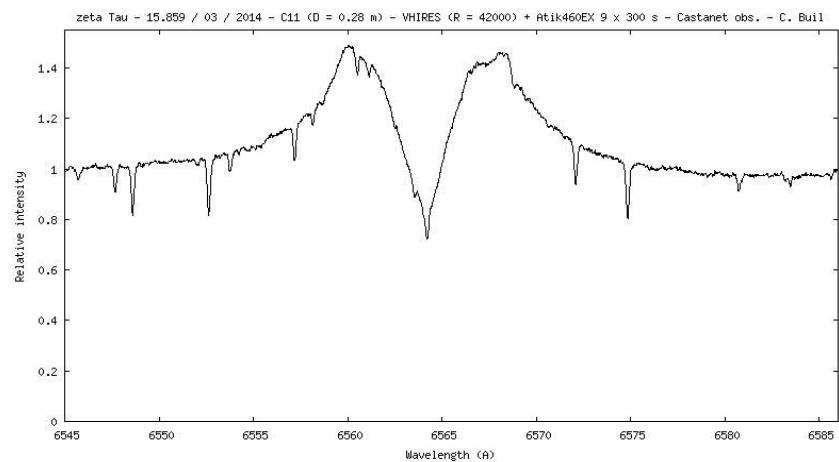


Fig. 15: ζ Tau (note details in the emission line, probably fast time evolving)

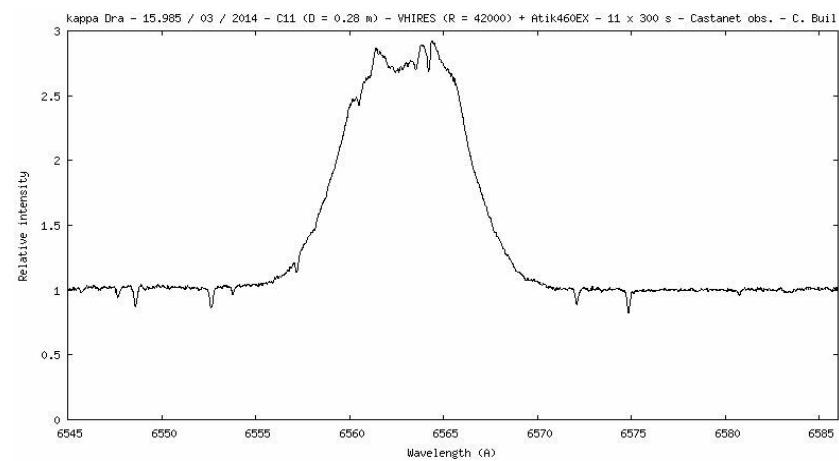


Fig. 16: κ Dra (note the diversity of H α profile from Be star to another):

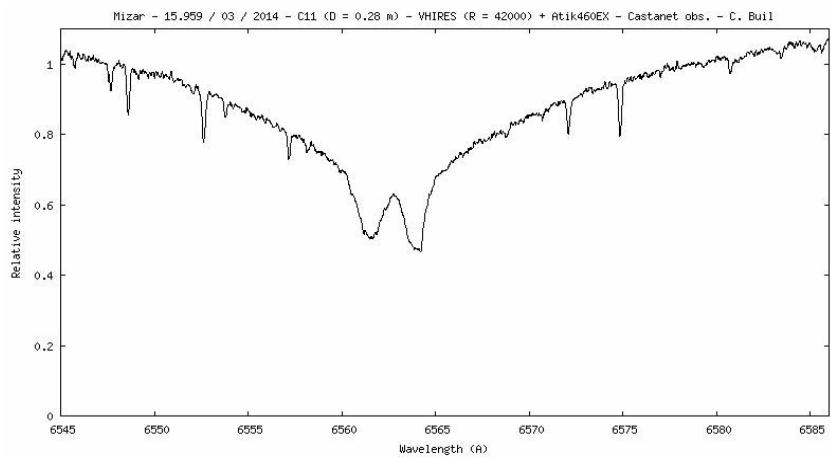


Fig. 17: A spectroscopic binary star (Mizar in Ursa Major):

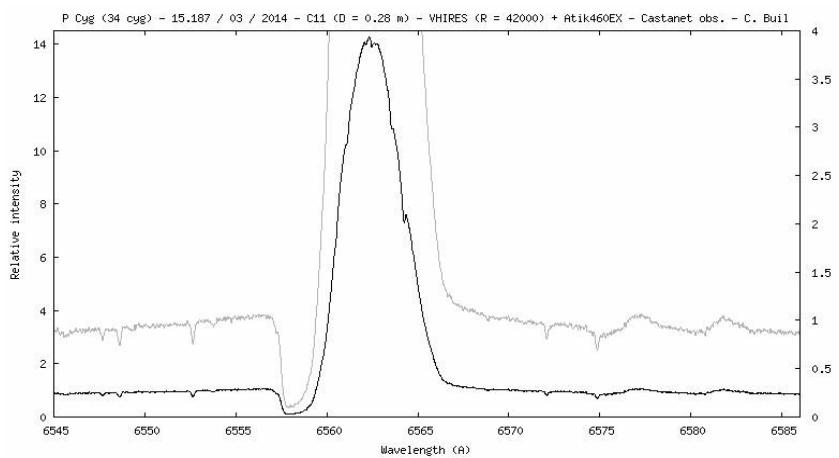


Fig. 18: The famous P-Cygni star (34 Cyg):

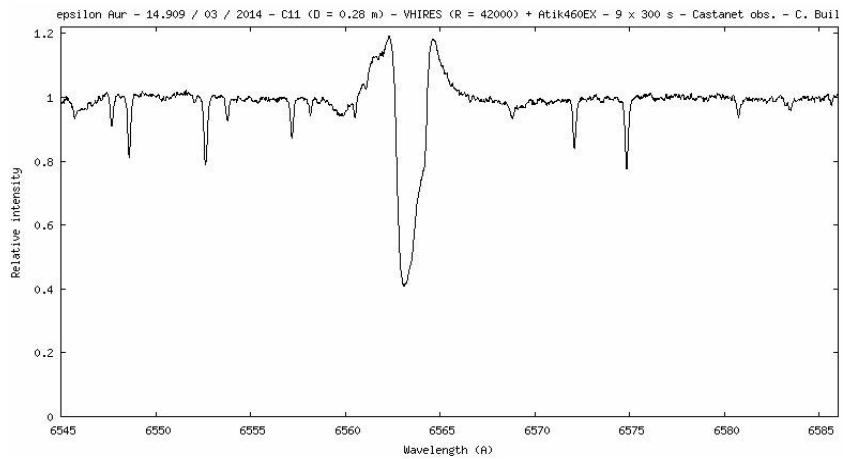


Fig. 19: The actual aspect of Ha profile in ε Aurigae system:

And some active stars:

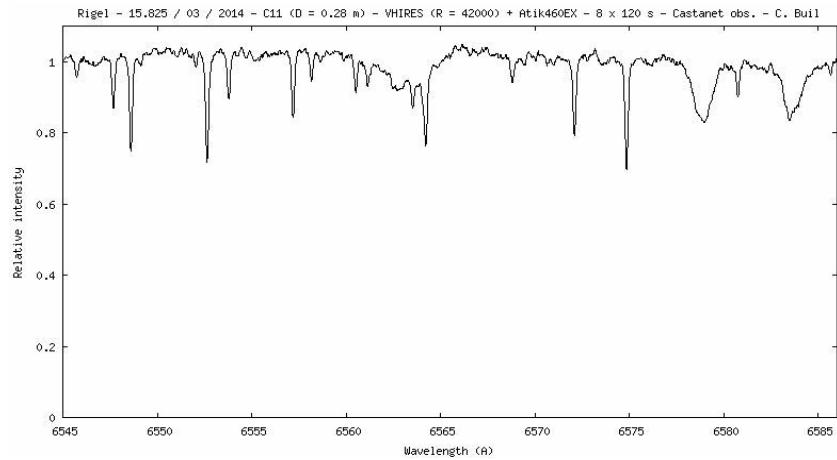


Fig. 20: The super giant Rigel (β Ori):

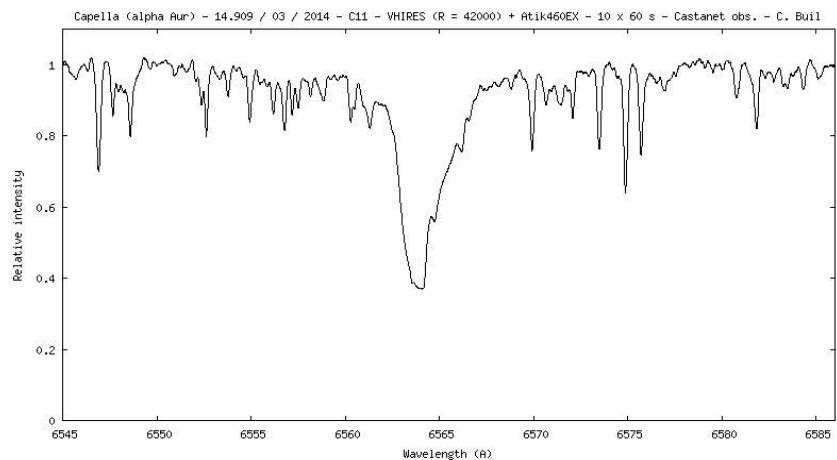


Fig. 21: a Auriga (Capella is not a quiet world, look the distorted aspect of H α profile)

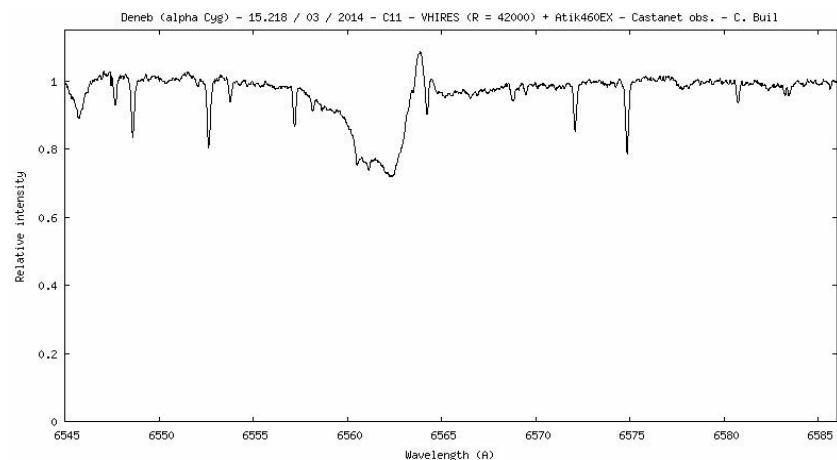


Fig. 22: The last object of this first light session with VHIRES, a Cyg (Deneb)

Complements:

