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Spectrophotometric study of southern symbiotic stars*

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Abstract. We have analyzed the optical spectra of 67 symbiotic stars and objects suspected of being symbiotic, and found 18 new symbiotic systems. This is the largest homogeneous set of optical spectrophotometric data for symbiotic binaries ever studied. We have derived the reddenings and distances for all systems, estimated the IR classes (S and D) for the new systems, and determined the location of the hot components in the Hertzsprung-Russell diagram.

Our study confirms the result of previous works, based on much smaller samples, that the hot components lie on the post-AGB tracks. We argue that most of them are white dwarfs for which accretion has reactivated the hydrogen shell burning, rather than hot white dwarfs that have recently ejected planetary nebulae.

The hot component luminosities are found to be correlated with the nature of the cool giant, and the luminosity in the λ6825 Å emission line. Our finding supports Schmid's interpretation of the 6825 emission in terms of Raman scattering of O VI 1032 by neutral hydrogen.

Key words: binaries: symbiotic – stars: fundamental parameters – Hertzsprung-Russell diagram – circumstellar matter

1. Introduction

Symbiotic stars are long period, interacting binary systems in which an evolved red giant star transfers material to its much hotter, compact companion. In most cases, the companion is a wind accreting white dwarf, although neutron star and disk accreting main sequence star companions are also found. In the majority of symbiotic systems, the accretion does not play a significant role as an energy source for the hot component, which resembles the central star of a planetary nebula, with a luminosity of $L_{\rm h} \sim 1000 L_{\odot}$ and a temperature of $T_{\rm h} \sim 10^5$ K (Mürset et al. 1991). The hot component ionizes the gas surrounding the binary system, giving rise to strong emission lines from a wide range of ionization states.

According to their near-infrared properties, symbiotic stars divide into two major classes: the **S** (stellar) type and the **D** (dusty) type. The majority of systems ($\sim 80\%$) belong to the S class and have near-IR colors consistent with stellar photospheric temperatures of 3000 K to 3500 K. The remaining objects are the D-type systems, and their near-IR colors indicate the presence of thermal radiation from hot, $T \sim 1000$ K, dust. The D-type symbiotics have also a Mira variable – instead of a red giant – as a primary star, and nebulae with significantly lower densities (e.g. Kenyon 1986; Whitelock 1987; Mikołajewska et al. 1988). The division of symbiotics into S and D types is likely to hold the key to an overall understanding of the symbiotic phenomenon, since many observational characteristics (e.g. outburst behavior, radio emission), and physical parameters (e.g. the nature of the cool component, density and size of the nebula, orbital periods: $\lesssim 1000$ days and $\gtrsim 15$ years, for S and D systems, respectively) are correlated with membership to a particular population (e.g. Mikołajewska 1997, and references therein). At present, the distinction seems to be one of orbital separation, whether or not the cool star has been permitted to evolve to a Mira state with substantial wind and dust production.

The variety of possible combinations involved in symbiotic binaries, combined with the complexity of their interactions, makes these systems very important for understanding the late stages of stellar evolution.

The aim of this study is to provide an optical spectrophotometric survey of a large sample of southern symbiotics and objects suspected for being symbiotic. The data are used to distinguish between S- and D-type symbiotics and to derive reddenings, spectroscopic parallaxes, temperatures and luminosities of the hot components, and physical conditions within the ionized nebulae. Our results confirm previous findings that the hot components in symbiotic binaries lie on the post-AGB tracks, and that the symbiotic nebulae are compact and dense in S-type systems, while they are extended and of much lower density in D-type systems.

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* Based on observations collected at the European Southern Observatory (ESO), La Silla, Chile
Tables 1 and 3 only available in electronic form at CDS, Table 4 also available in electronic form at CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr//Abstract html

We present our observations in Sect. 2, analyze them in Sect. 3, discuss the results in Sect. 4, and conclude with a brief summary in Sect. 5.

2. Observations

The optical spectra analyzed in this paper were obtained within the framework of a spectrophotometric survey of objects classified as planetary nebulae in various catalogues, that has been carried since 1984 by two of us (A.A. and B.S.). The low resolution spectra were taken during 5 observing runs, in April 1984, July–August 1985, January 1986, May 1989, and June 1990, with the 1.5 m telescope of ESO at La Silla, and the B&C spectrograph used in the spectral range 4000-7400 Å, with a 10 min exposure time for all objects (see Stenholm & Acker 1987, and Acker et al. 1989 for more details). Until 1987, the detector was the one-dimensional (2053 pixels) Image Dissector Scanner (IDS) with a resolution of 1500. From 1987 to 1991, a CCD (two-dimensional, 512×1024 pixels) became the detector, with a resolution of about 800. The spectra were reduced following the IHAP routines, using flatfield exposures, HeAr wavelength calibration spectra, and the spectra of standard stars (Hayes & Latham 1975) for flux calibration.

Emission line fluxes, derived by integrating the line profile above the linearly interpolated continuum, are listed in Table 1. These data have uncertainties of $\lesssim 15\%$ for strong lines and $\sim 20-30\%$ for weak lines and noisy spectra.

