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ASTRONOMY AND ASTROPHYSICS

Extragalactic symbiotic systems*

III. The stellar components of the systems in the Magellanic Clouds

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Abstract. We present multifrequency data, ranging from ultraviolet and optical spectroscopy to infrared photometry, of the confirmed symbiotic systems in both Magellanic Clouds (SMC1, SMC2, SMC3, N60, Ln358, N73, S154, S147, LMC1, N67, and S63), as well as of Sanduleak's star, whose nature remains unclear. Because of the known distance, the Magellanic symbiotic systems enable us to derive the luminosity functions and other basic parameters of the binary components.

We determine the spectral types, luminosities, and and temperatures of the cool components, and classify the objects in the s/d system which still seems applicable with the exception of Sanduleak's star. The most luminous red components are found in d-type symbiotics ($L \approx 12\,000$ $L_\odot$) whereas those of s-types have luminosities below 6000 $L_\odot$. Six objects (including the d-types) are of spectral type C, four of type K, and one of type M. The existence of s-types with a carbon star indicates that they either must be AGB stars or, if they are on the RGB, must have accreted carbon from their companion during its AGB evolution. In the HR diagram the symbiotic red components are located such that no deviations from single star evolution are recognizable. Also the separation between M and C stars occurs at the same location as for single stars.

We also determine the luminosities, radii and temperatures of the hot components. They are found to have remarkably similar characteristics ($L \approx 3000$ $L_\odot$, $T \approx 130\,000$ K, and $R \approx 0.1$ $R_\odot$). We propose that the hot components of the presently known symbiotic stars in the Magellanic Clouds mark the upper end of the luminosity function.

Key words: binaries: symbiotic – stars: carbon – stars: fundamental parameters – Hertzsprung-Russell diagram – stars: luminosity function – Magellanic Clouds

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* Based on observations obtained at the European Southern Observatory, La Silla, Chile, and on IUE observations

1. Introduction

Among interacting binaries, symbiotic stars are the widest systems. The stellar components, a red giant star and a very hot white dwarf, are embedded in an emission nebula. This nebula is produced by the ionizing radiation from the hot companion which excites part of the atmosphere or wind of the cool giant. Accurate measurements of the fundamental stellar parameters are indispensable for a sound understanding of the interaction processes and associated energetics, and for clarifying the evolutionary status of symbiotic stars. However, extinction and poorly known distances to targets within the Milky Way make it difficult to measure the luminosities of the stellar components in galactic systems. Both sources of uncertainty are eliminated if extragalactic symbiotics are studied.

Indeed, symbiotic binaries are luminous and conspicuous enough to be detected in the Magellanic Clouds. The first unambiguous assignment of symbiotic status to an object in the MCs was made by Feast & Webster (1974) to S63. Ten years later, Allen's (1984) catalogue listed five objects in the Magellanic Clouds. At present the count of confirmed symbiotics is at twelve with six in each the SMC and LMC. There are also a number of symbiotic candidates which, however, need better observations for confirmation.

In order to establish some of the physical parameters of symbiotic systems in the Magellanic Clouds we embarked on an observing program covering the wavelength range from the UV to the IR. Vogel & Morgan (1994, Paper I) and Vogel & Nussbaumer (1995, Paper II) have analyzed the UV spectra of 6 systems. Here, we present and analyze optical spectra for all accepted LMC and SMC symbiotics, together with further IUE data and IR photometry for more than half of the objects. In this paper we are mainly interested in the stellar continua. The emission line fluxes will be listed and analyzed in future publications. A description of the observations is given in Sect. 2. In Sects. 3 and 4 we examine the cool and the hot components, respectively, and we discuss the results in the evolutionary context of the Hertzsprung–Russell diagram in Sect. 5.

Table 1. Log of observations. The dates of observation are given together with references for the identification of the objects. All IUE spectra are taken in low resolution and through the large aperature. The HST spectra of S63 and Ln358 are discussed in Paper II.

Star	UV		Optical		IR	Finder chart
	Date	Spectrum	Telescope	Date	Date	
SMC1			1.54 m	20 – 23 Dec 1994		Morgan (1992)
SMC2			1.54 m	20 – 23 Dec 1994		Morgan (1992)
SMC3	30 Apr 93	SWP47572	1.54 m	20 – 23 Dec 1994		Morgan (1992)
N60	25 Oct 94	SWP52661	3.6 m	21 – 23 Nov 1993		Walker (1983)
Ln358	22 Nov 93	SWP49297/8	3.6 m	21 – 23 Nov 1993	13 Feb 1994	Walker (1983)
	1 Aug 94	HST FOS				
N73	16 May 93	SWP47678	3.6 m	21 – 23 Nov 1993	13 Feb 1994	Walker (1983)
S154	29 May 93	SWP47766	3.6 m	21 – 23 Nov 1993	11 Feb 1994	Remillard et al. (1992)
S147	23 Nov 93	SWP49303	3.6 m	21 – 23 Nov 1993	12 Feb 1994	Morgan & Allen (1988)
	15 May 93	SWP47671				
LMC1	28 Jan 93	SWP46836	3.6 m	21 – 23 Nov 1993	12 Feb 1994	Morgan (1992)
	29 Jan 93	SWP46844				
N67 (= CH95)	29 Jan 93	SWP46845	3.6 m	21 – 23 Nov 1993	12 Feb 1994	Cowley & Hartwick (1989)
	14 May 93	SWP47666				
Sanduleak's star	22 Aug 88	SWP34122	3.6 m	21 – 23 Nov 1993	12 Feb 1994	Allen (1980)
			1.54 m	20 – 23 Dec 1994		
S63 (= HV12671)	23 Dec 94	SWP53165	3.6 m	21 – 23 Nov 1993	12 Feb 1994	Feast & Webster (1974)
	19 Sep 94	HST FOS				

2. Observations

We carried out coordinated observations with the International Ultraviolet Explorer (IUE) and telescopes of the European Southern Observatory (ESO) to cover a wavelength region stretching from the satellite UV to the thermal IR. We attempted to obtain these data in a short time interval. Typical time separations between different observations were 2–3 months. Except for SMC3 and Sanduleak's star, the data are taken within about one year, which, for these symbiotic systems can be considered quasi–simultaneous. A summary of the observations which were used in this paper is given in Table 1.

2.1. *Optical spectroscopy*

Optical and near IR spectra were collected at La Silla with the 3.6 m ESO telescope during 3 nights in November 1993, and with the Danish 1.54 m telescope during 4 nights in December 1994. The spectra were flux calibrated by comparison with the standards LTT 1020 and EG 21 (Stone & Baldwin 1983, Baldwin & Stone 1984), which were observed three times per night. A selection of the observations are shown in Figs. 1 and 2. In Table 2 we give V magnitudes and B − V, V − I, and V − R colours obtained by multiplying the spectra with the filter functions of Bessell (1990). We consider 30% to be a conservative estimate for the flux uncertainty.

2.1.1. Observations with the 3.6 m telescope

The Cassegrain focus was equipped with the faint object spectrograph EFOSC1 and a 512 × 512 TEK CCD (ESO #26) with 27 μm pixel size.

Intermediate resolution spectra were taken in the echelle mode of EFOSC with the blue cross-dispersor. They effectively cover the regions 4200 Å $\lesssim \lambda \lesssim$ 8500 Å. The slit width was 1.5″ and the resulting resolution as measured from the width of arc lines was $\Delta\lambda \approx 4$ Å. Total exposure times ranged from 10 to 50 minutes.

For the flux calibration of the echelle observations, low resolution ($\Delta\lambda \approx 15$ Å) spectra were taken on November 23, 1993 under photometric conditions through a wide slit (5″). With the B300 and R300 grisms, a wavelength coverage of 3700 Å $\lesssim \lambda \lesssim$ 6900 Å and 6000 Å $\lesssim \lambda \lesssim$ 9800 Å was achieved. Exposure times ranged from 1 to 5 minutes.