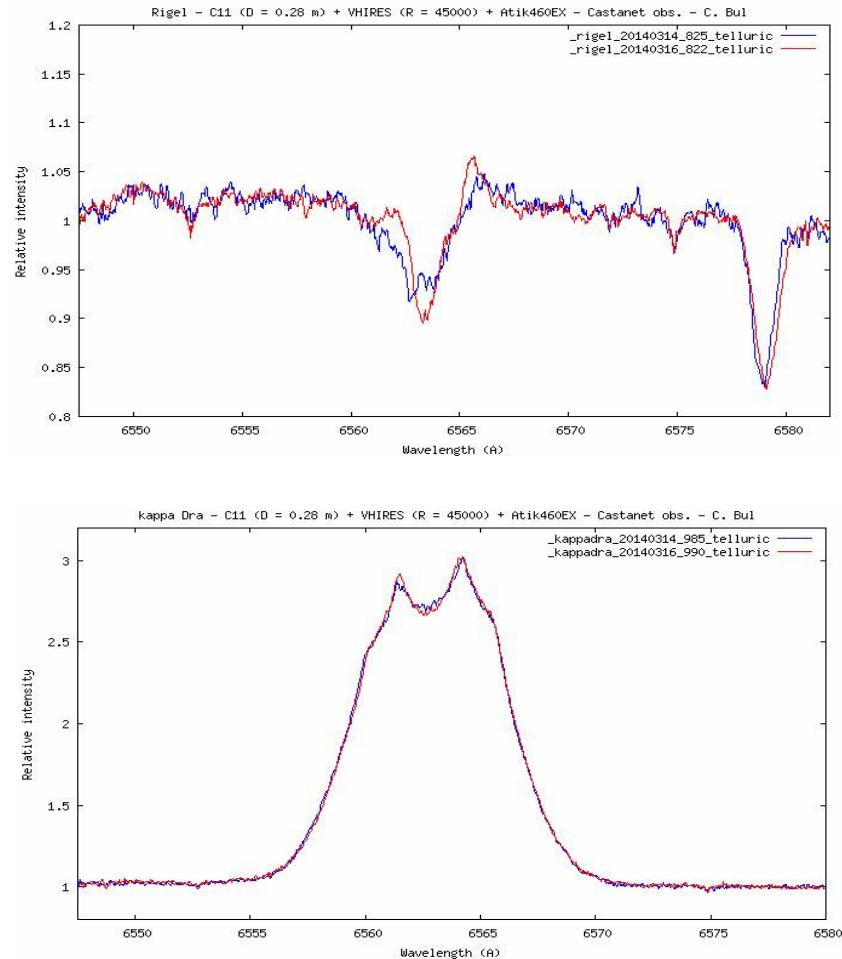


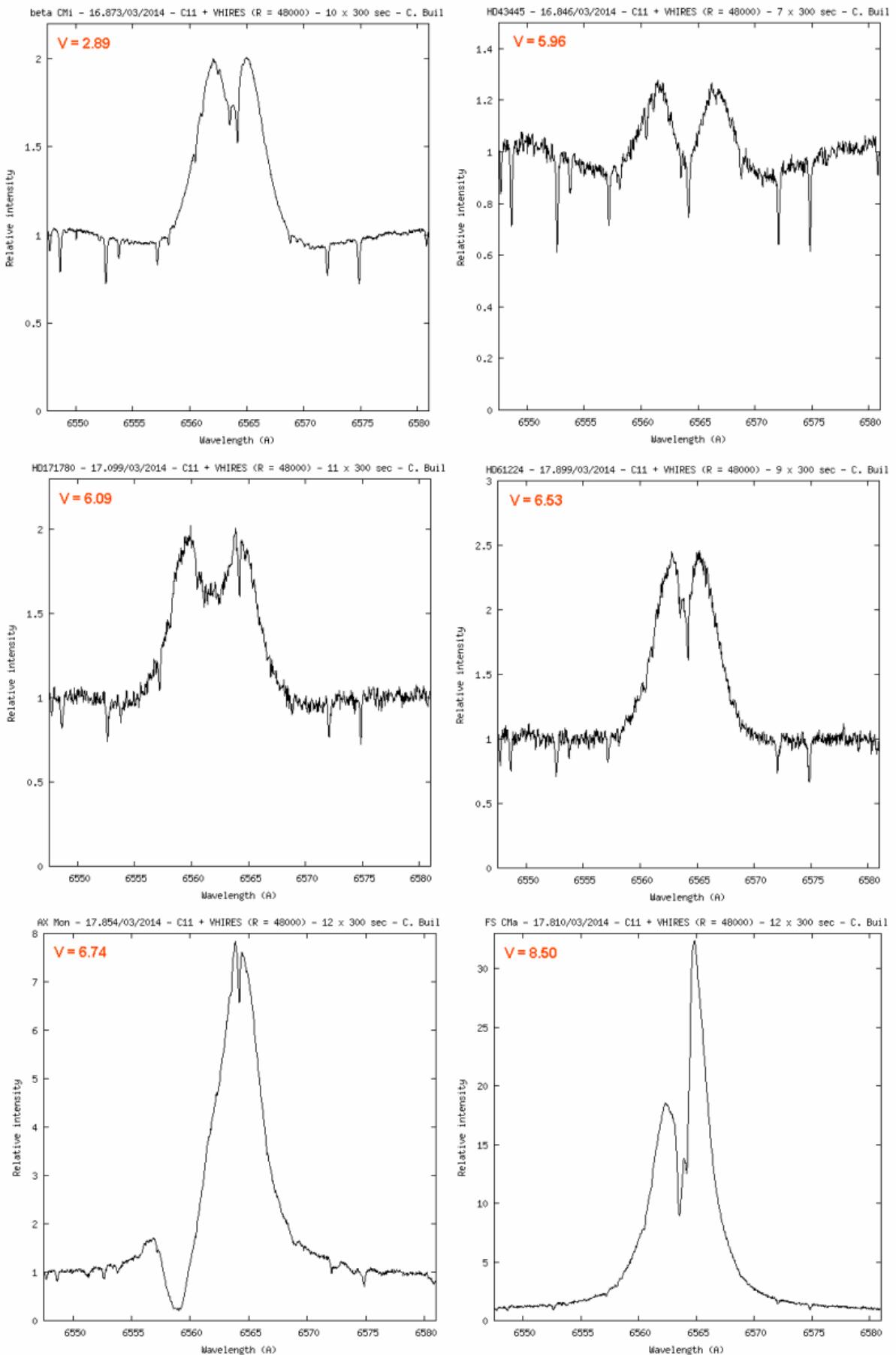
Fig. 23: Fast time evolution (two days) on β Ori (top) and κ Dra (telluric linesare removed for clarity)

Magnitude test on Be stars:

For astrophysical analysis, the reasonable signal to noise ratio of 50 for the red continuum is reached with a 28 cm telescope on $V = 6.0$ stars in a one hours exposure (stack of 12×300 sec. frames). For the same results, the corresponding magnitudes for a 40 and a 60 cm telescope is evaluated to $V = 6.6$ and $V = 7.3$ respectively.

Vmag and exposure time for the following spectra:

β CMi	Vmag = 2.89	Exposure time = 10×300 sec	R = 48000
HD3435	5.96	7×300	40000
HD 17180	6.09	11×300	48000
HD61224	6.53	9×300	48000
AC Mon	6.74	12×300	48000
FS CMa	8.50	12×300	48000



Projektkooperation in der Amateur-Astrospektroskopie

(von Ernst Pollmann)

Kommunikationsvielfalt und die Möglichkeiten der heutigen Digitaltechnik verändern in rasantem Tempo nahezu alle Bereiche unseres Lebens. Sowohl die Astronomie der Amateure als auch die professionelle Fachastronomie belegt dies nahezu täglich in beeindruckender Weise mit in Datenbanken verfügbaren Bildern und Entdeckungen. Natürlich sind auch in der beobachtenden Amateur-Astrospektroskopie diese, z. T. segensreichen Entwicklungen anzutreffen, welche dazu führen, dass in zunehmendem Maß Beobachtungsresultate im Austausch zwischen Einzelbeobachtern zu wichtigen Bestandteilen globaler, vielfach professioneller Projekt- und Forschungsvorhaben werden. Das Eremitendasein, noch vor gar nicht langer Zeit ein typisches Erscheinungsmerkmal in der Amateurastronomie, kann deshalb wohl heute ruhigen Gewissens der Vergangenheit zugeschrieben werden.

Die Einbindung individueller, amateurastronomischer Beobachtungsaktivitäten in internationale Gemeinschaftsprojekte, sowie die Teilhabe an professionellen Forschungsvorhaben ist inzwischen nahezu selbstverständlich geworden. So resultiert aus dieser Teilhabe in enorm starkem Maße auch die Motivation zu Einzelbeobachtungen, die nicht selten eine jahrelange Projektmitarbeit zur Folge haben. Was kann also dem Einzelbeobachter schöneres widerfahren, als in dieser Form in Gemeinschaftsvorhaben eingebunden zu sein. Vor diesem Hintergrund wäre aus meiner Sicht besonders die auf dem Sektor der Amateur-Astrospektroskopie international aktiv tätige Organisation mit Namen ARAS zu erwähnen, in der ich inzwischen seit vielen Jahren mitwirke. Das Acronym ARAS steht für „Astronomical Ring for Access to Spectroscopy“ wobei sich die Organisation selbst aus der Aktivitätsvielfalt international spektroskopisch aktiver Amateurastronomen speist. Es würde zu weit führen, die Vielzahl der z. T. von der professionellen Astronomie angeregten Kooperationsprojekte hier aufzuzählen, weshalb ich daher dem geneigten Leser eher ein Besuch der ARAS-Webseite unter <http://www.astrosurf.com/aras/> mit ihren weiterführenden Projektverlinkungen empfehlen möchte.

Die Periastron-Passage des Be-Doppelsternsystems δ Scorpis

Eines der herausragenden Kooperationsprojekte von professioneller Fachastronomie und Amateurastronomie der Vergangenheit war zweifelsfrei die sog. Periastron-Passage des Be-Doppelsternsystems δ Scorpis [1]. Dieses Ereignis im Juli 2011 stand besonders stark im Fokus spektroskopischer Radialgeschwindigkeitsmessungen (Radialgeschwindigkeit = RV). Eine im Sommer 2010 am OHP-Observatorium in Südfrankreich mit Fachleuten der professionellen Astronomie verabredete Kampagne führte zu unerwarteten Ergebnissen u. a. im RV-Verlauf, die die Existenz eines dritten Körpers im System δ Sco nicht ausschließen [2]. δ Sco ist ein helles, interferometrisch detektiertes Doppelsternsystem, bestehend aus einem Primärstern des Spektraltyps B0, einem Sekundärstern des vermuteten Spektraltyps B auf einem Orbit mit der Exzentrizität $e = 0.94$. Der Primärstern diente im 20. Jahrhundert als Standardstern zur Spektralklassifikation. Wegen der entdeckten Helligkeitszunahme im Sommer 2000, verursacht durch die Entstehung einer zirkumstellaren Gasscheibe um den Primärstern, stand δ Sco unter kontinuierlicher Beobachtung. Das System näherte sich im Jahr 2011 wieder einer Periastronpassage. Weil die damalige orbitale Periode systematische Fehler enthielt (die Periastronpassage in 2000 ereignete sich einige Monate später als nach interferometrischen Messungen vorhergesagt), war der für Juli 2011 vorhergesagte Zeitpunkt von erheblicher Bedeutung. Wegen der langen Orbitalperiode von ca. 11 Jahren und der hohen Bahnexzentrizität war dies eine der seltenen Gelegenheiten, tiefe Einblicke in die physikalischen Geschehnisse dieses Prozesses zu gewinnen. Zudem ist δ Sco einer der nahesten Be-Sterne mit einer Parallaxe von 6 Millibogensekunden und erlaubte somit, die äquatoriale Gasscheibe sowie Störungen in ihr interferometrisch aufzulösen. Präzise RV-Messungen (in Abb. 1 besonders die maximale Einsenkung bei ca. JD 2455740) ermöglichten es, wesentliche Verbesserungen in der Vorhersagesicherheit des Periastrons zu erreichen.

