

Physical conditions and elemental abundances in the symbiotic novae V 1016 Cyg, HM Sge and HBV 475[★]

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SUMMARY

We have obtained optical, near-infrared and UV spectra of the symbiotic stars HM Sge, V1016 Cyg and HBV 475. We present diagnostic diagrams which indicate that physical conditions vary strongly throughout the symbiotic nebulosities. In HM Sge and V1016 Cyg we find a steep electron-density gradient covering more than an order of magnitude from the lowest to the highest observed ionization stages.

We discuss the formation of hydrogen and helium recombination lines in dense nebulae in order to obtain He abundances. We emphasize that Balmer self-absorption and collisional excitation in He I are important processes in symbiotic nebulae. Their inclusion leads to considerably lower He abundances than previously reported. We obtain He abundances in HM Sge, which are consistent with the solar value. Also in V1016 Cyg and HBV 475 no He overabundance is found although some problems concerning the H I and He I lines remain unsolved.

We determine the abundances of C, N, O and Ne in all three objects and additionally Si, Ar and Fe in HM Sge and V1016 Cyg. Compared to solar, nitrogen is enhanced by a factor of 10 in HM Sge and HBV 475 and a factor of 3.5 in V1016 Cyg. The other elements are compatible with solar abundances.

The overall abundance pattern found in these symbiotic stars differs markedly from the one observed in nova ejecta. The H and He mass fractions in both HM Sge and V1016 Cyg are 0.72 and 0.25, in contrast to the hydrogen mass fractions $\lesssim 0.53$ observed in novae. We suggest that the material presently constituting these symbiotic nebulae has not undergone nova-processing.

The C, N, O abundances in V1016 Cyg are almost identical to the mean abundances observed in M and S giants. HM Sge shows the signs of a more advanced nuclear burning stage and can be interpreted as due to a wind of a highly evolved red giant. We also find no depletion of typical dust constituents like Si and Fe in the D-type symbiotics HM Sge and V1016 Cyg. We conclude that the dust observable in the IR is located outside the ionized nebulosity.

We suggest that symbiotic stars can be used to determine elemental abundances in red giants including Miras by means of nebular diagnostic tools. This may be particularly important for poorly known elemental abundances such as He.

1 INTRODUCTION

Symbiotic stars have gained increasing attention from many researchers over the past few years. Gradually, our understanding of some aspects of their nature and evolution has

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[★]Based on observations made with the Isaac Newton Telescope (INT) operated on the island of La Palma by the Royal Greenwich Observatory and *IUE* observations taken at VILSPA.

become clearer. Symbiotic systems consist of at least three components: a red giant star, an ionized nebula and a hot source of ionizing radiation. The red star can be seen directly in near-infrared spectra in most symbiotic systems. The origin of the nebulosity is more difficult to assess. Nussbaumer *et al.* (1988) demonstrated that the C/N and O/N abundance ratios in symbiotic nebulae show signs of CNO processing and coincide with those measured in red giant atmospheres. This is the first observational evidence

indicating that symbiotic nebulae consist of stellar material lost by the red giant.

The nature of the hot ionizing source is still enigmatic. Candidates range from white dwarfs and hot subdwarfs to main-sequence stars with accretion discs (see Webbink 1988, and references therein). For the purpose of this paper, the exact nature of the ionizing source is of no importance. Its existence is, however, very beneficial because it allows us to study the chemical composition of material apparently originating from the red giant star.

It has been recently suggested that Mira-containing symbiotic systems are in the same evolutionary status as short-period OH/IR sources and therefore are close to the onset of a superwind which is believed to lead ultimately to the formation of a planetary nebula (Schild 1989). The very strong wind in this phase peels off large parts of the stellar envelope and ejects layers possibly showing various degrees of CNO processing and He burning. The C/N and O/N ratios may be expected to change from the relatively uniform red giant values to the more widely scattered ratios observed in planetary nebulae (see Nussbaumer *et al.* 1988).

