

Symbiotic Stars

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Abstract Symbiotic stars are interacting binary systems composed of a white dwarf (WD) accreting at high rate from a cool giant companion, which frequently fills its Roche lobe. The WD usually is extremely hot and luminous, and able to ionize a sizeable fraction of the cool giant wind, because it is believed the WD undergoes stable hydrogen nuclear burning on its surface of the material accreted from the companion. This leads to consider symbiotic stars as good candidates for the yet-to-be-identified progenitors of type Ia supernovae. Symbiotic stars display the simultaneous presence of many different types of variability, induced by the cool giant, the accreting WD, the circumstellar dust and ionized gas, with time scales ranging from seconds to decades. The long orbital periods (typically a couple of years) and complex outburst patterns, lasting from a few years to a century, make observations from professionals almost impossible to carry out, and open great opportunities to amateur astronomers to contribute fundamental data to science.

1. Introduction

Observing symbiotic stars (hereafter SySts) is real fun and a great opportunity for the amateur astronomer (hereafter AA) to contribute fundamental, better to say “unique” data. In fact, the long orbital periods and outburst phases (measured in years) make observations by professionals almost impossible to carry out, especially for those that have to access, on highly competitive grounds, to telescopes at large observatories. SySts show variability over a wide range of time scales: seconds/minutes (accretion flickering), minutes/hours (rotation of the white dwarf), days/months (rotation, pulsations of the cool giant, recombination in the ionized circumstellar gas, shock fronts, bipolar jets), months/years (orbital periods, eclipses, reflection effects, ellipsoidal distortions, Mira pulsations), months/centuries (outbursts). Some of these types of variability are best seen and display larger amplitude in the red, others at blue wavelengths, as we will see later on in detail.

To enhance their value, to provide firmer grounds for physical modeling, and to allow astronomers to safely combine data collected by various AAs (sometimes different *generations* of AA), the photometric observations should be carried out in standard photometric bands, well-calibrated into accurate local photometric sequences by application of suitable color equations. Henden

and Munari (2000, 2001, 2006) have calibrated photometric sequences around eighty-one well-known SySts and are working to extend them to all other catalogued SySts. By adopting these photometric sequences, the AAs can bring their observations closer to (and easier to integrate with) data collected by professionals who frequently use the same photometric sequences for their observations or when reconstructing past photometric histories from measurement of old photographic plates preserved in plate stacks around the world (like those at Harvard, Sonneberg, Pulkovo, and Asiago).

Even though this review focuses on photometry, it's a pleasure to note how spectroscopy is now becoming wide-spread among AA. Useful low resolution spectra of about twenty known SySt in quiescence are within the grasp of AAs using 0.5m telescopes, and a similar number of additional SySts can be reached during their outburst phases. The $H\alpha$ is so bright that high resolution profiles of this emission line can be obtained for numerous SySts even with 0.5m telescopes. The profile and intensity of $H\alpha$ is deeply modulated by the orbital motion, and it strongly responds also to the ionization of the circumstellar gas, eclipses, outbursts, winds, bipolar jets, and so on: monitoring the $H\alpha$ of SySts is really fun! As a guideline, low resolution spectra should cover from 4000 to 7000Å at 2–5 Å/pixel, while high resolution observations of $H\alpha$ should cover an interval of 100–200Å at 0.1–0.35 Å/pixel.

2. A typical symbiotic star

Let's begin with outlining what type of binary system a typical SySt is, and to this aim Figure 1 presents the optical spectrum of Z Andromedae, a prototype of this class of objects (see also Skopal 2011). A SySt is composed of: (1) a late type giant (LTG), most frequently of M2-M5III spectral types, not pulsating (in only ~20% of the cases it pulsates like a long period Mira), with its strong TiO absorption molecular bands modulating the spectrum at red wavelengths. The LTG dominates spectra and photometry at R_c -, I_c -band wavelengths.; and (2) an extremely hot ($\geq 80,000$ K) and luminous (of the order of a thousand solar luminosities) white dwarf (WD). It orbits the LTG and accretes from it, both via wind capture or Roche lobe overflow. The WD is so hot that its emission is concentrated in the far ultraviolet and X-rays, and it becomes directly observable at U , B , and V bands usually only during outbursts when its outer layers expand and cool.