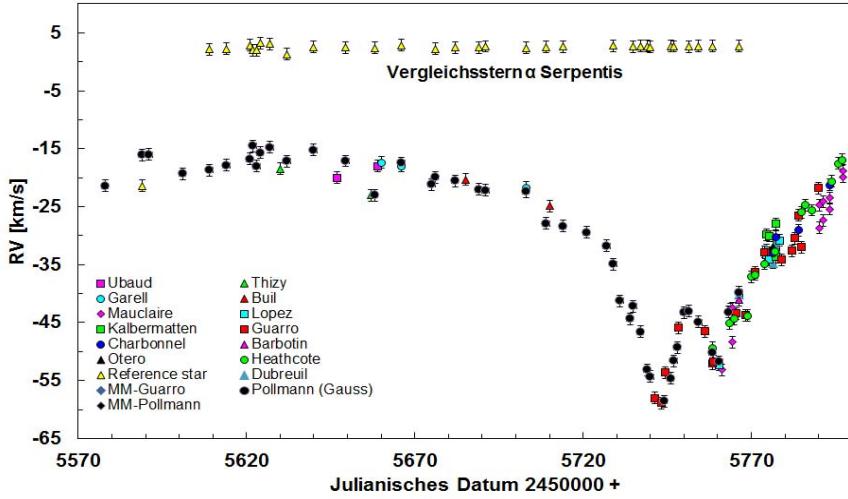
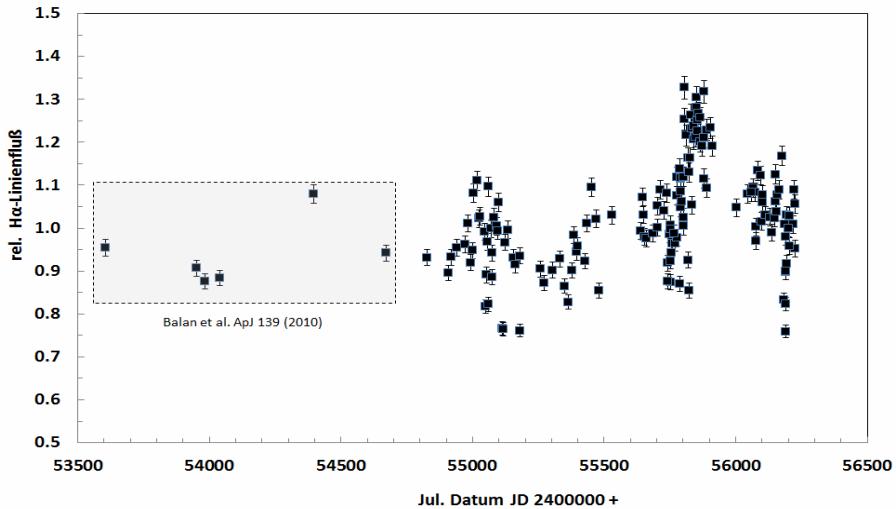


Abb. 1: Radialgeschwindigkeitsverlauf der H α -Emissionslinie im Spektrum von δ Scorpii. Die Vergleichsmessungen am Stern a Serpentis ($RV = 2.6 \text{ km/s} = \text{konst.}$) dienen der Beurteilung der Zuverlässigkeit der Messungen an δ Sco. Die zweite RV-Einsenkung bei etwa JD 2455760 lieferte einen Hinweis auf einen dritten Körper im System in der Nähe des Begleitsterns.

Langzeitmonitoring des LBV-Sterns P Cygni

Als zweites Beispiel einer internationalen Projektkooperation wäre das Langzeitmonitoring von photometrischer V-Helligkeit und zeitgleicher H α -Emissionsstärke (sog. Äquivalentbreite EW) am Leuchtkräftigen Blauen Veränderlichen (LBV)-Stern P Cygni zu nennen. Diese Projektkooperation verfolgt das Ziel, den intrinsischen (d. h. vom Stern selbst herührenden) H α -Linienfluss auf Basis dieser Messungen zu dokumentieren. Das inzwischen 26 Beobachter umfassende Projektkonsortium konnte Juni 2013 eine erfolgreiche Bilanz dieser in 2008 gestarteten Zusammenarbeit im AAVSO-Journal [3] als intrinsischen Langzeit-H α -Linienfluß vorstellen (Abb.2).



*Abb. 2: Langzeitmonitoring des relativen H α -Linienflusses aus Division von photometrischer V-Helligkeit / H α -EW.
Dieser Quotient ist dem tatsächlichen physikalischen Linienfluss proportional und liefert Informationen über die zeitliche Massenverlustrate des Sterns, seine Sternwinddichte und dessen Ionisationsstruktur*

Dabei wurde deutlich, dass ähnliche Ergebnisse aus Untersuchungen seitens der professionellen Astronomie [4], nicht die Ergebnisqualität unserer Amateurkampagne erreichten. Grund dafür war deren Verwendung nicht zeitgleicher EW- und V-Werte.

Ha-Emissionslinienstärke und Radialgeschwindigkeit von ζ Tauri

Die bereits seit längerem bestehende Zusammenarbeit mit Dr. Domagoj Ruzdjac vom Hvar-Observatorium der Universität Zagreb (Insel Hvar, Kroatien) am Be-Doppelstern ζ Tau, zeigt als drittes Beispiel die nutzbringende Zusammenführung von Beobachtungsdaten aus Amateur- und professioneller Astronomie. Die Ergebnisse eines gemeinsamen Langzeitmonitorings, an dem im übrigen 15 weitere Amateurbeobachter beteiligt waren, vorgestellt auf dem XIth HVAR-Astrophysical Colloquium „The Most Mysterious Binaries“ [5], resultierten u. a. aus der Beobachtung zeitlicher Veränderungen der Ha-Emissionslinienstärke (EW) und der Langzeitradialgeschwindigkeit (RV) als Folge des Gasscheibenverlustes um den Primärstern (Abb. 3). Außerdem konnte in meinen Daten in Zusammenarbeit mit Th. Rivinius (ESO-Chile) eine ca. 70-tägige, bis dahin nicht bekannte RV-Periode der HeI6678-Absorptionslinie gefunden werden.

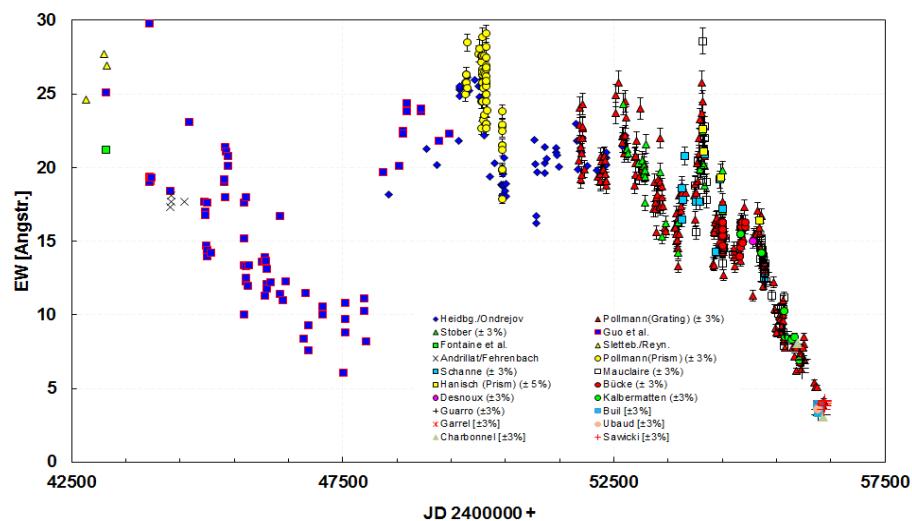


Abb. 3: Im Langzeitmonitoring von ζ Tauri spiegelt das historisch niedrige Niveau der Ha-Emissionsstärke (EW) von ca. 3.5 Å im April 2013 (Jul. Datum JD ca. 2456397) den nahezu vollkommenen Verlust der Be-Sternscheibe um den Primärstern wieder. Die Ha-Emissionsstärke ist direkt proportional der Masse einer solchen zirkumstellaren Gasscheibe.

Röntgenemission und zirkumstellaren Umgebung des Be-Sterns γ Cassiopei

Abschließen möchte ich diese, aus einigen typischen Beispielen bestehende Übersicht mit dem professionellen Forschungsprojekt zur „Untersuchung über die Beziehung zwischen der Röntgenemission und der zirkumstellaren Umgebung des Be-Sterns γ Cas“, in der EW- und RV-Messungen meines Kollegen Roland Bücke (Hamburg) und mir als wesentliche Bestandteile eingegangen sind (Abb. 4).

Es sind die oft jahrzehntelangen Beobachtungsdaten, an denen es der heutigen professionellen Astronomie vielfach mangelt und weshalb gerne auf den Datenfundus der Amateurastronomen zurückgegriffen wird. In zwei Veröffentlichungen sind die Ergebnisse dieser Untersuchungen beschrieben [6] und [7].

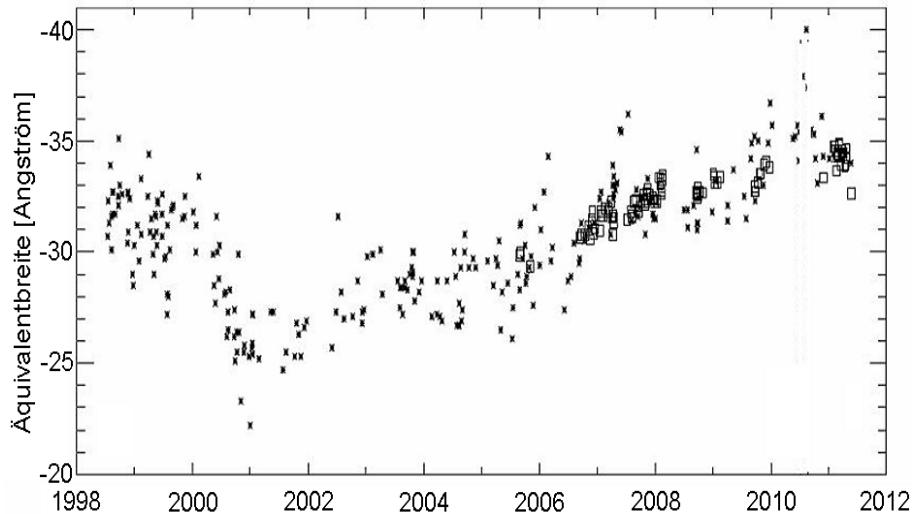


Abb. 4: Ha-EW Messungen von R. Bücke (Quadrate) & E. Pollmann (Sternchen). Bemerkenswert sind die rapide Zunahme ab etwa 2001, sowie die Spitzen bei 2007 und 2010. Die beiden letzten Ereignisse sind zeitgleich bei einer Zunahme der visuellen Helligkeit beobachtet worden.

Referenzen:

- [1] http://astrospectroscopy.de/proceeding_Miroshnichenko.pdf
- [2] <http://arxiv.org/abs/1302.4021v1>
- [3] JAAVSO Volume 41, 2013
- [4] Richardson, N., D. et al., Astron. J., 141, 120
- [5] <http://astrospectroscopy.de/Recent%20Observation%20of%20zeta%20Tau.pdf>
- [6] Smith, M. A., et al., A&A, 540A, 53S, 2012
- [7] Stee, Ph., et al., A&A, 545A, 59S, 2012

Intermediate Report January 2013 Campaign: Photometry and Spectroscopy of P Cyg

(by Ernst Pollmann & Wolfgang Vollmann)

Introduction

The international observing campaign, Photometry and Spectroscopy of P Cyg, begun in 2008, is a co-operative project of the American Association of Variable Star Observers (AAVSO), Active-Spectroscopy-in-Astronomy (ASPA) and Bundesdeutsche Arbeitsgemeinschaft Veränderliche Sterne (BAV). One goal of the campaign is the monitoring of the behaviour of the H α -line equivalent width (EW) and the contemporaneous changes of the V-band magnitude of P Cyg. Another goal is to gather further information about the intrinsic flux of this spectral line.