3. Analysis

3.1. New symbiotic stars

Eighteen objects in our survey were not included in the symbiotic star catalogues published by Allen (1984) and Kenyon (1986). Seven of them were reported as new symbiotic stars by Acker et al. (1988), while another 11 were found to be symbiotic systems by the present study. Mis-classified planetary nebulae found by the Acker-Stenholm spectrophotometric survey were also discussed by Acker et al. (1987), and Acker & Stenholm (1990).

The optical spectra of symbiotic stars are characterized by the presence of absorption features and continua appropriate for a late-type M giant, often a Mira or semi-regular (SR) variable, and strong nebular emission lines of Balmer H I, He II and forbidden lines of [O III], [Ne III], [Ne V], and [Fe VII]. Some symbiotics – the yellow symbiotic stars – contain K (or even G) giants or bright giants. The spectra of many symbiotic systems also show two broad emission features at λ 6825 Å and λ 7082 Å. These features have never been observed in any astrophysical object but symbiotic stars with high excitation nebulae. For many years there was no plausible identification for these lines. Recently, Schmid (1989) pointed out that the $\lambda\lambda$ 6825, 7082 lines are probably due to Raman scattering of the O VI $\lambda\lambda$ 1032, 1038 resonance lines by neutral hydrogen.

To classify an object as symbiotic star we adopted the following criteria.

Table 2. New symbiotic stars

Name	RA(2000) h	m	s	Dec(2000) °	’	”	V mag	K mag
He 2–156	16	21	08	–42	23	54	13.3	8.1
MaC 1–3	17	01	28	–47	45	34	18.2	
He 2–251	17	35	22	–29	45	20	18.0	7.3
W16-296	17	39	14	–25	38	06	15.5	
WR 99	17	39	18	–28	15	07	16.5	
He 2–275	17	45	31	–38	39	48	15.5	≥9.3
HD 316285	17	48	14	–28	00	54	9.2	8.75
ALS 2	17	52	04	–17	36	03	14.2	
MaC 1–9	17	55	53	–14	06	49	15.2	
AS 269	18	03	24	–32	42	22	13.9	8.5
AS 280	18	09	53	–33	19	42	13.2	≥9.4
He 2–376	18	15	46	–27	53	48	14.1	
AS 299	18	17	20	–28	09	54	12.5	7.07
K 3–9	18	40	24	–08	43	46	18.0	5.6
AS 323	18	48	36	–06	41	09	15.5	7.91
MaC 1–17	19	12	57	–05	21	20	15.6	
V352 Aql	19	13	34	+02	18	14	16.7	≥9.6
ALS 1	19	16	16	–08	17	52	14.8	

1. The presence of absorption features of a late type star; in practice these include TiO bands, and sometimes Na I lines.
2. The presence of emission lines of H I and He I and either
   – emission lines of ions with an ionization potential of at least 30 eV (e.g. [O III]), or
   – an A or F-type continuum with shell absorption lines from H I, He I, and singly ionized metals.

   The latter corresponds to the appearance of the symbiotic star at outburst.
3. The presence of the λ 6825 emission feature even if no features of the cool star (TiO bands) are found.

The new symbiotic stars, together with 7 stars identified as symbiotics by Acker et al. (1988), are listed in Table 2. In the two last columns of this table are approximate V and K magnitudes, respectively. The V magnitudes were estimated by integrating the spectra, convolved with a standard V filter response function. The accuracy of these estimates does not exceed ~ 0.1 mag for stars brighter than 15, and is $\lesssim 0.5$ mag for fainter objects. The K magnitudes are from Gezari et al. (1993), and Ivison & Seaquist (1995; K3–9).

Eight objects, MaC 1–3, He2–251, WR 99, He2–275, ALS 2, K 3–9, AS 323, and V352 Aql show a red continuum with TiO absorption bands, and numerous emission lines, including the λ 6825 emission feature. A weak λ 6825 emission also seems to be present in ALS 1. He2–275, ALS 2, K 3–9, AS 323, and ALS 1 were discussed as symbiotic stars by Acker et al. (1988). V352 Aql was considered as possible symbiotic star by Bond (1976), but for an unknown reason was not included in Allen's catalog (Allen 1984) and in Kenyon's list (Kenyon 1986). WR 99 was reported as a new Wolf-Rayet star by Allen (1979). The presence of a red continuum and the λ 6825, emission found so far only in symbiotic stars, strongly suggests a symbiotic nature for WR 99.

Another three objects, MaC 1–9, AS 299, and MaC 1–17, show M giant features together with the He II λ 4686 emission line.

He2–156 and He2–376, both included in Acker et al. (1988), are characterized by the presence of TiO bands, and emission lines of H I, He I, and [O III]. Acker et al. noted that they can be symbiotic or Me stars. Me stars, however, do not have such strong He I and [O III] emission lines, so we prefer a symbiotic classification for these systems. In fact, some low ionization symbiotic systems have optical spectra very similar to those of He2–156 and He2–376.

