SYMBIOTIC BINARIES

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A symbiotic binary system is a binary system that consists of a primary star, usually a red giant, and a companion star, usually a white dwarf or a neutron star. Symbiotic binaries can transit between two main phases: the burning phase and the accreting-only phase. The mass can transfer either through Roche lobe overflow or in the form of stellar wind, from a primary star to a companion star.

SIMBIOTSKE DVOJNE ZVEZDE

Simbiotska zvezda je dvojni sistem, ki je sestavljen iz primarne zvezde, ki je običajno rdeča orjakinja, in spremljevalne zvezde, običajno bele pritlikavke ali nevtronske zvezde. Simbiotske zvezde lahko prehajajo med dvema fazama: faza "gorenja" in faza "akrecije". Masa se v takem sistemu lahko prenaša preko Rocheovega ovala ali v obliki zvezdnega vetra, iz primarne zvezde na spremljevalno.

1. Introduction

Binary systems are systems in which two stars are gravitationally bound to each other and orbit around the center of mass of the system. The stars are typically very close to each other, but not always, and we can assume they are on circular orbits due to the gravitational interaction and mass exchange between them. Another approximation is that the stars generate a gravitational field as if they were point masses. This can be justified by much higher densities deep inside the star. Binary stars are important because most stars are in binary systems and they can help us understand the star formation. Their interactions can lead to supernovae or black hole merges. Another importance is that we can determine the fundamental properties of stars, for example their mass and radius. The orbital periods and the distances between two stars can be very different from system to system [1]. In this paper, we will focus on symbiotic binary systems.

2. Symbiotic binary stars

Symbiotic binaries are a class of interacting binaries. They consist of a companion star, which is accreting material from a primary star, usually a red giant. The majority of such systems contain white dwarfs as the companion star. The mass transfer between a red giant and a white dwarf can occur through Roche-lobe overflow or in the form of a stellar wind emitted by the giant. Roche lobe overflow occurs if the two stars orbit very closely and the tidal forces cause the matter to flow from the giant to the compact companion. In symbiotic binary systems, the separation between two stars is relatively large, and the mass is mostly transferred by stellar wind accretion. The orbital periods of symbiotic stars can vary from a few hundred to a few thousand days [2].

White dwarfs are compact objects at the end of the stellar evolution of intermediate and low-mass stars (such as our Sun). They have low luminosity, and they typically have masses between $0.6M_\odot$ and $1M_\odot$, where $M_\odot = 2 \times 10^{30}$ kg is the solar mass. Their radius is around $R = 0.01R_\odot \approx 7 \times 10^3$ km, where $R_\odot = 7 \times 10^5$ km is the solar radius. The size of a white dwarf is comparable to that of the Earth. Because of their small size and large mass, the mean density is $\rho = 10^6$ g/cm^3. Inside the white dwarf there is an equilibrium of two forces: the gravitational one is compensated by the gradient of the pressure of degenerate electrons [3]. In symbiotic binaries, there also exist more massive white dwarfs with masses close to the Chandrasekhar limit. This limit is the theoretical maximum mass for a stable white dwarf, which can be calculated by equation

$$M_{lim} = \frac{\omega_3^0 \sqrt{3\pi}}{2} \left(\frac{\hbar c}{G}\right)^{\frac{3}{2}} \frac{1}{(\mu_e m_H)^2} \ , \tag{1}$$

where $\omega_3^0 \approx 2.019236$ is a constant, $\hbar$ is the reduced Planck constant, c is the speed of light, G is the gravitational constant, m_H is the mass of the hydrogen atom and μ_e is the average molecular weight per electron, which depends on the chemical composition of the star. In the case of a white dwarf, where the matter is fully ionized, $\mu_e = 2$. The Chandrasekhar limit in the case of a white dwarf is $\approx 1.435\ M_\odot$ [4]. In the case of a white dwarf with mass close to the Chandrasekhar limit, there are recurrent nova outbursts or production of strong X-ray emission which is a consequence of accretion [2]. When a white dwarf accretes enough material to reach the Chandrasekhar limit it explodes. It is believed that supernova Ia is a result from that explosion [5].