P Cyg stars are characterized by very high luminosity and belongs to the spectral classes Ope to Fpe. Their irregular brightness variations, with time scales from weeks to months and to years, covers amplitudes up to several V magnitudes, connected with density inhomogeneity in their mostly spherical shell. P Cygni itself has been discovered on August 18th 1600, as its brightness suddenly had risen up to the 3th V magnitude. Also in the following century the star showed remarkable changes of brightness in the process from weeks to years, with occasional weakenings up to the limit of the visual visibility. Since 1786 no strong changes of the brightness did happen anymore. A slow brightness increase from 5.2 to 4.9 V magnitudes took place in the years 1786 to 1879. Since this

time the variable is a B1 super giant of the so called class the "luminous blue variable" (LBV-stars). Typically for these stars are the profiles of individual lines. They consist in the simplest case as an emission line with blueward shifted absorption component. Such profiles do point to a mass-loss of the star in form of a stellar wind. After the knowledge nowadays, P Cygni stars are in a development phase, which lies temporally before the Wolf-Rayet stage of massive stars. de Groot and Lamers could show [13] that the theory of this phase of development is applicable, and in further spectroscopic investigations by Lamers et al. [14], Makova [3-11] & Richardson et al. [12] the physically properties of P Cygni have been determined:

Spectral type: B1 Ia

$T_{\text{eff}} = 19300 \pm 2000 \text{ K}$

$R_{\text{star}}/R_{\text{sun}} = 76 \pm 14$

$L_{\text{star}}/L_{\text{sun}} = 5.86 \pm 0.3$

Details

In our campaign is assumed that the variability of the EW is caused by variations of the con-tinuum flux and not by variations of the line flux [3], which would indicate variations in the stellar wind density. Therefore, the variability of the continuum flux shall be our primary concern, when the properties of the stellar winds and rate of mass loss are studied. To find correlations of photometric to spectroscopic data, an AAVSO-call for observation was started at the beginning of the campaign, for measurements with photoelectric photometers (PEP) and DSLR measurements as well, based on the Johnson-V system. In the meantime 16 photometric observers are involved worldwide.

Photometric measurements

Fig. 1 shows the comparison of PEP-measurements (123) and DSLR measurements (141) until 4.Nov. 2012. Except for occasional outliers (which occurs in both) the observations on the 0.01mag accuracy level are rather alike on in the process.

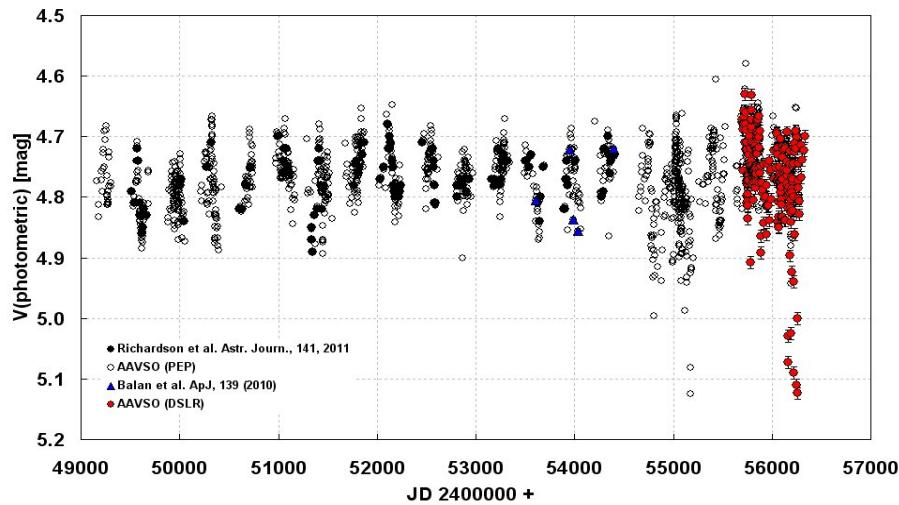


Fig. 1: Comparison of AAVSO-PEP observations with DSLR-observations

Photometric and spectroscopic changes in P Cygni seems to be weak anti-correlated on short- and long-term scales. We observed a total change of 35 Å in the equivalent width (EW) of the H α line and of ~ 0.25 magnitudes in the V-band brightness. Our observations extend from JD 2454671 (23 July 2008) through JD 2456244 (12 November 2012).

Results

Fig. 2 compares the time behavior of the V-brightness (upper) and the H α EW (lower) in our campaign. In addition the data from Richardson et al. [12] have been plotted. As can be seen, their used 20 day-average V magnitude does not recognize the quick variations, which was found very clear in our monitoring.

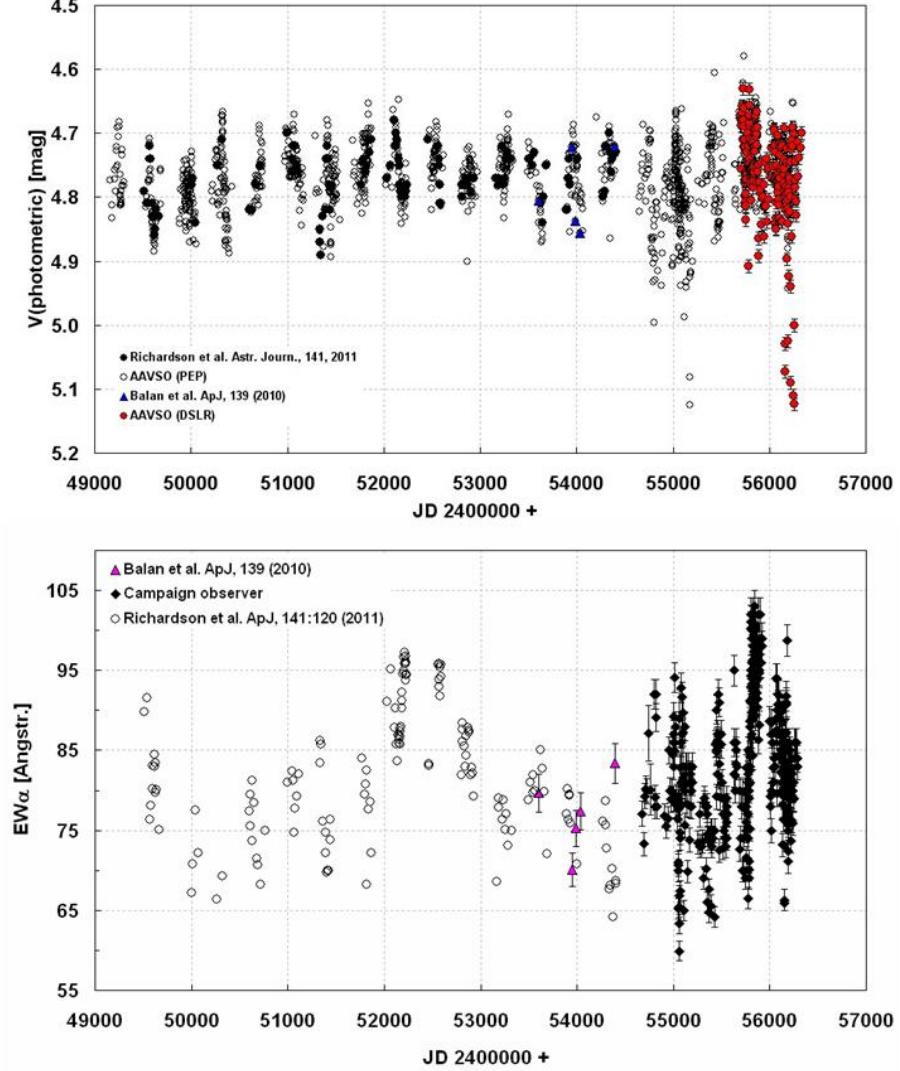


Fig. 2: Our photometric and spectroscopic observations of the V magnitude (upper) and the H α -EW (lower) during the campaign (including data of Balan et al. [1] & Richardson et al. [12]).

As can be seen in Fig. 2, when EW decreases, the contemporaneous stellar brightness increases and vice versa. Strict anti-correlation is expected if the variation of the continuum flux is independent from variations of the EW. If the H α line flux is constant over time, an increase of the continuum brightness will yield a smaller line flux from the measured EW and vice versa.

To find out if and how the flux obtained from the spectral line profiles varies, the EW measurements is corrected for continuum variations [2]. It is important to consider the absolute flux of the line because its variations are caused by the effects of mass loss, stellar wind density and changes of the ionization state of chemical elements in it. In the current campaign we have already obtained 170 nearly simultaneous measurements of the EW and the flux in the V-band.

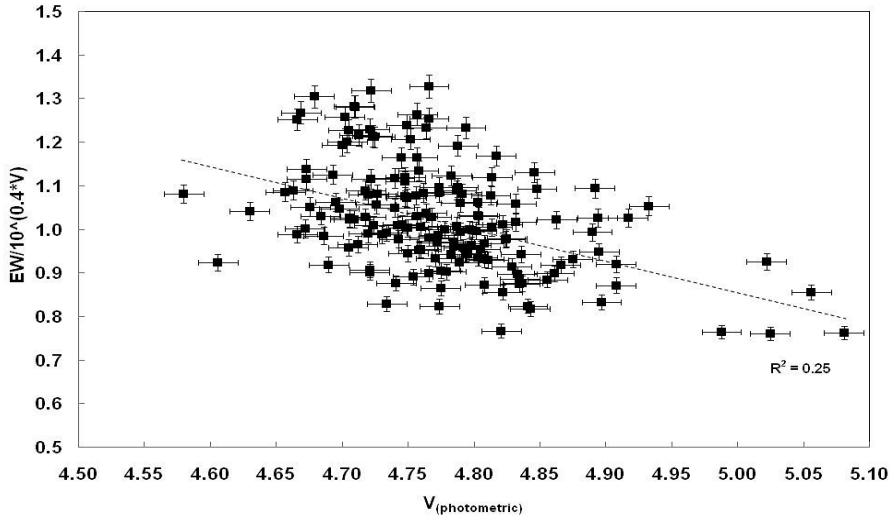


Fig. 3: Ha-line flux versus photometric V-brightness;
(170 contemporaneous measurements)

Fig. 3 attempts to display if and to what extent the intrinsic line flux (as continuum-corrected EW) depends on V-magnitude. From a statistical point of view one can say that the low 0.25 correlation coefficient (which should be zero after the continuum correction), with consideration of the measurement uncertainties, suggests the conclusion that the Ha line flux is independent of V-magnitude. Comparable investigations of this kind have been published by Richardson et al.[12]. The essential difference of these investigations (Fig. 3 of [3]) to our work is, that they used non-contemporaneous EW & Vphot for their consideration of correlations. Their selected 20-daily average shows a weakly suggested positive correlation, whereas our correlation result in Fig. 3 (this paper) does deliver an extremely small correlation coefficient of only 0,25 from 170 spectra. Thus, we have some doubts regarding the persuasive power of the positive correlation (which they found) of the relative flux with the interpolated magnitude. We would be very interested, together with the authors of [4], to perform a new, comprehensive analysis with the data from both investigations to clarify these circumstances. With consideration of the standard deviation and possibly other kind of errors, the temporal variation of the line flux of Ha in the plot of Fig. 4 will represent the result of variations in the mass loss rate, stellar wind density and changes of the ionization from August 2005 until November 2012. Although the data set of our monitoring of 170 spectra is of rather modest extent, we tried nevertheless to find a certain periodicity in the time behavior of the observed Ha line flux.