In an attempt to determine the helium and metal abundances of the symbiotic novae V1016 Cyg, HM Sge and HBV 475 we obtained quasi-simultaneous optical, near-infrared and UV spectra. We are particularly interested in the following issues:

- (a) are the derived abundances typical for red giants, supergiants or for novae?
- (b) are some elements depleted due to condensation in dust grains?

For a recent review and references on symbiotic novae see Viotti (1988). V1016 Cyg and HBV 475 had their outbursts around 1965 while HM Sge brightened by 5 mag in 1975. According to recent *IUE* observations, HM Sge is still evolving towards higher excitation (Nussbaumer & Vogel 1990) whereas V1016 Cyg and HBV 475 seem to have reached their maximum excitation.

HM Sge and V1016 Cyg show common properties in various wavelength regimes. Both belong to the D-type symbiotics (strong IR dust emission) and contain a Mira variable as late-type component (e.g. Taranova & Yudin 1983). They are also X-ray (Allen 1981) and radio emitters. VLA maps revealed almost circular objects with an angular diameter of about 0.5 arcsec (see Taylor 1988). Optical emission-line spectra of HM Sge and V1016 Cyg suggest an electron density $N_e \approx 10^6 \text{ cm}^{-3}$ in the ionized region.

The infrared spectrum of HBV 475 is dominated by stellar emission and it is therefore classified as an S-type symbiotic star. Its red spectrum reveals the presence of an M4 giant. Photometric and UV emission-line variations with a 960-d period were observed (Nussbaumer, Schmutz & Vogel 1986). No X-ray detections were reported and the radio flux is also much weaker than for HM Sge and V1016 Cyg (see Seaquist 1988). In HBV 475 many forbidden optical emission lines are weak or absent, pointing to a high electron density $N_e \geq 10^8 \text{ cm}^{-3}$.

2 OBSERVATIONS

The symbiotic stars V1016 Cyg, HM Sge and HBV 475 were observed during the first few hours of the nights of

1987 November 12–16 with the 2.5-m telescope (INT) at the RGO's La Palma Observatory, Canary Islands. The intermediate-dispersion spectrograph with the 235-mm camera and an RCA CCD detector (30- μm pixels) were used. A grating with a ruling of 400 lines mm^{-1} gave a dispersion of 3.1 Å per pixel and a coverage of 1600 Å. Several exposures were taken to cover the range from 3330 to 7190 Å and from 9550 to 11080 Å. The projected slit width was adjusted to the seeing which typically was 1 arcsec. Each object was also observed with a wide slit and flux standard stars were recorded regularly in order to allow spectrophotometric calibration in the range from 3330 to 7190 Å. All relevant spectra were taken at the parallactic angle which is particularly important for accurate spectrophotometry near the blue atmospheric cut-off. Calibration spectra of B stars were used to correct the telluric absorption features in the near-infrared.

The observations were reduced in a standard way by using the STARLINK (at RGO) and MIDAS (in Zürich) software packages. The main steps performed were flat-fielding, sky subtraction, wavelength and flux calibration. As an illustration of the data obtained we show in Fig. 1 the blue spectra of HBV 475 and V1016 Cyg.

The *IUE* spectra for V1016 Cyg and HBV 475 were taken on 1987 November 11 and December 3, respectively. These dates coincide well with the optical observations. In the spectrum of V1016 Cyg the three strongest lines He II $\lambda 1640$, C III $\lambda 1909$ and C IV $\lambda 1550$ were saturated. Because the measured flux in these lines between previous (1986 December) and following (1988 June) *IUE* observations differ by less than 10 per cent, we adopted the 1988 June values. HM Sge was observed with *IUE* in 1987 April and 1988 March. In this interval the lines of the highly ionized atoms Ne IV, Ne V and Mg V strengthened by approximately 20 per cent while the fluxes of O III, N III and C III decreased by about the same amount. All other lines

