# Portrait of the Be binary star system γ Cas

## Figure 1
**γ Cassiopeia is one of the brightest Be stars in the northern sky ...**

## Figure 2
**... where, for the first time in 1867, the Italian monk and astronomer Angelo Secchi discovered the Fraunhofer lines and the Hα emission line with a refractor. At the IAU General Assembly in Rome in 1922, type B emission line stars were briefly referred to as Be stars.**

**Be stars are so-called non-supergiant B stars, in whose spectra at least once emission lines of the Balmer series were found.**

## Figure 3
**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 can see the Balmer lines Hε, Hδ, Hγ, and Hβ, where the emission in Hβ turns these B stars into Be stars.**

**These star types are characterized by high temperatures of about 10,000 to 30,000 K, masses of about 3 to 20 solar masses and very high rotational velocities of up to 500 km/s.**

## Figure 4
**This high rotational velocity and the resulting centrifugal force causes the stars to deform in the equatorial zone and form a circumstellar gas disk around them, due to the associated mass loss of the order of about $10^{-8}$ solar masses/year.**

## Figure 5
**This picture now shows an artistic representation of the prototype of all Be stars in a way, as one imagines today the hydrogen gas disks around the central star.**

## Figure 6
**This picture shows a schematic representation of the inclined circumstellar disk relative to the central star. Epsilon (ε) is the angle of inclination of the disk of 45° with respect to the equatorial plane of the star. Omega (Ω) is the node line, S indicates the stellar axis of rotation, and D represents the axis of rotation of the disk.**

**Figure 7**
**The spectral appearance in the visible spectrum of γ Cas can be explained in this model presentation:**
**the central star of the type B0.5 IVe is surrounded by a thick, circumstellar hydrogen gas disk, which is the most conspicuous feature in the visible spectrum and can be recognized as Hα emission line.**
**Further explanation of the other features ...............**

**Figure 8**
**This picture shows a typical CCD raw spectrum of the Hα emission of γ Cas in the spectral range of about 6500 - 6700 Å with the absorption lines of atmospheric water vapor.**

**The well-known wavelengths of this so-called tellurics, are very helpful and serve for exact wavelength calibration.**

**Figure 9**
**The intensity scan of the raw spectrum then, reveals the actual profile structures of the Hα emission.**

**Access to the shell structures in stars is obtained for example by investigations of the kinematic line broadening.**

**Stellar absorption lines in Be stars are rotation-broadened. The width dimension of the lines is the projected, equatorial rotation velocity of the star multiplied by the sine of the axis slope in the line of sight of the observer.**

**Circumstellar emission lines of the gas disks or shells in Be stars, are also widened kinematically. The width measures the typical rotational and radial velocity of the circumstellar disk mass.**

**In this sense, these two velocities, measures the relative orientation of the symmetry axis of the star, as well as the circumstellar envelope.**

**The entire width of an emission line, is among others depending on the definition of the line wing profile and is affected by the underlying photospheric absorption.**

**The Hα profile shown here, is thus a superposition of the emission line profile, which is produced in the gas envelope of the star, and the underlying photospheric absorption line profile.**

As a photospherical profile, one could use the Hα absorption line profile, observed at γ Cas in August 1974. The result of such a profile subtraction, would be then the emission profile with different line strength.

For professional astronomers, the participation of amateur astronomers, in the sense of long-term monitoring of the emission strength of this Hα emission line, is of great interest.

**Figure 10**
This picture shows the Hα long-term behavior from 1971 to today, as collaboration of amateurs and the professional astronomy. The amateur observations, starts in 1994, could clearly show a minimum at the end of 2001, with a subsequent gradual increase to higher levels of emissions. Meanwhile an international consortium of 40 amateurs is involved in this monitoring.

**Figure 11**
An interesting discussion among professional Be-star researchers, has led to the question, of how far there is a possible correlation, between the Hα equivalent width and the UBV brightness of the star system.

It is known that the line of sight of the observer, exerts a significant influence on the profile of a spectral line. If we see for example the star "pole-on", that means viewing vertically from above on the rotational axis of the gas disc, then we see it under an inclination angle $i$ = 0°.

On the other hand, if we consider the star “edge on”, that means under an inclination angle $i$ = 90°, we see in its equatorial plane and its disk from the edge.

That is, depending on the inclination angle I, with respect to the line of sight of the observer, different sized areas of the illuminating disk contributes to the visual brightness of the system.

γ Cas is now seen at a inclination angle of 45°, and it is observed that the stronger the Hα emission is, the larger is also the visual brightness.

For some time now, astronomers at the University of Western Ontario (Canada), have been using suitable computer models to supplement or support such correlations, which is, why amateur research is also of large interest to professional researchers.

**Figure 12 (start double star animation)**
**What is remarkable about this binary star system is, that the until today invisible companion, which can be clearly detected in Hα radial velocity measurements, with an amplitude of about 8 km/s and a period of 203 days, has not yet been identified spectrally.**

**From September 2006 until today, we have also devoted ourselves to the long-term monitoring of this RV in an international consortium.**

**The Figure on the top shows the monitoring itself as a so-called time series. In order to investigate this time series more accurately by means of period analysis, it is necessary to eliminate the long-term trend recognizable therein in the form of a division of the original data by a suitable polynomial - in the present case a polynomial of the third order.**

The figure left below shows the period analysis of the data, the so-called Scargle periodogram, exempt from the long-term trend. Here we find the dominant period of 203,561 days with an accuracy of ± 0.205 days.

The figure below right shows the phase diagram of the determined period.

