Orbital and stellar parameters of symbiotic stars

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Abstract. This paper reviews current knowledge of symbiotic binaries, with special emphasis on their multifrequency observational characteristics, and basic parameters of the symbiotic system components. We start with a brief presentation of variable phenomena found in symbiotic stars. This is followed by a summary of the recent progress in determination of their orbital and stellar parameters. We also discuss basic properties of the symbiotic giants compared to single evolved giants as well as the nature of the hot component and its outburst evolution.

1. Introduction

Symbiotic stars were isolated as a separate class of spectroscopically peculiar stars by Annie J. Cannon, during her work on HD Catalog, in the beginning of XXth century. A typical symbiotic spectrum should display (Fig. 1) absorption features – such as TiO bands and neutral metals, and an associated red continuum typical for red giants, a blue continuum with the H I Balmer lines and jump in emission, and strong emission lines from relatively highly ionized species – He I, He II, [O III], etc., usually found in planetary nebulae. The simultaneous presence in a single object of low-temperature absorption features and emission lines that require high excitation conditions apparently points to their binary nature. In fact, binary models for symbiotic stars, in which a rather normal M giant was accompanied by a hot component resembling the central star of a planetary nebula, were proposed and discussed soon after their discovery (e.g. Berman 1932). Berman also proposed that the observed eruptive behaviour of some objects could be due to some kind of the hot component instability, perhaps similar to that responsible for a nova phenomenon. It is really impressive how close were these first models to the generally accepted present-day model.

According to this model, a typical symbiotic binary consists of an M-type giant transferring material to a much hotter, white dwarf companion via a stellar wind. The wind is ionized by the hot component giving rise to symbiotic nebula. In some systems the red giant is replaced by a yellow G–K-type giant, and the white dwarf by a main-sequence or neutron star. Most symbiotic stars (≈ 80 %) contain a normal giant and their near-IR colours show the presence of stellar photosphere, $T_{\text{eff}} \sim 3000$–4000 K; these are classified as S-type (stellar) systems. The remaining 20 % of symbiotic systems contain Mira-type variables and their near-IR colours are consistent with the combination of a reddened Mira and warm ($T \sim 1000$K) dust shell; these are classified as D-type (dusty) systems.
Figure 1. Quiescent optical/ultraviolet spectra for symbiotic stars. Strong TiO bands in the red spectrum of CI Cyg, indicate an M4−5 III primary; they are absent in the yellow, galactic halo system AG Dra with a K3II–III primary. The intensity of the UV continuum and He II emission lines require similar temperature, \( \gtrsim 10^5 \) K, and luminosity, \( \sim 1000 L_\odot \), of the hot component in both systems, whereas the CNO emission lines in AG Dra are systematically weaker than those in CI Cyg which reflects low metallicity of AG Dra. Another difference is the presence of strong high-excitation forbidden lines (e.g. [Fe vii], [Mg v], [O iii]) in CI Cyg which are not visible in AG Dra.
Since the presence of an evolved red giant is indispensable to make a symbiotic binary, the system must have enough space for such a large star. Symbiotic stars are thus interacting binaries with the largest orbital separations, and their study is essential to understand the interactions of detached and semi-detached binary stars. Mass accretion onto the hot component also plays a very important role in driving the basic properties and evolution of symbiotic stars, and involves energetic phenomena relevant to many other astrophysical objects. The presence of both an evolved giant with heavy mass loss and a hot companion copious in ionising photons also results in a rich and luminous circumstellar environment surrounding the interacting stars.

Such a complex multi-component structure makes symbiotic stars a very attractive laboratory to study various aspects of stellar evolution in binary systems. It is worth to mention here the very interesting relatives of symbiotic stars: GX 1+4 – consisting of an M6 III giant and a neutron star companion, and the peculiar black hole binary GRS 1915+105 recently discovered to comprise a K giant companion (Greiner et al. 2001), which are among the most exotic and variable X-ray binaries. It is very important to set firm links between symbiotic stars and related objects, in order to understand the role of these binaries in the formation of stellar jets, planetary nebulae, novae, supersoft X-ray sources and SN Ia. Many of those are issues concerning the late stages of stellar evolution which are presently poorly known, but with important implications on our un-
derstanding of stellar pulsations and chemical evolution of galaxies, as well as of the extragalactic distance scale.