2.1.2. Observations with the 1.54 m telescope

The Danish 1.54 m telescope was used with DFOSC, a focal reducer spectrograph/camera similar to EFOSC and a Thompson CCD with 1024 × 1024 19 μm pixels (ESO #17). With two settings using the intermediate resolution grisms #3 and #5, the useful spectral coverage was 4500 Å $\lesssim \lambda \lesssim$ 9100 Å. Exposure times were up to 15 minutes. Although we used a wide slit of 5″, the resolution was close to nominal ($R \approx 600$) because of good seeing conditions. The nights were not photometric and only a relative flux calibration is possible. The data reduction for SMC3 was hampered by the contamination with stars of NGC 269, a cluster in the line of sight to SMC3.

2.2. *IR photometry*

For eight of our objects, JHK fluxes of high precision were obtained in February 1994 with the IR photometer attached to ESO's 2.2 m telescope. For the brighter objects it was also possible to collect L and M magnitudes. The detector was a cooled

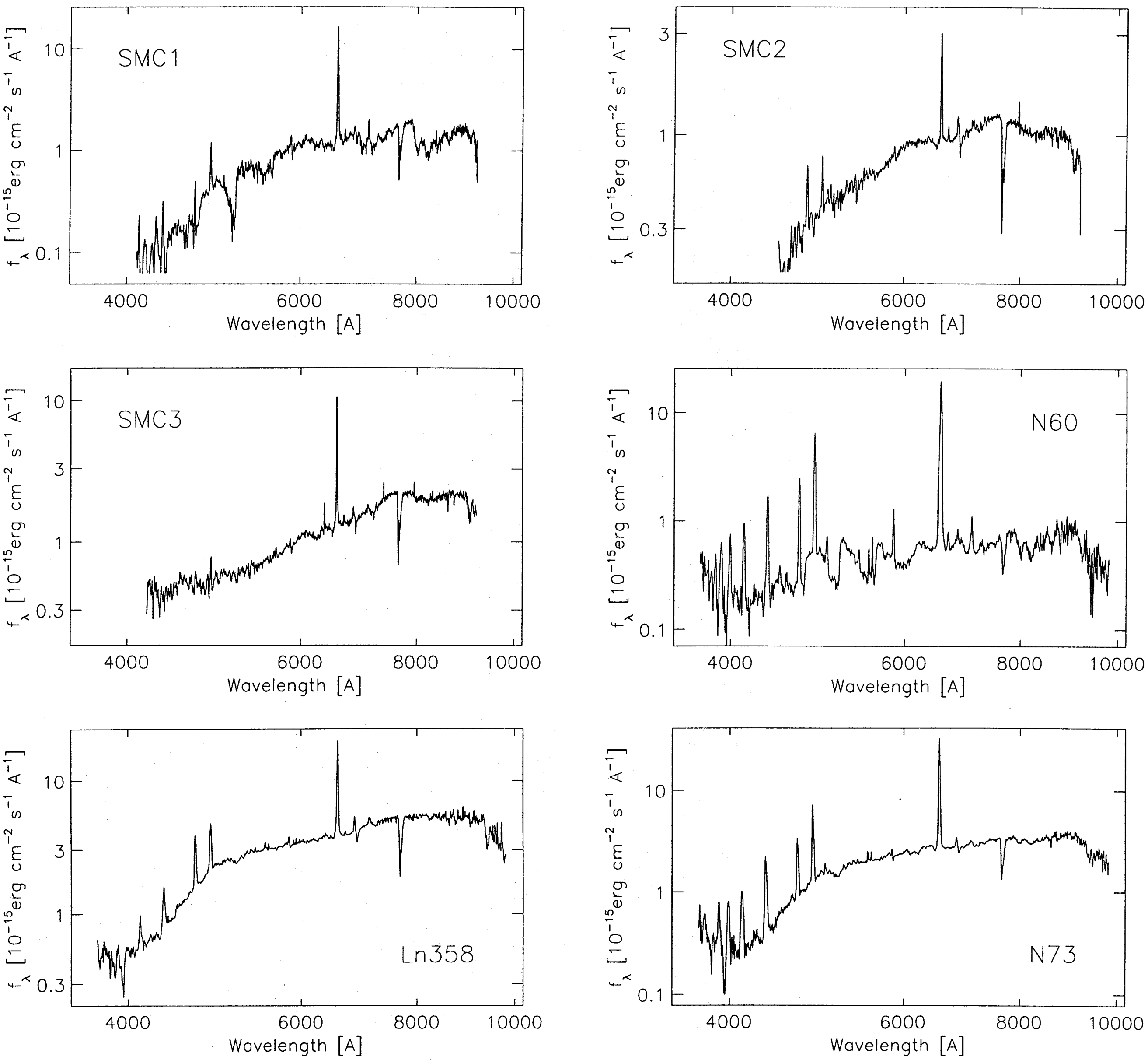

Fig. 1. EFOSC optical spectra of the SMC symbiotics. The flux calibration of SMC1, SMC2, and SMC3 is only crude.

InSb photovoltaic device. A circular diaphragm with a diameter of 12″ was used. The observations were made either in chopping mode at 8 Hz or nodding the telescope with a throw of 15″. The observations were carried out as a service by P. Bouchet. The results are summarised in Table 2. The magnitudes can be converted into flux units with the factors for ESO infrared filters given by Bersanelli et al. (1991).

K band magnitudes of the then known symbiotic systems are listed in Allen's catalogue (1984). For the objects which we have in common, his values agree closely with ours. The JHK magnitudes of S147 from Morgan & Allen (1988), and of S63 and Sanduleak's star from Kafatos et al. (1983) agree as well with our measurements. Therefore, it seems that our targets have a roughly constant IR emission, although the available data are scarce and not aimed at detecting variability.

2.3. *UV spectra*

With only two exceptions, all our targets have been observed in the ultraviolet by IUE (own and archive data). In addition, S63 and Ln358 have been observed with the FOS (Faint Object Spectrograph) on the Hubble Space Telescope (see Paper II). Although the faintness of our targets pushes IUE to its limit, reasonable spectra for many Magellanic Cloud targets can still be obtained during an 8 hour shift. Since September 1992, IUE has been affected by a stray light disturbance in its acquisition and guiding system. The long exposures needed for our extra-