Finally, four objects are possible symbiotic stars. W16–296 displays a red continuum typical of a reddened K giant with strong emission lines of H I, He I, and weak [O III]. HD 316285 and AS 269 have emission line spectra resembling those of Be stars, but their continuum slopes suggest a G-type star. In particular, the JHK colors of AS 269 (Gezari et al. 1993) are consistent with a reddened G5–K2 giant, while the IRAS fluxes (IRAS Point Source Catalog 1985) locate this object in the flux-ratio diagrams of Kenyon et al. (1988) very near to the yellow D'-type symbiotic system HD 330036, which contains a G type giant surrounded by a warm dust shell. AS 280 shows an A-type continuum with prominent emission lines, including a strong He II λ 4686 emission line. It could be a symbiotic star in outburst.

3.2. Reddening and IR classification

Extinction parameters were estimated from optical H I, He I and He II recombination lines as well as collisionally excited [Fe VII] lines. We assumed the reddening to be represented by a standard interstellar extinction curve (e.g. Seaton 1979).

For D-type systems, it was assumed that the H I recombination lines are formed under case B conditions. In the case of S-type symbiotics there are significant departures from case B, and the reddening-free H_α/H_β ratio is $\sim 5-10$ (e.g. Mikołajewska & Kenyon 1992a; Proga et al. 1996), due to self-absorption effects. Self-absorption in dense nebulae was studied by Netzer (1975). Using his results, we can derive both the optical depth in H_α and the color excess, E_{B-V}. The accuracy of E_{B-V} derived from H I is 0.1 mag.

The calculations of Proga et al. (1994) demonstrated that He I emission line ratio distinguishes between S- and D-type systems, in that $I(6678)/I(5876) \approx 0.25$ for D types, while $I(6678)/I(5876) \gtrsim 0.5$ and $I(7065)/I(5876) \approx 0.84$ for S types. Thus, using the He I ratios both the reddening and the IR type can be determined. The accuracy of determined in this way E_{B-V} is ~ 0.3.

The He II $\lambda\lambda$ 4686, 5411 lines also provide a useful reddening estimate. We assumed that the average intensity ratio $I(4686)/I(5411)$ = 13 (case B). The accuracy of E_{B-V} is $\sim$ 0.15 mag.

Finally, the [Fe VII] $\lambda\lambda$ 6087, 5721 lines originate from the same upper level, and their relative intensities depend only on the transition probabilities, $I(5721)/I(6087)$ = 0.65. Unfortunately, the accuracy of E_{B-V} derived from the [Fe VII] lines is only ± 0.5 mag.

Table 3 lists our reddening estimates together with IR classification. The values of E_{B-V} derived from various emission ratios generally fall within a fairly narrow range given by their accuracies, and we adopt weighted means (given in the last column of Table 3) for the rest of this study.

For several systems included in our sample there are published reddening estimates. De Freitas Pacheco & Costa (1992) and Costa & de Freitas Pacheco (1994) derived E_{B-V} from the Balmer line ratios for He2–38, V835 Cen, V347 Nor, He2–171, and SS 122, and got values very close to our estimates. Pereira (1995) reported the reddening estimates for He2–38, V852 Cen, V835 Cen, V347 Nor, He2–171, KX TrA, V455 Sco, AE Ara, and SS 122 based on the ratios H_γ/H_β and H_δ/H_β. For all systems but V347 Nor and SS 122 his estimates of E_{B-V} are systematically lower, by ~ 0.5 mag or more, than our estimates and those of Costa & de Freitas Pacheco.

In systems with dust the reddening towards the cool component can be much higher than that estimated for the emission line region (e.g. Whitelock 1987). We derived the reddening towards the cool components by comparing their J–K colors (Munari et al. 1992) with the average J–K colors for Mira variables (Glass et al. 1995) for D-type systems, and with those for normal field giants (Frogel et al. 1981) for S types. The resulting values generally agree with those derived from the emission lines for the S-type symbiotics, while in some D-type systems they are much higher. This means that in these D-type symbiotics the emission region is located outside the dust shell.

Gutiérrez–Moreno et al. (1995) have recently proposed a diagnostic diagram for separating symbiotic stars from planetary nebulae, based on the relation between the optical [O III] lines. Their diagram also separates very well the S- and D-type symbiotic systems: D- and D'-type symbiotics are located in the region with $10^6 < n_e < 10^7$ cm^{-3}, while S types are close to the high-density limit. The location of systems with measurable [O III] lines in the [O III] 5007/H_β, [O III] 4363/H_γ diagram confirms our classification based on the He I line ratios.

For the known symbiotic stars, our types derived from He I lines agree with those given by Allen (1984) with two exceptions. V347 Nor (He2–127) was classified as M7 III with dust (Allen 1980), while both the He I ratios, and the location in the [O III] 5007/H_β, [O III] 4363/H_γ diagram are consistent with an S-type system. V4141 Sgr (Th4–4) is reported as S-type system in Allen (1984), while the He I ratios suggest rather a D–type system. The IRAS colors of V4141 Sgr (IRAS PSC 1985) are practically identical with the IRAS colors reported for V347 Nor by Kenyon et al. (1988). Another system – SS 122 – was reported as a possible symbiotic Mira by Whitelock (1988), but our classifications, as well as IR spectroscopy (Allen 1980, 1984), locate this object among the S-type symbiotics. Our classification, as based on the emission line ratios, refers to density in the symbiotic nebula. Although generally the nebulae are compact and dense – $n_e \sim 10^8 - 10^{10}$cm^{-3} – in S-type systems, while they are very extended and with significantly lower densities – $n_e \sim 10^6$cm^{-3} – in D-types (e.g. Allen 1980; Proga et al. 1994; Mikołajewska 1997), some exceptions are always possible, especially in the case of systems with extreme characteristics.