The large temperature and luminosity of the WD (much larger than accountable by release of potential energy of accreting material, or by plain thermal irradiance along the cooling track) are explained by assuming that the WD undergoes stable hydrogen nuclear burning on its surface of the material accreted from the LTG (Munari and Buson 1994; Sokoloski 2003). The presence of many Super-Soft X-ray Sources (SSSx) among SySts is a direct confirmation of this scenario (many other SySts are not detected as

SSSx simply because there is so much circumstellar material around them that the X-rays are all locally absorbed). To keep the nuclear burning stable, the WD has to accrete at a high rate (a rate much larger than in the other types of interacting binaries, like the cataclysmic variables). This rate is fine tuned by the mass of the WD: below the critical value, the nuclear burning switches off; above it the material accreted in excess expands under the effect of the huge radiation pressure, and the overall structure would thus resemble a red giant star (in such a case our binary system would appear as if composed of two red giants in mutual orbit, no emission line would be seen, and the object would not be classified as a SySt).

The stable nuclear burning at the surface of the WD has one very important implication for SySts. Contrary to novae, where the nuclear burning is a highly explosive process that ejects into space essentially all the accreted material, the non-explosive burning occurring in SySts (both during quiescence and outbursts) allows the WD to retain the accreted matter, and stably grow in mass. If the companion LTG has enough material to transfer, the WD can grow in mass until the Chandrasekhar limit of $1.4 M_{\odot}$ is reached, at which point the WD could explode as a type Ia supernova (Munari and Renzini 1992). The exact nature of the precursors of SN Ia is still a matter of debate, but there is wide consensus that SySts are promising candidates.

There are two additional very important components in a typical SySt: circumstellar gas and dust. A SySt is embedded in a great amount of circumstellar gas (hereafter CG), created mostly by the wind blowing off the LTG, and which is ionized by hard radiation from the WD. The ionized fraction of the CG extends up to 100 astronomical units from the central binary, and it gives rise to two spectacular phenomena (compare the spectrum of the prototype SySt Z And in Figure 1): (i) very bright emission lines (in particular $H\alpha$) adorning the spectrum at all wavelengths and tracing conditions of high ionization (Allen 1984 classification criterion dictates the presence of emission lines from HeII or higher ionization species like [Fe VII] or [NeV]), and (ii) a bright blue continuum that, over U and B bands, is much brighter than the LTG, frequently pushing the $U-B$ colors of SySts to largely negative values. If the number of energetic photons emitted by the WD goes up, also the amount and the brightness of the ionized circumstellar gas increases, and the reverse holds true. Thus the CG acts like a calorimeter, reverberating for us at optical wavelengths what the embedded WD does in far ultraviolet and X rays. Photo-ionization modeling of the observed flux of emission lines (corrected for reddening) can accurately fix the luminosity and temperature of the WD without the need for observations by orbiting satellites in the far ultraviolet and X-rays.

Circumstellar dust is almost always present when the LTG is a Mira variable. The dust is concentrated around the LTG and can be so thick as to cause spectacular extinction: in He 1-36 Allen (1983) estimates that the circumstellar dust dims the LTG by 20 magnitudes in the V band while the external ionized

gas is left unaffected. Sometimes the SySts harbouring a Mira variable undergo periods of what seems to be protracted dust extinction. It is believed that this is caused by the dust being concentrated in a shadow cone produced by the LTG itself, where the dust is shielded from the disruptive ionizing radiation of the WD. Periodically, along the orbital motion, the SySt is seen through such dust cone and an attenuation results.

SySts belong mostly to the Old Bulge/Thick Disk stellar population of the Galaxy and as such they appear concentrated toward the plane of the Galaxy and in particular its central regions. We know about 300 SySts, and the total population in the Galaxy is estimated to range from 30,000 (Kenyon *et al.* 1993) to 300,000 (Munari and Renzini 1992). Symbiotic stars have been discovered also in external galaxies, including the Magellanic Clouds, M31, M33, IC 10, NGC6822, and the Draco dwarf galaxy. Most of the known SySts have been discovered as emission-line objects during objective prism surveys of the Milky Way, and many were originally classified as compact planetary nebulae (PNe); the true nature of some transition objects is still hotly debated (for example, V471 Per = VV-8). Additional SySts lie probably still unrecognized among poorly studied PNe. There is a natural and smooth overlap between PNe with binary nuclei and SySts, the main difference being: in PNe the ionized gas has been ejected by the progenitor of the current WD nucleus, while in SySts the gas is blown off the LTG companion and that ejected by the WD progenitor has already long gone.