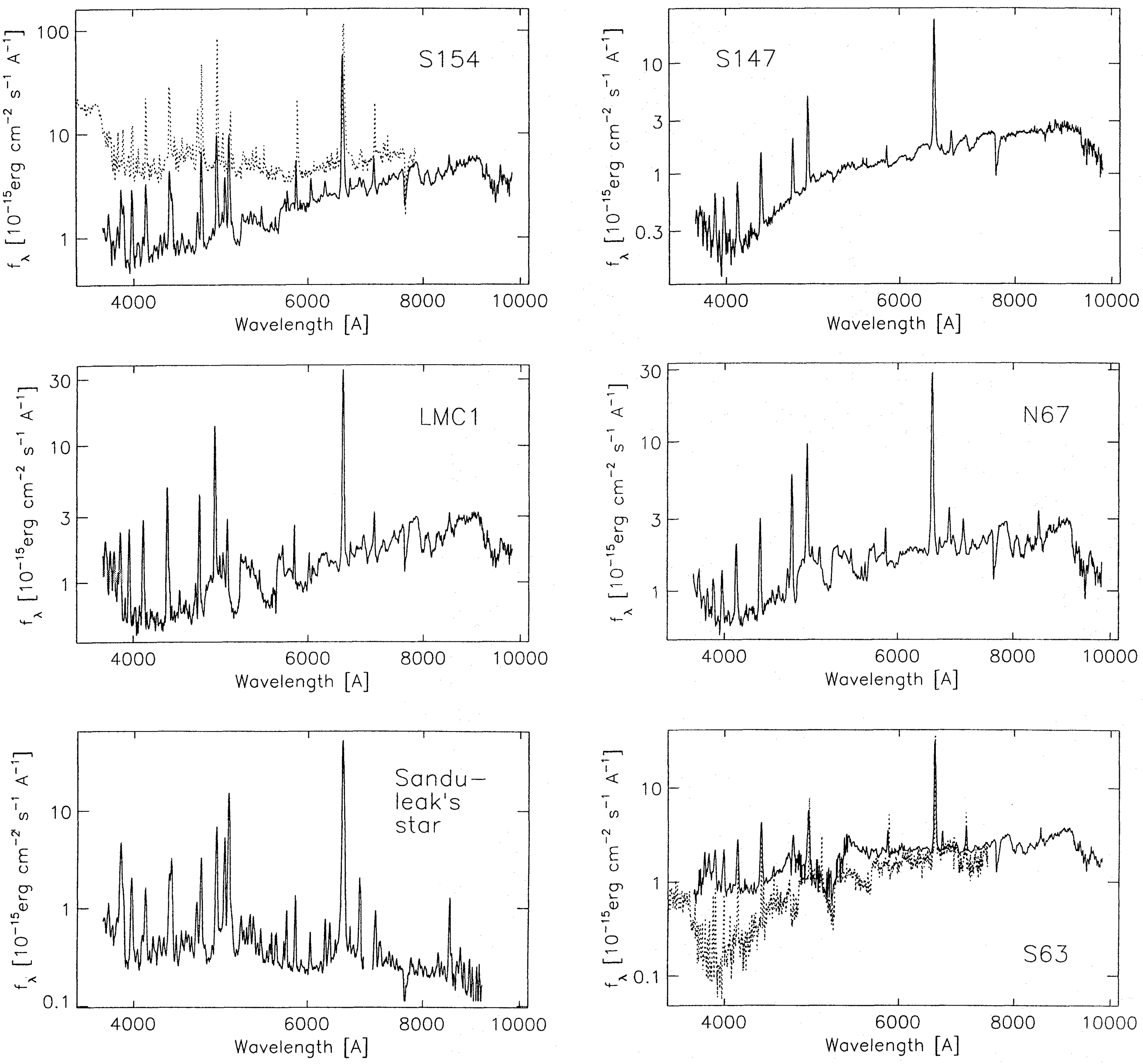

Fig. 2. Optical spectra of the LMC symbiotics. The red part of Sanduleak's spectrum is taken with DFOSC, all the other spectra are taken with EFOSC1. The dotted curves are spectra published previously: S154 in February 1989 (Remillard et al. 1992) and S63 in 1978 (Allen 1984).

galactic objects were therefore done in segments. After each segment, the target had to be recentered in the large aperture. This may result in a somewhat smeared spectrum on the IUE SEC Vidicon detector. Nevertheless, we believe that these spectra have an accuracy in the absolutely calibrated fluxes comparable to the normal IUE standard, and we therefore do not specify the segmentation.

In Fig. 3 we show the previously unpublished IUE spectrum of N73. UV spectra of most of the other objects can be found in Paper I and II, or Kafatos et al. (1983).

3. Parameters of the cool components

3.1. s- and d-types

According to Webster & Allen (1975), two classes of symbiotic stars can be distinguished:

- dusty-type symbiotics in which cool dust emission dominates the IR spectrum
- stellar-type symbiotics in which photospheric emission of a "normal" red giant dominates the IR.

In the Galaxy, d-type symbiotics normally contain a Mira variable as the cool component, and the two binary components are widely separated. The nebular density is low enough so that a forest of forbidden emission lines is seen in the optical spec-

Table 2. Magnitudes of symbiotic stars in the Magellanic Clouds. The uncertainty of V is approximately $0\overset{m}{.}3$. The V magnitudes in brackets are from Morgan (1992) and not simultaneous to our measurements.

Star	B − V	V	V − R	V − I	J	H	K	L	M
SMC1		(16.2)	1.5	2.3					
SMC2		(16.2)	1.3	2.2					
SMC3		(15.5)	1.5	2.7					
N60	0.9	17.1	1.4	1.8					
Ln358	1.6	15.2	1.2	2.2	12.56 ± 0.04	11.63 ± 0.03	11.43 ± 0.03		
N73	1.7	15.6	1.3	2.1	12.73 ± 0.04	11.80 ± 0.03	11.55 ± 0.02		
S154	1.1	15.7	1.5	2.5	12.64 ± 0.03	11.25 ± 0.02	10.05 ± 0.02	8.27 ± 0.08	7.6 ± 0.2
S147	1.5	16.2	1.3	2.3	13.03 ± 0.02	12.10 ± 0.02	11.85 ± 0.02		
LMC1	0.8	16.2	1.3	2.1	12.10 ± 0.01	10.84 ± 0.01	9.92 ± 0.01	8.54 ± 0.03	8.1 ± 0.4
N67	1.0	15.9	1.2	2.0	12.58 ± 0.02	11.76 ± 0.02	11.40 ± 0.02	11.5 ± 0.5	
Sanduleak's star	0.3	16.9	1.4	0.7	14.92 ± 0.07	14.53 ± 0.06	13.01 ± 0.04		
S63	1.0	15.7	1.2	1.9	12.54 ± 0.02	11.66 ± 0.02	11.33 ± 0.02	10.9 ± 0.3	

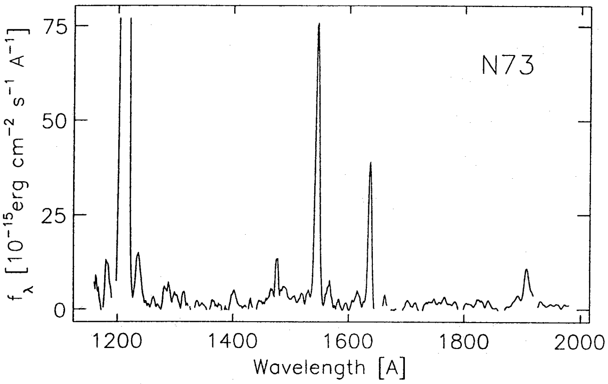

Fig. 3. IUE shortwave spectrum of N73.

trum. s-types have closer orbits, the nebular density is higher, and optical emission lines are mainly due to allowed transitions of hydrogen and helium.

In Fig. 4 we compare our IR colours of the MC symbiotics with those of galactic symbiotic systems. With the exception of Sanduleak's star (cf. Sect. 5.5), there are no differences between these populations. It is obvious that N60, Ln358, N73, S147, N67, and S63 are s-types, whereas LMC1 and S154 are d-types.

The IR colours of Sanduleak's star do not resemble any other symbiotic star. In this case and for those objects for which we do not have IR photometry, we use the visual emission line spectrum to discriminate between s and d types. In the case of Sanduleak's star the line spectrum indicates type d, whereas for SMC1, SMC2, and SMC3 it indicates type s. Since the emission line spectrum is a less reliable classification criterion, we list the results for these stars with colons in Table 4.

3.2. *Spectral classification*

The spectral classification of the red components in symbiotic systems is hampered by the presence of optical nebular emission. This mainly leaves classification criteria based on molec-

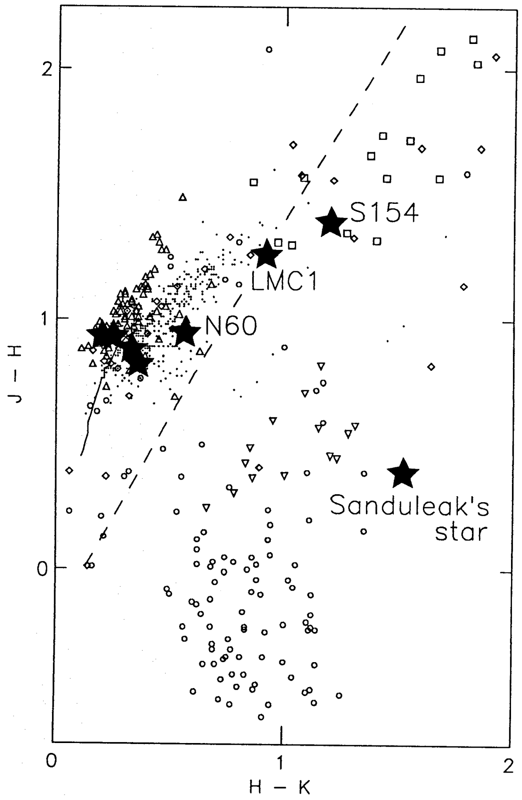

Fig. 4. Infrared colours of Magellanic Cloud symbiotic stars (filled stars). The stars to the left are Ln358, N73, S147, S63, and N67. The IR colours of N60 are from Wood et al. (1995). For comparision, a selection of galactic symbiotic stars of d- (□) and s-type (△) from Munari et al. (1992) is displayed, as well as planetary nebulae (o; Whitelock 1985 and Preite-Martinez & Persi 1989), C stars and LPVs (periods; Westerlund et al. 1991, Wood et al. 1983), OH/IR objects (◇; Wood et al. 1992), Be supergiants (▽; Zickgraf et al. 1986, 1989, 1992, Gummersbach et al. 1995), luminosity class III stars (full line; Koorneef 1983), and black bodies (dashed).

ular absorption bands. In the near IR, the nebular continuum is less of a problem because it usually is considerably weaker than the stellar continuum. In the optical and near IR spectra of all but one object we clearly discern a dominating contribution from the cool component. No clear signature of a late type star is visible in the spectrum of Sanduleak's star.