Both V347 Nor and SS 122 contain very late M giants – M7 III, and M7.5 III, respectively – and probably represent a transition region between S- and D-type systems. V4141 Sgr is a low ionization system, with the hot component's temperature $T_{\rm h} \lesssim 55\,000$ K. Proga et al. (1994) demonstrated that in some S-type systems the He I $I(6678)/I(5876)$ ratio declines by a factor of ~ 2 in outbursts during which $T_{\rm h}$ decreases, and the ionization stage is low. Thus, in such a case the distinction between the S- and D-type systems may be very ambiguous.

Finally, three of the new symbiotic stars reported in this paper – MaC 1–3, He2–251 and K3–9 – have been tentatively classified as D-type systems based on very weak He I λ6678 lines. Near IR photometry (Gezari et al. 1993) and the IRAS fluxes (IRAS PSC 1985) for He2–251 and K3–9 support this classification: they are consistent with very heavily reddened Mira-type symbiotics. K3–9 was also reported as radio luminous symbiotic Mira by Ivison & Seaquist (1995).

3.3. Spectral type of the cool component and distance

Kenyon & Fernandez–Castro (1987) showed that the red TiO bands at λ 6180 Å and λ 7100 Å, together with the VO 7865, are good temperature indicators for K–M stars. Both TiO bands fall into the wavelength range covered by our spectra. We used the TiO indices as defined by Kenyon & Fernandez–Castro

$$[\mathrm{TiO}]_1 = -2.5\log(F_{6180}/[F_{6125} + (F_{6370} - F_{6125}) \times (6180 - 6125)/(6370 - 6125)]) \quad (1)$$

$$[\mathrm{TiO}]_2 = -2.5\log(F_{7100}/[F_{7025} + (F_{7400} - F_{7025}) \times (7100 - 7025)/(7400 - 7025)]) \quad (2)$$

To construct these indices 30 Å bandpasses were used. Since we did not measure any standard K–M giants, the calibration of the [TiO] indices with spectral type given by Kenyon & Fernandez–Castro was adopted. Such an approach was possible as our spectra have similar resolution as those used by Kenyon & Fernandez–Castro.

Our estimates are summarized in Table 4, together with previous estimates, mostly by Allen (1980). Comparison of these estimates with those by Allen based on near IR spectra, shows that our estimates must be considered only as upper limits – in fact, the symbiotic giants may have later spectral types. This is because in most cases our spectra do not have well exposed continua, and the TiO band depths can be seriously underestimated. In some systems, the estimates are complicated due to the presence of many weak emission features which veil the underlying TiO bands.

Spectroscopic parallaxes for the S-type systems were derived by combining the K photometry given in Allen (1984) and Table 2 with $M_{\rm K}$ values for normal giants (Frogel & Whitford 1987). The K magnitudes were corrected for interstellar reddening. In the case of systems for which Allen's spectral types were available, we adopted the later of the two spectral types listed in Table 4. The accuracy of such derived distances is not better than 20–30%, and can be underestimated for systems with poorly exposed continua and/or systems with TiO bands affected by the presence of the hot component.

When the K magnitude was not available – which was the case for a few of the new symbiotic stars listed in Table 2 – we used the V magnitudes combined with $M_{\rm V}$ values given by Straizys (1982). For systems with unknown spectral type for the cool component (HD 316285 and WR 99), we assumed $M_{\rm V} \sim -1$ (M3 III). Since the V magnitude may be contaminated by contributions from the hot component and the nebular continuum, these distances (put in brackets) are very approximate, and should be considered as lower limits.

To derive $M_{\rm K}$ values for the symbiotic Miras – D-type systems – we used the period-luminosity relation (Glass et al. 1987)

$$M_{\rm K} = 1.69 - 3.79\log P \quad (3)$$

with pulsation periods given in Whitelock (1988; He2–38, V835 Cen, V852 Cen, He2–147). For systems without known periods (K 3–9, V704 Cen, He2–171, H2–5, He2–251) an average period of $\sim 420^{\rm d}$ (Whitelock 1988) was assumed. The K magnitudes from Allen (1984) and Table 2 were corrected for $A_{\rm K}$ derived from the IR colors if available, otherwise the reddening correction estimated from the emission lines was applied. In the latter case the true distance can be lower.

Finally, for the D' system HD 330036, we assumed a G5 II giant. The presence of a G5 III giant would reduce the distance to $\sim$ 1 kpc. However, the presence of dust and very prominent nebular emission in HD 330033 indicates intensive mass loss from the cool component, which makes the presence of a normal G-type giant unlikely.

Our distance estimates are given in Table 4.

The mean $|z|$ for the objects in our study is $<|z|> = 380 \pm 60$ pc for S-type systems, and $<|z|> = 400 \pm 100$pc for D-type systems. Our results, though lower than $<|z|> = 500$ pc obtained by Allen (1980), are consistent with an old disk population.