For typical mass loss rates from a giant star to the white dwarf, the accretion rate is $10^{-9} - 10^{-7}\ M_\odot \mathrm{yr}^{-1}$, and the matter transfers in the form of a stellar wind. The luminosity generated by the accretion process is given by the equation [6]

$$L_{acc} = \frac{GM\dot{M}}{R} \ , \tag{2}$$

where M is the mass of the companion object, R is the radius of the companion object and $\dot{M} \approx 10^{-9} - 10^{-7} \mathrm{M}_\odot \mathrm{yr}^{-1}$ is the accretion rate. If we assume that the mass of the red giant is $M \approx M_\odot$ and that the radius is $R \approx 10^9$ km, the luminosity is $\approx 10^{23} - 10^{25}$ W [6].

In the following, we will compute the Eddington luminosity, which is the maximum luminosity a star can have when there is a balance between the force of radiation and the gravitational force. First we consider a spherically symmetric accretion. Another assumption that we make is that the accreting material is fully ionized, and that it mainly consists of hydrogen. At this point, the infalling flow stops. If we have an ideal gas, the conservation of momentum for each gas element is given by Euler's equation in hydrostatic equilibrium where the mean acceleration is equal to zero

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{\nabla p}{\rho} - \nabla \Phi = 0 \ , \tag{3}$$

where u is the velocity of gas, p is the pressure, ρ is the density and Φ is the gravitational potential. In our case, the pressure is mainly the consequence of radiation, and we can write it in terms of radiation flux F_{rad}. The first term of the Euler equation can be written as

$$-\frac{\nabla p}{\rho} = \frac{\kappa}{c} F_{rad} \ , \tag{4}$$

where κ is the opacity and can be written as $\kappa = \sigma_T / m_p$ for ionized hydrogen. Here, σ_T is the cross section for Thomas scattering for the electron and m_p is the mass of a proton. Now we can express luminosity which is defined as

$$L = \int_S F_{rad}\ \mathrm{d}S = \int_S \frac{c}{\kappa} \nabla \Phi\ \mathrm{d}S = \frac{c}{\kappa} \int_S \nabla \Phi\ \mathrm{d}S \ , \tag{5}$$

where we assumed that κ is constant. Then we use the Gauss theorem and Poisson equation for gravity ($\nabla^2 \Phi = 4\pi G \rho$) [7]. The equation can be written as

$$L = \frac{c}{\kappa} \int_V \nabla^2 \Phi\ \mathrm{d}V = \frac{4\pi G c}{\kappa} \int_V \rho\ \mathrm{d}V = \frac{4\pi G M c}{\kappa} \ . \tag{6}$$

We finally arrive at the following expression for luminosity, that is also called the Eddington luminosity

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T} \approx 1.3 \times 10^{31} \left(\frac{M}{M_\odot}\right) \mathrm{W} \ . \tag{7}$$

where M is the mass of the compact object. We can also compute the corresponding maximum accretion rate, called the Eddington accretion rate

$$\dot{M}_{Edd} = \frac{L_{Edd}}{\epsilon c^2} \approx 2.3 \times 10^{-8} \left(\frac{M}{M_\odot}\right) M_\odot \mathrm{yr}^{-1} \ , \tag{8}$$

where ϵ is the radiative efficiency of the accretion process, and it is a dimensionless quantity [8]. It can be calculated as $\epsilon = L/(\dot{M}c^2) = \frac{GM_a}{R_a c^2}$, where M_a and R_a are mass and radius of the accreting star, respectively. In the case of a white dwarf, $\epsilon \approx 10^{-4}$ [9].