The goals of this presentation is to present recent progress in the determination of orbital and stellar parameters of symbiotic stars, and to provide input for more detailed discussion of such important topics as: basic properties of the symbiotic cool giant components compared to single evolved giants; the nature of the hot component and the physics of its outbursts; the origin of the symbiotic circumstellar nebulae, and their links with planetary nebulae; evolutionary paths leading to symbiotic stars and to their progeny, and many others. We start with a brief description of variable phenomena found in symbiotic stars in Section 2. The recent progress in determination of their orbital and stellar parameters is summarized in Section 3. We discuss basic properties of the symbiotic giants compared to single evolved giants (note that symbiotic Miras are discussed in detail by P.A. Whitelock) in Section 4 as well as the nature of the hot component and its outburst evolution in Section 5.

2. Light curves and variability

The composition of symbiotic stars, specifically the presence of a red giant and its accreting companion, places them among the most variable stars. They can fluctuate in many different ways. In addition to periodic changes due to the binary motion, both the cool giant and the hot component can also show intrinsic variability (Fig. 2). For the red giant, these can be radial pulsations (all D-type and some S-type systems) and semiregular variations (S-type) of the giant, with timescales of the order of months and years as well as long-term light changes due to variable obscuration by circumstellar dust (mostly D-type), solar-type cycles, etc. Mass accretion onto the hot component also results in different variable phenomena with timescales from seconds and minutes (flickering and QPO) to years and decades (nova-like eruptions). The examples of light curves for well-studied, though not yet completely understood, systems: RX Pup, CI Cyg and CH Cyg, which are representative for different variabilities observed in these objects are also presented and discussed by Mikołajewska (2001).

The wealth of variable phenomena found in symbiotic stars is really a challenge for patient observers in any spectral range and makes these systems excellent targets for long-term monitoring programs, especially that they do not need large telescopes. This also explains how and why symbiotic systems could so effectively elude their physical nature. In fact, the binary nature of all symbiotic stars was definitely confirmed, by both direct measurement of the binary motion as well as direct detection of the hot component continuum in ultraviolet spectral range, only in the 1980’s, whereas various problems concerning their intrinsic variability and its relation to their binary nature remain still unresolved.

3. Orbital parameters

Although periodic photometric changes, with periods of 200–1000 days and amplitudes increasing towards short wavelengths, were detected in many symbiotic stars already in the 1930s, they were generally not associated with binary mo-
The first symbiotic stars announced to be eclipsing binaries were AR Pav (Mayall 1937) and CI Cyg (Hoffleit 1968).

By now, the orbital periods are known for about 40 systems (Belczyński et al. 2000; Table 1). About half of them are eclipsing binaries whereas the reflection effect is responsible for the periodic light modulation in other systems. So far, only six systems, T CrB, CI Cyg, EG And, BD–21 3873, BF Cyg and YYHer (Belczyński et al. 2000; Mikołajewska et al. 2002a,b) show the ellipsoidal light variations of a tidally distorted red giant. All systems with measured orbital