3.2.1. Carbon stars

SMC1, N60, S154, LMC1, N67, and S63 obviously contain a carbon rich star. There is a number of classification systems for C stars, but the scheme defined by Yamashita (1972) has been most widely used. In this scheme two main indices are assigned to the spectrum of a carbon star. They are most sensitive to the atmospheric temperature and carbon abundance, respectively. Other elemental abundances and the $^{12}C/^{13}C$ isotopic ratio are marked with additional letters if unusual.

We did not have the opportunity to observe classification standards with our instrumental setup. However, Cohen (1979) translated Yamashita's indices into ratios of monochromatic fluxes which we measure in our spectra. First, we removed emission lines from the spectra and subtracted a nebular continuum contribution that corresponds, according to the output of a photo ionization code, to the measured Hβ flux (Table 5). Subsequently we corrected the spectra for the radial velocity shift, and folded them with a Gaussian in order to degrade the spectral resolution to Cohen's. The resulting Yamashita indices are given in Table 3. The individual indices are given with an additional decimal, as obtained by linear interpolation of Cohen's Tables 2, 3, and 6, in order to better illustrate the spread. The corresponding spectral types are listed in Table 4. SMC1 is listed with columns since this spectrum has lower resolution and a lower signal to noise ratio.

Cohen's temperature sensitive colours '[52,66]' and '[57,66]' did not yield "allowed" values for all objects. We attribute that failure to uncertainties in our or Cohen's colour calibration. Therefore, our T-index relies only on the Na I D absorption as was originally suggested by Yamashita (1972). The interpretation of the sodium index is more complicated (e.g. Keenan 1993), and it is likely that the relation between $T^{\rm cool}$ and the sodium index is not the same for low metallicity stars as for galactic C stars.

For comparison purposes, we also evaluated the spectra of the galactic symbiotic C stars S32 and UKS-Ce1 which were recorded with the same EFOSC setup. Schmid (1994) classified these spectra by direct comparison with the spectral tracings of C stars in Yamashita (1972). Using Cohen's flux ratios we find slightly different spectral types: C1,0J for S32 (Schmid: C1,1) and C3,3J for UKS-Ce1 (Schmid: C4,5J). We consider the differences as typical uncertainties for our classification procedure.

We also determined the CN and C_2 equivalent widths, defined by Westerlund et al. (1991), in an analogous manner as for the Cohen indices. Fig. 5 compares our targets to Westerlund et al.'s sample of Magellanic C stars. It appears that CN/C_2 has the same average value in symbiotic C stars as in single MC

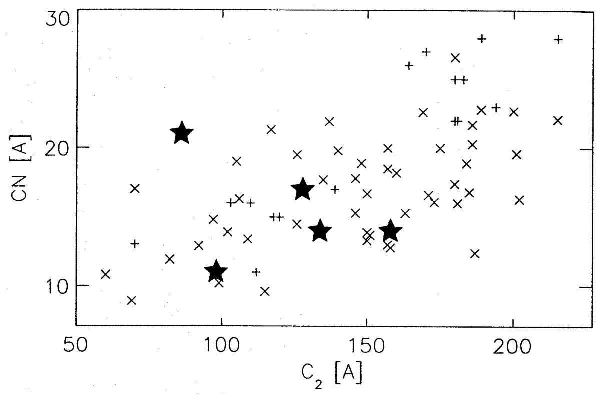

Fig. 5. CN versus C_2 absorption in the symbiotic C stars compared to the ratios for the C stars in Westerlund et al. (1991; ×: SMC; +: LMC)

carbon stars with the possible exception of N67 which may be CN enhanced.

A remark on S154 may be appropriate. This object was first described by Remillard et al. (1992) who identified it as the optical counterpart of an X-ray source. It shows large amplitude ($\Delta B \approx 3^{\rm m}5$) variations. Our magnitude is in accordance with minimum brightness. In the spectra of Remillard et al. (1992), covering the period 1984 – 1989 (dashed in Fig. 2), no signature of a cool star could be discerned. Meanwhile, the nebula has strongly faded, and molecular absorption features have become visible that were veiled by the nebula in the earlier spectra. Those bands now confirm that S154 is indeed a symbiotic object and that it hosts a carbon star as suggested in Paper I on the basis of the chemical composition of the nebula.

3.2.2. Oxygen rich cool components

The red components in the SMC2, SMC3, Ln358, N73 and S147 systems belong to the oxygen rich spectral sequence. The spectral type of S147 was determined by comparing the spectrum in the region around the TiO bands $\lambda\lambda$7054,7088 with those of spectral standard stars of type M recorded with ESO's 1.52 m telescope. The standards were taken from the list of Keenan & McNeil (1989). For the other stars we used the comparison spectra given in Jaschek & Jaschek (1987) and Jacoby et al. (1984).

The spectrum of S147 resembles that of ν Vir (M1 III), whereas it is later than HD 95 578 (M0 III) and earlier than HD 107 003 (M2 III). We therefore classify it as M1. Morgan & Allen (1988) reported TiO to be basically absent in 1986 and classified the cool component as K5. In our spectra we clearly detect the TiO bands at $\lambda\lambda$4954, 5167, 5448, 5847, 6158, 7054, 7088, 7126 and 7744.

The spectrum of N73 is similar to the one of S147, but with somewhat weaker TiO bands. The MgH λ4780 and TiO λ4761 features, which are a useful classification criterion for K giants, indicate K7 which we adopt here. The Ba II lines λ4554 and λ4934 are conspicuous in this object. N73 was classified mid-M by Sanduleak & Pesch (1981) whereas Morgan (1992) allocated K0 – K2.

Table 3. C indices of symbiotic carbon stars as defined by Cohen (1979) and Westerlund et al. (1991)

Index		Indication for	N60	S154	LMC1	N67	S63
Cohen/Yamashita	T	Temperature	3.4	1.6	3.6	2.8	2.0
	C1	C_2	2.5	2.1	2.4	2.1	1.6
	C2	C_2	3.4	2.5	3.5	2.4	1.2
	C3	C_2	3.3	1.7	3.7	1.8	1 :
	CC	^{13}C / ^{12}C	3.3	3.0	< 3	3.4	4.3
	CN	^{13}C / ^{12}C	4.1	3.6	< 3	3.3	4.1
Westerlund et al.	W(4820-5220) [Å]	C_2	128	98	134	86	158
	W(5720-5840) [Å]	CN	17	11	14	21	14

Table 4. Parameters for the stellar components of Magellanic Cloud symbiotic systems. See text for the definitions of the different temperature columns.