Symbiotic stars have been identified by spectral properties, which are typical for cold stars and at the same time for stars with high temperatures. Because these properties cannot exist in the same star, there has to be a symbiotic system that consists of one cold giant star and one hot compact star. Such systems have TiO lines present in their optical spectrum, which results from the red giant's photosphere and is common in stars with lower temperatures, typical for the coolest M giants. On the other hand, there were also some emission lines of Hα and He II present. These lines are present in the hottest O-type stars. These two features, and also emission lines typical for planetary nebulae, which consist of ionized gas ejected from a red giant, can be seen in figure 1 [10].

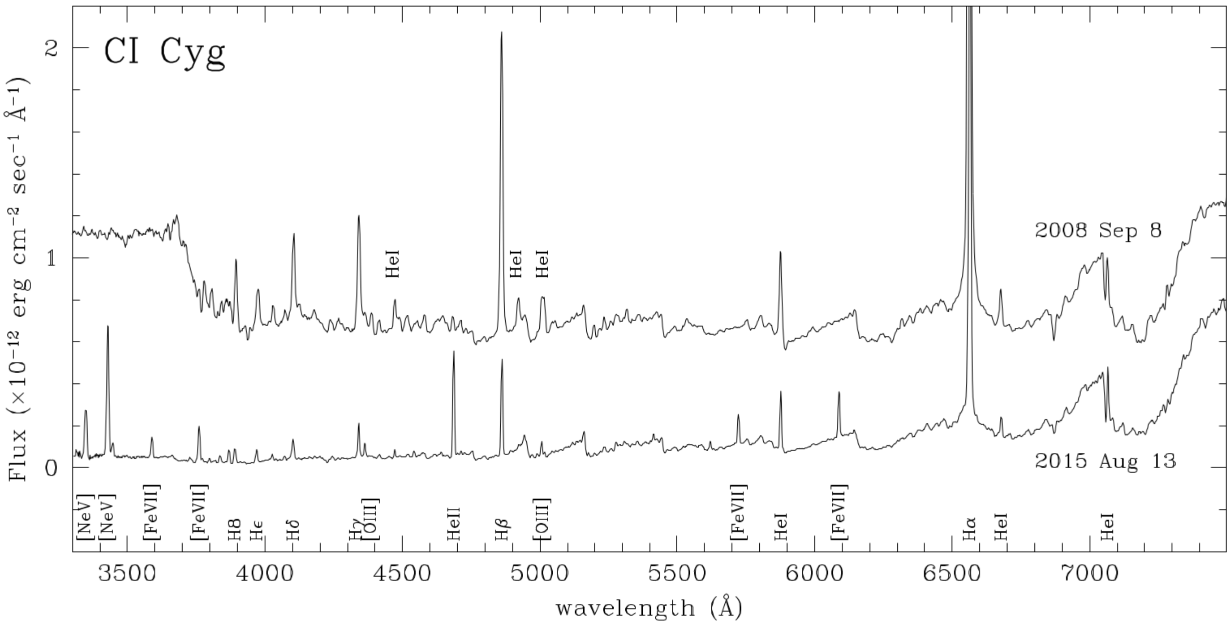

Figure 1. Spectrum of the symbiotic star CI Cyg at outburst peak (upper line) and at its minimum (lower line). At the outburst peak there can be seen a difference in ionization degree and more emission lines [10].

Generally, there are two phases of symbiotic stars: accreting-only stars and burning-type stars. In the first phase, the optical spectrum is dominated by the red giant and there are none or only very weak emission lines present in the spectrum. In the second case, there is a strong nebular continuum present and a rich emission line spectrum [12].

