<u>Mass transfer in Binary-System VV Cep</u>

Fig: 1
Two of the best known and largest stars in space, which can be found hidden and close together within a dark interstellar cloud of dust in the constellation Cepheus, are μ Cephei and the extraordinary variable binary star VV Cephei. Both stars are so called super giants with visual magnitudes of 4.0 (μCep) and 4.9 (VVCep) respectively. If the dust cloud would not dim the light of the stars μ Cep had a visual magnitude of 1.97 and VV Cep of 2.91.

Fig: 1a
Currently the radius of μ Cep is estimated to be somewhere between 1200 and 1650 solar radii or 5.6 to 7.7 AU, whereas today the estimates for VV Cep are about 1600 solar radii. VV Cep is an exceptional and unequaled sample of an eclipsing stellar system with a mass exchange between its components, in which a blown up light M2-super giant (Class Iab) with an extended atmosphere is circled by a much weaker hot blue-white main sequence star of spectral class B0Ve, which already has started the „thermonuclear“ hydrogen-fusion into helium, causing tidal force disturbances at its considerably larger and less dense companion.

Fig: 2
The hot B0 companion circles the M2 super giant with a radius of about 13 solar radii at a mean distance of about 19-20 AU with a period of 20.4 years, an eccentricity e = 0,34-0,35 and an inclination of 76-77° with the unusual fact to be surrounded by an extended hydrogen cloud.

Spectroscopic investigations revealed that this hydrogen disk with its radius of 650 solar radii can be explained by mass transfer between the stars or mass ejections of the M-star even though there is a large mean distance of 20-25 AU between them. According to investigations of (Wright 1977) the mass of the M-star is determined to be 2-3 and the Be-star 8 solar masses.

The M-class super giant fills its Roche-surface and generates a gas stream close to its periastron-passage, which forms an accretion disk around the Be-star. The variable mass transfer of around 4×10^{-4} solar masses/year between both components can result in considerable disturbances of the cloud/disk of the Be-star.

Many scientists showed a strong interest for the nature of the hot companion during the last years or decades. Nevertheless its spectral type and temperature remain, even today, very ambiguous. Estimates are ranging from an early B- or O-type to an A0 star.

The mass transfer in the range of 4×10^{-4} solar masses per year, which certainly influences the development of the smaller Be-star, is probably the main reason for the recurrent changes of the orbital period. Today we believe that the M super giant is most likely in the fusion phase during which helium is combining to carbon and it will ‘soon’ explode as supernova.

Both components are a ‘close’ double star with significant tidal disturbances, radiation interaction and interrelated gas streams even though there is a long orbital period of 20.4 years.

Fig: 3
Both, the M super giant and the Be star, are offering excellent opportunities to observe and study their outer shells or atmospheres during as well as outside the eclipses.

The dimension of the fog like shell around the Be star was determined by Peery (1965) to be less than 1/18 of the diameter of the M super giant's photosphere and is according to investigations by Wright & Hutchings (1971) not spherically symmetrical but rather in the direction of the star's equator more dense as in the case of a normal Be star.

This seems to be quite logical in view of the remarkable stream of gas in this system. It means that the Hα-emitting shell is fed from outside and collapses only in the polar regions of the central star.

The violet and the red (V- and R-) components into which the emission line of the VV Cep spectrum is split can be linked to the radiation of the gas shell around the Be star. Due to its counter clockwise rotation around the central star, in relation to the line of sight of the observer, it results in a blueshift by moving towards the observer (V-component) and a redshift by moving away (R-component) from the observer.

Fig: 4
The long term monitoring of the variations in intensity of both components (so called V/R relation) results in important information about:

1. peak intensity as a measure of the mass or density of the gas in its shell expressed in equivalent width EW of the emission
2. the direction of motion of the gas shell's region

According to investigations of Wright (1977) the source of the central absorption in the profile of the Hα-emission line is caused by the transferred and absorbed material between observer and shell of the Be-star.

Because of the mass transfer from M-star towards its Be-star companion in the VV Cep system, the presence of the strong Hα emission can be well explained as being created in the outer shell of the companion.

The gas stream coming from the M-star spirals around the Be-star. Due to the inclination of 77° it has to be expanded far more than just a ring around the central star. Moreover it has to less dense in the polar regions than around the equator.

Hα-V/R-measurements by Kawabata et al. (1981) during the eclipse 1976-1978 demonstrated that mass and density distribution inside the disk is not homogeneous. The stronger violet emission peak (V) may be resulting from a higher density/mass in the left side of the disk seen in its counterclockwise motion.

Fig: 5
Since July 1996, i.e. more than 12 years, the monitoring of VV Cep is performed by the observatory of Vereinigung der Sternfreunde Köln using a selfmade slit-grating spectroscope mounted to a C14 Schmidt-Cassegrain-Telescope.

On the left the spectroscope with CCD-camera at the C14 Schmidt-Cassegrain-Telescope; on the right the 20 cm Schmidt-Cassegrain-Telescope as guiding system with Philips-Webcam mounted to the eyepiece cross guide.

Here the specification of the spectrograph:

- Collimator: PENTACON 135mm, f/2,8 (ZEISS, DDR)
- Grating: 1800 l/mm (fixed adjustment for Hα)
- camera optics: SOLIGOR 200mm, f/3,5
- CCD-camera: NOVA 402ME (from Astroelektronik Fischer)
- Dispersion = 27 Å/mm at Hα
- Resolution $R = \lambda/\Delta\lambda \sim 14000$

Using this equipment more than 200 spectra have been recorded meanwhile.