3.4. Temperature and luminosity of the hot component

To estimate the temperature of the hot component in a symbiotic binary system, Mürset & Nussbaumer (1994) suggested a very simple formula of the form $T_{\rm h}[1000\ {\rm K}] = \chi_{\rm max}[{\rm eV}]$, where $\chi_{\rm max}$ is the highest observed ionization potential. The accuracy of this method is $\sim$ 10%, provided that the highest ionization stage is indeed observed. We adopted their relation for the determination of our hot component temperatures. The highest ionization stage, as well as the corresponding temperature, observed in each system are presented in Table 4. The highest ionization stages easily observed in the optical spectra of symbiotic stars are those of Fe^{+6} and O^{+5}. The method thus fails for $T_{\rm h} \gtrsim 115\,000$ K. The method also fails for S-type systems with small and dense nebular regions, and with $54\,000\ {\rm K} \lesssim T_{\rm h} \lesssim 115\,000$ K. This is because of the lack of strong permitted emission lines corresponding to the highest

Table 4. Physical parameters

Star	Type	Sp This study	Sp Other	d[kpc]	Ion	$T_h[10^3$ K]	$L_h[L_\odot]$
He2–38	D	M0	≥M5	2.2	O^{+5}	114	13000
He2–87	S		M7	3.5	O^{+5}	114	700
St2–22	S	M2	M	5	He^{+2}	54 ÷ 100	600
V704 Cen	D			16	O^{+2}	35 ÷ 55	6000
V852 Cen	D		M	4.3	He^{+2}	54 ÷ 90	10000
V835 Cen	D		M5	1.9	O^{+5}	114	28000
V347 Nor	S		M7+D	10	O^{+5}	114	11000
Hen 1092	S	M5	K5	5.7	O^{+5}	114	1700
HD 330036	D'		G+D	4	He^{+2}	54 ÷ 80	1600
He2–147	D	M7	M8.5+D	3	He^{+2}	54 ÷ 80	100
He2–156	S	K5	M1	3.4	O^{+2}	35	3900
He2–171	D		M+D	5	O^{+5}	114	12000
He2–173	S	M3	M	2.8	He^{+2}	54 ÷ 100	700
He2–176	S		M7	2.6	O^{+5}	114	4300
KX TrA	S	M3	M6	3	O^{+5}	114	7500
MaC 1–3	D	M2		(3)	O^{+5}	114	≥ 3000
V455 Sco	S	M1	M6	2.8	O^{+5}	114	2000
AS 221	S	M1	M4	4	O^{+5}	114	1800
H2–5	D	M6	M	4.8	O^{+5}	114	300
Th3–7	S	M3	M5	6	O^{+5}	114	820
Th3–17	S	M3	M3:	5	O^{+2}	35 ÷ 55	100
Th3–18	S	M2	M2:	4.2	O^{+5}	114	750
Th3–20	S	M3	M	5.2	O^{+5}	114	2600
Th3–29	S	M3		3	O^{+5}	114	240
Th3–30	S	M1	K5	3.8	O^{+5}	114	100
Th3–31	S		M5	4.3	O^{+2}	35 ÷ 55	290
M1–21	S	M1	M2	3	O^{+5}	114	700
He2–251	D			8.5	O^{+5}	114	5700
W16–296	S	K5		(2)	He^{+}	24 ÷ 54	≥ 100
WR 99	S			(1)	O^{+5}	114	≥ 3000
AE Ara	S	M3	M2	2.3	He^{+2}	54 ÷ 80	1000
UU Ser	S	M4	M	6	O^{+5}	114	1500
AS 241	S	M1	M6	6.3	He^{+}	24 ÷ 35	940
He2–275	S	M3		≥8.5	O^{+5}	114	≥ 960
HD 316285	S				O^{+2}	35 ÷ 55	
V4141 Sgr	D			7	O^{+2}	35 ÷ 55	1400
ALS 2	S	M2		(3)	O^{+5}	114	500
AS 245	S	M2	M6	4.5	O^{+5}	114	3500
He2–294	S	M3	M3	5.5	O^{+5}	114	430
Bl3–6	S	M3		(4)	O^{+5}	114	≥ 600
MaC 1–9	S	M2		(3)	He^{+2}	54 ÷ 75	≥ 500
V2416 Sgr	S	M2	M5.5	1.3	O^{+5}	114	460
AS 269	?			0.6	He^{+}	24	
Ap1–8	S	M4	M0	5.3	O^{+5}	114	570
SS 122	S		M7.5	4.8	O^{+5}	114	12000
H2–38	D		M8.5	7.2	O^{+5}	114	20000
SS 129	S	K5	K	1.7	O^{+5}	115 ÷ 130	100
V615 Sgr	S	M2	M	3.6	He^{+2}	54 ÷ 65	800
AS 280	S				He^{+2}	54 ÷ 110	
Ap1–9	S	K5	K4	2.5	He^{+2}	54 ÷ 70	200
AS 281	S	M3	M5.5	4.5	O^{+5}	114	2800
V2506 Sgr	S	M2	M	5	O^{+5}	114	700
V2756 Sgr	S	K5	M2:	4	Ca^{+4}	67 ÷ 110	900
HD 319167	S	M3	M3	4	He^{+2}	54 ÷ 80	1000
He2–374	S	M4	M	2.5	Fe^{+5}	75 ÷ 100	1300
He2-376	S	M2		(4)	O^{+2}	35 ÷ 55	≥ 200
AS 299	S	M0		2.4	He^{+2}	54 ÷ 70	430
V2601 Sgr	S	M5	M	6.1	He^{+2}	54 ÷ 80	90
K 3–9	D	M3		3.6	O^{+5}	114	14000
AS 316	S	M3	M4	4.5	O^{+5}	114	2000
AS 323	S	M3		4.5	O^{+5}	114	1200
AS 327	S	M0	M2	3	O^{+5}	114	2700
Pe2–16	S	K5	M5	5.5	O^{+5}	114	6200
V1413 Aql	S	M0	M5	5	O^{+2}	35 ÷ 55	400
MaC 1–17	S	M1		(7)	He^{+2}	54 ÷ 90	≥ 740
V352 Aql	S	M3		≥9.6	O^{+5}	114	≥ 1600
ALS 1	S	M3		(6)	He^{+2}	54 ÷ 80	≥ 500