Symbiotic stars spend most of their life in the accreting-only phase. When the white dwarf accretes enough material on its surface, the nuclear burning of accreted material begins. If the accreted matter is electron degenerate, the burning process can be explosive. In the case of degenerate gas, the equation of state of the degenerate hydrogen is independent of temperature and the star will not expand due to increase of temperature. The temperature can rise until the degeneracy is lifted and the thermonuclear runaway reaction makes the envelope explodes. In this process, the envelope is ejected with high velocities. We call this a nova outburst, which can repeat periodically on time scales of years to decades if the white dwarf's mass is close to the Chandrasekhar limit. On the other hand, if the accreted matter is not electron degenerate, the nuclear burning is slow and in thermal equilibrium. It can take a few years to reach maximum brightness and a few decades to burn the accreted envelope and return to the quiet phase [12].

The accreting-only stars are difficult to separate from single giant stars because the emission lines of the white dwarf are very weak, but it is believed that there are a lot of them. On the other hand, the burning-type stars can be easily detected at optical wavelengths throughout the Galaxy and beyond because of their prominent nebular emission line spectrum. Most of them are found in the Galactic plane and Galactic bulge. Using traditional approaches for discovery of accreting-only symbiotic stars is limited to ≈ 1 kpc from the Sun, because of the limited sensitivity of current X-ray satellites [12].

3. Burning Symbiotic stars

In burning symbiotic stars, the amount of material burnt on the surface of the white dwarf is equal to the material accreted from the red giant. This process is almost stationary and therefore the nuclear burning does not stop, because accretion is too low. A consequence of continuous nuclear burning is that the envelope does not expand to the red-giant dimension, because the accretion is too high. The white dwarf in this type of system is radiating close to the Eddington limit, and accretion could stop before material, the white dwarf has burnt, can be refilled. There are two possibilities for this to happen. The first one is that nuclear burning conditions are only fulfilled temporarily, and they are followed by an accreting-only phase to refill the envelope of the white dwarf. The second one is that the Eddington limit is avoided by discrete accretion episodes like that of a massive disk dumping mass onto the white dwarf during low-amplitude outbursts. Orbital periods of burning symbiotic stars range from 1 to 4 years. Most of them seem to belong to the metal-rich Galactic bulge population [10].

4. Accreting-only symbiotic stars

Symbiotic binaries that consist of a red giant and a white dwarf or neutron star emit in UV and in X-rays. This happens because the hot ionized plasma hits the hotspot, which is a point on the accretion disk. The X-ray and UV luminosity in accreting-only symbiotic stars is low, so they can be found only up to 1 kpc from the Sun. If the compact object is a white dwarf, the luminosity is larger in UV than in X-rays, because the energy of emitted photons depends on the radius of a white dwarf. The grater the radius, the smaller the energy of emitted photons. Neutrons stars, because of their smaller radius, emit more in X-rays than in UV [10].

The two most distinctive characteristics of optical spectra of accreting-only symbiotic stars are a near-UV excess and weak emission lines from the hydrogen Balmer series. They are shown in figure 2. Both characteristics come from the accretion disk forming around the white dwarf. In figure 2 we show two epochs: one in active phase (red) and one in quiet phase (black). In the active state, the accretion rate is high, and it causes a brightening of the accretion disk around the white dwarf and this indicates the binary nature. In the quiet phase, there is no UV excess and no detectable emission lines [12].

The states of symbiotic stars are time-dependent and can be identified by different spectral properties. Figure 3 shows the observed profile for the Hα emission line for one symbiotic star

