The Be and shell star Pleione in the Pleiades

Figure 1:
One of the probably most intense researcher in the field of envelope- and Be-stars was born in Danzig and emigrated to the United States in 1927, this was Arne Slettebak of Norwegian descent.

In his 1988 work “The Be Stars”, he summarizes nearly a century of research on this star type so well, that it is only natural to mention this important work here.

According to his investigations, a portion of up to 50% of the stars of the spectral type B and the luminosity class III to V (the so called "nonsupergiant") has in addition to the usual absorption lines also emission lines in the spectrum. Such objects are called Be stars.

Figure 2: Pleione in the Pleiades
The star Pleione or 28 Tau is such a Be star and a member of the Pleiades cluster. Hα emission was first detected in 28 Tau by Pickering in 1890. It is 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 years cycle.

Figure 3: Artistic Representation
Because of the periodic changes of the spectral characteristics of the Be phase to the Be-shell phase and back, and because the disk is not in the equatorial plane but slanted to the equator, (probably caused by the companion star in the periastron), it preceeds around the central star linked with corresponding variations of the Hα line profile.

Figure 4: Schematic representation of the formation of emission and shell lines in Be stars

The emission lines in the visible spectral range, are mainly bright components of the lower members of the Balmer series of hydrogen.

Not infrequently, in addition to the emission lines, sharp, narrow absorption lines are observed which, like the emissions, occur in a gas envelope surrounding the star.

Only stars that temporarily or constantly show such envelope absorption lines, are also referred as shell stars.

An important property of the Be and shell stars is their high rotational velocity compared to normal B stars, which can be deduced from the strong broadening of the photospheric absorption lines.

Around the rotating B-star, forms a shell of diluted gas of the order of 10^{-18} m^3 and a temperature around 10000 K. Its effective extent is between three and ten stellar radii.

Today we know, that in the outer regions of the shell, the rotational velocity decreases with increasing star distance.

In addition to the photospheric spectrum (-.-.-.), which consists of a continuum and strongly rotation-broadened absorption lines, one observed due to the rotational movement in the region (I) violet-shifted emission lines, and red-shifted emission lines from the region (II).

The energy, needed to excite the shell emission, provides the ultraviolet continuum radiation of the central star.

The central depression of the emission lines, is explained by the fact, that the contribution of the region (III), which is obscured by the star and can not be seen by the observer.

At the same time, the material of the region (IV) between the observer and the stellar disk, can absorb radiation in the area of the central wavelength of the line, and deepen the line depression.

If there is enough absorbing matter in the region (IV), and assuming a disc-shaped shell, the shell absorption lines (-------------) are formed in the observers line of sight, towards the equatorial plane

Due to the low radial velocity and the low gas pressure, the shell lines are very narrow.

Figure 5:
In almost all well-studied Be stars, changes in the intensity of the emission lines were found.

In the stellar classification, the suffix e in Be stands for emission, that means, for B-stars with emission lines in their spectra.

Here we see the Balmer lines Hε, Hδ, Hγ, and Hβ, where the emission in Hβ turns these B stars into Be stars.

In many cases, this even goes to the complete disappearance of the Be characteristic. Shell stars often appears only temporarily.

Some stars are the purest transformation artists: they appear to the observer as normal B-stars, at times as Be-stars and at times as shell stars. Typical timescales for such changes are several years to decades. So for example also in Pleione (28 Tau) in the Pleiades.

Figure 6:
During the past 100 years, Pleione has shown a notable phase change:

as a Be phase until 1903,
a B phase from 1905 to 1936,
a Be shell phase from 1938 to 1954,
a Be phase from 1955 to 1972,
a Be shell from 1972 to 1988,
and a Be phase from 1989 to 2006.

So far, there has been clearly observed two shell phases, in 1938–1954 and 1972–1988.
The wide lines of hydrogen and helium observed at that times indicates, that the fast rotating star was surrounded by a ring or shell of thin gas with low angular rotation.

In 1951, the shell almost disappeared, which was determined by measurements of the radial velocity of the shell and the star, so that Pleione remained as an ordinary B-star, until in 1972 again began a shell phase, which ended in 1987-88.

The duration of this shell phase lasts about 16 years. The third shell phase started in 2006 and it has to be continued up to 2022. Since 2012 the star is definitely in a maximal shell phase.

Figure 7: Struve's rotation model

Single, fast-rotating stars of the spectral class B, are unstable in their equatorial regions, and can there form a lenticular (linsenförmig) around the star rotating gas disc, which is also the origin for the observable emission lines in the spectrum, which was confirmed incidentally impressive by interferometric measurements on the star α Eridani.

This rotation model is confirmed by observations in the infrared and by polarization measurements, but observations in the ultraviolet shows that the overall situation is not as simple as it seems.

There must be other causes, as radial velocity measurements showed that the rotation velocity was insufficient to cause gravity to be removed by the centrifugal force at the equator and to form the circumstellar shell.

There are now six different explanatory models
- the rotation-based model of stellar winds
- the Spheroidal / Ellipsoidal model
- the variable mass loss model
- the decelerated Be-Star model (spherical / elliptical), by mass loss slowed model
- the model of non-radial pulsations
- and finally the binary star model

Although a huge amount of new data has been gained since the dawn of Be-star research, there is still no uniform model for Be-stars.

Pleione, a typical Be star or shell star and bright member of the nearby open cluster Pleiades, could be in the second contraction phase after the hydrogen in the core is depleted.

And because of the preservation of angular momentum, the diminishing star therefore rotates faster and faster, and the shell could arise when the critical rotational velocity is reached.