Star	Cool component							Hot component		
	Classification		L^{cool}	$T^{cool}_{h\nu}$	T^{cool}_{BB}	R^{cool}	T^{dust}_{BB}	T^{hot}	L^{hot}	R^{hot}
	s/d	Spectral Type	[L$_\odot$]	[K]	[K]	[R$_\odot$]	[K]	[kK]	[L$_\odot$]	[R$_\odot$]
SMC1	s:	C3,2:								
SMC2	s:	K								
SMC3	s:	late K – early M						see Paper IV		
N60	s	C3,3	1 100 :	3 350 :	–	100 :	–	$\leq$ 145	3 000 $\pm$ 1 000	$\geq$ 0.085
Ln358	s	mid K	5 500	4 000	–	150	–	140	4 000	0.11
N73	s	K7	4 500	3 850	–	150	–	130 $\pm$ 10	3 000 $\pm$ 1 000	0.10
S154	d	C2,2	12 000	–	3 000	400	950	140 $\pm$ 15	3 000 $\pm$ 1 000	0.092
S147	s	M1	2 300	3 750	–	110	–	$\leq$ 135	3 000 $\pm$ 1 000	$\leq$ 0.12
LMC1	d	C4,3	11 000	–	3 100	360	1 300	125	3 000	0.12
N67	s	C3,2	3 300	3 350	–	170	–	130 $\pm$ 30	2 000 $\pm$ 1 000	0.082
Sanduleak's star	d:							130 $\pm$ 20	2 400 $\pm$ 1 200	0.092
S63	s	C2,1J	3 900	3 000	–	230	–	85	7 500	0.40

Table 5. Helium and hydrogen emission line fluxes used for determining the extinction and the hot component's temperature. The fluxes are given in units of 10^{-14} erg cm^{-2} s^{-1} Å^{-1}

Line	N60	Ln358	N73	S154	S147	LMC1	N67	Sanduleak's star	S63
Hβ λ4861	9.0	6.7	19	18	7.9	23	16	10	18
He I λ5876	1.4	1.1	1.3	5.6	0.9	2.5	1.9	1.6	3.0
He II λ4686	3.9	5.2	8.4	13	2.7	7.2	11	5.3	3.7*
He II λ1640	10:	20:	30	47	15:	52	20:	10	23
E_{B-V}	0.07:	0.08:	0.09	0.17	0.06:	0.0	> 0.3	> 0.3	0.02

: uncertain; * broad line (FWHM 12 Å)

Our spectrum of Ln358 does not display any TiO features but has strong Ca II λ3970 absorption as well as some G band absorption at λ4300 which may be refilled by Hγ emission. Comparison with the spectra of Jacoby et al. (1984) indicates a mid K spectral type which we adopt. Sanduleak & Pesch (1981) classified Ln358 as late K to early M star while Morgan (1992) describes it as featureless.

Our optical spectra of SMC2 and SMC3 are rather noisy. In SMC3 we detect the TiO bands $\lambda\lambda$5847,6158. The spectrum looks very similar to N73 and we classifiy it as late K to early M. In SMC2 we only detect a trace of the TiO band λ5847 and therefore can only allocate a K spectral type.

3.3. Luminosity and temperature

In Table 4 we list the luminosities, L^{cool}, of the cool components in our symbiotic systems. The luminosities were obtained by removing nebular emission lines from the optical spectra and integrating the optical and IR data. In the case of the d-types LMC1 and S154, the IR fluxes contain photospheric as well as dust emission; the integral is the luminosity of the cool component if the dust is heated by the cool star alone. Throughout this Paper we take a distance of 50 kpc and 60 kpc for the LMC and SMC, respectively (Panagia et al. 1991, Westerlund 1991). As the spectra were not corrected for a contribution from the nebular continuum, and the IR data represent the IR spectrum only in a crude way, we estimate the uncertainty of these luminosities to reach up to 20%.

Temperatures of red giants are not easily determined by comparison with black bodies because their spectra differ strongly from Planck curves. In Table 4 we list for the s-types $T_{h\nu}$, which we define as the temperature of a black body that emits photons with the same average energy as our object (see the equation in Vogel 1990). For the oxygen rich stars this temperature agrees well with what is expected from their spectral types but the discrepancies are larger for the carbon stars. There is one M giant in our sample, S147, and its J − K colour can be compared to the model photospheres of Bessell et al. (1989) yielding $T_{eff} = 3400$ K. We thus believe that our $T_{h\nu}$ approximate the true effective temperature to within 10%.

LMC1 and S154 can not be described with a single temperature because the photospheric emission is strongly affected by the dust. T_{BB}^{cool} and T_{BB}^{dust} are derived by a two component black body fit by eye. The fitting procedure is not very objective, and we estimate that T_{BB}^{cool} represents the photospheric temperature with an uncertainty of $\sim$ 20%.

Our data are not sufficient for deriving the luminosity and the temperature of N60. The optical continuum of N60 however resembles that of N67 if scaled by a factor of 3. As most likely values we therefore take $T^{cool} \approx 3350$ K and $L^{cool} \approx 1100\ L_{\odot}$.

The radii in Table 4 are derived from L^{cool} by taking $T_{h\nu}^{cool}$ or T_{BB}^{cool} as the effective temperature.

4. Parameters of the hot components

In this section we estimate the luminosities and temperatures of the hot components in the MC symbiotic systems. For this purpose we use optical and UV emission line intensities and also the UV continua if detected. These fluxes need to be reddening corrected and we therefore address first the question of interstellar extinction.

4.1. Extinction

Extinction coefficients for the Magellanic Cloud symbiotics were derived by comparing the measured ratio of the He II lines λ1640 and λ4686 with theoretical case-B recombination. For this ratio we assume a theoretical ratio of 7 (Hummer & Storey 1987), which we consider appropriate for the electron densities and temperatures in symbiotic nebulae. The derived E_{B-V} values are given in Table 5. For N60, Sanduleak's star, and S63 we do not have simultaneous optical and UV line fluxes. Nevertheless, our data yield reasonable reddening coefficients, consistent with the values given by Kafatos et al. (1983).

For the SMC, we adopted the extinction law of Hutchings (1982), which matches the galactic curves for $\lambda \gtrsim 2500$ Å, but shows higher extinction values in the far UV. We note that this extinction curve represents a mean for the SMC. LMC extinction curves, which are known to depend on the region were investigated by Nandy et al. (1981), Koornneef & Code (1981), Clayton & Martin (1985), and Fitzpatrick (1985). The first two papers sampled the 30 Dor region, where the reddening is locally enhanced. The two recent studies divided the observed stars into 30 Dor and non–30 Dor targets, with the result that the non–30 Dor subgroup yields a weaker extinction, not very different from the average Milky Way curve. For our LMC targets we adopt the non–30 Dor extinction curve of Fitzpatrick (1985).

4.2. Temperature and luminosities

The stellar parameters of the hot components are summarized in Table 4. The values for Ln358, LMC1, and S63 were derived by fitting the He II λ1640 recombination line flux and the adjacent continuum (Table 5) in the manner described by Mürset et al. (1991).

To N60, N73, S147, and Sanduleak's star we apply the same analysis as outlined in Paper I. This requires the equivalent width of He II λ1640 and the continuum flux in the UV. In order to measure this flux, the IUE spectra were smoothed with a running 50 point box.

The temperature and luminosity of N67 and S154 were taken from Paper I. SMC3 seems to host an extraordinarily hot object which will be investigated in detail in Paper IV (Jordan et al. 1995).

5. Discussion

5.1. The cool components

5.1.1. s- and d-types

It is noteworthy that the s/d classification scheme for symbiotic stars also seems to work in the Magellanic Clouds where many of the red giants are carbon stars. With the exception of Sanduleak's star, all symbiotics neatly fit into the system. About one fourth of the MC symbiotics are of type d, in agreement with the galactic ratio. Within the statistical limits, there seems to be no trend in this ratio with metallicity. There is, however, a significant difference between the LMC and the SMC where no d-type is detected so far (Table 6).

In accordance with variability and dust formation, one may speculate that galactic d-types contain AGB stars as cool components whereas s-types contain RGB stars. Those MC d-types for which we have spectral types are carbon stars. This fits well into the galactic picture: Single carbon stars can only be formed on the AGB or perhaps during the core helium burning phase just preceding it. However, four additional C stars are among the s-types. This indicates that Magellanic s-type symbiotics can be on the AGB. Furthermore, according to Wood et al. (1995) one of the oxygen rich s-types, N60, contains a mira-type cool component. This is, to our knowledge, the first mira detected in an s-type system. It confirms the presence of AGB stars among s-types in the Magellanic Clouds. The fact that AGB cool components without dust formation are found in the LMC, but probably not in the Galaxy, is possibly due to the lower metallicity. In this case, dust is only observed at the very tip of the AGB where the mass loss is largest. Indeed, our d-types are clearly the most luminous stars in our sample, and with $M_K \approx -8\overset{m}{.}5$ they are close to the tip of the branch (cf. e.g. Fig. 2 of Wood et al. 1983).