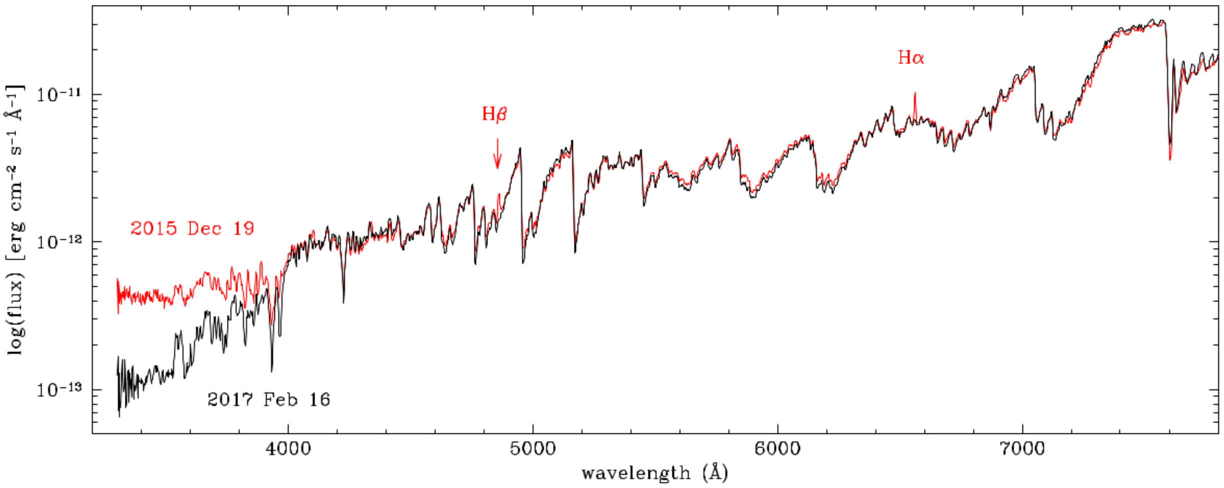

Figure 2. Two spectra of SU Lyn, an accreting-only symbiotic star in low (black) and high (red) accretion rates [12].

from 2015 to 2020. Epoch marked with *b* corresponds to the lowest accretion rate and shows no Hα emission line and has a UV excess close to zero. At optical wavelengths, this system appears as a normal and single red giant, not as a binary star. The white vertical line represents the Hα rest wavelength. During epoch *b*, the velocity of Hα absorption is almost the same as that of the red giant. During other epochs, the Hα absorption is blue-shifted compared to absorption in the photosphere of the red giant. It originates in a gentle stellar wind blowing from the inner regions of the accretion disk or forming in the outer regions of expanding wind of the red giant. Epoch *c* on figure 3 shows the appearance of a second, distinct, and faster-moving absorption component. It reduces its velocity during the following months and finally merges with the slower pre-existing absorption component. The epoch *a* in figure 3 represents the condition of the highest accretion rate and strong near-UV excess. In the right panel of figure 3 there is B, V lightcurve which shows the brightness of a star over some period of time. In our case, the lightcurve varies for an amplitude of 0.7 in magnitude with no periodicity that would correlate to the spectral features around the Hα line. There is no change in color and the behavior of the accretion disc that can be associated with these changes, so the variability originates from the cool giant. This is due to the unstable nature of its convective outer layers and its thin atmosphere. Different colors on the right panel represent different telescopes acquiring data independently [12].

5. Characterization of symbiotic binary stars

Symbiotic stars have high excitation emission lines in their optical spectrum. As a consequence of mass loss from the giant, symbiotic stars are surrounded by a dense gaseous nebula. The hot component ionizes the gas around the binary system and via the process of recombination produces strong emission lines in a wide range of ionization states. The identification of symbiotic stars should be taken with caution because other stars can show similar characteristics, for example, radial pulsators [11].

In figure 4, there are two typical examples of Hα and Hβ emission lines for symbiotic stars (top panel) and for radial pulsators (bottom panel). In radially pulsating stars, the outward moving material in the stellar envelope is colliding with the gas that was lifted in the previous cycle and is now falling inward, which results in a shock. This shock has sufficiently high energy to excite emission in the hydrogen atoms. The biggest difference in the spectrum between symbiotic stars and radial pulsators is in the shape of emission line and in their lightcurves. It is believed that the