ionization potential for this temperature range, while the forbidden emission lines are either very faint or absent due to high nebular density. We solved this problem by setting the upper limit for T_h by the He II 4686/H_β ratio.

The luminosities of the hot components given in the last column of Table 4 are derived from the fluxes of He II 4686, and H_β. We assumed a blackbody spectrum for the hot components, and that H I and He II emission lines are produced by photoionization followed by recombination (case B). The flux observed in an emission line at a wavelength λ is

$$F(\lambda) = \frac{S(i)\epsilon(\lambda)}{\alpha_B}\left(\frac{R_h}{d}\right)^2 \quad (4)$$

and

$$L_h = 4\pi R_h^2 \sigma T_h^4 \quad (5)$$

where $S(i)$ is the number of ionizing photons for element i emitted per unit time from unit area of the hot component, $\epsilon(\lambda)$ is the emission rate, and α_B is the recombination rate. Using values for H_β and He II 4686 from Osterbrock (1989) we get:

$$L_h = 1.7 \times 10^{18} \frac{F(\text{He II } 4686)}{S(\text{He II})} T_h^4 \left(\frac{d}{1\text{kpc}}\right)^2 L_\odot \quad (6)$$

$$L_h = 3.6 \times 10^{18} \frac{F(H_\beta)}{S(\text{H I})} T_h^4 \left(\frac{d}{1\text{kpc}}\right)^2 L_\odot \quad (7)$$

The number of H^0 and He^+ ionizing photons – S(H I) and S(He II), respectively – are unique functions of T_h, and can be calculated for each system. For most systems the two equations yield results differing by less than $\sim$ 30%, and the adopted luminosities are the average values, while in few cases where the differences were larger, we chose the value derived from the He II line. We estimate that the luminosities in Table 4 have accuracies of a factor of $\sim$ 2, mostly due to uncertainties in our reddening and distance estimates.

We can compare our hot component luminosity estimates with those reported by Pereira (1995). Except for V347 Nor and SS 122, his values are systematically lower, by a factor of $\sim$ 10, than ours. The reason for these discrepancies lies in the much lower values of reddening adopted by Pereira (see also Sect. 3.2).

4. Discussion

Although our determination of the parameters of individual systems are loaded with uncertainties, the large number of systems in our sample should ensure feasibility of the average properties of a symbiotic binary resulting from our study.

Fig. 1 shows the Hertzsprung-Russell diagram for the hot components of 65 symbiotic binary systems from our sample. Most objects cluster around temperatures $T_h \sim 10^5$ K, and luminosities $L_h \sim 1\,000 L_\odot$, although the scatter is very large, especially in luminosity. Similar temperatures and luminosities

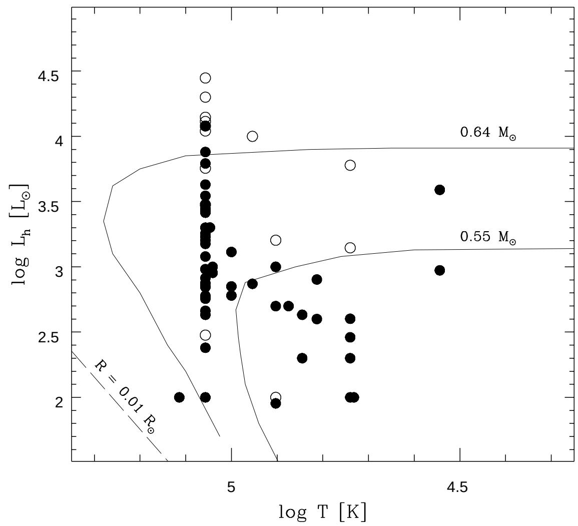

Fig. 1. The hot components of symbiotic binaries in the H-R diagram. Dark and open symbols correspond to the S- and D-type systems, respectively. The dashed curve is a line of constant radius, the solid curves are the evolutionary tracks from Schönberner (1989).

