Part III

Stellar Variability

General Observational Characteristics of Symbiotic Binaries

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Abstract

Symbiotic stars are interacting binary systems, in which a red evolved giant star transfers material to its hotter compact companion. This paper summarizes the basic observational characteristics of these binaries as well as some of the parameters of their components.

Introduction

Symbiotic stars are heterogeneous group of objects with a wide variety of behaviour of their emission, but a basic characteristics of their optical spectrum is simultaneous presence of features associated with a cool giant star and emission lines of high excitation. Another important characteristics is their photometric variability, which is realized on different time scales. Some of these objects go through eruptions resembling classical novae. The eruptions alternate with stages of quiescence when different kinds of a change of the light are observed. Sometimes the light practically does not vary, in other cases it undergoes cyclic modulation on a time scale of years. Some stars display rapid photometric variability on time scales of hours and even some minutes. The eruptions of one group of the symbiotic stars develop very slowly and the decline of their optical light to its quiescent level lasts dozens of days. The photometric variations of the symbiotics are accompanied by changes of their colour as well as by spectral variations.

Multiple criteria and quantitative requirements for classification of the symbiotic stars have been appeared through the history of their observations (Boyarchuk 1969, Allen 1979, Nussbaumer 1982). Because of the variety of their behaviour Kenyon (1986) writes that "every known symbiotic star has, at one time or another, violated all the classification criteria invented in the past 50 year". That is why this author regards that the observed properties of the symbiotic stars or stars with combination spectra may be briefly summarized as:

1. "the absorption features of a late-type giant star (a G, K or M star which is not obviously a main sequence or a super giant star); these include CaI, CaII, NaI, FeI, H_2O, CN, CO, TiO and VO, among others;
2. bright HI and HeI emission lines and either
   (a) additional bright lines of ions with an ionization potential at least 20 eV (e.g. [OIII]) and an equivalent width exceeding 1 Å, or
   (b) an A or F-type continuum with additional absorption lines from HI, HeI and singly ionized metals."

   The second point (b) represents the spectrum of a typical symbiotic star during its outburst phase.

1 Symbiotic stars as binary systems

Symbiotic stars are now commonly accepted as binary systems, in which a red giant star transfers material to its hotter companion. The binarity has been proved in four different ways. The first one is based on optical photometric data, which showed eclipses in some systems like AR Pav (Mayal 1937) and CI Cyg (Hoffleit 1968a, Belyakina 1991). By now about 30 symbiotics have known orbital periods and $\sim$50% of them are eclipsing systems (Mikolajewska 1997).

The second way is related to obtaining the elements of the spectroscopic orbit. The orbital periods are of several hundred days of the vast majority of the symbiotics. For the rest of them they are of several thousands days. The cool giant is the more massive system component having mass of ~ 1–3 $M_{\odot}$ and the mass of its compact companion in the most cases is ~ 0.3–0.7 $M_{\odot}$. The separations of the most systems are obtained to be in the interval $1 \div 3$ AU, but there are, also, some groups of objects whose separations are close to 10 AU or more.

Very important argument in favour of binarity of the symbiotics is the availability of the orbital parameters of few systems obtained by means of spectropolarimetric observations of the Raman scattered $\lambda\lambda$ 6825, 7082 ÅÅ emission lines. One result is that the orbital period of 80 years and inclination of about 60° of V1016 Cyg were obtained which is the first direct estimate for orbital parameters of symbiotic Mira (Schild & Schmid 1996).

The presence of a hot secondary component in the symbiotic binaries was directly established for the first time by the IUE satellite. Its data revealed a strong UV continuum in practically every observed star.

2 The cool component, the infrared properties and the space distribution

Symbiotic systems divide into two major classes, s- and d-type, according to the infrared spectrum, emitted by their cool components (Webster & Allen 1975). Mürset & Schmid (1999) have presented spectral classification of the cool giants in symbiotic systems, composing a catalogue of 179 objects. 165 of these objects are galactic ones and 13 of them belong to Magellanic Clouds and Draco C-1. The catalogue gives also a classification into s-, d- and d′-types. The majority of the systems (133) are related to s-type, 30 systems are related to d-type, 7 of them – to d′-type and 9 objects have no IR classification.

S-type systems have near-IR colours consistent with those ones of the normal cool giants, or with a stellar photosphere with a temperature of about 3000 – 4000 K. The IR continuum of these systems is emitted by their cool components and is practically invariable.