3. Various types of variability seen in symbiotic stars

In describing the major types of variability displayed by SySts we will refer to observations carried out in the Johnson *UBV*-Cousins $R_c I_c$ bands. Similar considerations hold true for the corresponding bands of the Sloan *u'g'r'i'z'* system. The main types of variability seen in SySts are:

- *ellipsoidal*, when the cool giant fills its Roche lobe. Due to orbital motion, the area of the Roche lobe projected onto the sky varies continuously, with two maxima (when the binary system is seen at quadrature) and two minima (when the cool giant passes at superior or inferior conjunctions) per orbital cycle. Popular examples of SySts showing ellipsoidal distortion of their light-curve are T CrB (orbital period 227 days, amplitude $\Delta m = 0.3$ magnitude) and BD-21.3873 (orbital period 285 days, amplitude $\Delta m = 0.2$ magnitude). The ellipsoidally modulated I_c -band light curve of LT Del is illustrated in Figure 2;
- *heating-reflection effect*, caused by the hard radiation field of the hot and luminous WD (radiating mainly in the X-ray and far ultraviolet domains) that illuminates and heats up the facing side of the LTG (which thus reprocesses to the optical domain the energy received in the X-ray and far ultraviolet

from the WD). The heated side of the LTG is therefore brighter and hotter (bluer) than the opposite side (which is not illuminated by the WD radiation field). During an orbital period, the heated side comes and goes from view, causing a sinusoid-like light-curve characterized by a single sharp minimum and a broader, single maximum (compare the *B*-band light-curve of LT Del in Figure 2). The effect is strongly wavelength-dependent, being maximum in the *U* band and declining in amplitude toward the I_c band where it is usually undetectable. It is also stronger in systems seen equator-on, and vanishes for those seen pole-on. The amplitude may be fairly large, as in LT Del where it accounts for $\Delta B = 0.7$ (compare Figure 2) and $\Delta U = 1.6$, $\Delta V = 0.2$ (Arkhipova and Noskova 1988). The heating-reflection effect is the principal tool to derive orbital periods of SySts (Mikolajewska 2003);

- *pulsation*, like that of a Mira variable (about 20% of the known SySts harbor a Mira). Popular examples are R Aqr (pulsation period of 386 days, minima as faint as $V = 12$, maxima as bright as $V = 5$ magnitudes) or UV Aur (pulsation period of 395 days, minima as faint as $V = 11$, maxima as bright as $V = 7.5$ magnitude);
- *rotational*, of both the LTG and the WD. The rotation period of the LTG is of the same order as of the orbital one, thus measured in years. The rotation period of the WD is instead measured in hours, and its photometric amplitude is always pretty small;
- *eclipses of the WD* (and/or the ionized gas around it) by the LTG. Sometimes the eclipses escape detection by optical photometry during quiescence because the WD is small in radius and radiates mostly in the X-rays and far ultraviolet. During the outbursts the white dwarf emission shifts to longer wavelengths and becomes conspicuous in the optical, thus allowing the eclipses to be detected if the orbital inclination is sufficiently large. Classical examples of SySts for which the eclipses passed undetected in quiescence and instead became outstanding features of the outburst light-curve are FG Ser and V1413 Aql. Because the eclipsing body is cool and the eclipsed one is hot, the visibility of eclipses increases toward shorter wavelengths (for example for FG Ser in outburst it was $\Delta V = 1.4$, $\Delta B = 1.9$, and $\Delta U = 2.3$ magnitudes);
- *re-processing* by the CG of the energy radiated by the WD. The amount of ionized CG (and therefore its luminosity) is directly related to the amount of energy radiated by the WD and its *quality*, that is, the fraction of radiated photons which are energetic enough to ionize hydrogen and thus make it shine. A change in the WD radiation output would reflect in a different amount of ionized CG, and therefore in a variation of its brightness, especially in *U* and *B* bands;

