Hα line profile study during periastron passages of the companion in the binary star Pleione

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Abstract: *Medium-resolution spectroscopy of the binary system 28 Tau (Pleione), obtained over the time period October 2004 (JD 2453300) to January 2020 (JD 2458 852) by the ARAS Spectroscopy Group and the "Three College Observatory" (University of North Carolina at Greensboro), has been used to determine the central depression depth (CA), V/R ratio and equivalent width (EW) of the Hα emission. We found an exact temporal coincidence of the CA maxima with the minima of V/R and EW caused by gravitational influence of the companion star during the periastron passages.This had never been observed during the maximum shell phase in the years around 1980, nor during the initial shell phase around August to October 1974.*

Mittelauflösende Spektroskopie am Doppelsternsystem 28 Tau (Pleione), durchgeführt im Zeitraum Oktober 2004 (JD 2453300) bis Januar 2020 (JD 2458 852) von der ARAS Spectroscopy Group und dem „Three College Observatory“ (University of North Carolina) in Greensboro) diente der Bestimmung der Tiefe der zentralen Absorption (CA), des V/R-Verhältnisses und der Äquivalentbreite (EW) der Hα-Emission. Wir fanden eine genaue zeitliche Übereinstimmung der CA-Maxima mit den Minima von V/R und der EW, die durch den Gravitationseinfluss des Begleitsterns während der Periastronpassagen verursacht wurden. Dies war weder während der maximalen Shell-Phase in den Jahren um 1980, noch während der ersten Shell-Phase von August bis Oktober 1974 beobachtet worden.

Introduction

Circumstellar envelopes in Be stars must possess a cylindrical symmetry in accordance with their polar axes of rotation. More specifically, the envelope must be a rather thin disk because stellar light directed toward the observer is not absorbed by the disk in most cases (Hanuschik, 1995). At high angles of inclination, very narrow absorption lines under the continuum are often observed in addition to the central intensity.

These types of absorption lines are also called shell lines, although it seems that these shell lines are based on a simple perspective effect. If the observer's line of sight in the direction of the central star intersects areas of the disk at high angles of inclination, shell-type absorptions can occur. But other mechanisms are also capable of causing central depression in the Hα double peak emission:

- shear broadening caused by anisotropic Doppler gradients in rotating disks that are seen at a high angle of inclination (Horne & Marsh, 1986)
- obscuration of rear parts of the disk by the central star
- shell-type absorption

These three effects predominate at high angles of inclination and lead to a "lower-than-usual" central depression. However, only the last effect is a real shell absorption of the photospherical light by the disk and leads to a central line intensity below the adjacent continuum. Silaj et al. (2010) found that Hα profile types do not uniquely determine the inclination angle *i* of a Be star + disk system. They found that many singly-peaked spectra were best represented by a model created at i = 45◦, and that many doubly-peaked spectra were best represented by a model created at i = 20◦, which further indicates that the Hα profile type is not solely a function of *i*. It is simply not possible to assign inclination angles from Hα profile types alone.

Pleione (28 Tau, HD 23862) is a B8Vpe star (Hoffleit & Jaschek, 1982) and a member of the Pleiades cluster. Hα emission was first detected in 28 Tau by Pickering (1890). It has been known to exhibit prominent long-term spectroscopic variations and cyclic changes in its spectrum from a Be phase to a Be-shell phase since the 19th century. Since 1938, an alternation of Be-shell and Be phases has been reported with a 35-36 year cycle. A comprehensive summary of observations of this star is given in Hirata (1995) and Hirata et al. (2000).

The variations of the spectrum of 28 Tau from 1938 to 1975 have been described in detail by Gulliver (1977), who gives a well documented bibliography of the star. Because of the periodic changes in the spectral characteristics of a Be phase to a Be-shell phase (and back), and because the disk “for some reason” (probably caused by the companion star in the periastron) is not in the equatorial plane but slanted to the equator and precesses around the central star, corresponding variations of the Hα line profile are observable (Hummel, 1998).

Katahira et al. (1996) analyzed shell RV´s from the two consecutive shell phases separated by some 34 years, and concluded that 28 Tau is a spectroscopic binary with an orbital period of 218 days. The forming of a new disk and observation of the Hα EW and the line wings between November 2005 and May 2007 have been impressively documented by Katahira et al. (2006), Tanaka et al. (2007) and Iliev (2000).