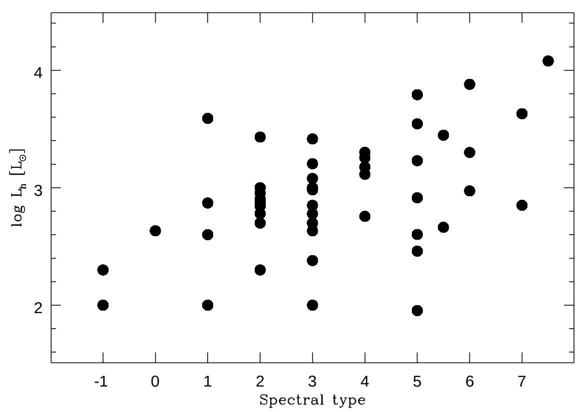

Fig. 2. The hot component luminosity vs. spectral type of the M giant for S-type symbiotic systems.

were obtained by Mürset et al. (1991) for $\sim$ 20 nearby systems observed with the IUE, and by Mürset et al. (1996) for 11 symbiotics in Magellanic Clouds). A luminosity of $\sim 1\,000 L_\odot$ therefore seems to be representative for the entire population.

The hot components in symbiotic binaries lie on the post-AGB tracks, in the region occupied by central stars of planetary nebulae. It is, however, unlikely that all of them have recently ejected planetary nebulae and are evolving along a white dwarf cooling curve for the first time. The expected lifetime of the high-luminosity phase in the absence of accretion is $\lesssim 10^5$ yr, as compared to $\sim 10^7$ yr expected for the red giant phase (e.g. Iben 1982; Schönberner 1983). Such a scenario thus requires the two binary components to have roughly equal masses while on the main sequence, and cannot account for the observed frequency of symbiotic stars.

Among the brightest and the hottest objects in our sample are the D-type systems. In particular, only two systems – He2–147 and H2–5 – have $L_h < 500 L_\odot$, while the remaining ten systems have $L_h > 1\,000 L_\odot$, with the average $< L_h >= 12\,000 \pm 2\,000 L_\odot$. The two low L_h systems, are also the only D-type systems in which the late giant's absorption features are visible, in the high L_h systems the cool component's spectrum is veiled by strong blue continuum related to the hot companion. This result suggests that the hot component's luminosity is somehow related to the nature of the cool component. The effect seems to be also present in the S-type symbiotics. In Fig. 2, we plot the hot component luminosity versus the spectral type of the M giant for S-type symbiotic systems. In spite of very large scatter of L_h within each spectral class, there is some correlation in the sense that the brightest hot components are the companions of the coolest M giants.

It is hard to believe that such high luminosities are powered solely by accretion. Symbiotic red giants have mass loss rates of $\sim 10^{-7} M_\odot\ yr^{-1}$, and this represents maximum accretion rate attainable only in the case of Roche lobe-filling giant. Most symbiotics, however, interact by wind-driven mass loss instead of Roche lobe overflow (see below), so the expected accretion rate is of order of $10^{-8} M_\odot\ yr^{-1}$ or less, and the corresponding accretion luminosity is of order of 10–100 $L_\odot$. Although mass loss rates up to $10^{-5}\ M_\odot\ yr^{-1}$ can be expected for the Mira variables in D-type systems (Schild 1989), large separations between the components ($\sim 10-100$ times larger than for S-type systems) result in similar accretion rates and luminosities. The situation changes radically if the symbiotic white dwarfs burn hydrogen-rich material as they accrete it. The range of accretion rate at which this is possible is in general a function of the white dwarf mass (Iben 1982; Sion 1997), and for $M_h \sim 0.4-0.6 M_\odot$ (Mikołajewska 1997, and references therein) the accretion rate of $\sim 10^{-8}\ M_\odot\ yr^{-1}$ should be sufficient to power the typical hot component in symbiotic binary. We can thus expect that many systems are actually in – or close to – the steady burning configuration. In addition, recent model calculations of Shara et al. (1993) demonstrate that low mass, $\lesssim 0.6 M_\odot$, white dwarfs accreting hydrogen rich gas at a rate of $\sim 10^{-9}\ M_\odot\ yr^{-1}$ undergo extremely slow nova eruptions with the constant luminosity phase lasting for hundreds of years.

Unfortunately, although the thermonuclear model can account for the high luminosities of the symbiotic hot components, it does not explain why these luminosities should be correlated with the cool giant type.