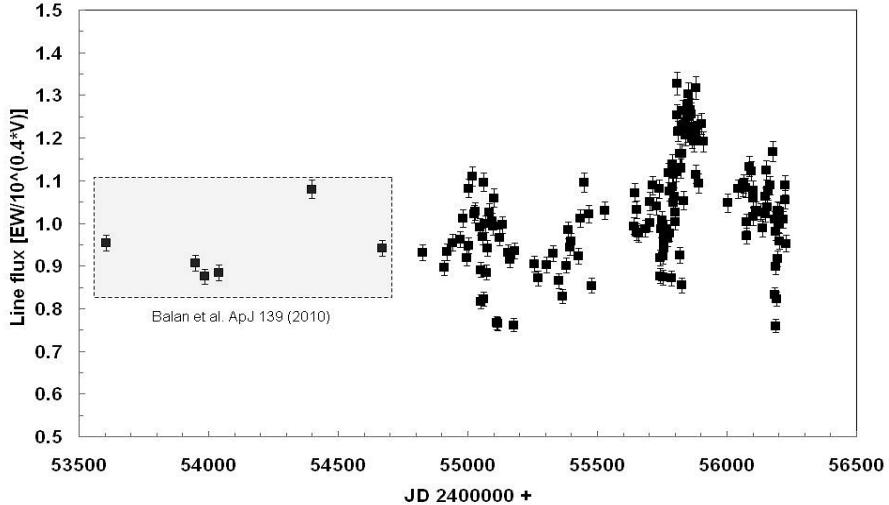


Fig. 4: The intrinsic Ha-line flux from
JD 2453605 (2005/08/22) to JD 2455911 (2012/11/12)

The usage of the period search program AVE did detect three dominant periods in the power spectrum, 242d, 363d and 600d (Fig. 5). Although the 600d period finds a certain confirmation in Markova's investigations about variability of the H α EW at [5], our data set is, so far, still too limited to give these three periods a greater degree of confidence.

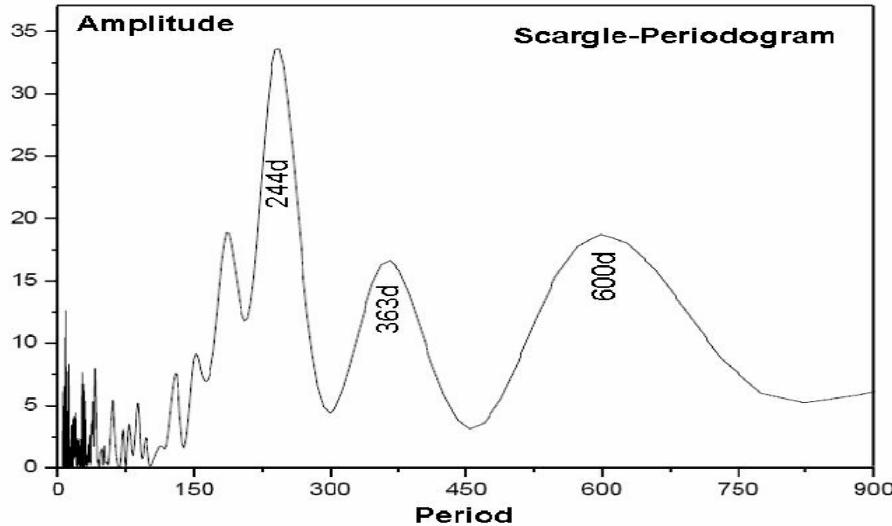


Fig. 5: Scargle periodogram with data from Fig. 4

Variations of the mass loss rate manifest themselves in P Cyg generally also in a varying absorption depth and proportionally to it in a varying emission strength of the HeI line at 6678 Å, which is developed in the helium-forming zones closer to the star due to its higher excitation potential.

While Markova preferentially investigated the correlations of velocity variations to variations of emission and absorption intensity in only 58 spectra at HeI λ 3926, λ 3867, λ 4471, as well as NII λ 4630 and Si IV λ 4116 [6], our more extensive spectrum collection (> 160 spectra from 2003 to 2012 at HeI λ 6678) does clearly show the variability of the emission and absorption intensity and their correlation to each other. Fig. 6 shows "extreme" HeI6678-spectra, taken between April 2003 and Nov. 2012 for illustration of the variability of the absorption depth and the emission strength as a consequence of a variable mass loss rate of the star (in units of the normalized continuum).

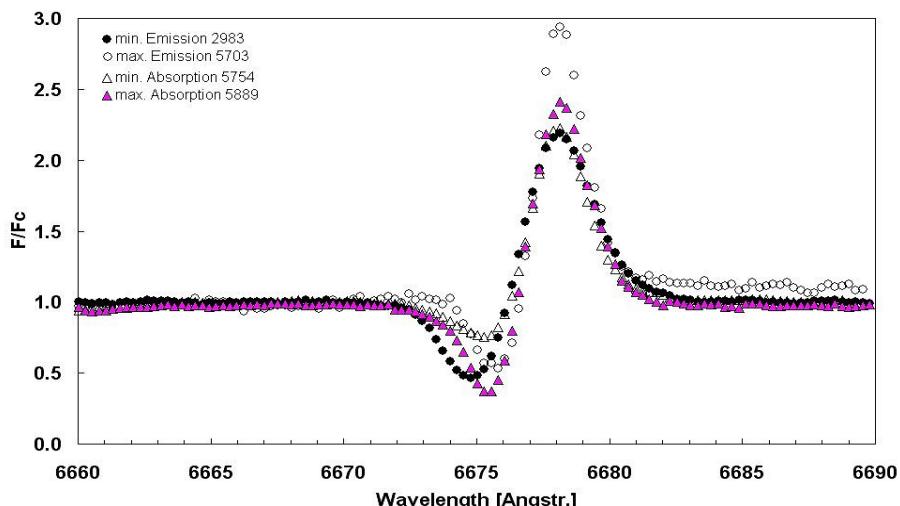


Fig. 6: Variability of the absorption depth and emission strength in extreme-profile-spectra (JD 2452983, 2455703, 2455754, 2455889)

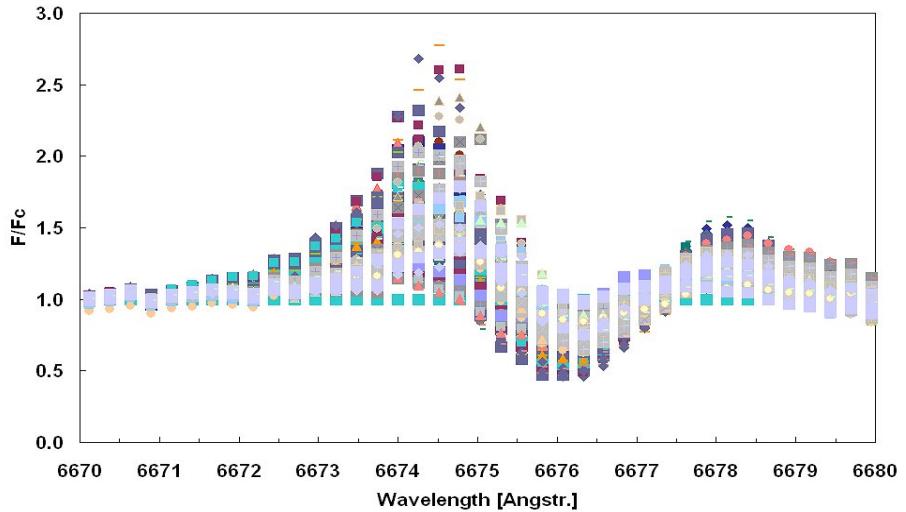


Fig. 7: Division spectra with absorption maximum at 6674.5 \AA related to a maximum-intensity-spectrum at JD 2455703

In the plot of Fig. 7 it can be clearly seen, that a portion of the profile at 6674.5 \AA varies 2.8/1.5 times stronger than the variation of the emission intensity at 6678.138 \AA .

The grey-scale diagram of the 100 spectra in Fig. 8 clarifies, that the absorption maximum around 6675 \AA is shifting with times towards shorter wavelengths and could be due to increasing optical depth as a result of increasing mass-loss.

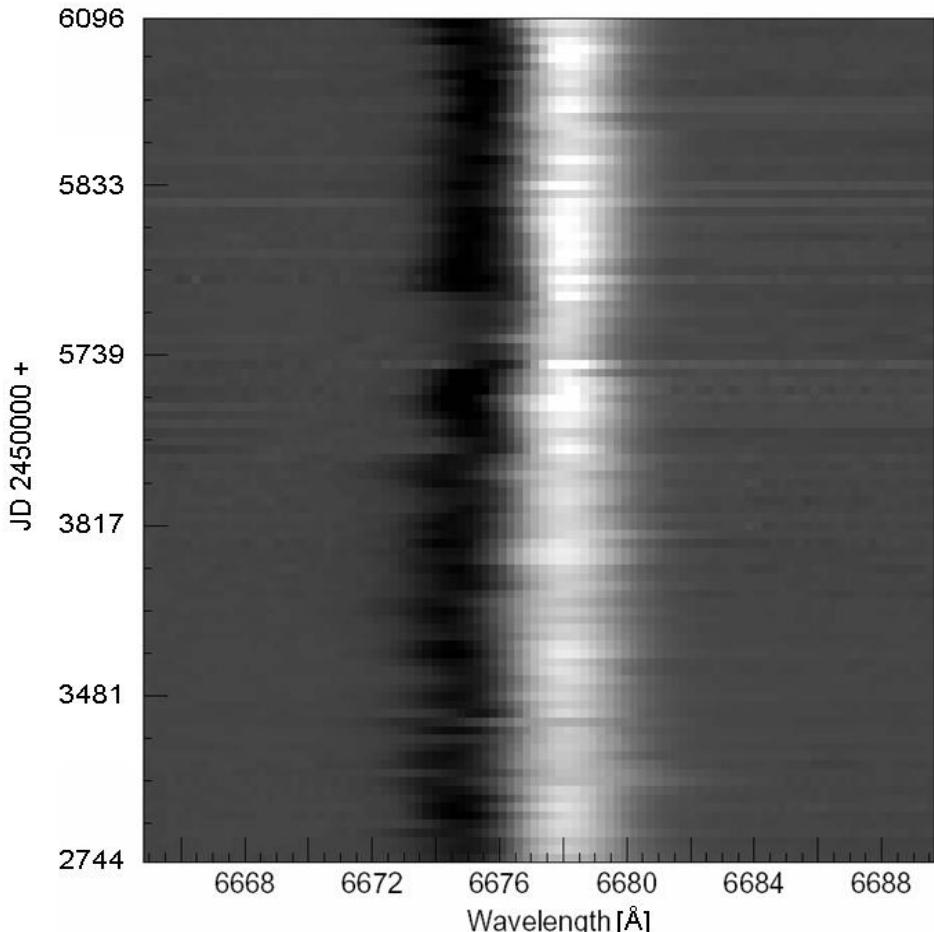


Fig. 8: The moving absorption maximum (around 6675 \AA) of the He6678 line profile with time. 100 Spectra sorted by Julian Date

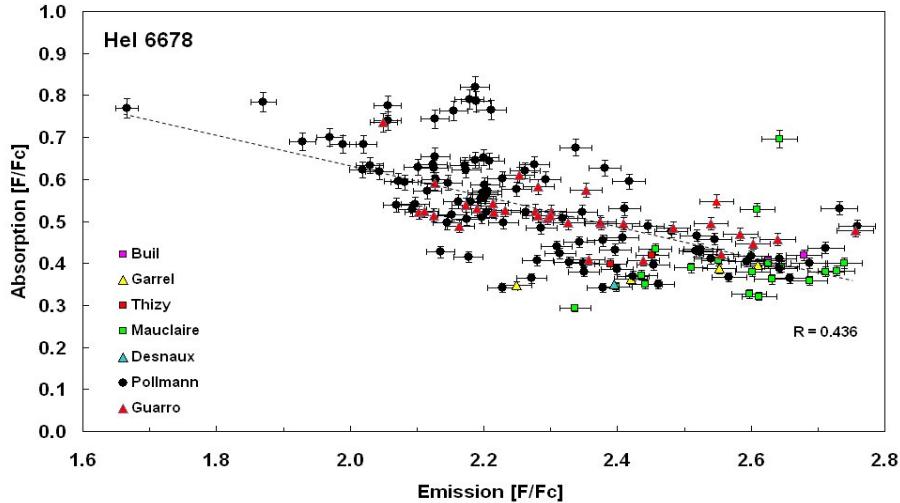


Fig. 9: Variability of the absorption depth versus emission strength of the HeI6678 line (April 2003 until Nov. 2012)

The plot of absorption depth versus emission strength in Fig. 9 shows, that both measured variables are related only with a correlation quality of ~ 0.44 . Even if the emission comes by recombination, one would expect that a higher density (= higher mass loss) produces both, more absorption and more emission. The small coefficient of correlation could therefore be an expression for not implausible temperature variations in the stellar wind, whereby the absorption can increase also without change of mass loss, thereby without the emission increases. The following observers took part at the project:

AAVSO (Vmagnitude):

Ormsby, R. E. Crumrine, J. Fox, K. Hutton, N. Stoikidis, D. Williams, E. G. Williams, Ch. L. Calia, Th. L. Peairs, J. G. Horne, M. Durkin, D. Loughney, W. Vollmann, G. Galli, E. Høeg, D. R. Garcia.