The ARAS spectroscopy community (http://www.astrosurf.com/aras/) has been investigating the change of the V/R ratio and the radial velocity (RV) of the Hα double peak profile since 2012 (Pollmann, 2015). The RV results in that investigation agreed very well with those of Katahira et al. (1996) and Nemravova et al. (2010).

The observation and study of the Hα emission line and its profile of this binary system reveal at least five types of variabilities:

1. the equivalent width (EW)
2. the red and blue line wings
3. the intensity ratio of the V-to-R component of the Hα line profile
4. the radial velocity (RV)
5. the central depression depth (CA)

Fig. 1 shows the variation of the Hα line profile at some typical epochs:

1974: the early shell phase
1981: the shell maximum phase
1999: the Be phase with maximum emission
2004: the Be phase

One can readily see that the profiles changed from the edge-on type (shell-line profile) to the surface-on type (wine-bottle type), implying that the disk inclination angle changed significantly.

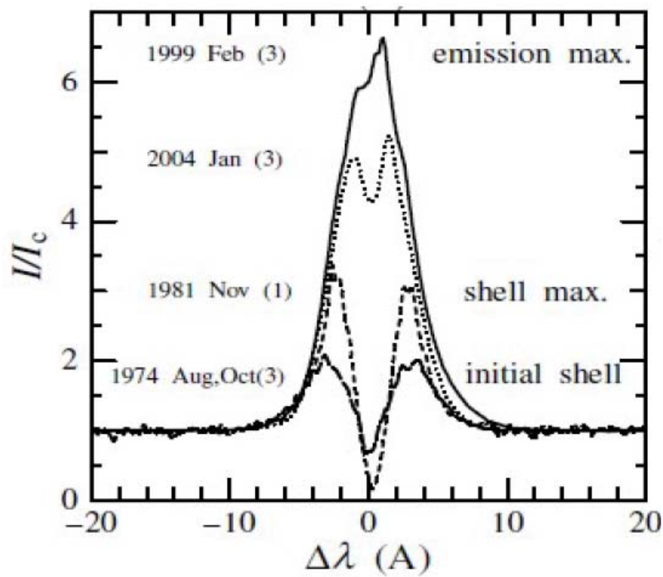

Fig. 1: Variation of the Hα line profile at some typical epochs
(with kind permission of R. Hirata, ASP Conference Series, Vol. 361, 2007)

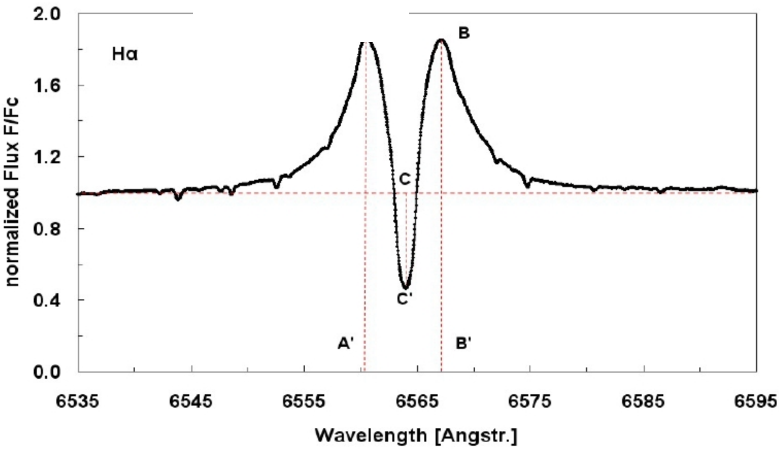

Fig. 2: Measured quantities illustrated on an Hα line profile: (AA') and (BB') emission peaks, depth of the central depression (CC'). The horizontal line marks the normalized continuum.

The depth of the Hα CA is defined as the difference between the local continuum level (equal to unity) and the minimum value at the line minimum intensity (Fig. 2). While the Hα emission line samples the disk as a whole, the region probed by the shell lines, represented by the depth of the central depression CC', is restricted to the line of sight. The diagnostics they provide should not be ignored, as their properties reflect the structure and dynamics of the disk in the observer's direction.

In the literature it is assumed (Schaefer et al. 2010) that the changes in CA are caused by a different angle or density distribution of the disk plane with respect to the observer´s line of sight, as a consequence of the disk precession around the primary star. Since 28 Tau is a binary, any tilt or change in the projected position angle of the disk may be modulated by the tidal force of the companion (Martin, et al. 2011).