• *outbursts*. There are three basic types of outburst displayed by SySts: (1) Type A—the one most frequently seen in SySts, presents amplitudes of $\Delta B = 2\text{--}5$ magnitudes (invariably declining toward red wavelengths) and durations of a few years, usually with many different maxima and minima during a single outburst episode. After such a train of multiple maxima, the SySt returns to flat quiescence conditions where it stays for a period of time usually much longer than spent in outburst. Light curves typical of such type of outburst are shown in Figure 3. Their cause is probably an increase in the mass transfer from the LTG to the WD. While the nuclear burning at the surface of the WD continues, the extra transferred material causes the WD to react by expanding its outer envelope. This expansion occurs at roughly constant luminosity and therefore causes a drop in the surface temperature (following the black body law $L = 4\pi R^2 \sigma T^4$), from $\geq 80,000$ K to $\sim 12,000\text{--}7,000$ K. The peak of the WD radiation field shifts from the X-rays to the optical, where the SySt appears much brighter, in “outburst.” The much cooler radiation field from the WD is thus lacking energetic photons, and the high ionization emission lines quickly disappear from SySts undergoing this type of outburst; (2) Type B—outbursts lasting for about a century, like the example of BF Cyg shown in Figure 4 or other well known cases, like V1016 Cyg, HM Sge, and AG Peg. All of them are characterized by a rapid rise to maximum (a couple of years at most), and then a slow, century-long decline with superimposed a lot of other smaller amplitude activity; (3) Type C—we could call them “a nova within a symbiotic binary.” Outstanding examples are RS Oph, T CrB, and V407 Cyg, all being celebrated recurrent novae, characterized by very rapid evolutions (from a few weeks to a few months). The WDs of these systems are quite massive, close to the Chandrasekhar limit, and undergo eruptions like those of normal novae every few decades. The light curve of the 2010 such eruption of V407 Cyg is shown in Figure 5, and the spectacular evolution of $H\alpha$ is presented in Figure 6 (which is within the observational possibilities of 0.7-m AA telescopes equipped with high resolution spectrographs). In quiescence, the slowly expanding LTG wind is ionized only in the immediate vicinity of the WD (sharp and weak $H\alpha$). When the WD undergoes a true nova eruption, the initial intense flash of hard radiation ionizes a vast fraction of the LTG wind still slowly expanding (sharp component in the March 15, 2010, $H\alpha$ profile). The suddenly ionized LTG wind soon starts to recombine to neutral conditions, which it completes in less than a week, while the fast nova ejecta began to expand around the WD (broad component in the March 15, 2010, $H\alpha$ profile). As the fast nova ejecta attempt to continue their expansion within the pre-existing dense and slow wind blown off the LTG, they are progressively slowed down (resulting in the narrowing of the $H\alpha$ profile for April 7, 2010, spectrum in Figure 6). After some months, the nova ejecta have been almost entirely stopped by the pre-existing slow

wind. The low electronic density characterizing the cavity the nova ejecta have swept within the LTG wind allows feeble emission from forbidden lines to appear (see the [NII] emission lines at 6548 and 6584 Å flanking H α in the profile for September 22, 2010, in Figure 6).

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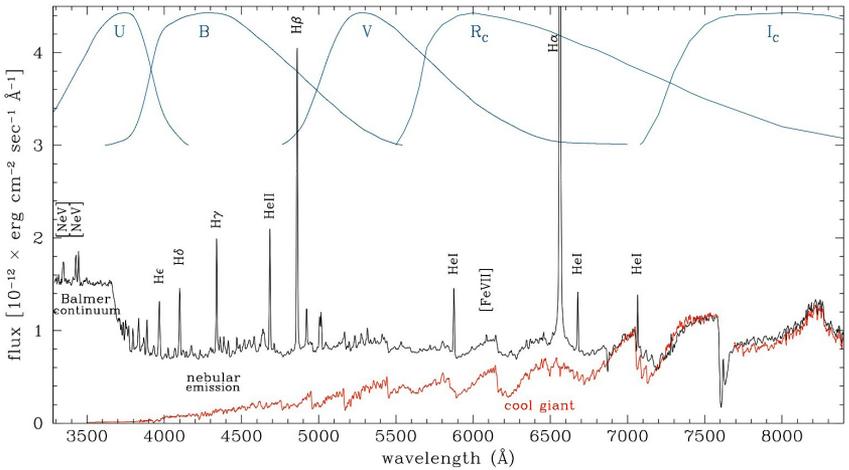