Table 6. Statistical properties of the SMC, LMC, and galactic symbiotic population.

	Galaxy	LMC	SMC
Single giants:			
C : M ratio	$\lesssim 0.01$ [1)]	$0.4 - 2$ [1)]	$1 - 55$ [1)]
Cool components of symbiotic systems:			
C : M ratio	0.03 [2)]	4 : 1	2 : 0 or 2 : 1
M : K ratio	10 [2)]	1 : 0	1 : 3 or 0 : 4
s : d ratio	4 [3)]	3 : 3	6 : 0
Average parameters for the hot components:			
$\left\langle \log\left(\frac{L^{\rm hot}}{\rm L_\odot}\right)\right\rangle$	2.4 ± 1.1 [4)]	3.5 ± 0.2	3.5 ± 0.1
$\langle T^{\rm hot}\rangle$ [kK]	105 ± 50 [4)]	120 ± 20	135 ± 05
Spatial distribution:	old disk [5)]	outermost regions	

References: 1) Blanco et al. (1978), Jaschek & Jaschek (1987); 2) compiled from the literature by Mürset (1994); 3) Allen (1984); 4) see caption of Fig. 7; the symbiotic novae are not included for the average luminosity; 5) Duerbeck (1984).

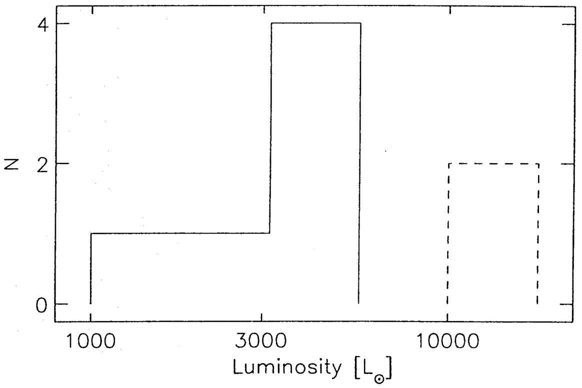

Fig. 6. Luminosity function of the cool components in the Magellanic Cloud symbiotic systems. The dashed line shows the d-types and the full line the s-types.

5.1.2. Temperature and luminosity

The cool components of galactic symbiotic systems are commonly assumed to be either mira-type stars with a luminosity of the order $\log(L^{\rm cool}/{\rm L_\odot}) \approx 4$ (d-types), or normal red giants of luminosity class III and hence $\log(L^{\rm cool}/{\rm L_\odot}) \approx 3$ (s-types). There exist, however, hardly any direct measurements for these luminosities since the distances are usually estimated by *postulating* this property. The known distance to the MCs provides the means to derive luminosities of the symbiotic systems without additional assumptions. Indeed, we find a bimodal luminosity distribution (Fig. 6) with the two d-types at $L^{\rm cool} \approx 12\,000~{\rm L_\odot}$ and s-types with $L^{\rm cool} \lesssim 6000~{\rm L_\odot}$.

While the d-types fit into the galactic picture all our s-type cool components are much more luminous than assumed for galactic s-types. This is also reflected in the HR diagram (Fig. 8): the LMC giants are located above the galactic stars of luminosity class III. This again indicates that most or all presently known symbiotics in the MCs may contain an AGB star and would be d-types if born with galactic metallicity. A galactic RGB symbiotic would, at the distance of the MCs, have a magnitude around $V \approx 18^{\rm m}$, which is below the present threshold for surveys suitable to identify symbiotics. On the other hand, the RGB entends to higher luminosities in the MCs (e.g. Schaller et al. 1992, Mould & Aaronson 1980). Therefore we can not definitely clarify the evolutionary status of the s-types with oxygen rich cool components.

5.1.3. The K- to M-type ratio

In the galaxy, most symbiotic stars contain a cool component of spectral type M, and only a minor fraction contains a K-type star (see Table 6). In the SMC, in contrast, there seems to be a strong predominance of cool components of type K. The same predominance is, however, also seen for evolved field stars (Sanduleak 1989). Thus, the cool components of symbiotic stars may just reflect the different populations of field giants.

5.1.4. The ratio of carbon-rich to oxygen-rich objects

The number ratio of C to M giants is a strong function of the metallicity of the parent galaxy. Table 6 compares the symbiotic ratios to the ratios of field giants. According to Persson et al. (1983), there is no difference in the ratio of carbon to oxygen rich stars between the SMC and LMC if the numerous K-type stars are included. The carbon to oxygen ratio of the giants in the symbiotic stars is compatible with the ratio for single giants.

In the HR diagram, the C-type cool components are not different from other carbon stars in the Magellanic Clouds. There is no obvious difference between the cool components of symbiotic systems and single red giants. This favours evolutionary scenarios where the (original) secondary is not influenced by the binarity. In particular, there is no need to explain the carbon abundance by a former mass transfer episode as in the case of two carbon symbiotics in the Galaxy (Schmid 1994).

5.2. The hot components

Figs. 8 and 7 show the HR diagram and the luminosity and temperature distribution of the hot components in MC symbiotics, of galactic symbiotic novae, and of other galactic symbiotics. The strong concentration of the MC objects at $L^{\rm hot} \approx 3000~{\rm L_\odot}$, $T^{\rm hot} \approx 130\,000$ K, and $R^{\rm hot} = 0.10~{\rm R_\odot}$ strikingly contrasts with the galactic symbiotics, which scatter over large portions of the HR diagram. We believe that the latter scatter is indeed real although the determinations of the parameters of individual galactic objects are loaden with uncertainties.

5.2.1. Luminosity

Among the galactic objects, the symbiotic novae, which are probably powered by a thermonuclear event on the white dwarf, are clearly more luminous than other symbiotic objects (see

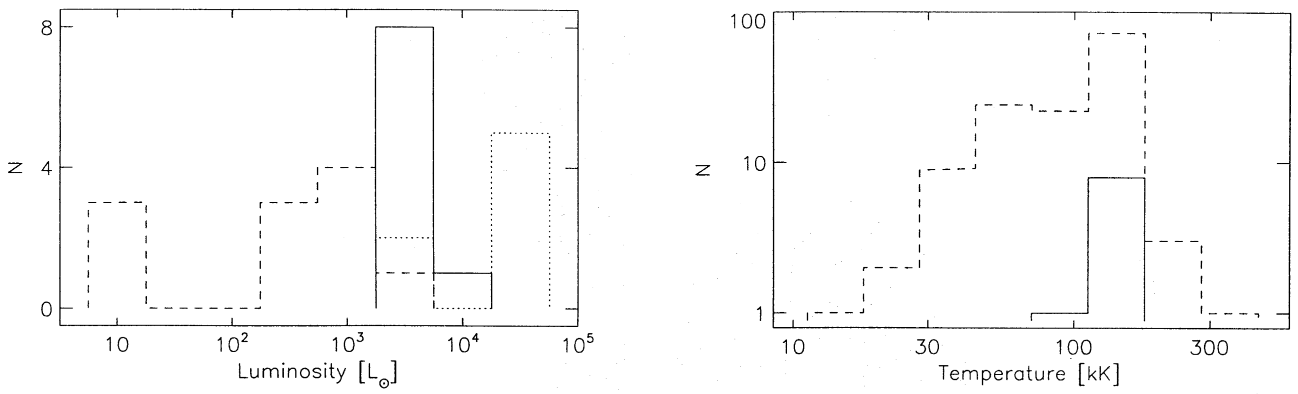

Fig. 7. Left: Luminosity functions of the hot components in MC symbiotics (full line), galactic symbiotic novae at maximum (dotted), and other galactic symbiotics (dashed). **Right**: Histogram of $T^{\rm hot}$ for MC (full line) compared to the galactic(dashed) symbiotics.
The galactic values were taken from Mürset et al. (1991), Schmid & Nussbaumer (1993), Mürset & Nussbaumer (1994) and Mürset (1994).