Observation and Results

Despite the results of Silaj et al. (2010) mentioned above, we try to understand the variation of the central depression CA, caused by a one-armed spiral structure may form during periastron passages (Hayasaki & Okazaki 2004, 2005), as well as the profile parameters EW and V/R in relation to the influence of gravity of the companion star during the periastron passages. In the following, we describe the observed, simultaneous changes of these parameters, which in our understanding are mutually confirmed without contradiction.

For the investigation presented here, more than 430 representative spectra of the time span October 2004 (JD 2453300) to January 2020 (JD 2458852) were taken from the data bases of AAVSO, BAA and BeSS. The Hα spectra were obtained with 0.2m to 0.4m telescopes with a long-slit (in most cases) and echelle spectrographs with resolutions of R = 10000-20000. All spectra included the 6400−6700 Å region, with a S/N of ~100 for the continuum near 6600 Å.

The spectra have been reduced with standard professional procedures (instrumental response, normalization, wavelength calibration) using the program VSpec and the spectral classification software package MK32. Fig. 3 summarizes the long-term monitoring of all above-mentioned parameters: EW, CA and V/R.

The increase of the EW (Fig. 3a) with a simultaneous decrease of CA (Fig. 3b) during each individual periastron phase means that due to the tidal torque from the companion (Martin, et al. 2011), the Hα line intensity may become larger and the emission peaks (V and R) become closer, showing a variable intensity behaviour (Fig. 3c), because of the disc density increase.

So, during each periastron passage, the parameter EW, V/R and CA periodically offer the opportunity to evaluate the typical, characteristic change of each, in agreement with the others. All the mutual confirmations of these parameters are shown in the spectra, a process that repeats every time during the periastron passage of the companion star.