Spectroscopy (Hα-EW)

M. Fuji, B. Mauclaire, J. Guarro, B. Hanisch, E. Pollmann, Th. Garrel, V. Desnoux, O. Thizy, J. N. Terry, Ch. Buil, St. Charbonnel, P. Dubreuil, A. Lopez, Th. Lemoult, F. Teyssier, from literature: Balan et al. [6].

The data of EW, V(phot) and line flux are available at the following website:

http://astrospectroscopy.de/Data_PCyg_Campaign/Campaign_data_2013.txt

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Doppler tomography of the circumstellar disk of π Aqr.

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Received - ; accepted -

ABSTRACT

Aims. The work is aimed at a study of the circumstellar disc of the bright classical Be star π Aqr.

Methods. We analysed variations of a double-peaked profile of the H_{α} emission line in the spectrum of π Aqr that was observed during various orbital phases in 2004–2012. We applied the Discrete Fourier Transform (DFT) method to search for periodicity in the peak intensity (V/R) ratio. Doppler tomography was used to study the structure of the disc around the primary.

Results. The dominant frequency in the power spectrum of the H_{α} V/R ratio is $0.011873 \text{ day}^{-1}$ corresponding to a period of $84.2(2)$ days which is in agreement with the recently reported orbital period of the system, $P_{orb} = 84.1$ days. The V/R ratio shows a sinusoidal variation phase-locked with the orbital period. Doppler maps of all our spectra show a non-uniform structure of the disc around the primary: a ring with the inner and outer radii at $V_{in} \approx 450 \text{ km s}^{-1}$ and $V_{out} \approx 200 \text{ km s}^{-1}$, respectively, along with an extended stable region (spot) at $V_x \approx 225 \text{ km s}^{-1}$ and $V_y \approx 100 \text{ km s}^{-1}$. The disc radius of $\approx 70R_{\odot} = 0.33 \text{ AU}$ was estimated assuming Keplerian motion of a particle in a circular orbit at the disc outer edge.

Key words. binaries: spectroscopic — circumstellar matter — stars: emission-line, Be — stars: individual (π Aquarii) — techniques: photometric — techniques: spectroscopic.

1. Introduction

Classical Be stars are fast-rotating non-supergiant B-type stars with Balmer series emission lines in their spectra. The emission lines are explained in terms of recombination that occurs in a geometrically thin, equatorial,cretion circumstellar disc, according to a model first proposed by Struve (1931), then modified and further developed by many authors, and confirmed recently by direct interferometric observations (Quirrenbach et al. 1997; Gies et al. 2007; Carciofi et al. 2009; Grzenia et al. 2013). The relative intensity of the emission lines usually vary on time scales from days to decades and sometimes they may even disappear entirely. It is widely accepted that the origin of the variability is caused by processes occurring in the circumstellar disc and non-radial pulsations of the B-star photosphere (Porter & Rivinius 2003). Typically the dominant feature in Be star spectra is an asymmetric double-peaked H_{α} emission line.

Most Be stars exhibit variations in the ratio of the blue (violet) and red emission peaks (V/R variations) of the Balmer

emission lines on a time scale of a few years. A generally accepted explanation of these variations is global oscillations in the circumstellar disc caused by formation and evolution of a one-armed spiral density pattern that slowly precesses around the star (Kato 1983; Okazaki 1991, 1997). The main observational properties of the V/R variations and theoretical suggestions were summarized in Mennickent et al. (1997). The most complete compilation of Be stars showing the V/R variations contains 62 objects (Okazaki 1997). Eleven of them were known to be binaries at the time. The time scale of the V/R variations is typically much longer than rotational periods of the star or the disc and does not correlate with orbital periods of the binaries. However, some binary systems, φ Per (Bozic et al. 1995; Gies et al. 1998), V696 Mon (Peters 1972), 4 Her (Harmanec et al. 1976; Koubek et al. 1997), V744 Her (Doazan et al. 1982), κ Dra (Juza et al. 1991), ϵ Cap (Rivinius et al. 1999) and FY CMa (Rivinius et al. 2004) present an exception from the rule. For example, in the

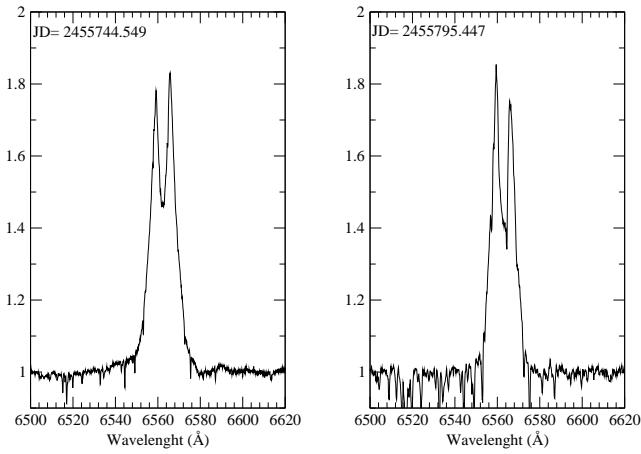


Fig. 1. V and R dominated examples of π Aqr H_α profiles. Epoch of observations are shown.

case of 4 Her, the V/R variations are orbital phase-locked and coherent over more than 80 cycles (Štefl et al. 2007).

π Aqr (HR 8539, HD 212571) is a bright, rapidly rotating ($v \sin i \approx 300 \text{ km s}^{-1}$) classical Be star with a variable mass loss. Analyzing its H_α line profiles and photospheric absorption during its discless phase in 1996–2001, Bjorkman et al. (2002) suggested that π Aqr is a binary system with an orbital period of $P_{\text{orb}} = 84.1$ days. The system consists of two stars with masses $M_1 \sin^3 i = 12.4 M_\odot$ and $M_2 \sin^3 i = 2.0 M_\odot$, and the orbit is viewed at an inclination angle of $50^\circ - 75^\circ$. The components mass ratio and separation are $M_2/M_1 = 0.16$ and $a = 0.96 \sin^{-1} i$ AU, respectively. Using the evolutionary tracks from Schaefer et al. (1993), the effective temperature $T_1^{\text{eff}} = 24000 \pm 1000$ of the primary component, and its luminosity $\log(L_{\text{bol}}/L_\odot) = 4.1 \pm 0.3$, (Bjorkman et al. 2002) estimated the primary's mass to be $M_1 = 11 \pm 1.5 M_\odot$.

Variability of the Balmer line profiles of π Aqr, which appeared double-peaked most of the time, have been reported by McLaughlin (1962) and Pollmann (2012). McLaughlin (1962) observed strong V/R changes ranging from 0.5 to 4.0, and several periods of absence of bright emission lines (1936–1937, 1944–1945, 1950). Based on the π Aqr spectra obtained between October 2004 and August 2011 together with the available spectra of the data base BeSS¹, Pollmann (2012) found a dominant frequency in the power spectrum of the V/R ratio that correspond to a period of 83.8 ± 0.8 days. This value coincides within the errors with the above mentioned orbital period of the system.

In this paper we attempt a new period analysis of the V/R variations in the H_α line profile of π Aqr and probe the disc structure based on spectroscopic observations obtained over multiple orbital cycles of the system. In Sect. 2 we describe our observations, in Sect. 3 period analysis of the H_α line profile variation is presented. The Doppler tomography of the system and modeling of the circumstellar disc are presented in Sect. 4.2, and the results and conclusion are presented and discussed in Sect. 5.

2. Observation and data reduction

Seventy two spectra were obtained in 2004–2006 with the 1.0 m telescope of the Ritter Observatory of the University of Toledo (Toledo, OH, USA) using a fiber-fed échelle spectrograph with a Wright Instruments Ltd. CCD camera. The spectra consisted

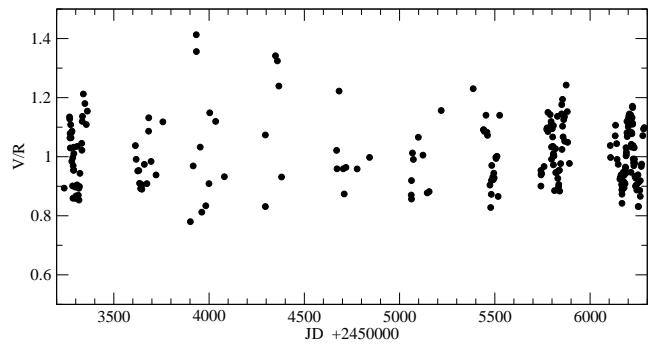


Fig. 2. Variation of V/R ratio of the H_α during reported observation.

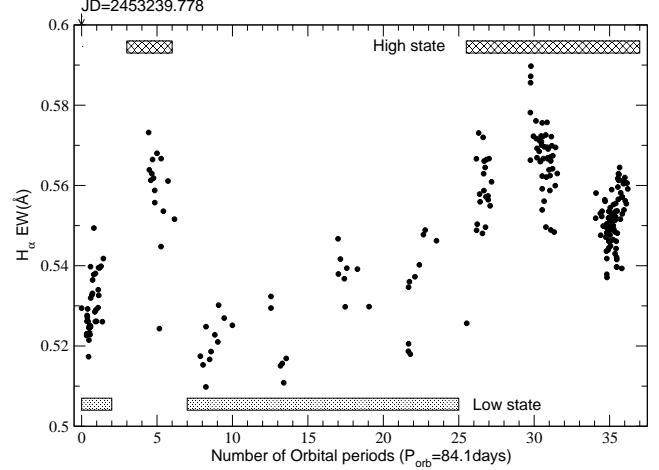


Fig. 3. The equivalent width of H_α emission line vs. of the orbital cycles of the system. The epoch of beginning of observations is shown too. The notes and bands in figure mark values of the H_α equivalent widths selected for "high" and "low" state.

of nine non-overlapping ~ 70 Å orders in the range 5285–6597 Å with $R \approx 26000$. Five spectra were obtained in September–December 2012 at the 0.81 m telescope of the Three College Observatory (near Greensboro, NC, USA) using a fiber-fed échelle spectrograph manufactured by Shelyak Instruments and an SBIG ST-7XMEI CCD camera. The spectra cover a range 4600–7200 Å with a $R \approx 10000$. These data were reduced with IRAF².