Figure 8: Artistic representation of a double star orbit

Since the study of two successive shell phases by the Japanese amateur astronomer Katahira, which were published in 1996, Pleione is now also known as Be binary star system with a period of 281 days and a large orbital eccentricity of e = 0.6

According to these investigations, the companion star could be either a neutron star, a black hole or a dwarf star with very low mass. Whereby the last variant is assumed to be the most probable.

Interestingly, in 2007 the astronomer Roberts found a third companion star at 4.66 arcsecond with spectral type M5 using adaptive optical photometry and astrometry.

Because of the periodic changes of certain spectral features in the transition from the Be phase to the Be shell phase and back, and because the gas disc is not in the equatorial plane but to this inclined by a periodically variable angle, corresponding variations of the Halpha line profile are observable.

Figure 9: Hirata's Hα line profiles at different epochs

The observation and investigation of the Hα emission line and its profile in this binary system yields at least five types of variability:

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 absorption depth (CA)

This picture shows the variation of the Hα line profile in some typical epochs:
1974: the early shell phase, 1981: the maximum phase of the shell,
1999: the Be phase with maximum emission, and 2004 the Be phase.

The question is, how can we understand the causes of the variability of the central absorption core in Hα?

Figure 10:
This Figure illustrates parameters measured in the Hα line profile:

- the emission peaks (AA') and (BB'),

- the central absorption depth (CC '),

The horizontal line marks the normalized continuum.

The depth of the Hα absorbent core is defined as the difference between the local continuum (equal to one) and the minimum at the minimum line intensity.

While the Hα emission line scans the disk as a whole, the area represented by the envelope line through the depth of the central absorption CC' refers to the line of sight of the observer.

The diagnostic capabilities of central absorption should not be overlooked, as this absorption depth reflects the structure and dynamics of the disk in the line of sight of the observer.

Figure 11:
For the study presented here, 350 representative spectra from the period October 2004 (JD 2453300) to April 2019 (JD 2458600) were taken from the BeSS database.

The Hα spectra were obtained with telescopes from 0.2m to 0.4m with a (mostly) long slit and Echelle spectrographs with resolutions of R = 10000-20000. All spectra included the range of 6400-6700 Å with a signal to noise ratio of about 100 or better in the continuum near 6600 Å.

The reduction and wavelength calibration of the spectra was performed with the programs VSpec and MK32.

This figure shows in the upper plot the monitoring of the central absorption depth of the Hα emission since November 1999 (JD 2451500) until April 2019 (JD 2458600) in a combination of observations of the ARAS spectroscopy group with observations of Kalju Annuk from the Tartu Observatory (Estonia), and in the lower plot for the same time range the course of the Hα equivalent width.

We can see that until November 2006 the EW has steadily dropped to a value of about 25 Å. Until then, the star was in its loading phase with a subsequent transition to the formation of the shell phase.

Remarkable in this monitoring is the fact that the periodic CA variability, which was pronounced from September 2011 (JD 2455830) until today (April 2019), was absent in the period before September 2011.

Since 28 Tau is a binary star system or possibly even a triple system, any inclination or change in the projected position angle of

the disc, and thus its axis of rotation, may be modulated by the tidal action of the companion or companions.

Figure 12:
It is assumed in the literature (by Schaefer et al. in 2010) that the changes in CA are caused by a variable angular and / or density distribution in the disk plane with respect to the line of sight of the observer as a result of the disk precession around the primary star.

This can be manifested in a pitching movement in observer view or by a wobbling movement of the disk axis, as described in studies by Schaefer et al. in the Be binary star zeta Tauri.

In the shell phase, this typical tumbling motion in observer perspective leads to the periodic disc precession and manifests itself in the spectrum as a variable absorption depression in the middle of the Hα emission.

Figure 13:
The star's activity phases, where the disc precession as a result of the companion periastron passages result in large changes in central absorption depth, radial velocity, and Hα-V/R-ratio, become called "maximum shell phases," according to a publication by HIRATA in 2007.

This diagram shows the pronounced cyclical CA variability during the maximum shell phase since the beginning of December 2011 (JD 2455900) until April 2019 (JD 2458600), which of course raises the question of the period of this time behavior.

Figure14:
The period analysis of the CA time series data shown in the upper diagram, the so-called Scargle-Periodogram, has been performed using the program AVE (Barbera 1998) and has led to the period of 217.98 days.

The diagram below shows the corresponding phase plot of this period.

Figure 15:
The CA period of 217.98 d corresponds very exactly with the period of the V/R ratio and the radial velocity and has been published already by me at the IBVS-Journal No. 6239 in 2015.

This exact match during the maximum shell phase as a result of disk precession has not been observed interestingly, during the shell phase in the years around 1980 and August to October 1974, probably due to an insufficient observation density.

Now it is well known, and thus it is nothing new, that the precession of the disk depends on its size or radius and its mass due to gravitational effects. This relationship is described in publications by Katz et al. (1982), Larwood et al. (1996) and by Lubow & Ogilvie (2001).

Figure 16:
Against this background, it seems not uninteresting to localize the periodic CA variability in the long-term monitoring of the Hα-EW.

It is noticeable that this period coincides approximately with an EW range in which the disc has its minimum mass and / or its minimum volume.

It appears that only a certain minimum of disk mass and / or disk volume has to be reached in order to create disk precession due to the gravitational influence of the orbital companion.

Because of the known relationship between mass and precession, it will be interesting to see if the expected increase in disk size or disk volume in the coming years will change the precession period of 217.98 days. It would be expected anyway.

Thank you.