The near-IR colours of d-type systems are greater than of normal late-type stars and indicate a presence of warm dust shells with $T_d \sim 1000$ K. Moreover, IR photometric data show that d-type systems contain long-period, P$\sim$ 300^d–600^d, Mira variables (Whitelock 1987).

The systems of d′-type in the catalogue of Mürset & Schmid (1999) have several special characteristics. One of the most important is the presence of a F, G or K giant instead of a cooler star. The systems containing cool components of these spectral types are included in the small group of yellow symbiotics. These yellow symbiotics divide also into s- and d′-type systems.

As far as the orbital periods of the d-type systems R Aqr and V1016 Cyg are known only and these periods are long (about $10\,000^d$ and $29\,000^d$ (Schild & Schmid 1996) respectively) it is supposed that all d-type systems have long orbital periods. On this basis the symbiotics are divided into two classes:

1. Short period s-type systems ($P_{orb} \sim 500^d \div 1000^d$).
2. Long period d-type systems ($P_{orb} \sim 10\,000^d$).

According to Whitelock (1987) and Kenyon et al. (1988) the mass-loss rate of s-type systems is of $\sim 10^{-7}$ $M_\odot$ yr^{-1} and of d-type systems – of $\sim 10^{-5}$ $M_\odot$ yr^{-1}.

Most galactic symbiotics belong to the intermediate or old disk population (Allen 1980). From the other hand most s-type yellow systems belong to the old metal-poor (halo) population.

3 The hot component

The UV/optical light of many symbiotic systems shows that a basic characteristics of their behaviour is the alteration of quiescent periods and active phases. The light curve during the active phases is determined by the intrinsic variability of the hot component. Kenyon (1986) supposes that symbiotic systems are naturally divided into three distinct groups on the basis of the number and the duration of their outbursts during the active phases:

1. Recurrent novae (SyRNe). This group has a prototype the star T CrB.
2. Classical symbiotic stars (ClSS). The prototypes of this group are considered to be CI Cyg and Z And.
3. Symbiotic novae (SyNe), with a prototype AG Peg.

The light curve of the recurrent novae is characterized with a presence of two brightenings. The first of them is of a greater amplitude and the whole active phase lasts less than one year. The active phases of the classical symbiotic stars are realized on time scale of a few years when they undergo occasional 1–3 mag eruptions. The U light of the system AG Dra, classified as a classical symbiotic star by Mürset & Schmid (1999), during its active phase 1994–1998 and after it is displayed in Figure 1. The symbiotic novae have undergone a single slow outburst of several magnitudes and duration of one or several decades.

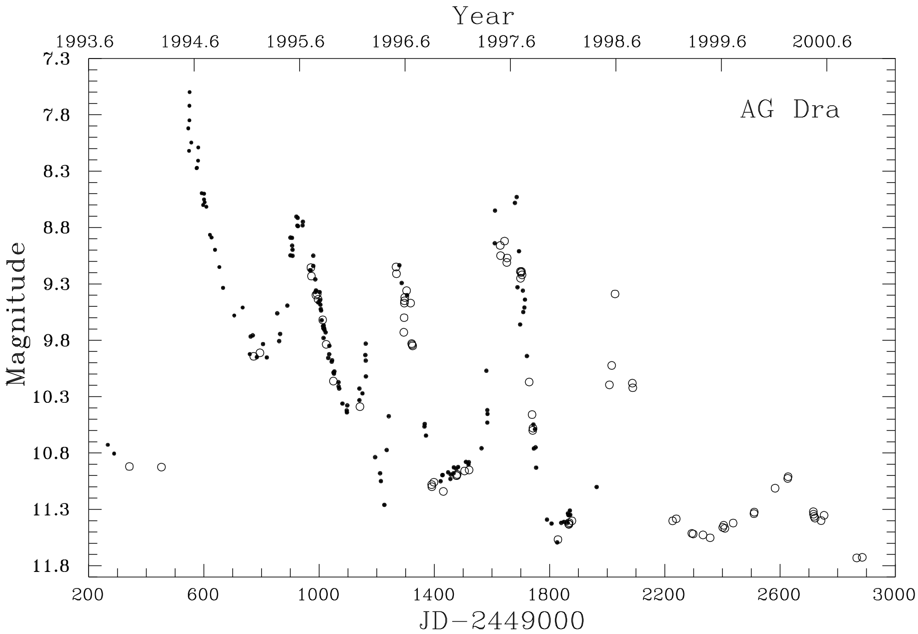

Figure 1: The U light curve of the symbiotic binary AG Dra during its 1994 – 1998 active phase and after it. The brightenings are due to the increased emission of its circumbinary nebula. The dots indicate the data of Skopal (1998) and Petrik et al. (1998) and the circles – the data of Montagni et al. (1996), Tomova & Tomov (1998) and Tomov & Tomova (2000).