Figure 1. Optical spectrum of Z And in quiescence (Dec. 22, 2011, Asiago 1.22m telescope), with major emission lines identified. The contribution by the cool giant is highlighted, and the transmission profiles of Johnson UB and Cousins R_C I_C bands are overlotted. The H α line is truncated to enhance visibility of the rest.

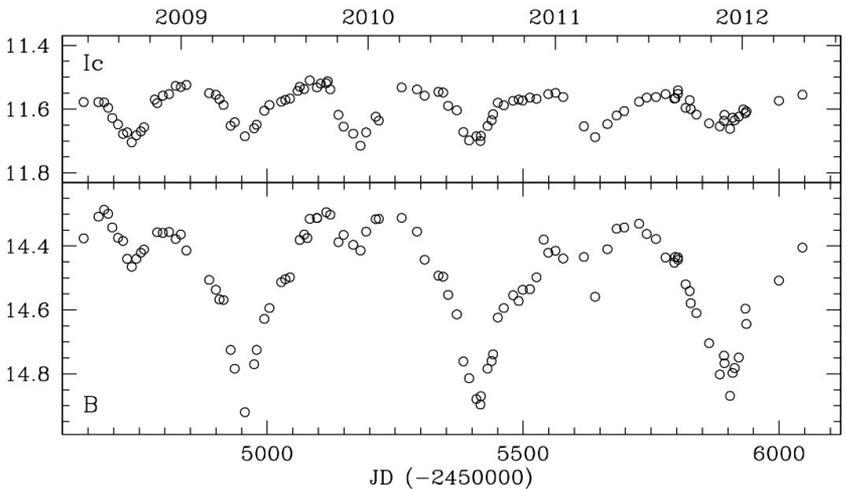


Figure 2. Recent light curve of the symbiotic star LT Del in quiescence (ANS Collaboration observations). The B-band lightcurve at the bottom is dominated by the heating-reflection effect, with one deep minimum per orbital period (when cool giant passes at inferior conjunction). The I_C-band light curve at the top is modulated by the ellipsoidal distortion of the cool giant filling its Roche lobe (two equal maxima and two equal minima per orbital period).

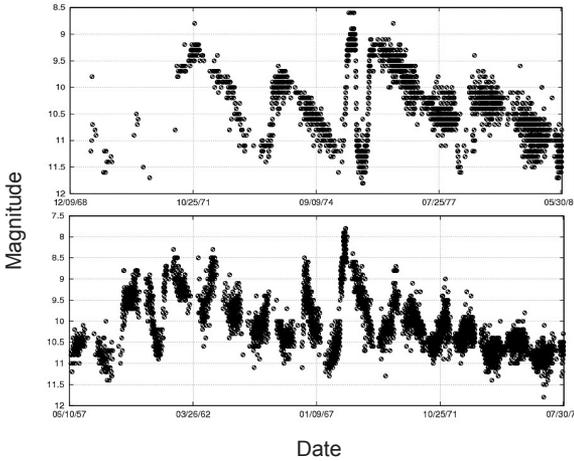


Figure 3. AAVSO light curves for the 1970–1978 outburst of CI Cyg (top) and 1957–1973 outburst of Z And (bottom). They are classical examples of type A outbursts of SySts, characterized by a train of multiple maxima before the system returns to quiescence and where it will remain for a period of time usually much longer than spent in outburst.