| Star     | $P$ [days] | $K_2$ [km/s] | q | $\gamma_0$ [km/s] | $\epsilon$ | $T_0$ [JD$^1$] | $a_p \sin i$ [R$_\odot$] | $f(M)$ [M$_\odot$] |
|----------|------------|--------------|---|-----------------|-------------|----------------|--------------------------|-----------------|
| EG And   | 482.6      | 7.3          | -95.0 | 0              | 50804$^4$  | 70             | 0.020                    | 1               |
| AX Per   | 682.1      | 7.8          | 2.3  | -117.4         | 0           | 50964         | 105                       | 0.033           |
| BD Cam   | 596.2      | 8.5          | -22.3 | 0.092          | 42794$^2$  | 99.7          | 0.037                    | 1               |
| V1261 Ori| 642        | 7.5          | 79.7 | 0.07           | 46778$^3$  | 95             | 0.028                    | 1               |
| BX Mon   | 1401       | 4.3          | 6.7  | 29.1           | 49530      | 104            | 0.0076                   | 1               |
|         | 1259       | 4.6          | 29.1 | 0.49           | 49680      | 103            | 0.0092                   | 1               |
| SY Mus   | 624.5      | 7.4          | 12.9 | 0              | 49082$^3$  | 91             | 0.026                    | 1               |
| TX CVn              | 199       | 5.7          | 2.3  | 0.16           | 45195$^2$  | 22             | 0.004                    | 1               |
| RW Hya   | 370.2      | 8.8          | 12.4 | 0              | 49072      | 65             | 0.026                    | 1               |
| BD-21 3873 | 281.6     | 10.6         | 203.9 | 0              | 49087$^3$  | 59             | 0.035                    | 1               |
| T CrB    | 227.57     | 23.9         | 0.6  | -27.8          | 0           | 47913$^3$     | 107                       | 0.322           |
| AG Dra   | 549        | 5.9          | -147.2 | 0             | 50775      | 64             | 0.0115                   | 2               |
| KX TrA   | 1350       | 6.8          | 2.3  | -123.7         | 0.29       | 51703         | 175                       | 0.039           |
| AE Ara   | 812        | 5.4          | 4    | -15.7          | 0           | 50217         | 87                        | 0.0133          |
| RS Oph   | 455.7      | 16.7         | 0.35 | -40.2          | 0           | 50154$^4$     | 150                       | 0.221           |
| V343 Ser | 451.3      | 2.6          | -5.63 | 0.14           | 50398$^3$  | 23             | 0.0008                   | 3               |
|         | 450.5      | 2.7          | -5.63 | 0.14           | 50398$^3$  | 23.5          | 0.0009                   | 3               |
| FG Ser   | 633.5      | 6.9          | -73.3 | 0              | 51031      | 87             | 0.022                    | 2               |
| AR Pav   | 604.5      | 10.9         | 2.5  | -68.3          | 0           | 48139         | 130                       | 0.079           |
| V443 Her | 594        | 2.5          | -55.5 | 0              | 50197      | 30             | 0.0010                   | 2               |
| FN Sgr   | 568.3      | 10.5         | 2.1  | -53.7          | 0           | 50269         | 118                       | 0.0689          |
| BF Cyg   | 757.2      | 6.7          | 3.6  | -3.75          | 0           | 51395         | 100                       | 0.0239          |
| CH Cyg   | 5700       | 4.9          | -57.7 | 0.47           | 54086      | 478            | 0.045                    | 1               |
|         | 756.0      | 2.6          | -60.6 | 0              | 46644      | 39             | 0.0014                   | 1               |
|         | 5292       | 4.8          | 0.06 | 54592$^2$      | 500        | 0.060         | 1                        |                 |
| CI Cyg   | 855.3      | 6.7          | 3    | 18.4           | 0           | 45242         | 114                       | 0.027           |
|         | 853.8      | 6.7          | 15.0 | 0.11           | 50426      | 112            | 0.026                    | 1               |
| V1329 Cyg| 956.5      | 7.9          | 2.9  | -23.1          | 0           | 51565         | 149                       | 0.0481          |
| CD-4314304 | 1448      | 4.4          | 27.6 | 0              | 45290$^3$  | 126            | 0.013                    | 1               |
| AG Peg   | 1442       | 4.6          | 27.5 | 0.22           | 45560$^2$  | 128            | 0.014                    | 1               |
| Z And    | 786.8      | 6.7          | -1.8 | 0              | 50260      | 102            | 0.024                    | 2               |
| CD-27 8661 | 763.3     | 10.5         | -5.5 | 0              | 49280$^3$  | 158            | 0.092                    | 1               |

References: [1] – Belczyński et al. 2000, and references therein; [2] – Fekel et al. 2000, and references therein; [3] – Fekel et al. 2001, and references therein; [4] – Ferrer et al. 2002; [5] – Mikołajewska et al. 2002a; [6] – Quiroga et al. 2002a,b; [7] – Brandi et al. 2002.