According to Kenyon (1986) the symbiotic novae are divided into two subgroups depending on the appearance of their spectrum at maximum visual light:

(a) systems, whose optical continuum reminds this one of A–F supergiant;

(b) systems, whose spectrum reminds this one of planetary nebula.

There are seven known symbiotic novae. AG Peg (the beginning of the outburst was around 1850), RT Ser (1909), RR Tel (1944) and PU Vul (1978) are from the first type. V1329 Cyg (1964), V1016 Cyg (1964) and HM Sge (1975) are from the second type. After the initial increase of the light all symbiotic novae evolve at roughly constant luminosity ($\sim 10^3 \div 10^4$ $L_\odot$) towards very high temperatures of about 100 000 K. The spectroscopic data show that the hot components of all of them experienced a wind mass-loss, observed in some lines of H I, HeI, HeII, CIV, NIV and NV at phase after the maximum visual light. However, there is a marked difference in the wind velocities v_∞ between type (a) (with giant phase) and type (b) (without giant phase) symbiotic novae. The line profiles of the stars of type (a) indicate velocities of $v_\infty \sim 500 \div 1000$ km s^{-1} whereas these ones of the type (b) indicate much greater velocities $v_\infty \sim 2000 \div 3000$ km s^{-1} (Schmid 2000). The AG Peg system is the brightest one and the literature provides many wind line observations. It has been concluded that its hot component has ejected ~ 1–$2\,10^{-4}$ M$_\odot$ throughout the eruption (Kenyon et al. 1993).

During the outbursts of some classical symbiotic stars (Z And or FG Ser type) an early-type spectrum develops and progressively dominates over the TiO bands of the cool giant at longer wavelengths (Munari 1997). The high ionization permitted emission lines progressively decrease in integrated absolute flux. These are indications of the cooling and the expanding of the hot component whose continuum contributes to the UV and visual region. The decrease of the temperature and the expanding of the hot component in this way leads rather to re-distribution of the emitted energy than changes of its luminosity. These systems are believed to experience a constant luminosity phase and their outbursts are supposed to be caused by nuclear activity of the white dwarf. Expanding shells and mass outflow from their hot components are often observed (Schmid 1999)

There is, also, another type of behaviour of the classical symbiotic stars (YY Her type, Munari 1997) during the active phase. In this case an increase of the integrated absolute flux of the high- ionization and forbidden lines during the rise to maximum is observed. Moreover, a blue continuum develops. These characteristics are not indication of a cooling of the outbursting star and a constant luminosity phase.

The explanation of the outburst behaviour of the recurrent novae meets essential difficulties. The current observations support the presence of a white dwarf in all systems of this group. The IUE observations indicate a constant-luminosity phase lasting ~ 50 days in RS Oph and V3890 Sgr, which is a strong argument for a thermonuclear runaway nature of the eruptions. On the other hand the ejected mass is too small $\sim 10^{-7}$ M$_\odot$ yr^{-1}, being a very small fraction of the whole material accreted between outbursts, which does not support the assumption for thermonuclear runaway (Munari 1997).

Some of the hot components of the symbiotic binaries having very high temperature (~ 1–$2\,10^5$ K) are sources of a supersoft X-ray continuum, emitted at frequences below $h\nu \approx 0.4$ keV. According to the X-ray classification of the symbiotic stars an emission of such a kind is related to a type α energy distribution (Mürset 1997) and is interpreted as produced by a very hot photosphere (T>120 000 K). It could be of a white dwarf with solar composition or could be very hot (T$\sim$300 000 K) WR-type atmosphere of a star with heavy mass-loss ($\dot{\rm M} \sim 10^{-5}$ M$_\odot$ yr^{-1}).

The brightest X-ray symbiotic star is AG Dra. Greiner et al. (1997) estimated the temperature of the hot component of this system of $\sim$170 000 K at its quiescence. For explanation of the X-ray luminosity of this component they supposed that the burning rate of hydrogen from the giant's wind is equal to its accretion rate that was obtained to be $\sim 3.2\,10^{-8}\ M_{\odot}\,\mathrm{yr}^{-1}$ at the adopted distance. This high accretion rate needs a regime of a steady state burning at the surface of a white dwarf. This conclusion is in agreement with the high temperature, based on the continuum energy distribution. It can be thus expected that many systems whose hot components maintain high temperature are actually in- or close to- the steady burning configuration.