Fig. 7). Symbiotic novae are scarce, and it is quite possible that SMC3 (not included in Figs. 8 and 7, see Paper IV) is the only one in our sample. The identification as a symbiotic nova requires long term light curves which are not yet available for the MC objects.

The luminosity function of the hot components in the MCs has a narrow peak coinciding with the high luminosity end of galactic luminosity function of non-nova symbiotics. Observational selection effects favour the detection of systems with the most luminous hot components, in particular in the MCs and with an intrinsically very bright companion. The galactic as well as the MC data therefore suggest that 4000 $L_\odot$ is the upper limit for the luminosity of the hot components of non-nova symbiotics.

The nature and energy source of the hot components of the non-nova symbiotic systems is unknown. In principle, the energy souce could be nuclear burning or gravitational potential energy set free by accretion. A luminosity of 4000 $L_\odot$ would require an accretion rate of the order $\dot{M} \sim 10^{-5.5}$ $M_\odot$/yr. This seems implausibly high and argues for nuclear burning as energy source.

Assuming that the core-mass–luminosity–relation (e.g. Joss 1987) is valid, we can conclude that the hot components of non-nova symbiotic systems have a mass below $M^{\rm hot} \lesssim 0.6$ $M_\odot$. Munari & Renzini (1992) proposed symbiotic stars to be the progenitors of type I supernovae. The low mass derived here renders this proposition rather implausible.

5.2.2. Temperature

Fig. 7 displays the temperature histogram for the hot components in MC systems. It is remarkable that we see a concentration towards high temperatures although there is no a priori observational preference for the detection of highly excited symbiotic nebulae.

Temperature determinations rely on similar ideas for both, galactic and MC objects. A different temperature distribution is already apparent in the raw optical and UV spectra: Galactic symbiotics cover a large range of nebular ionization. While in some objects helium is hardly doubly ionized, other objects emit [Mg VI], for instance. In contrast, all Magellanic symbiotic stars except S63 are highly ionized, as can be seen e.g. from their Raman features (Schmid 1989).

If the hot stars are identical for the galaxy as for the clouds, we have to conclude that the most luminous hot components of non-nova symbiotics all have the same, high temperature, and the same radius.

5.3. Spatial distribution

In the Galaxy, symbiotics seem to coincide spatially and kinematically with an old disk population (Wallerstein 1981, Duerbeck 1984). They have a larger scale height than planetary nebulae and classical novae. Furthermore, there are also some halo objects (e.g. AG Dra). Fig. 9 shows the spatial distribution of the known symbiotic stars in the MCs. The shaded regions show the main bodies of the clouds which are dominated by relatively young stellar populations. Older populations like planetary nebulae and classical novae roughly form a concentric spheroid reaching out to much larger radii (see Westerlund 1990 for a review). Symbiotic stars are strikingly confined to the outermost regions of the clouds, further out than classical novae and planetary nebulae. We conclude that the MC symbiotics belong to a fairly old population, older than novae and planetary nebulae, the bulk of which have an age of ~ 3.5 Gyr (Meatheringham et al. 1988). We thus find the same result as galactic studies, but somewhat more pronounced.

Despite of the uncertainties involved and the poor number statistics, we can attempt an order of magnitude estimate of the symbiotic population in the galaxy and the MCs. In the luminosity function for galactic non-nova hot components (Fig. 7), only one out of a dozen objects coincides with the high luminosity end determined for the MC distribution. Assuming that the galactic and MC luminosity functions are identical and that all high luminosity symbiotics in the MCs have been detected, we expect that the Clouds contain $\sim 10^2$ symbiotics with an AGB cool component. With $\sim 10^2$ times more stars, the Milky Way will then have $\sim 10^4$ AGB symbiotics, i.e. d-types. These

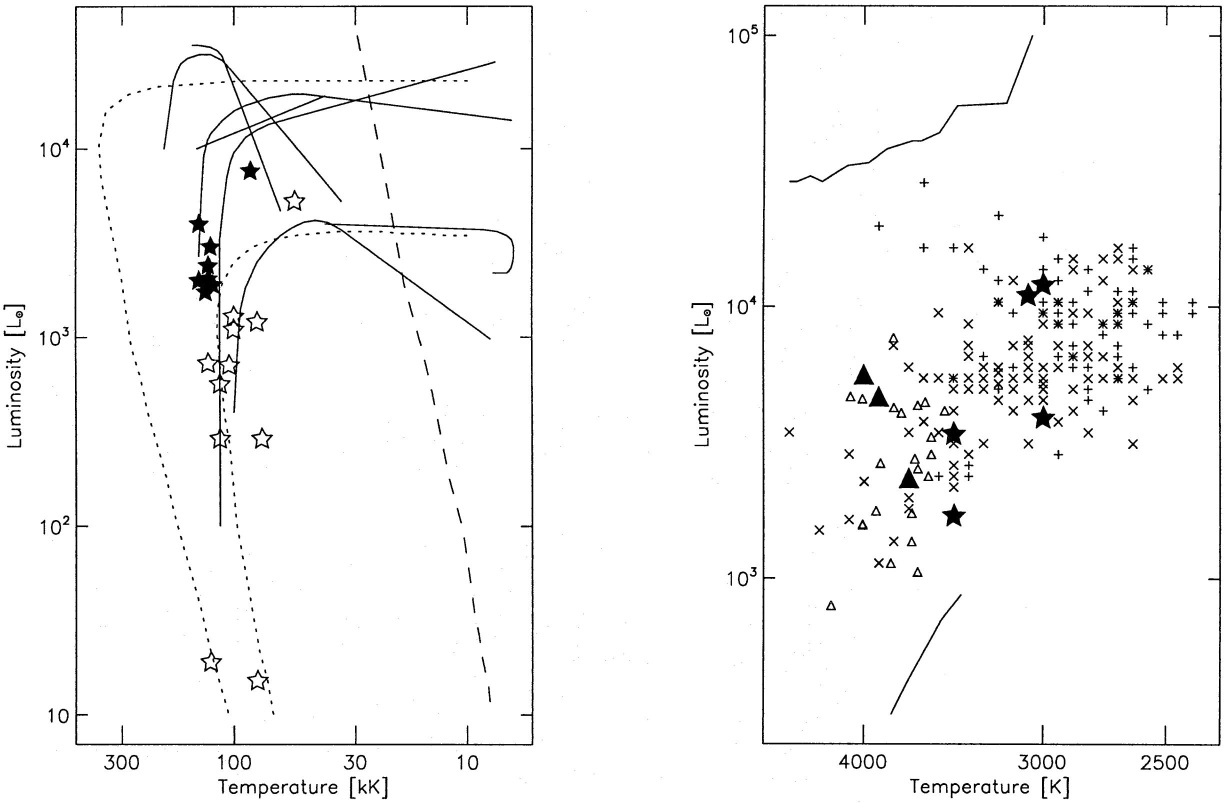

Fig. 8. Left: HR diagram of the hot symbiotic components in the Magellanic Clouds (filled symbols) and the Galaxy (open symbols). For comparison, smoothed evolutionary tracks of symbiotic novae (full lines; after Mürset & Nussbaumer 1994) and theoretical evolutionary tracks for post-AGB stars with core-masses of 0.6 $M_\odot$ and 0.9 $M_\odot$, respectively (dotted; from Vassiliadis & Wood 1994) are shown. The dashed line represents the main sequence. **Right:** HR diagram of the cool symbiotic components in the Magellanic Clouds. Filled stars represent the carbon symbiotics and the filled triangles the oxygen rich objects. For comparison, C stars in the LMC (+) and SMC (×) and K- or M-type stars in SMC clusters (△) from Westerlund et al. (1991) and the loci of luminosity class III and I giants according to Schmidt-Kaler (1982) are displayed.

make up $\approx$ 20% of the full population (Table 6), which may therefore comprise the order of $\sim 10^5$ objects.