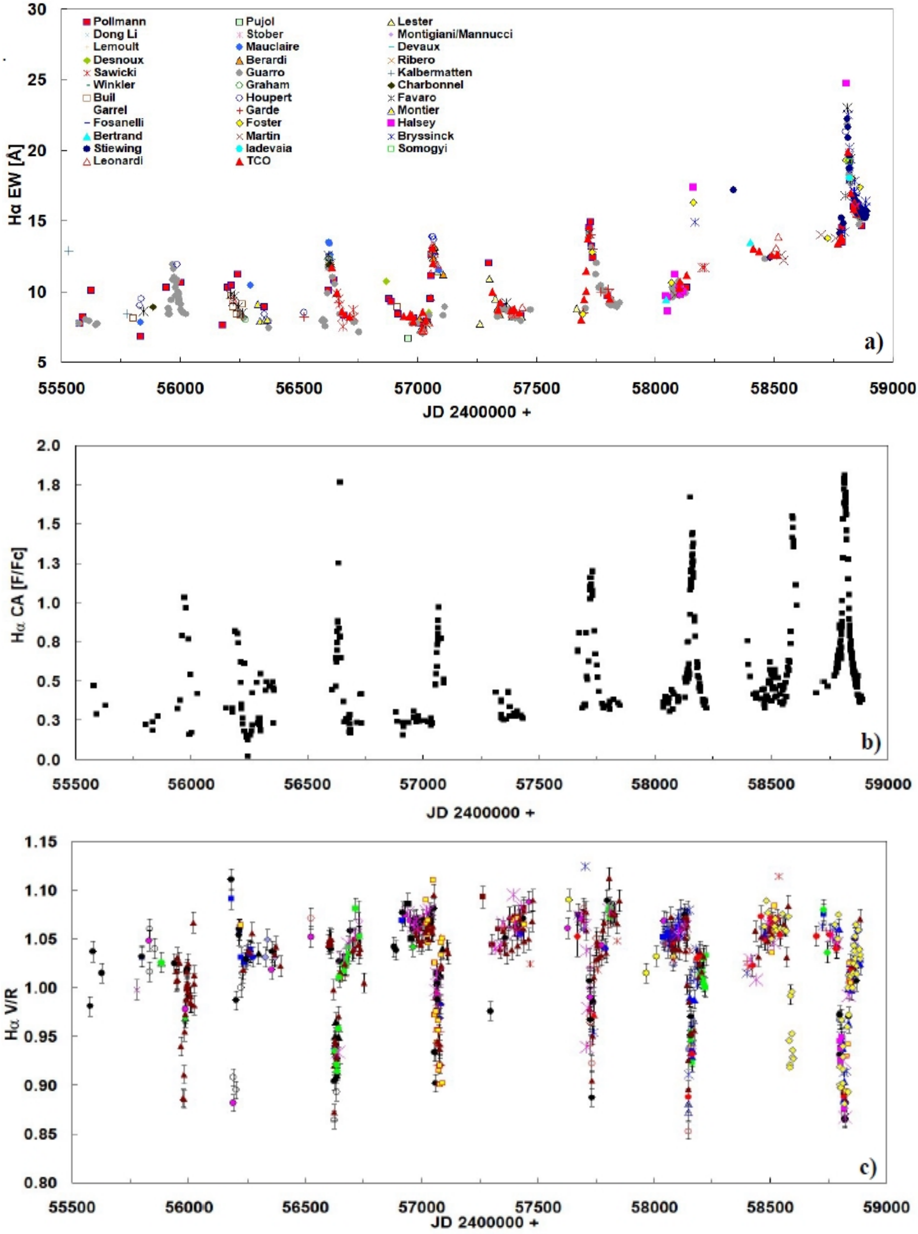

Fig. 3: Simultaneous changes of the disk Hα parameter EW, CA, V/R, during periastron passages from December 2010 to February 2020

The clearly pronounced periodicity of the parameter CA suggests, of course, doing a period analysis. This is shown in Fig. 4 as periodogram and as phase diagram in Fig. 5.

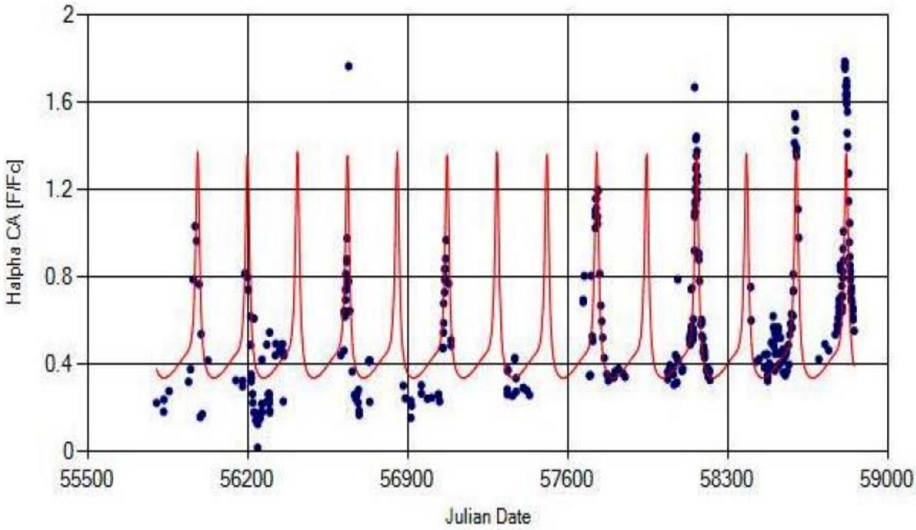

Fig. 4: Period analysis of the Hα profile parameter CA
for 14 periastron passages; Period = 218.0167 d (± 0.0732)

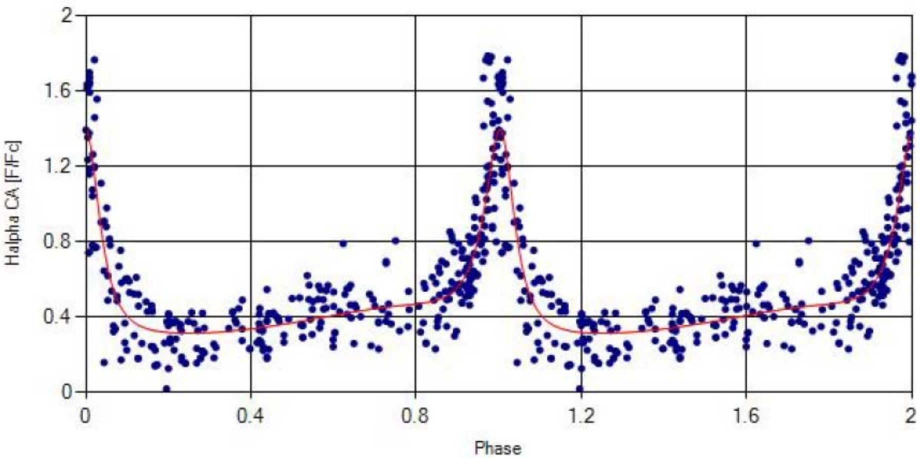

Fig. 5: Phase diagram of the found period in Fig. 4

This period of 218.0167 days agrees very well with the period of the V/R ratio and the shell radial velocity found by Katahira et al. (1996), Nemravova et al. (2010) and Pollmann (2015). Katahira et al. (1996) analyzed shell RV´s from the two consecutive shell phases separated by some 34 years, and found for this spectroscopic binary an orbital period of 218 days. Those phases of activity of the star which are a result of the periastron passages of the companion, are manifest as strong changes in the central depression depth Hα CA, the Hα EW and Hα V/R, and according to Hirata (2007), are referred to as "maximum shell phases".