4 The nebula

At the quiescent phase the symbiotic nebula forms as a result of the mass-loss of the cool stellar component. In some other cases, related to the active phase, it results from the mass outflow of both stellar components. The nebula gives rise to the emission spectrum which is characterized by the simultaneous presence of lines requiring different excitation conditions. However the symbiotic nebulae distinguish themselves from the planetary nebulae by very prominent permitted and intercombination (HI, HeI, HeII, OIII], CIV, NV) emission lines and relatively weak forbidden lines ([OIII], [NeIII]).

The Balmer series of some systems consists of narrow emission lines of nebular type. These systems are characterized by orbital variations of the profiles of the first Balmer members, determined by the optical depth changes, which from their side depend on density's unhomogeneity. Van Winckel et al. (1993) created a classification system of the symbiotic stars, based on their Hα profiles. They suggested that the Hα emission profile affected by self-absorption can be an indicator for the mass-loss rate of their cool components, whose atmospheres are ionized by a hot star. Later this idea was quantitatively considered by Schwank et al. (1997), who calculated a variety of models of an expanding atmosphere of a cool giant of s-type symbiotic system. The atmosphere of the giant is irradiated and ionized from the outside by the hot stellar component. The Hα profile depends on its luminosity, the binary separation, the mass-loss rate of the cool giant and the velocity of its wind. Schwank et al. calculated the profile at phase when the hot component is to the observer, supposing that the line is mainly due to recombination. The profile includes an absorption which moves from the center of the line to its short wavelength-side depending on the velocity of the absorbing particles. When the mass-loss rate of the giant increases, the ionized portion decreases and the transition zone between the ionized and the neutral volumes shifts outwards approaching the hot component. An outward shift of this zone in a region with higher velocity gradient leads to an increase of the difference between the velocity of the absorbing particles and that of the underlying recombination region, and, consequently, to a blue shift of the absorption. So the position of the absorption can be an indicator of the mass-loss rate.

The formation of the emission lines of other atoms was studied by Proga et al. (1998). They calculated their fluxes and found also that thermal pressure is important in accelerating ionized regions of the wind of the giant.

The emission lines at $\lambda\lambda$ 6825 Å and 7082 Å are detected only in the symbiotic spectra. Until recently these emissions were not identified but later it turned out (Schmid 1997) they appear as a result of Raman scattering of the photons with wavelengths $\lambda\lambda$ 1032 Å and 1038 Å of the OVI resonance transitions. In symbiotic systems the OVI emission appears near the hot component and is converted by neutral hydrogen into Raman photons in the extended atmosphere and wind of the cool giant. In this process an OVI photon excites atomic hydrogen from its ground state $1s^2S$ to an exited state, followed by the emission of a photon leaving the atom in the lower $2s^2S$ state and the emission of a Lyα photon. Between the wavelengths of these photons exists the next relation $1/\lambda_{\rm Raman} = 1/\lambda_{\rm OVI} - 1/\lambda_{\rm Ly\alpha}$. It can be derived the scattering efficiency $N_{\rm Raman}/N_{\rm OVI}$ from the measured fluxes of the OVI lines and the Raman lines if there are simultaneous UV and optical spectral data. That parameter provides information about the extent of the scattering region with respect to the region emitting the OVI lines.

An OVI photon entering the region of the neutral hydrogen of the giant's wind can be undergone to Raman scattering either directly or after one or several processes of Rayleigh scattering. The Raman photons appeared in the first way contain more information about the general structure and motion of the scattering region. ¿From his theoretical considerations Schmid (1992) came to the conclusion that roughly the half of the Raman photons are directly scattered. A formula about their number is given in the work of Schmid & Schild (1994).

The wavelength of the direct scattered photon is determined by the motion of the scattering atom relative to the OVI emitting ion (Schmid & Schild 1994). That is why the process of direct scattering leads to a wavelength shift of the Raman lines whereas the multiple scatterings cause only broadening of the incoming OVI profile. Schmid & Schild (1994) proposed a simple model which account for the basic properties of the Raman profiles. In every symbiotic system where the wind of the giant is partly ionized two regions can be distinguished according to the velocities of their particles relative to the OVI source. The first of them is spherical one, situated between the components and has a radius equal to the half of the binary separation. The scattering H^o atoms in this region have an approaching velocity relative to the OVI source and lead to the blue shifting of the Raman photons. The H^o atoms of the outer part of the giant's wind have a receding velocity relative to this source leading to the red shifting of the Raman photons. So the different components of the Raman profiles are formed in different regions of the symbiotic nebula.