$T_0$ – time of inferior spectroscopic conjunction of the giant; $^1$ – Julian Date = 2 400 000 + JD listed in table; $^2$ – time of the passage through periastron; $^3$ – time of maximum velocity.

period but R Aqr belong to the S- type, and most of them have periods between $\sim 200–1000$ days (Table 1; Fig. 3). Moreover, all systems with $P_{\text{orb}} \gtrsim 1000$
days except for the yellow symbiotic CD−43 14302 contain very cool giants with spectral type ≥ M6. The longest orbital period thus far estimated in symbiotic system is the 44-yr period of the symbiotic Mira R Aqr. The orbital periods of symbiotic Miras with thick dust envelopes (D-type) could be even larger. In general, the binary separations in D-type systems must be larger than the dust formation radius. Assuming a typical dust formation radius of ∼5 × RMira, and RMira ∼1−3 au, the minimum binary separation is a ≥20 au, and the corresponding binary period is Porb ≥ 50 yr, for any D-type system. Thus the orbital period distribution seems to be the result of compromise between the minimum binary separation yet providing enough space for the evolved giant and the minimum mass accretion rate required for triggering the symbiotic phenomenon.

Table 2. Mass estimates for symbiotic binaries

| Star   | P [days] | Ecl. | i [deg] | Mr[M⊙] | Mg[M⊙] | Com.  |
|--------|---------|------|---------|--------|--------|-------|
| EG And | 481     | Y    | 90      | 1.5 ± 0.6 | 0.4 ± 0.1 | ET    |
| AX Per | 680.8   | Y    | 90      | 0.9 ± 0.2 | 0.37 ± 0.06 | BA    |
| BX Mon | 1401    | Y    | 90      | 3.0 ± 1.5 | 0.45 ± 0.21 | BA    |
| SY Mus | 625     | Y    | 90      | 1.3 ± 0.25 | 0.43 ± 0.05 | ET    |
| RW Hya | 370.2   | Y    | 90      | 1.6 ± 0.3 | 0.48 ± 0.06 | ET    |
| T CrB  | 227.57  | N    | 60      | 0.7 ± 0.2 | 1.2 ± 0.2 | BM    |
| KX TrA | 1350    | ?    | 90      | 1.0 ± 0.3 | 0.41 ± 0.04 | He II W |
|        |         |      |         | 135     | 2.7    | 1.2 SP |
| AE Ara | 812     | N    | 60      | 2.0 ± 1.2 | 0.51 ± 0.2 | He II W |
| RS Oph | 455.7   | N    | 45      | ≥0.40    | ≥1.1    | BA    |
| FG Ser | 650     | Y    | 90      | 1.7 ± 0.7 | 0.60 ± 0.15 | ET    |
| AR Pav | 604.5   | Y    | 90      | 2.5 ± 0.6 | 1.0 ± 0.2 | BA    |
|        |         |      |         | ≥70     | ≤3      | ≤1.2  |
| FN Sgr | 568.3   | Y    | 90      | 1.4 ± 0.2 | 0.66 ± 0.08 | BA    |
|        |         |      |         | ≥70     | ≤1.7    | ≤0.8  |
| BF Cyg | 757.2   | Y    | 90      | 1.8 ± 0.6 | 0.51 ± 0.1 | UVEL  |
|        |         |      |         | ≥70     | ≤2.2    | ≤0.6  |
| CI Cyg | 855.3   | Y    | 90      | 1.3 ± 0.3 | 0.43 ± 0.04 | He II EL |
|        |         |      |         | ≥79     | ≤1.6    | ≤0.52 |
| V1329 Cyg | 956.5 | Y  | 86     | 2.1 ± 0.5 | 0.74 ± 0.08 | H I W, SP |
| AG Psc | 816.5   | N    | ≤60     | ≥1.8    | ≥0.46   | He II EL |

BA – blue absorption system; UVEL – ultraviolet emission lines; He II W – He II emission wings; H I W – H I emission wings; He II EL – He II emission line; SP – i from spectropolarimetry; ET – the cool giant mass from v sin i and evolutionary tracks (Mürset et al. 2000, and references therein; Schild et al. 2001); BM – light curve synthesis combined with radial velocity curve (Belczyński & Mikolajewska 1998).

In a binary with Porb ≥ 1 yr, the expected amplitude of radial velocity changes is rather low, K∗ ∼5–10 km s−1. Nevertheless, modern observations with photon-counting detectors and new methods of analysis have allowed to derive spectroscopic orbits from the radial velocities of the red giant for most of the bright symbiotic stars (Table 1). It is interesting that vast majority of symbiotic stars have circular (or nearly circular, e ≤ 0.1) orbits, and a significant eccentricity has been found only for BX Mon, KX TrA, CH Cyg and CD−43 14304, which have also the longest orbital periods, Porb > 1000 days. The eccentricity-period distribution for symbiotic stars is significantly different.
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Figure 3. Distribution of (a) binary periods, (b) mass ratios, (c) hot component and (d) cool giant masses, respectively. The shaded regions denote the symbiotic recurrent novae.

from the $e$-$P_{\text{orb}}$ distribution in other binaries with late-type giants, which show significant fraction of eccentric orbits among systems with $P_{\text{orb}} \lesssim 1000$ days (e.g. Fig. 9 of Jorissen & Mayor 1992).