The amateur community contribution to the campaign involved 14 observers from Germany, France, Spain, Mexico, Switzerland, and the USA. They used 0.2 m to 0.4 m telescopes with long-slit (in most cases) and échelle spectrographs with a spectral resolving power from $R = 1000$ to $R = 22000$. Data reduction was performed using MaxIm-DL 3.06 (Diffraction Limited, Sehgal Corp.) for Pollmann's data, while the most other amateurs data were reduced with software packages developed for amateur spectrographs, such as VSpec³ and IRIS⁴. Spectral line parameters were measured with the spectral classification software package MK32⁵. No systematic difference in the V/R ratios or the H_α line equivalent widths (hereafter EW_{H_α}) were found between professional and amateur data.

² IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

³ <http://www.astrosurf.com/vdesnoux/download.html>

⁴ http://www.astrosurf.com/buil/isis/isis_en.htm

⁵ <http://www.appstate.edu/~grayro/MK/MKbook.html>

¹ <http://basebe.obspm.fr/basebe>

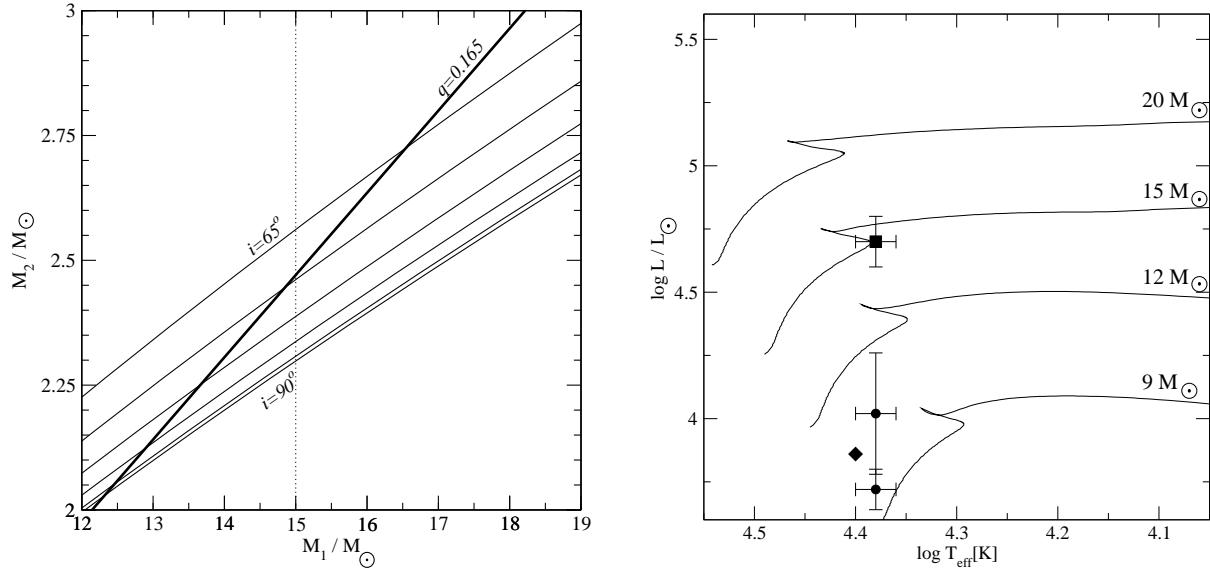


Fig. 5. **Left panel:** M_2 vs M_1 relationships for different inclination i of the system orbital plane obtained from the mass function $f(M) = \frac{K^3 P_{\text{orb}}}{2\pi G} = 0.041 M_\odot$. The inclination range is 65° — 90° with a step of 5° from top to bottom. The solid-line corresponds to mass ratio of the system $q = 0.165$. Main-sequence stars with $T_{\text{eff}} = 24000\text{K}$ are located the left from the dotted-line. **Right panel:** A Hertzsprung-Russell diagram with recent determinations of fundamental parameters of π Aqr. Solid lines show evolutionary tracks of stars with rotation from Ekström et al. (2012). Initial masses are indicated by numbers at the corresponding track. Filled circles show the positions based on the luminosity calculated using the two HIPPARCOS distances (see text), the diamond shows data from Hohle et al. (2010), and the filled square shows parameters adopted in this paper.

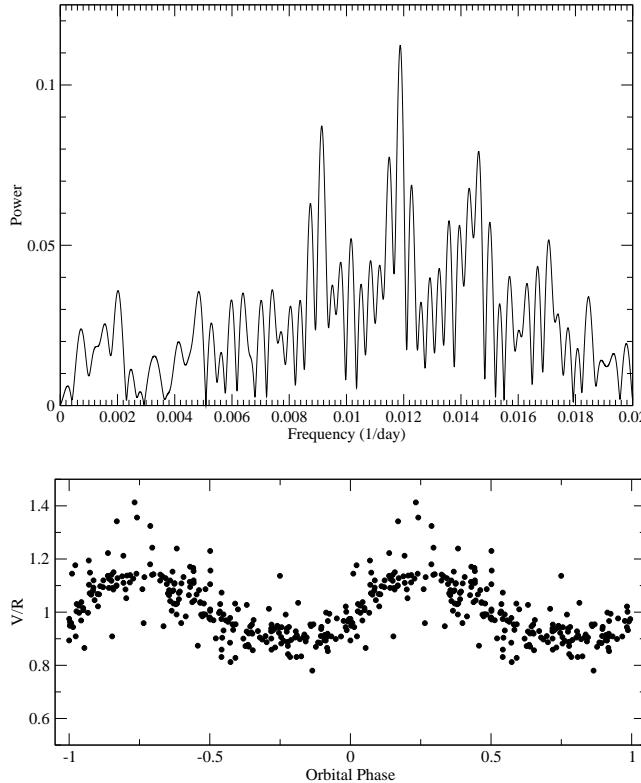


Fig. 4. Top). The power spectrum of V/R variation. Bottom) The V/R ratio folded on the orbital period of the system 84.1 day. $\phi_{\text{orb}} = 0.0$ corresponds to the inferior conjunction of the secondary.

3. Variability of the H_α line

As noted before, the H_α line profile of π Aqr is double-peaked and strongly variable. Examples of the H_α line profile for two

epochs of observations are shown in Figure 1. We measured the V/R ratio in the H_α emission line using peak intensities of the V and R components which were separately fitted with a single gaussian. The values of the V/R ratio vary in the range of 0.8 — 1.2 (Fig. 2) and do not correlate with EW_{H_α} (Fig. 3). The latter ranges between 0.52 and 0.58 Å and shows no periodicity. We refer to the spectra with a stronger H_α line ($\text{EW}_{H_\alpha} \geq 0.54\text{\AA}$) as to a “high state” and to those with a weaker H_α line as to a “low state” for the following analysis. The Discrete Fourier Transform (DFT) method⁶ was used to search for periodicity in the V/R variation during our observations. The dominant frequency in the power spectrum is $0.011873 \pm 0.000028 \text{ day}^{-1}$ corresponds to a period of 84.2 ± 0.2 days that is in agreement with the system orbital period of $P_{\text{orb}} = 84.1$ day found by Bjorkman et al. (2002). The resulting power spectrum and the V/R ratio folded with the dominant frequency are presented in Figure 4. Therefore, we conclude that the V/R variations in π Aqr are locked with the orbital period, at least on a time scale of ≈ 3000 days or 35 orbital cycles. The shape of the V/R variation curve is sinusoidal.

4. Doppler tomography and Disk model.

4.1. System parameters

There is an apparent discrepancy between the dynamical and the evolutionary mass of the system that was outlined, but not resolved by Bjorkman et al. (2002). A system brightness during the discless epoch (1996–2001), $V = 4.85$ mag, along with an interstellar extinction of $A_V = 0.15$ mag and a HIPPARCOS distance $340^{+105}_{-70}\text{pc}$ (Perryman & ESA 1997) result in an absolute visual magnitude of $M_V = -2.96^{+0.50}_{-0.58}$ mag, while a more recent distance 240^{+17}_{-15}pc (van Leeuwen 2007) gives an $M_V = -2.20^{+0.15}_{-0.16}$ mag. Applying a bolometric correction of

⁶ <http://www.univie.ac.at/tops/Period04/>

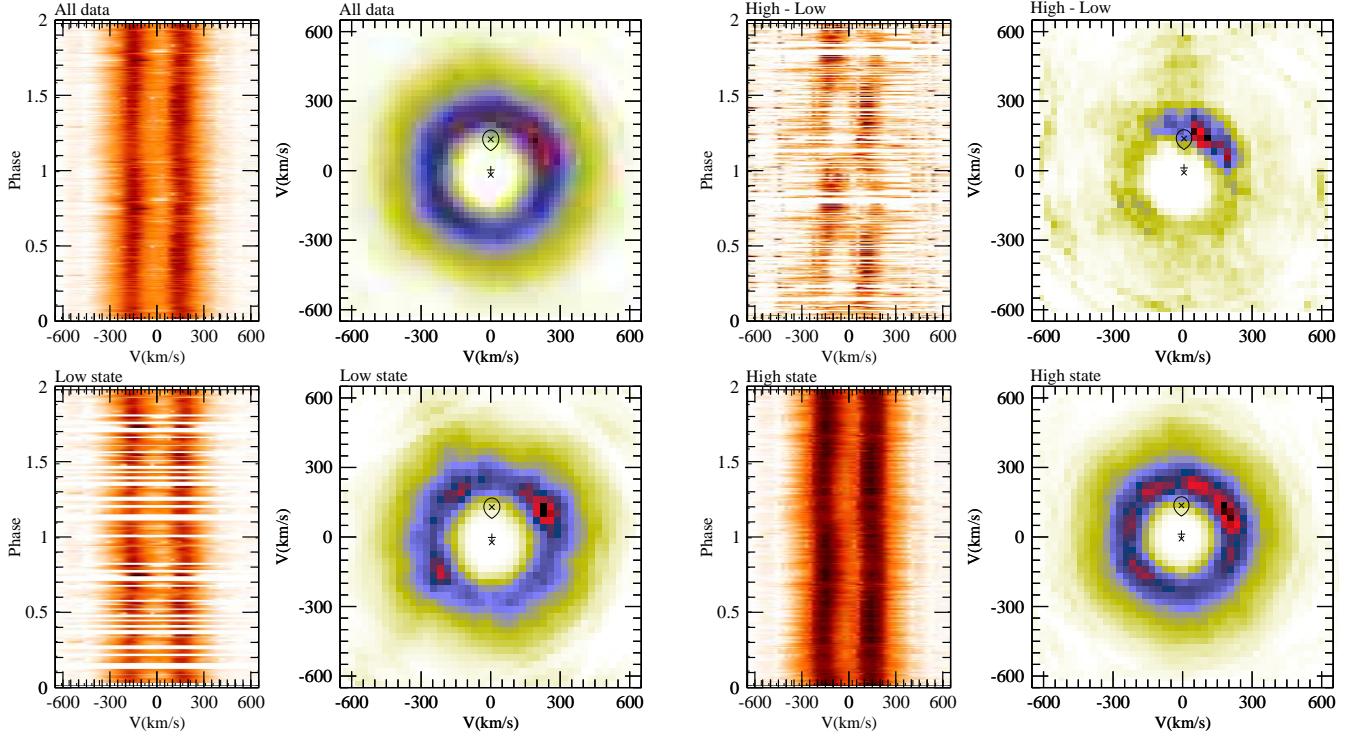


Fig. 6. The trailed spectra around H_{α} line folded with the orbital period of the system and the corresponding Doppler maps are shown. The orbital period of $P_{orb} = 84.1$ days, the primary mass of $M_1 = 14.0M_{\odot}$, and the mass ratio of $q = 0.16$ are used to overlay positions of the stellar components on the Doppler maps. The inclination angle $i = 70^{\circ}$ is arbitrarily chosen based on suggestions by Bjorkman et al. (2002). $\phi_{orb} = 0.0$ corresponds to the inferior conjunction of the secondary.