According to the theory of binary evolution, semidetached binaries with red giant donors can be dynamically unstable, and recent publications demonstrate that the systems with large mass ratio, $q \equiv M_g/M_h \gtrsim 0.8$, are always unstable (Webbink 1988; Pastetter & Ritter 1989). While the mass ratio of a typical symbiotic binary is $\sim 2-3$ (Mikołajewska 1997), the vast majority of symbiotic systems do not show any dramatic activity that would indicate they are in the state of runaway mass transfer. Moreover, the short lifetime in this stage, $\sim 100-1\,000$ yr (Webbink 1988) indicates that the ratio of semidetached to detached symbiotic systems should be very low, a few per cent or less. So, it is reasonable to assume that most symbiotic binary systems are far from a semidetached configuration. As the bi-

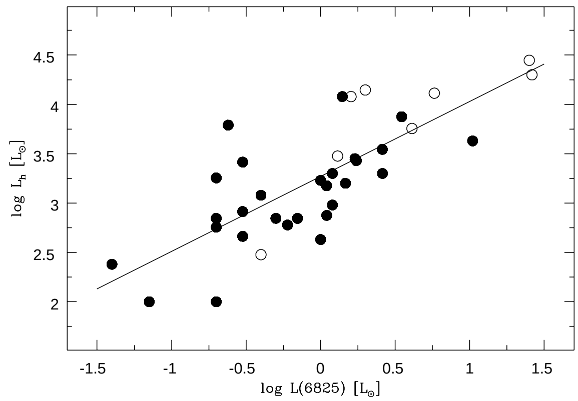

Fig. 3. The hot component luminosity vs. luminosity in the $\lambda\,6825$ emission line for S (dark circles) and D (open circles) systems, respectively. The solid line corresponds to $\log L_{\rm h} = 0.76 \log L(6825) + 3.27$; the rms dispersion $\sigma = 0.39$ ($L_{\rm h}$).

nary separation scales with the orbital period, it is more likely that the coolest giants (that is with the largest radii) will be found in binaries with the longest periods. In fact, among ~ 30 symbiotic binaries with known binary periods (Mikołajewska 1997), the coolest giants seem to favor the systems with longer periods. On the other hand, Webbink (1988) noted that the white dwarf masses in symbiotics should increase with increasing orbital period if the symbiotic binaries are the products of quasi-conservative evolution. In particular, many S-type systems may contain helium white dwarfs with masses lower than 0.5 $M_\odot$. Mikołajewska & Kenyon (1992b) found a correlation between the luminosities of the hot components and orbital periods for symbiotic novae and related systems. They also argued that this correlation implies a relation between white dwarf mass and orbital period, if the hot components lie on the plateau of the white dwarf cooling curves. Thus, the relation between the luminosity of the hot component and the cool giant type may in fact reflect a tendency for both the more evolved giants and the more massive white dwarfs to inhabit symbiotic systems with longer orbital periods.

Finally, the hot component luminosity is apparently correlated with the flux of the $\lambda\,6825$ emission line. The relation

$$\log L_{\rm h}/L_\odot = 0.76 \log L(6825)/L_\odot + 3.27 \quad (8)$$

fits the data quite well (Fig. 3). This correlation supports Schmid's (1989) idea that the 6825 emission is due to Raman scattering of O VI 1032 by neutral hydrogen. To be efficient, Raman scattering needs special conditions. In particular, a large number of scatterers – in this case H^0 atoms – are necessary, and only intrinsically very strong emission lines will give rise to strong enough scattered lines. So, the best circumstances are expected for symbiotic systems that possess extended circumstellar envelopes, and thus have the required large number of H^0 atoms, together with very luminous hot companions. The coolest M giants in S-type systems, as well as the Mira variables in D-class, can naturally support the large circumstellar envelope, since they have strong stellar winds. In addition, they are also among the brightest and the hottest systems (Figs. 1–2). The strong mass loss from the cool components in these systems is also likely to be responsible for high $L_{\rm h}$'s, since their hot components can in general accrete more material, and the interactions between the components can be much more intensive.

5. Summary

We have analyzed the optical spectra of 67 symbiotic stars and objects suspected of being symbiotic, and found 18 new symbiotic systems. This is the largest homogeneous set of optical spectrophotometric data for symbiotic binaries ever studied. We estimate the reddening towards all systems from various emission line ratios. TiO band depths in the red part of spectrum are used for spectral classification of the cool giants. Distances are derived from the spectral parallaxes of the cool giants for S-type systems, and from the period-luminosity relation for symbiotic Miras (D-type systems). To derive the hot component temperatures, we use the relation between radiation temperature and the highest observed ionization potential (Mürset & Nussbaumer 1994). The hot source luminosity is estimated from the H_β and He II 4686 emission line fluxes.

Our study confirms the result of previous works based on smaller samples, that the hot components in symbiotic binaries are located in the same region of the Hertzsprung-Russell diagram as the central stars of planetary nebulae. Simple arguments based on stellar evolution show that they are cold white dwarfs with hydrogen shell burning reactivated by accretion, rather than hot white dwarfs that have recently rejected planetary nebulae.

The hot component characteristics correlate with the cool giant nature. Generally, D-type systems tend to have a more luminous and hotter hot component. A weak correlation of $L_{\rm h}$ with spectral type of the cool giant seems to hold in the case of the S systems. For both types of symbiotic binaries, the hot component luminosity is correlated with the flux in the Raman scattered $\lambda\,6825$ emission line. These correlations probably reflect the fact that the coolest M giants in S-class, as well as the Mira variables in D-type systems, possess strong stellar winds allowing more material to be accreted by their hot components, therefore allowing the interactions between them to be more intense. It is also possible that the S-type systems with the shortest periods ($\lesssim 500^{\rm d}$), are inhabited by white dwarfs with masses lower than masses of white dwarfs populating the S-type systems with longer periods, and D-type systems.

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