In several cases, the motion of the hot component was also measured from either the blue absorption features or the optical and UV emission lines and broad emission line wings, and the masses of both components could be derived (Table 2). For some systems, the component masses were derived by combining the mass function for the red giant with the giant mass calculated from $v\sin i$ measurements and evolutionary tracks (e.g. M"urset et al. 2000). The distributions of mass ratios and masses of the symbiotic binary components are shown in Figure 3b–d. All systems except BX Mon and the symbiotic recurrent novae T CrB and RS Oph have the mass ratio, $q = M_g/M_h$, between 2 and 4. The very high mass ratio for BX Mon is based on only 2 measurements of the radial velocities of the blue absorption lines, and has to be confirmed by further observations covering at least one orbital period. The cool giant masses are all between 0.6–3.2 $\text{M}_\odot$, with a peak around 1.6 $\text{M}_\odot$ (the average is 1.7 $\pm 0.1 \text{M}_\odot$). The masses of the hot component are all between 0.4–0.8 $\text{M}_\odot$ (with the average at 0.53 $\pm 0.05 \text{M}_\odot$) except those of AR Pav, T CrB, and RS Oph, and they fall into the range of masses expected for white dwarfs. In both symbiotic recurrent novae, the cool giant is the less massive component, and its mass, $M_g \lesssim 0.8 \text{M}_\odot$ is lower than the mass of any other symbiotic giant, whereas their hot com-
ponents, with $M_b \sim 1.1$–1.3 $M_\odot$ are the most massive, and their masses are sufficient to become a Ia supernova.

Finally, the direct measurements of hot component masses can be used to test the possible relation between white dwarf mass and orbital period (Mikołajewska & Kenyon 1992a). The data from Table 2 are plotted in Figure 5 (left panel), and they do not show any significant correlation with the orbital period. We must, however, note that the estimates for BX Mon and KX Tra, the only systems with longer periods, $P_{\text{orb}} > 1000^d$, are among the most uncertain results in Table 2.

4. The cool giant

Based on near IR spectra, Mürset & Schmid (1999) classified the cool giants in about 100 systems, and found that for S-type systems the spectral types cluster strongly between M3 and M6, with a peak at M5, whereas the distribution of symbiotic miras peaks at spectral types M6 and M7. They also noticed a strong bias towards later spectral types when compared to red giants in solar neighborhood, and that the frequency of mira variables is higher among symbiotic giants. This predominance of very late, and thus more evolved, giants in symbiotic systems indicates that large radius and high mass loss from the cool giant is the key parameter for triggering the symbiotic phenomenon in binaries.

The process of mass transfer – Roche lobe overflow or stellar wind – is one of fundamental question in relation to symbiotic binaries. Although, wind accretion is obviously the case for companions of symbiotic Miras, at least in some of the S-type systems, the cool giant could, in principle, fill its tidal lobe. Amongst the main evidence for the predominance of wind-accretion is the fact that ellipsoidal light variations, characteristic of tidally distorted stars, are rarely observed for symbiotic stars. However, the general absence of such changes may be in fact due to the general lack of systematic searches for the ellipsoidal variations in the red and near-IR range where the cool giant dominates the continuum. This is best illustrated by CI Cyg, BF Cyg and YY Her, in which only the quiescent $VRi$ and near-IR light curves show a modulation with half-orbital period as expected for ellipsoidal variability of the red giant whereas the $UB$ light curves do not show clear evidence for such changes (Mikołajewska 2001; Mikołajewska et al. 2002a,b). Interestingly, such changes have been thus far found only in systems with multiple outburst activity whereas there are apparently absent in two non-eruptive systems, V433 Her and RW Hya (Mikołajewska et al. 2002c).