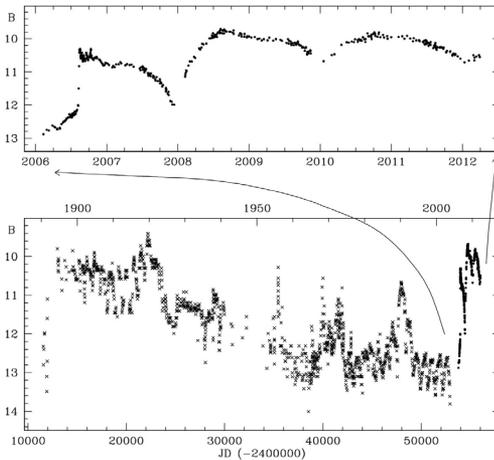


Figure 4. The historical B-band light curve of the symbiotic star BF Cyg. The object entered a major outburst around 1894, and took the whole of the 20th century to decline back to quiescence conditions, while displaying a lot of superimposed activity (including eclipses of the outbursting WD by the cool giant). In 2006, BF Cyg entered a new major outburst; whether it will last long as the previous one is a matter of speculation (crosses from Leibowitz and Formigini 2006; dots from ANS Collaboration observations).

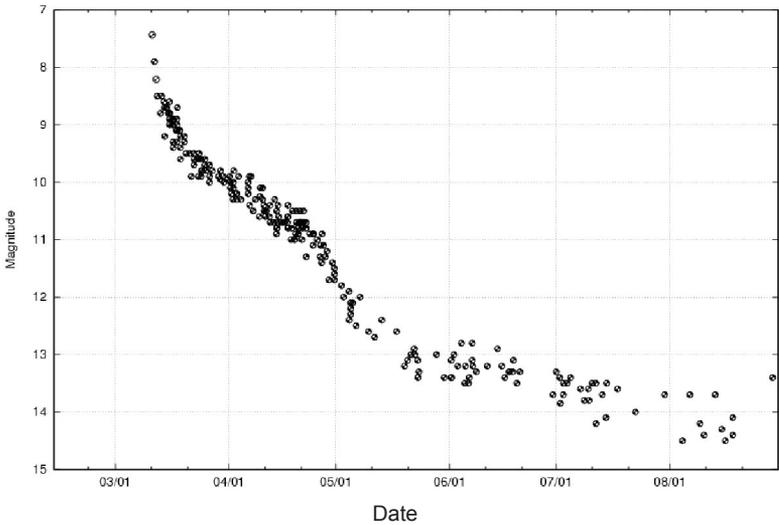


Figure 5. AAVSO light curve of the outburst of V407 Cyg during the spring-summer of 2010.

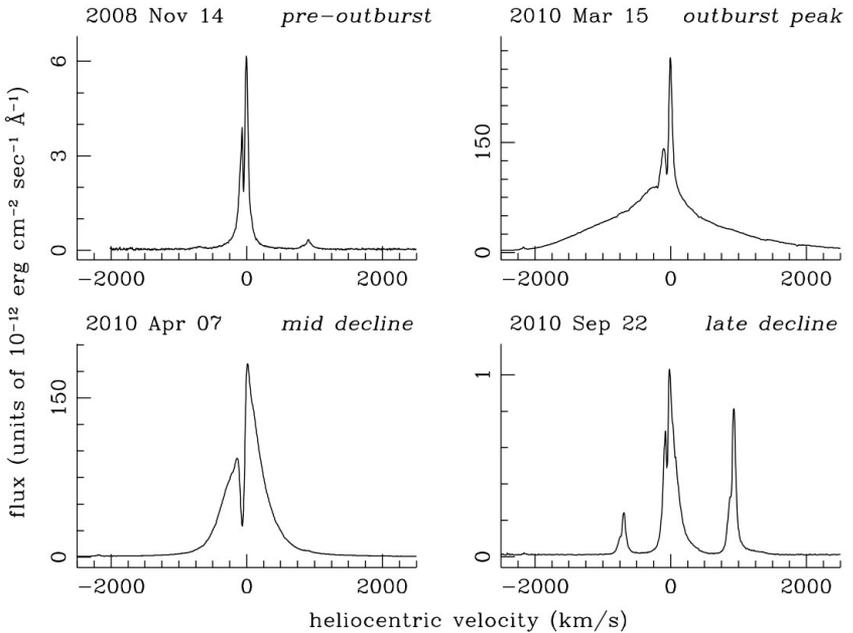


Figure 6. Evolution of the H α emission line profile of V407 Cyg during the 2010 outburst. Note the ordinate scale which is different in each panel (adapted from Munari *et al.* 2011).