$BC_V = -2.36 \pm 0.10$ mag for $T_{eff} = 24000 \pm 1000K$ (Miroshnichenko 1997), one gets a luminosity of $\log L/L_{\odot} = 4.02 \pm 0.24$ for the larger distance and $\log L/L_{\odot} = 3.72 \pm 0.08$ for the smaller one. The location of these fundamental parameters in the Hertzsprung-Russell diagram (Fig.5, left) correspond to the evolutionary masses of $10.5 M_{\odot}$ and $9.5 M_{\odot}$, respectively (Ekström et al. 2012). Both these values are noticeably lower than the primary's dynamical mass $M_1 \sin^3 i = 12.4 M_{\odot}$ from Bjorkman et al. (2002). Since the radial velocity curves of both companions were well-established over the entire discless period, the dynamical mass seems to be more reliable than the evolutionary mass. For the most probable orbital inclination to the line of sight is $i = 65 - 85^{\circ}$ (Bjorkman et al. 2002), the primary's mass range comes to $12.5 - 17.0 M_{\odot}$ (Fig.5, right). This mass range requires a higher luminosity for the system. However, according to new evolutionary models with rotation taken into account (Ekström et al. 2012), a star with $T_{eff} = 24000K$ gets beyond the main-sequence if its mass exceeds $\sim 15 M_{\odot}$. As Be stars are considered to be main-sequence objects (e.g., Frémat et al. 2006), we therefore adopt a mass of $14.0 \pm 1.0 M_{\odot}$ for the primary. This constrains its luminosity at $\log L/L_{\odot} = 4.7 \pm 0.1$, which in turn leads to $M_V = -4.64 \pm 0.25$ mag and a distance of 740 ± 90 pc. A separate study of stars near the object's line of sight (which is beyond the scope of this paper) is needed to verify this result. Nevertheless, the mass adjustment will only change the circumstellar disc scale, but not the qualitative results of our modelling. In Table.1 we present summary of adopted parameters of π Aqr binary system.

Table 1. Adopted parameters of π Aqr.

Period	84.1(1) days
M_1	$14.0(1.0) M_{\odot}$
T_{1}^{eff}	$24000(1000)$ K
$\log L/L_{\odot}$	4.7(1)
R_1^{*}	$13.0(1.4) R_{\odot}$
v_c	453 km s^{-1}
M_V^{*}	-4.64(25)
q mass ratio	≥ 0.165
i system inclination	$65^{\circ}-85^{\circ}$
M_2	$2.31(16) M_{\odot}$
a separation	0.96 AU
Distance	740(90) pc

* based on L/L_{\odot} and T_1^{eff}

1σ uncertainties are given in parentheses.

4.2. Doppler tomography

The H_{α} line profiles of π Aqr were recorded at various orbital phases of the system. Our finding that the V/R variations are locked with the orbital period suggests an idea that the H_{α} line profile variability is caused by a complex structure in the circumstellar disc. We used Doppler tomography (Marsh & Horne 1988) to study the structure of the disc around primary in π Aqr. The Doppler maps were built by combining time-resolved spectra of the object using the maximum entropy method as imple-

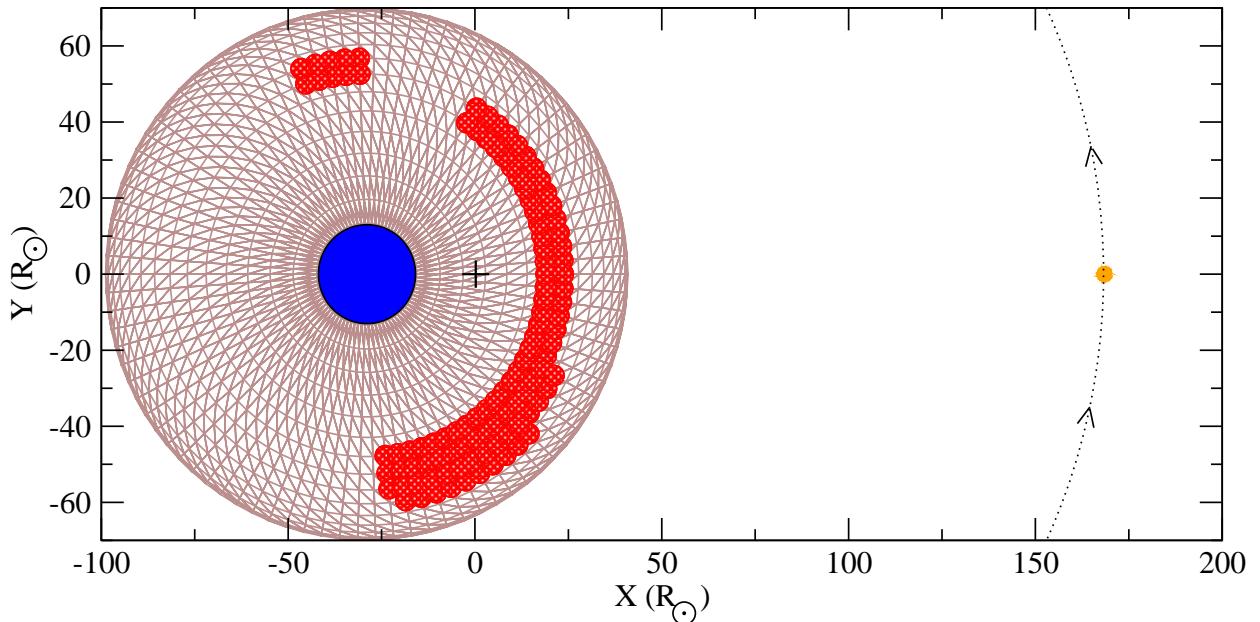


Fig. 7. The geometrical model of π Aqr. The blue and orange filled circles mark the primary and the secondary, respectively. The decreton circumstellar disc is shown in brown colour. The red regions in the disc are constructed on the basis of the Doppler tomography and correspond to a one-armed spiral density pattern. Scales of both axes are given in solar radii. Arrows show the direction of the binary rotation, and the cross indicates the centre of mass of the system. Parameters of the system are given in Table 1.

mented by Spruit (1998)⁷. Figure 6 shows trailed spectra around the H_{α} line and their corresponding Doppler maps of all spectra (top, left panel), “low” (low, left panel) and “high” (low, right panel) states, and a difference between each spectrum in a “high” and the average spectrum in the “low” state (top, right panel). The orbital period of $P_{\text{orb}} = 84.1$ days, the primary mass of $M_1 = 14.0 M_{\odot}$, and the mass ratio $q = 0.16$ (Table 1) are used to overlay positions of the stellar components on the Doppler maps. The inclination angle $i = 70^{\circ}$ is arbitrarily chosen based on discussion in the previous section. $\phi_{\text{orb}} = 0.0$ corresponds to the inferior conjunction of the secondary. The location of the main components in the system, such as the position of the centre of mass, the primary, the secondary, and the Roche lobe of the secondary star, are indicated. The Doppler maps of all spectra show a non-uniform structure of the disc around the primary: a ring with the inner and outer radii at $V_{in} \approx 450 \text{ km s}^{-1}$ and $V_{out} \approx 200 \text{ km s}^{-1}$, respectively, together with an extended stable region (spot) at $V_x \approx 225 \text{ km s}^{-1}$ and $V_y \approx 100 \text{ km s}^{-1}$. We note that $EW_{H_{\alpha}}$ is a function of the total flux and surface brightness distribution of the disc. The “spot” is brighter and more extended in the “High” state compared to the “Low” state. However, the brightness of the extended region is significantly lower than the total disc brightness and corresponds to an S-wave that can be seen only in “High-Low” trailed spectra. The disc radius of $\approx 65 R_{\odot} = 0.33 \text{ AU}$ was estimated assuming Keplerian motion of a particle in a circular orbit at the disc outer edge.

Based on the results of the Doppler tomography the geometrical model of the π Aqr system is presented in Figure 7.

5. Discussion and Conclusion

In this paper we attempted a new period analysis in the V/R variations in the H_{α} line profile of π Aqr and probe the primary’s circumstellar disc structure, based on spectroscopic observations

obtained over multiple orbital cycles of the system. The main conclusions of our data analysis are:

— We re-analyzed fundamental parameters of the system. We found that primary star has a mass of $M_1 = 14 \pm 0.1 M_{\odot}$ and a radius of $13.0 \pm 1.4 R_{\odot}$. The latter is nearly twice as large as that of a ZAMS star with the same mass. The inclination of the system is enclosed in the range of $65^{\circ} - 85^{\circ}$ degrees.

— The V/R variations for the H_{α} line of π Aqr shows a sinusoidal behaviour with a period that coincides with the orbital period of the system. Therefore, based on the results of Bjorkman et al. (2002), Pollmann (2012), and the analysis presented here we propose to include π Aqr in the list of Be binaries that show orbital phase-locked V/R variations. The V/R variations reported here were coherent over more than 35 cycles.

— There is an S-wave in the H_{α} trailed spectra, and the Doppler tomograms demonstrate a corresponding bright extended spot within the circumstellar disc. The radius of the primary’s circumstellar disc is $\sim 65 R_{\odot}$. The spot is located in the outer part of the disk that faces the secondary. The position of the spot in the disk is stable, but its relative intensity correlates with the $EW_{H_{\alpha}}$ value. In general, the structure of the spot looks like a one-armed spiral density pattern. However, there is a faint hint of the second arm at the opposite side of the disc. The brightest part of the spot begins at $\approx -90^{\circ}$ from the major axis of the system and continues to $\sim 120^{\circ}$ counterclockwise with decreasing intensity (Figures 6 and 7).

Long-term V/R variations in Be stars are well explained by a model of global one-armed oscillations in the equatorial discs first proposed by Kato (1983) and developed by Okazaki (1991, 1997). In this model the one-armed perturbation slowly (on a time scale of ~ 10 years) precesses in the opposite direction to the semi-Keplerian motion as a result of pressure forces in the

⁷ <http://www.mpa-garching.mpg.de/~henk/pub/dopmap>

disc. Taking into account deviation from a $1/r$ point potential leads to a slowly revolving prograde oscillation mode also with a very long time scale semi-periods (Papaloizou et al. 1992). The following studies include other effects, although the number of free parameters and their large range lead to a low predictive power of these models (Fiřt & Harmanec 2006).

A significant number of Be stars are binary systems (Porter & Rivinius 2003; Oudmaijer & Parr 2010; Miroshnichenko 2011). Nevertheless, in the current models, the oscillation period weakly depends on the orbital parameters. For example, Oktariani & Okazaki (2009) found that the oscillation period increases with increasing binary separation and/or decreasing binary mass ratio. However, two well-established examples of orbital phase-locked systems 4 Her and π Aqr have relatively large separations and small mass ratios 0.06–0.016 (Koubsky et al. 1997) and 0.165 (Bjorkman et al. 2002), respectively. Therefore, we must underline that, in fact, there is a number of Be systems with phase-locked V/R variations, but no explanation currently exists for this phenomenon within the framework of the one-armed oscillation model. It is likely that careful accounting of tidal effects from the secondary on the structure of acretion circumstellar disc can improve the situation. In any case, it is very important to continue observing π Aqr and other phase-locked systems spectroscopically, photometrically, and interferometrically to search for more clues to their nature.

Finally, the data, presented in this paper, manifest a further increasing role of the amateur spectroscopy in stellar astrophysics (c.f., Miroshnichenko et al. 2013).

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