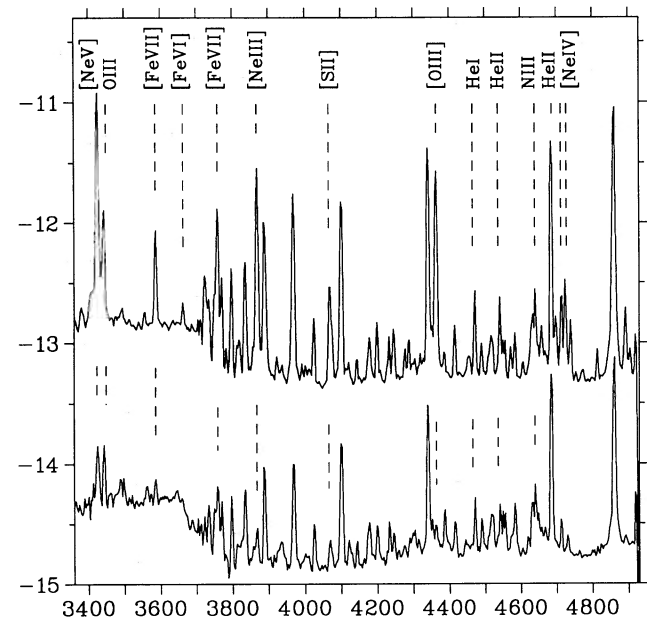


Figure 1. Blue spectra of V1016 Cyg (top) and HBV 475 (bottom) obtained with the INT. The vertical axis is in units of $\log f_\lambda$ with the spectrum of HBV 475 shifted by -1 .

varied less than the observational uncertainty (see Nussbaumer & Vogel 1990). In the following we use the mean line fluxes from these two dates.

The *IUE* data were obtained in the framework of an ongoing monitoring program of symbiotic stars at the Institute for Astronomy in Zürich. A detailed discussion of these observations will be presented elsewhere by H. Nussbaumer, H. M. Schmid and M. Vogel.

3 EXTINCTION

We determine extinction parameters from optical and UV H I and He II recombination lines as well as from the collisionally excited [Ne V] and [Ne IV] lines. We assume that the reddening can be represented by a standard interstellar extinction curve $f(\lambda)$ (e.g. Seaton 1979).

The [Ne V] $\lambda\lambda 1575, 2973$ lines originate from the same upper level. Their intrinsic relative intensities thus depend only on the transition probabilities. In Ne^{+3} the levels $^2P_{1/2}$ and $^2P_{3/2}$ are slightly separated in energy, so that the corresponding lines to a lower-lying level are blended. Therefore the [Ne IV] $\lambda 4720/\lambda 1602$ ratio depends slightly on the nebular densities according to the population ratios between the two ^2P levels. But this density dependence amounts to only about 5 per cent and we take the mean theoretical value of 0.25.

The [Ne IV] and [Ne V] lines are relatively weak and the accuracy of the measured fluxes is ≈ 15 per cent. This leads to an observational error of ± 0.20 (Ne V) and ± 0.12 (Ne IV) in the reddening parameter c . The atomic data for the neon lines were taken from the compilation of Mendoza (1983).

For the H I and He II recombination lines we assume that emission occurs under case B (Hummer & Storey 1987) conditions with a mean electron temperature $T_e = 20\,000$ K in the H⁺ zone and $T_e = 25\,000$ K in the He⁺² zone. As mean electron density we take $N_e = 10^7 \text{ cm}^{-3}$ for HM Sge and V1016 Cyg and $N_e = 10^9 \text{ cm}^{-3}$ for HBV 475 (see Section 4.2). We derive extinction parameters from ratios $H\beta/H\gamma$, $H\beta/H\delta$ He II $\lambda 1640/\lambda 3203$ and He II $\lambda 1640/\lambda 4686$. It seems that the absolute calibration of the *IUE* and optical spectra are fairly accurate because the difference Δc

between the excitation parameters from the He II ratios $\lambda 1640/\lambda 3203$ and $\lambda 1640/\lambda 4686$ amount to only 0.03, 0.10 and 0.02 for HM Sge, V1016 Cyg and HBV 475 respectively.

The assumption that recombination occurs under case B conditions may be invalid at very high densities. This is shown to occur in the lower Balmer lines of HBV 475 and HM Sge (see Section 5.1). We find, however, no deviations from case B in the He II recombination lines.