Interestingly, the exact temporal periastron-accordance of EW, CA and V/R observed by us during the current maximum shell phase (started approx. October 2004, JD 2454300), was not observed during the shell phases in the years around 1980 and from August to October 1974. Presumably this is due to insufficient observation density.

On the basis of the pronounced correlation of Hα EW and the central depression depth CA found in this study, it does seem interesting to localize the time period of the periodic CA variability of Fig. 4 in the long-term monitoring of Hα EW in Fig. 6 (red circle). Here we adopt the convention that positive Hα EW is the flux above the continuum. It is striking that this time range coincides approximately with an EW range in which the disk has its more or less minimal mass and/or its minimal volume. The relatively strong and rapid EW variations during this time section may be due to the high cadence of observations which were able to capture these changes.

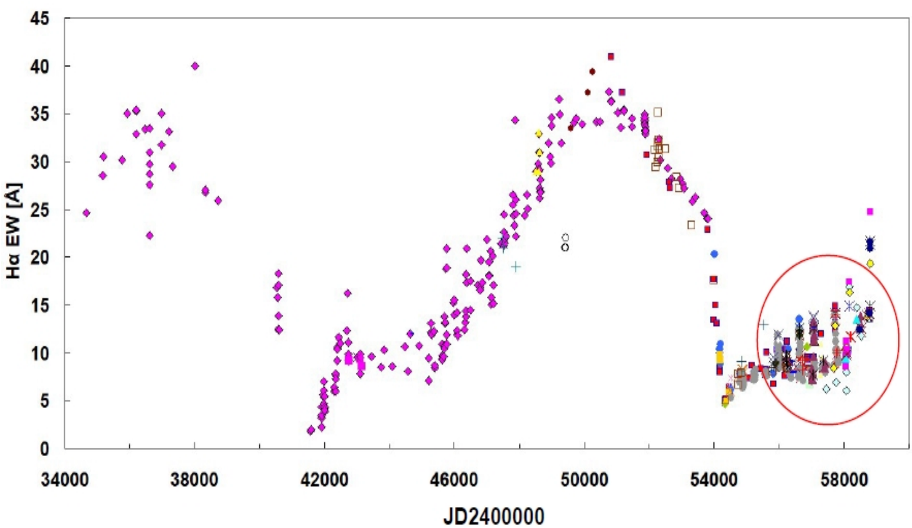

Fig 6: Long-term monitoring of the Hα EW in 28 Tau since October 1953 as a combination of professional and amateur observations by the following observers:

Amateur observations since JD 2450840, January 1998;
(accuracy of the EW determination (±) 5%):

It appears that a certain minimum of disk mass and/or disk volume has to be reached in order to allow the gravitational influence of the companion on the disk and its density (Martin, et al. 2011). It will be interesting to see whether the expected increase in disk mass and disk volume will change the orbital periastron period of 218.0167 days in the next few years. In any case, it would be expected.

Acknowledgements
I am grateful for the ARAS spectroscopy group collaboration, as well as Sara and Carl Sawicki (Alpine, Texas) for their improvements in language. The following observers contributed with their spectra:

Th. Garrel, C. Sawicki, J. Montier, J. S. Devaux, M. Pujol, M. Leonardi, V. Desnaux, P. Berardi, Ch. Buil, K. Graham, St. Ubaud, B. Mauclaire, H. Kalbermatten, F. Houpert, E. Pollmann, N. Montigiani, M. Mannucci, J. N. Terry, J. Guarro, J. Martin, Th. Lemoult, O. Garde, St. Charbonnel, T. Lester, A. Favaro, Dong Li, P. Fosanelli, A. de Bruin, B. Hanisch, A. Heidemann, E. Bertrand, E. Barbotin, J. Foster, J. Ribeiro, O. Thizy, E. Bryssinck, A. Halsey, A. Stiewing., D. Iadevia, A. Mirsoshnichenko, S. Danford.

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