5.4. Symbiotic progenitors

Strong mass loss is thought to be an essential ingredient for the symbiotic phenomenon to develop. This mass loss from the red component is required for the hot component to acquire sufficient material to feed its nuclear burning as well as for symbiotic spectra to appear. Because of the lower metallicity in the MCs, mass loss rates may be generally reduced. If this is indeed the case, it could have interesting consequences in relation to the population of stars becoming symbiotics:

- A narrower range of initial masses will proceed through a symbiotic phase. Only the most massive stars evolving through RGB and AGB will become symbiotic. The lowest mass of a star which can become symbiotic will by higher in the MCs than in the Galaxy.
- the lifetime in the symbiotic phase will be shorter because the necessary mass loss is only present for shorter intervals.
- The frequency of symbiotic stars per unit mass is lower in the MCs than in our Galaxy.
- The initial mass ratio of the primary to the secondary star will be closer to one in the MC.

5.5. Remarks on Sanduleak's object

Even among symbiotic objects, Sanduleak's star is extraordinary (cf. Kafatos et al. 1983, Michalitsianos et al. 1989) and deserves some comments.

The IUE spectrum is strikingly dominated by nitrogen lines (e.g. Kafatos et al. 1983). This indicates that the nebular matter has gone through CNO processing, as in the case of young symbiotic novae (e.g. Mürset & Nussbaumer 1995). With optical telescopes we find a rich, high ionization spectrum typical for a d-type symbiotic. However, the continuum is faint, flat and compatible with purely nebular emission – no trace of a cool star is discernible. Up to the K band, Sanduleak's star is fainter by at least a factor 5 than other systems (Fig. 10). The IR energy distribution is strange, and the IR colours do not resemble any other symbiotic object (Fig. 4).

The presence of a red giant is crucial for the symbiotic phenomena, but the cool star is not always visible in the optical spectral range. HM Sge, for instance, exhibits a purely nebular spectrum (see Fig. 4 in Mürset et al. 1991) because the cool

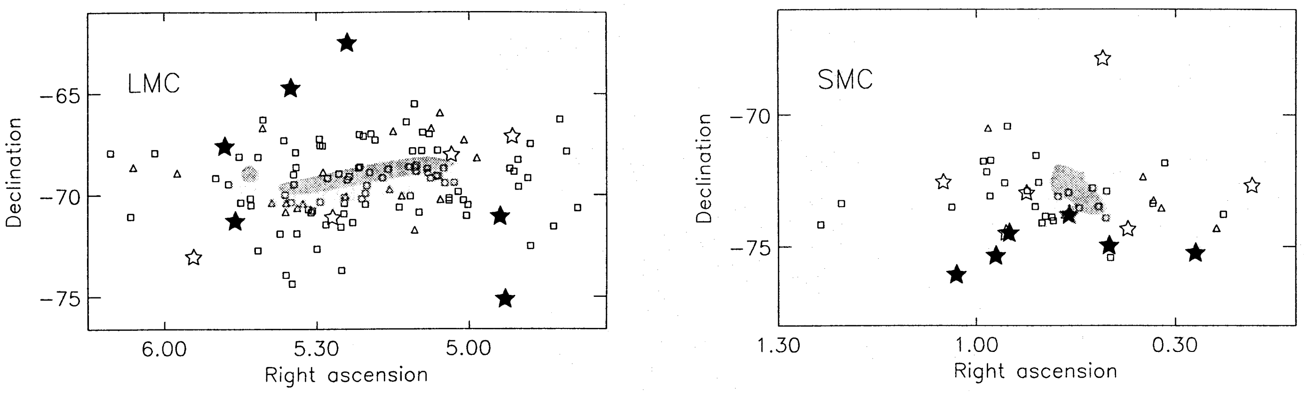

Fig. 9. Location of the symbiotic stars in the Magellanic Clouds. Full stars are the confirmed objects investigated in this Paper, open stars are some suspected symbiotics. Triangles show classical novae (van den Bergh 1988), and squares show planetary nebulae (Sanduleak et al. 1978). The bar and the 30 Doradus region in the LMC, as well as the main body of the SMC are indicated as shaded areas.

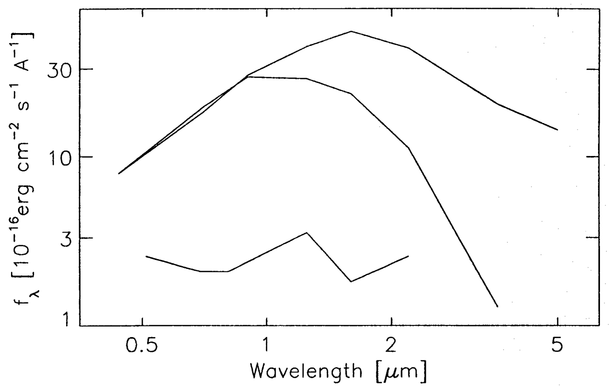

Fig. 10. Infrared continua of LMC1 (top curve), N67, and Sanduleak's star (lowest curve).

star is obscured by dust. However, somewhere the red giant's luminosity has to come out, and an object like HM Sge is much brighter than Sanduleak's star in the JHK bands. The IR observations indicate that there is no cool giant in Sanduleak's system.

So far, Sanduleak's star rather resembles a planetary nebula of type I. However, Sanduleak (1977) reports strong line variations. Besides, the IR colours are not typical for planetary nebulae either (Fig. 4), except if it has an unusually heavy extinction which is not possible for an object detected with IUE. The IR colours of B[e] stars (e.g. McGregor et al. 1988) come closest to those of Sanduleak's star. But for a B[e] star (or an LBV as advanced by Michalitsianos et al. 1989), the luminosity is too low and the excitation extremely high.

In the spectrum of Sanduleak's star we find the Raman scattered emission features $\lambda\lambda$6830,7088 (see Schmid 1989). These features require very strong O VI $\lambda\lambda$1032,1038 emission in the vicinity of neutral hydrogen and have, up to now, only been observed in symbiotics and those recurrent novae which contain a red giant (e.g. RS Oph). The presence of the Raman features thus favours a symbiotic classification. Furthermore, the Raman features also tell us that the cool star can not be hidden by dust, since large amounts of dust would absorb the O VI photons before they are Raman scattered. (The Raman features in HM Sge are very weak.)

There are thus conflicting classification indications, and the nature of Sanduleak's star remains enigmatic.

6. Conclusions

From the Magellanic Cloud symbiotics it is straightforward to derive the spatial distribution, luminosity functions, and other statistical data. Because of observational selection effects, there is a strong bias towards high luminosity systems. The MC systems therefore provide important informations at high luminosities, whereas the galactic data rather represent the most common symbiotic objects. We conclude:

i) for the population:

- The symbiotic systems belong to a population with an age in excess of $\approx$ 4 Gyr. They are hence confirmed to be low mass objects.
- If the hot components of galactic symbiotics statistically have similar properties, we expect $\sim 10^5$ symbiotics for the galaxy, or 1 ppm of all stars.

ii) for the cool components:

- Due to selection effects, we presently know mainly, if not exclusively, MC symbiotics with an AGB object as cool component.
- There is no evidence that they have been affected by the binarity.
- With 4 K-, 1 M-, and 6 C-types the frequencies of the different spectral types differ considerably from the galactic ones. But the tendency seems to follow the field stars and is probably due to the lower metallicity.

iii) for the hot components:

- The hot components of the presently known MC objects mark the upper end of the luminosity function of the hot components of those symbiotic systems that are not symbiotic novae. This limit is at $L^{\rm hot} \approx 4000\ {\rm L}_\odot$, demonstrating that the source of the luminosity is nuclear burning.

– These high luminosity end objects are uniformly characterized by a radius $R^{\rm hot} \approx 0.1\ {\rm R}_\odot$ and a temperature $T^{\rm hot} \approx 130\,000$ K.

iv) for some particular objects:

– N60 is the first symbiotic mira with s-type IR colours.
– S154 definitely is a symbiotic star.
– The classification of Sanduleak's star remains uncertain.

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