Based on a sample of 8 symbiotic systems with accurate orbits and estimated radii of the red giants, Schild et al. (2001) argued that none of the symbiotic giants with known radii (derived from the measured $v\sin i$ in 6 cases, and from eclipse contacts in AX Per) fills its Roche lobe. We note, however, that they did not included in their sample any of the systems with evident ellipsoidal changes. Similarly, Fekel, Hinkle & Joyce (2002) derived the $v\sin i$ values and estimated the cool giant sizes for 13 symbiotic systems. Their sample includes CI Cyg, BF Cyg and T CrB, however only CI Cyg has large Roche lobe filling factors $R_g/R_L \sim 0.8$, whereas the giants in both BF Cyg and T CrB, with $R_g/R_L \sim 0.3$ and $\sim 0.4$, are far from filling their tidal lobes. The rotational velocity consistent with a synchronously rotating Roche lobe-filling giant was found in CI Cyg and
AX Per (Kenyon et al. 1991; Mikolajewska & Kenyon 1992b). Recently, Orosz & Hauschildt (2000) have shown that rotational broadening kernels for tidally distorted giants can be significantly different from analytic kernels due to a combination of the nonspherical shape of the giant and the radical departure from a simple limb darkening law. As a result, geometrical information inferred from $v \sin i$ measurements of cool giants in binary systems, and in particular in symbiotic stars, is likely biased. Summarizing, in our opinion, the question whether the symbiotic giants, at least in some of the active S-type systems, are tidally distorted or not remains open as long as we do not have good near-IR light curves which would confirm or exclude such possibility.

Mass-loss rates for the symbiotic giants derived from either the cm and mm/submm radio observations (Seaquist, Krogulec & Taylor 1993; Mikolajewska, Ivison & Omont 2002a,b) or from analysis of IRAS data (Kenyon, Fernandez-Castro & Stencel 1988) are of order of $10^{-7} \, M_\odot \, \text{yr}^{-1}$, and they are systematically higher than those reported for single M giants, which again suggests that high mass-loss rate for the giant is essential to produce the symbiotic star.

Whitelock & Munari (1992) suggested that the symbiotic giants may be related to the metal-rich M stars found in the Galactic Bulge and elsewhere, i.e. they have low masses, $\sim 1 \, M_\odot$, and $Z \gtrsim Z_\odot$. They also noted that the mass-loss rates of the symbiotic giants although systematically greater than for the local bright giants are similar to those of the Bulge-like stars. Their findings, however, have not been confirmed by direct estimates of elemental abundances. In particular, Nussbaumer et. al. (1988) found that the CNO abundance ratios deduced from UV emission lines for 24 symbiotic stars are best fitted by normal red giants. Moreover, carbon abundances and $^{12}\text{C}/^{13}\text{C}$ ratios have been obtained by fitting synthetic spectra to the observed first-overtone CO absorption features in K-band spectra of 7 northern and 6 southern symbiotic systems (Schmidt & Mikolajewska 2002, and references therein). In all cases, subsolar carbon abundances and $^{12}\text{C}/^{13}\text{C}$ have been found, which indicates that the surveyed symbiotic giants are indistinguishable from local normal M giants, in agreement with the abundance studies based on nebular emission lines.

5. The hot component and activity

The typical hot components of symbiotic binaries appear to be quite hot ($T_{\text{eff}} \gtrsim 10^5 \, \text{K}$) and luminous ($L_h \gtrsim 10^2 - 10^3 \, L_\odot$) and overlap into the same region in the H-R diagram as the central stars of planetary nebulae (Fig. 4; Mürset et al. 1991; Mikolajewska, Acker & Stenholm 1997). There is also no significant difference between the symbiotic hot components in our Galaxy and those in the Magellanic Clouds, except that the latter might be slightly hotter. It is hard to believe that such high luminosities are powered solely by accretion, as they would require accretion rates of $\sim a \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$. Although symbiotic giants have high mass loss rates, of $\sim 10^{-7} \, M_\odot \, \text{yr}^{-1}$ and more, in most cases they interact via stellar wind instead of Roche lobe overflow, and the expected accretion rate is an order of magnitude lower. The situation radically changes if the symbiotic white dwarfs burn hydrogen-rich material as accrete it. The accretion rate of order of $10^{-8} \, M_\odot \, \text{yr}^{-1}$ is then sufficient to power the typical hot component with $M_h \sim 0.5 \, M_\odot \, \text{yr}^{-1}$. 
Figure 4. The hot components of symbiotic stars in the H-R diagram. Data from Mürset et al. (1991) and Mikolajewska, Acker & Stenholm (1997) are plotted as diamonds and circles, whereas filled and open symbols represent the galactic S- and D-types, respectively. Stars correspond to the symbiotic stars in the Magellanic Clouds (Morgan 1992; 1996). The solid curves are the evolutionary tracks from Schönberner (1989), the dashed lines correspond to constant radii.