The scattered light shows also a polarization, which is 100% when the scattering angle is 90°. It decreases gradually for other angles and is equal to 0% (no polarization) when the angle is 0° or 180° (Schmid 1997). Since the binary system rotates relative to the line of sight the scattering geometry rotates too and the polarized light changes with the orbital phase. That is why the spectropolarimetric observations of Raman lines give the possibility to determine some of the orbital parameters of the symbiotic systems – the orbit inclination and orientation (Schmid & Schild 1997a,b). For an inclined orbit the polarization maximum will realized at quadratures when the angle between the direction from the OVI source to the scattering region and the line of sight is close to 90°. In this way the polarization minimum must be expected at conjunctions.

When the inclination of the orbit is small, the scattering configuration is always close to right angle. In this case high percentage polarization with small orbital amplitude must be observed.

The data for the emission line fluxes are used to obtain physical conditions within the symbiotic nebulae. These data indicate nebular densities of $n_e \sim 10^8$ to 10^{10} cm^{-3} in s-type and much lower $n_e \sim 10^6$ cm^{-3} in d-type symbiotics (Kenyon 1986). The more detailed study of the nebulae of some systems (e.g. Kenyon et al. 1993, Mikolajewska et al. 1995) showed that their electron temperature is about 15 000 K. This means that radiation and not collisions are in general responsible for their ionization. The symbiotic nebulae can be also radio sources (Seaquist & Taylor 1990). Free-free radio continuum has been detected from about 25% of all symbiotic systems. The radio emission is correlated with the IR properties. This correlation is expressed essentially in the fact that all d-type systems are radio sources. Moreover, the systems with the greatest mass-loss have the greatest radio luminosity.

In a number of cases the symbiotic nebulae seem to be X-ray sources as well. Some of these cases are related to the eruptive phases of the symbiotics when their hot stellar components generate a wind outflow with a high velocity. This wind interacts with the wind of the cool giant, modifying significantly the structure of the nebula and creating a shock region which gives rise to X-ray emission of $\sim 1L\odot$ (Willson et al. 1984, Nussbaumer & Walder 1993). The X-ray continuum energy distribution is typical of a very hot (T $> 10^6$ K) optically thin plasma and peaks at about $h\nu \approx 0.8$ keV. According to the X-ray classification of the symbiotic stars a continuum of such a kind is related to a type β energy distribution (Mürset 1997). This type of X-ray emission is representative of all symbiotic novae. There is one type of symbiotic X-ray emission more, which is related to a hot plasma and not to a stellar photosphere and that is why it should be noted in this section. This type of emission (γ) was observed in the spectrum of GX1+4 (Predehl et al. 1995), being thought to appear in a high energy (50 keV) relativistic plasma (Mürset 1997).

Concluding remarks

The multifrequency observations of symbiotic stars show that they are long-period interacting binaries consisting of a cool giant primary component and a hot companion. The nature of the cool giant plays a key role in the interaction between the components. The size of the giant and its mass-loss rate determine that distance between the components at which the transferred mass is sufficient for realizing symbiotic phenomenon. On this base we have two classes of symbiotic binaries: s-type having normal red giants with a mass-loss rate of $\sim 10^{-7}$ M$_\odot$ yr^{-1} and orbital periods of $\sim 1 \div 15$ yr, and d-type having Miras with a mass-loss rate of $\sim 10^{-5}$ M$_\odot$ yr^{-1} and periods of $\sim 15 \div 100$ yr.

The analysis of the UV and X-ray spectra revealed that the secondary components of the symbiotic systems are in the most cases luminous ~ 1000 L$_\odot$ white dwarfs with temperature of $\sim 10^5 \div 2\,10^5$ K. They are supposed to be powered by thermonuclear burning of the material accreted from the giant's wind. Some of these objects probably undergo a single, very prolonged hydrogen shell flash on the surface of a white dwarf with a low mass. The other ones are assumed to be in a steady burning configuration.

The symbiotic nebulae appear as a result of the mass-loss of one or both stellar components of the binary and give rise to the recombination continuum and the emission lines. They distinguish themselves from the planetary nebulae by higher densities and temperatures resulting in appearance of very prominent permitted lines of high excitation and relatively weak forbidden lines. During the active phases characterizing with a mass-loss of the hot components, shock regions of the stellar winds are generated. In these cases the symbiotic nebulae give rise to X-ray emission up to several solar luminosities.

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