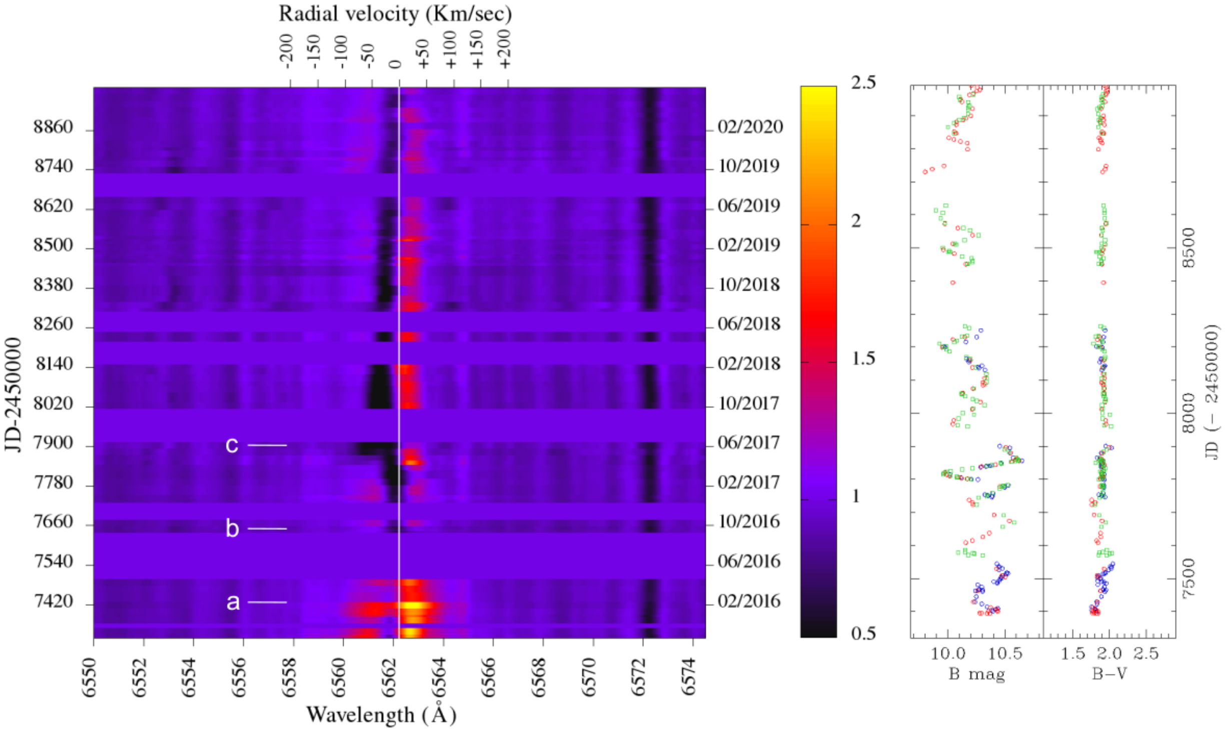

Figure 3. Temporal sequence spectra showing the changes in the Hα profile of SU Lyn from 2015 to 2020. The white line represents the rest wavelength of Hα. On the right are the corresponding B, V light curves [12].

Hα emission in symbiotic stars originates in the gentle wind blowing off the accretion disk or in a wind flowing away from the red giant. Red profiles on the left panel represent the typical spectrum of a single red giant, while the black line represent the spectrum of a symbiotic star (top panel) and a radial pulsator (bottom panel). The middle panel shows the result of subtracting the red profile from the black one. The Hα emission line in symbiotic stars is always broader than the Hα line of radial pulsators.

The Hα emission line in symbiotic stars is stronger than Hβ line in most observed cases. This emission originates from the accretion disk. On the other hand, the Hβ emission line of radial pulsators is stronger than the Hα line, and originates from the internal shock regions of a red giant. Also the Hα emission profile in symbiotic stars is blue-shifted, while in radial pulsators is red-shifted. Another difference is variability in the lightcurve, which we can see on the right panel. To obtain the lightcurves and detect periodicities of here examined stellar systems, one must have hundreds of individual observations over a few years. The lightcurve of a pulsating star shows a regular, long period, and sinusoid-like variations of magnitude from few to more than 10 mag. The lightcurve of a symbiotic star shows significant variability in magnitude, but it does not have a large amplitude like radial pulsators. Symbiotic stars also do not have a regular period [12].