According to the theoretical studies, the hydrogen-shell burning luminosity should be a function of the underlying core mass. Unfortunately, there is no unique core mass-luminosity relationship for accreting white dwarfs because it depends significantly on the thermal history of the white dwarf: generally hot white dwarfs must have larger masses than the cold ones to reach the same luminosity during the hydrogen-burning phase (Iben & Tutukov 1996). However, for the symbiotic systems with known component masses (Table 2) we are in a position to determine which of the theoretical mass-luminosity relations is applicable in their case. The positions of the symbiotic hot components in the luminosity versus mass plane together with different mass-luminosity relationships are plotted in Figure 5 (right panel). The symbiotic white dwarfs seem to cluster around the mass-luminosity relations for stars leaving the AGB with CO core, and those leaving RGB with a degenerate He core, for the first time. It is possible that the white dwarf descendant of the more massive component could still be hot at the onset of mass transfer from the less massive red giant.
Figure 5. Mass-orbital period relation (left) and the mass-luminosity relation (right) for the hot components. Closed symbols represent systems with Z And-type multiple outburst activity, open circles – noneruptive systems and symbiotic novae, and stars – accretion-powered systems, namely, symbiotic recurrent novae at quiescence and EG And. The upper solid curve is mass-plateau luminosity relationship for accreting cold white dwarfs (Eq. 6 of Iben & Tutukov 1996), the dashed curve is the Paczyński-Uus relation (e.g. Paczyński 1970) for AGB stars with a CO core, and the dotted one the relation for helium dwarfs (Eq. 7 of Iben & Tutukov 1996).

The hot components in many symbiotic systems show intrinsic variability (Fig. 2). Based on this activity we distinguish between ordinary or classical symbiotic stars, which show occasionally 1−3 mag eruptions with time scales from months to a few years (such as Z And, CI Cyg and AG Dra), and symbiotic novae that have undergone a single outburst of several magnitudes lasting for dozens of years. Figure 6 shows outburst evolution of selected symbiotic systems. The outburst behaviour of AG Peg and RX Pup is consistent with a thermonuclear nova eruption. In both systems the outburst develops very slowly: the rise to maximum takes months, and the decline to the pre-outburst stage lasts dozens of years. AG Peg is the record-holder among all symbiotic novae: its eruption began in 1850’s, and the hot component maintained a constant luminosity, \( L_h \sim 3000 \, L_\odot \), for at least 100 years. The evolution of RX Pup was much faster, the constant luminosity (plateau) phase lasted for only 11 years, and the maximum plateau luminosity, \( < L_h > \sim 15,000 \, L_\odot \) was about 5 times higher than that of AG Peg. These difference in the outburst evolution can be accounted for by different white dwarf masses: higher in RX Pup than that in AG Peg. RX Pup is also a possible recurrent nova.

Unfortunately, the thermonuclear models do not account for the multiple outburst activity of Z And, AG Dra (Fig. 6), and other classical systems. In most of them, the hot component maintains a roughly constant luminosity whereas its effective temperature varies from \( \sim 10^5 \) to \( \sim 10^4 \) K, and Z And is a good example of such an outburst. Contrary to this behaviour, luminosity of the
hot component of AG Dra increases by a factor of $\sim 10$ whereas its temperature increases during the early stages of each eruption and then decreases as the outburst continues. A possible and promising explanation of this activity involves changes in mass transfer and/or accretion disk instabilities. There are many arguments in favour of such explanation. First, the hot companion of all symbiotic giants which fill or nearly fill their tidal lobes show the multiple outburst activity. Moreover, even if the giant does not fill its Roche lobe, its wind is likely focused towards the secondary and/or towards the orbital plane which would facilitate an accretion disk formation (e.g. Gawryszczak, Mikołajewska & Różyczka 2002; Mastrodemos & Morris 1999).