Fig: 6
The passed observation time frame also includes the eclipsing event of the Be-star and its disk from 1997 to 1999. As mentioned before, the Hα-emission line is the only indication of the presence of the disk. Picture 4 shows the monitoring of the Hα-equivalent width (EW) since July 1996 until today.

The eclipse of the emitting Be-star disk by the M-super giant started in March 1997 and ended after 673 days. The period from contact 1 to contact 2 lasted 128 days, from contact 3 to contact 4 171 days. The full eclipse period was 373 days.

Probably the most interesting feature in this fig. are the stochastic changes of Hα-EW with a variation range of about 10 Å and extremes of up to around 25 Å. The strong fluctuations of Hα-EW, which have been observed since the end of the eclipse until today, can most likely be explained by a variable mass transfer from the M-star towards the Be-star disk as described by Wright (1977) and Stencel et al. (1993).

Variations in the disk's temperature as well as density in relation to this process can thus be expected. We also have to assume that the M-super giant influences the rate of mass transfer with its semi regular 116 day period of pulsation. As obviously the disk is the source of the Hα-emission it seems to be the best candidate for an explanation of the permanent intensity changes.

From the findings of this observation material alone it is not yet possible to judge to what extent these fluctuations are due exclusively on varying contributions by mass transfer between the two components or from the disk itself, or both together.

Fig: 7
Long term spectroscopic observations clearly outside the eclipses of 1956/57 and 1976-78 have only been published by Wright (1977).
These provide by the V/R-relation of the Hα-emission for the first time a rough explanation about a possible quasi cyclic behavior of the structure of density of the Be-star disk.

By this research almost the complete phase is covered by measurements, however, there are an insufficient number of observations for a reliable analysis.

Since November 2000 for the phase section 0.14-0.53 own V/R data with good density of observations could be added to those of Wright for an explanation of this possible relationship. It became evident how dramatically the V/R-relation is changing.

Unfortunately phase section 0-0.1 could not be covered as telescope and spectroscope were not available. Therefore the inexplicably high increase of V/R in the Wright (1977) measurements could not be confirmed.

Nevertheless the combined data confirm clearly the factual phase related chronological development of the V/R-relation: i.e. an obvious decrease to about half of the value at the beginning at about phase 0.4 and at the same time clearly visible variability of the V/R-value itself. This apparent V/R-phase dependence asks for a more detailed evaluation of the individual spectra of the relevant sections of phase.

Fig: 8

This fig. shows a polar view the orbit of the hot B0-companion around the M-super giant (from: Hopkins et al.: UBV Photometry of VV Cephei; Proceedings for the 25th Annual Conference of the Society for Astronomical Sciences, May 23-25, 2006).

For 09/1999 a first own spectrum from 11/1999 with a Hα-V/R-value of 2.23 is compared. The R-component of the double peak represents the area of the Be-disk facing the M-super giant, which at this time is moving away (redshift) in relation to the line of sight from the observer due to its counterclockwise rotation.

On its way to periastron the Be-star gets more and more into the region of influence of mass transfer, i.e. the region where matter from the outermost parts of the atmosphere of the M-star moves towards the Be-star disk.

The spectrum of orbital phase 09/2003 proves this clearly as the R-component (which in turn represents the area of the disk facing the M-star) has gained intensity related to the V-component (V/R = 1.17).

At the time of periastron passage in 10/2004 this effect of feeding the disk by mass transfer from the M-star becomes even more evident. In the relevant chronologically matched spectrum the R-component exceeds the intensity of the V-component just a bit (V/R = 0.97).

In the orbital phase 11/2005 the filled up Be-star's disk facing the M-star just barely moves towards us, as seen from an observers point, and therefore the spectrum is already slightly blueshifted.

For the upcoming orbital phase 11/2009 a somewhat too early spectrum already from 08/2009 is opposed. Already now it can be seen that the left part of the Be-disk, represented by the V-component, has a higher intensity and consequentially also a higher density of matter as seen from an observers point of view.

This is in total correspondence with observations of Kawabata during the 1976-78 eclipse, stating that the stronger represented V-peak is caused by an increased density/mass in the left part of the disk.

Fig: 9
As already mentioned the EW of the Hα-emission is the unique indication for the existence of the gas disk around the Be-star.

With the existing data it could be investigated if actually at the time of periastron an increase of the strength of emission, caused by the mass transfer from the M-super giant into the Be-star disk, can be proven.

As clearly shown in this fig., the EW increases outside the eclipse with a certain divergence of up to 10 Å to a maximum value and decreases afterwards in a similar way. A polynomial fit (2^{nd} degree) results in the dashed equalized curve with the calculated time of periastron passage marked.

This curve confirms actually and essentially that the EW of the Hα-emission as indication for the Be-star disk and its mass or density is the more determined by the mass transfer from the M-star the closer it comes to periastron.

It also becomes evident that this mass transfer is subject to remarkable variations which is apparent from the dispersion of the EW. It remains to be seen how in particular the Hα-V/R-behaviour will be with increased distance from periastron and decreased distance from apastron in January 2015.