**Figure 13**
**Although this analysis of the period looks quite satisfactory at first, we can recognize certain anomalies in the course of time of the radial velocity on closer inspection.**

**Figure 14**
**These becomes particularly clear in a temporally higher resolution representation. This anomaly has probably been observed many times in the past, according to information from our consulting professional astronomers, but has not been followed or respected.**

According to this observation by our professional consultants, a third body would not be excluded in this binary system.

**Of course, it is clear that we continue to have an intensive exchange of results with the professional astronomy.**

**Figure 15:**

**Spectroscopically, γ Cas has been studied in the past until the 1990s, predominantly in the area of the Hα line. Only with the establishment of a research branch for Be Stars at the Ruhr-University Bochum under the direction of Prof. Dachs and Dr. Reinhard Hanuschik, 1993-94, studies were carried out with the aim to learn more about the kinematics of the circumstellar disks around Be star.**

**This included above all, investigations on the Helium lines, those areas of the Be star disc in the immediate vicinity of the central star. Based on model calculations by the Japanese researcher Okazaki (1991 to 1997), it was assumed that so-called "one-armed density zones" around the star also precede in these disk areas close to the stars.**

**These equatorial density enhancements were found to be located at about 1.5 star radii away from the stellar surface. In 1998, the French astronomer Phillip Stee confirmed that for the HeI emission line at 6678 Å, the excitation and ionization of helium in an extended range to about 2.3 star radii, was responsible.**

**Figure 16**

**Thus, this HeI emission at 6678 A has become an important diagnostic feature for the study of near-star activity areas. It was recognized that a time-dependent photospherical mass loss of the primary star, density variations and thus the typical double-peak profile variations - known as the so-called V/R ratio - results in this emission.**

**The V/R ratio is the peak height ratio of the violet to the red emission peak and describes as a major feature density variations in the gas disks of Be stars. Until about 2012, there was no information in the literature about possible V/R periodicities of the HeI-6678 double peak emission line in the spectrum of γ Cas.**

**Figure 17**

**The accuracy of the V/R measurements is essentially determined by the signal to noise ratio and the accuracy of the local continuum. In addition, the definition of line wings and the underlying photospheric absorption line profile is important.**

**To calculate the V/R ratio, the violet and red absorption minima**

previously linked by linear interpolation have been divided, thus achieving the required normalization according to F/Fc = 1.

Another method for separating the emissions from the photospheric absorption profile is the subtraction of a fitted, theoretical absorption profile. A comparison of these two methods on one and the same spectrum resulted in a deviation from the linear interpolation in the order of 0.01% in V/R.

The V and R intensities in this way separated from the photospheric absorption profile, are then the line maxima used for further evaluation. The achieved accuracy of the V/R measurements averaged about ± 2%.

**Figure 18**

In collaboration with three colleagues from the ARAS spectroscopy group, we were able to work out results of the V/R variability of HeI 6678, which were previously unknown by γ Cas.

The spectra were taken by me in the observatory of the Verinigung der Sternfreunde Köln, and by my colleagues in America, Spain and France. In all cases, the LHIRES III spectrograph with its spectral resolution of about 17000 was used.

The signal to noise ratio in the continuum near the emission averaged about 1000, but usually higher than 1500, with an exposure time of about 300-400 sec per single spectrum.

In this long-term monitoring of the HeI 6678 emission, the variability of the V/R ratio is quite obvious. However, it must be remembered that since the beginning of monitoring in August 2009 to date only 10 orbital periods have been recorded.

We found that these variabilities have periods that had nothing to do with the orbital period.

**Figure 19**

Of course, we used Fourier period analysis to find out to what extent clear periodicities actually exist. We find in the power spectrum (Fig. above) a dominant peak with a period of 465 days, which is still quite wide and which makes the analysis uncertain by a certain amount. However, we are confident that with further future observations we will improve our results, in order get to a more exact period.

The Fig. below shows the phase diagram of the found 465d period. This period analysis was done with the program Spec-TSA of my colleague Roland Bücke in Hamburg.

This found 465d period, with its rather large distance to the orbital period of 203 days, nevertheless indicates a considerable reliability of the periodic V/R behavior.

Such periodic phenomena in the time behavior of different spectral lines in the spectrum of Be stars ultimately lead to a better understanding of the structure of their circumstellar gas disks.

**Figure 20**

Also, the radial velocity of this star-near emission ring of Helium occasionally shows a remarkable behavior of the radial velocity.

In the Fig. above we can see the monitoring from radial velocity measurements by the famous Be star researcher Peter Harmanec - labeled here as H2000 - combined with measurements of members of the ARAS spectroscopy group

The enormous change of radial velocity within the H2000 time section (Fig. 1) leads to the question of the responsible causes.

A comparison to the Hα-EW of the same time section seems to be therefore of interest. Fig. 2 shows for this time section an EW decrease of ~ 45% from the original 40-45Å to ~ 25 Å.

The Hα EW is an indicator of the total mass of the gas disc around the primary star, which rotates counterclockwise together with the photosphere-near Helium ring (HeI 6678) around the primary.

**Kepler´s third law:** M1 * a1 = M2 * a2

Mass loss of the disk of the half of its original mass in this binary system, with its masses M1 for the companion and M2 for the primary star plus disk would mean that also the distance a2 of the primary star plus disk to the common center of gravity, has to change, which a change of the (radial) velocity vector up to the H2000 radial velocity maximum at about JD 2451500 would result.

**From ~ JD 2451800 however, a different relationship would apply. From this point, the EW shows a steady increase which corresponds to a growth of the disc.**

**However, since the disk is fed by mass loss of the primary star with otherwise constant mass M2, this process has no consequences of the change of the distance a2 to the common center of gravity and of the (radial) velocity vector.**