The timescales for these eruptions are very similar to those of the hot component luminosity changes (high and low states) in symbiotic recurrent novae (T CrB, RS Oph and RX Pup) between their nova eruptions and the accretion-powered system of CH Cyg and MWC 560. During bright phases, in all these systems the optical data indicate the presence of relatively cool B/A/F-type shell source while the UV/optical emission lines require a much hotter source.
with a roughly comparable luminosity (Mikołajewska et al. 2002d). Similar double-temperature structure of the hot component is observed in the Z And-type systems during their outbursts. In AX Per, AR Pav, FN Sgr and possibly other active systems, the A/F-type absorption lines trace the orbit of the hot component, and they are probably formed in a geometrically and optically thick accretion disc and in a gas stream (Mikołajewska & Kenyon 1992b; Quiroga et al. 2002a,b; Brandi et al. 2002). Other evidence for the presence of an accretion disks in the active symbiotic stars include: the ellipsoidal shape of the blue continuum source during outburst; presence of secondary periods (always 10–20% shorter that $P_{\text{orb}}$) in the outburst light curves, similar to the superhumps in CVs (Mikołajewska et al. 2002c); bipolar geometry of outflows associated with the hot component activity in CI Cyg, AG Dra and other systems (Mikołajewska & Ivison 2001; Mikołajewska 2002; Tomov, Munari & Maresse 2000). It is possible that both the activity of the classical Z And-type symbiotic stars and the high and low states of accretion-powered systems are related to the presence of an unstable accretion discs, with the only difference that the hot component in the former burns more or less stably the accreted hydrogen whereas not in the latter.

Finally, Mikołajewska & Kenyon (1992a) argued that the outburst evolution of CI Cyg and AX Per are best explained by the presence of an unstable thick disk around a low-mass main-sequence accretor. We must, however, note that the quiescent characteristics of their hot components are consistent with a hot and luminous stellar source powered by thermonuclear burning. In particular, they fall in the same region in the HR diagram as the hot components of other symbiotic stars (Fig. 4). Their outburst evolution is also very similar to that of Z And, FN Sgr, and other multiple-outburst systems, which apparently points to common mechanism of the outburst and the nature of their hot component. Unfortunately, it will remain uncertain as long as we do not have a good theoretical model accounting for both their quiescent and outburst characteristics.

6. Concluding remarks

The nature of the cool giant plays the key role in the symbiotic phenomenon because it constrains the size of the binary system, which must have enough room for a red giant, and yet to transfer enough material to the companion and give rise to the symbiotic apparition. As a result, we have two distinct classes: the S-type with normal giants and orbital periods of $\lesssim 15$ yr, and the D-type with Mira primaries and periods of $\gtrsim 50$ yr.

Most S-type systems have $P_{\text{orb}} \sim 200–900$ days and circular orbits. A typical S-type system consists of a low-mass M3–6 giant (< $M_g$ > 1.7 $M_\odot$) transferring material to a hot, ~ $10^5$ K, white dwarf companion (< $M_h$ > 0.5 $M_\odot$). Although most symbiotic stars seem to interact by wind-driven mass loss, at least some of the systems with multiple outburst activity may contain a Roche-lobe filling (or nearly filling) giants.

Symbiotic M giants have subsolar carbon and $^{12}$C/$^{13}$C abundances, and they are indistinguishable in this respect from local M giants. They have, however, systematically higher mass-loss rates than single giants, which suggests that high mass-loss rate for the giant is essential for triggering the symbiotic activity. The chemical abundances derived from nebular emission lines suggest
that the main body of symbiotic nebulae is formed from material lost in the giant wind, whereas the hot companion is responsible for its ionization and excitation.

The typical hot component of a symbiotic binary appears to be a luminous, $\sim 100-10^4 \, L_\odot$, and hot, $\sim 10^5 \, K$, white dwarf powered by thermonuclear burning of the accreted hydrogen. The position of the symbiotic white dwarfs in the mass-luminosity plane indicates that they could be hot and luminous at the onset of mass transfer and symbiotic activity. Although we still do not have satisfactory explanation of the multiple outburst activity, there is increasing evidence that it may related to the presence of unstable accretion discs.

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