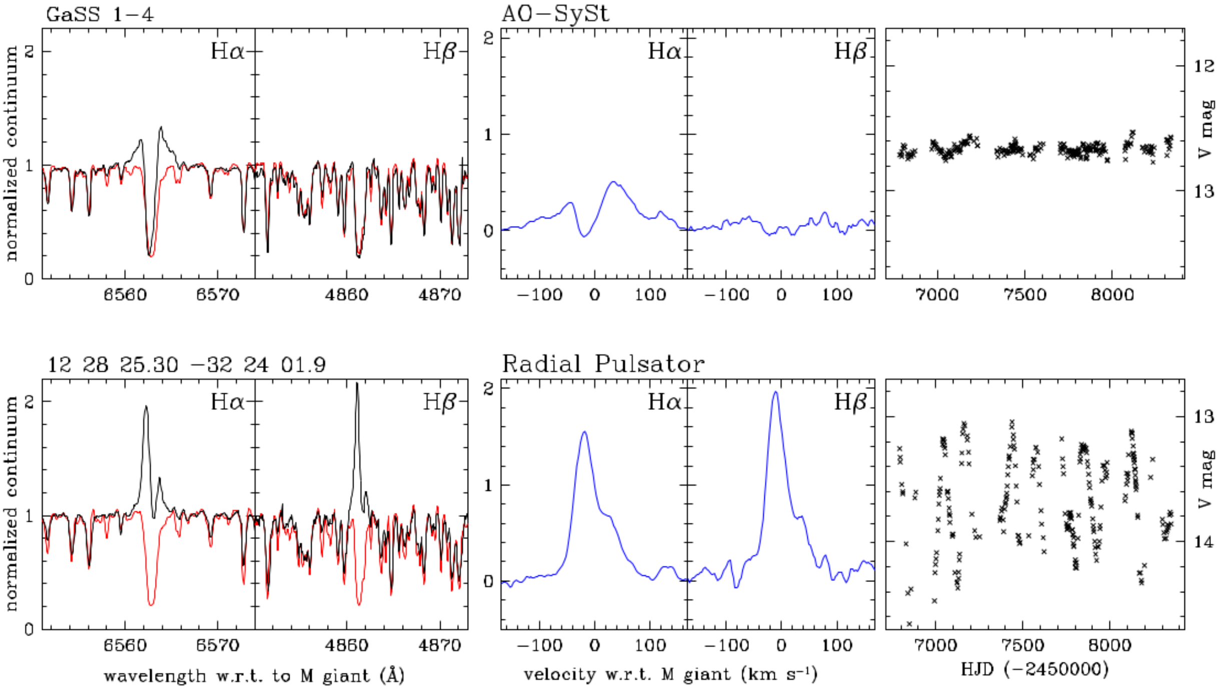

Figure 4. On the left panel there are examples for Hα and Hβ profiles (black) for a symbiotic star (top row) and for a radial pulsator (bottom row). The red profile represents the spectrum of a single red giant. In the middle panel there is the result of substraction between black and red profiles. On the right panel is the corresponding lightcurve in V magnitude for each type of star [12].

6. Conclusion

Symbiotic binary stars are interacting binaries with long orbital periods. They consist of a primary star, usually a red giant, and a companion star, usually a white dwarf or neutron star. The separation between the stars is relatively large, so the matter transfers from a red giant to the surface of a compact star through Roche lobe overflow or in the form of stellar wind. In the paper, we focused on the symbiotic binaries where the compact object is a white dwarf. The accretion of stellar wind from the red giant onto the surface of the white dwarf makes them a promising Type Ia supernova progenitor. Because of the novae outbursts they are considered to be one of the candidates responsible for enrichment of interstellar medium with lithium.

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