The results of the different reddening determinations (Table 2) agree reasonably well for V1016 Cyg and, when disregarding the parameters from the Balmer decrement, also for HM Sge. Surprisingly, for the high-density object HBV 475, the extinction values from the recombination lines of H I and He II agree well.

Earlier determinations of extinction parameters for these objects used UV line ratios and the 2200-Å feature of *IUE* spectra (Nussbaumer & Schild 1981; Nussbaumer & Schmutz 1983; Mueller & Nussbaumer 1985). These results are consistent with ours in the case of HM Sge and V1016 Cyg but a lower value was derived earlier for HBV 475 (Nussbaumer & Schmutz 1983). Correction of the 2200-Å bump in an *IUE* spectrum of HBV 475, taken in 1988 April, gives $c \approx 0.6$ (M. Vogel, personal communication).

The variance in the extinction values determined by different methods gives an indication of the errors involved. We adopt the mean values $c = 0.87 \pm 0.15$ for HM Sge, $c = 0.53 \pm 0.15$ for V1016 Cyg and $c = 0.85 \pm 0.30$ for HBV 475.

4 PHYSICAL CONDITIONS

4.1 Emission-line intensities

In Table 3 we summarize the observed and dereddened line fluxes of the optical and UV observations. The accuracy of the optical observations longwards of 3800 Å is 10 per cent for strong lines and about 20 per cent for weak lines. At shorter wavelengths, larger errors are possible because of decreasing detector sensitivity and increasing atmospheric absorption. Since there is some overlap between our optical and UV spectra we can assess the quality of the optical observations. In the case of HM Sge and HBV 475 the agreement was good, whereas for V1016 Cyg a difference of about 30 per cent occurred. We adjusted in V1016 Cyg the optical line fluxes in the range 3400–3700 Å with respect to the *IUE*

Table 1. Log of observations.

object	Date	Instrument	wavelength range [Å]	resolution [Å]
HM Sge	Apr 3, 1987	IUE	1200–3350	6/0.2
	Nov 12, 1987	INT	9550–11080	6
	Nov 14–16 1987	INT	3330–7190	6
	Mar 25, 1988	IUE	1200–3350	6/0.2
V1016 Cyg	Nov 11, 1987	IUE	1200–3350	6/0.2
	Nov 12, 1987	INT	9550–11080	6
	Nov 14–16, 1987	INT	3330–7190	6
	Jun 19, 1988	IUE	1200–3350	6/0.2
HBV 475	Nov 12, 1987	INT	9550–11080	6
	Nov 14–16, 1987	INT	3330–7190	6
	Dec 3, 1987	IUE	1200–3350	6

Table 2. Extinction parameters for HM Sge, V1016 Cyg and HBV 475.

method	HM Sge	V1016 Cyg	HBV 475
[Ne V] lines	0.75	0.41	–
[Ne IV] multiplets	0.92	0.66	–
Balmer decrement	(0.43)	0.48	0.89
He II lines	0.95	0.57	0.81
adopted mean value	0.87	0.53	0.85
Extinction parameters from the literature:			
UV lines, 2200Å	0.89	0.41	0.5

Table 3. Observed and dereddened emission lines relative to $H\beta (= 100)$.

λ	HM Sge		V1016 Cyg		HBV 475	
	obs	der	obs	der	obs	der
1206 SiIII	—	—	1.5:	12.6:	—	—
1240 NV	17	453	80	590	30	752
1335 CII	<1.5	<26	1.0:	5.6:	<2	<32
1371 OV	1.2:	18:	2.7	14.1	3.1:	44:
1397 SiIV	3.2	45	15.7	79	—	—
1533 SiII	—	—	1.3:	5.6:	—	—
1486 NIV]	21.5	253	23.2	104	12.2	136
1550 CIV	85	906	204	867 ⁺	68.4	693
1575 [NeV]	2.6:	27:*	4.3	17.9	—	—
1601 [NeIV]	5.0	50	4.6	18.9	—	—
1640 HeII	44	427	85	343 ⁺	74	683
1664 OIII]	10.7	103*	21.1	84	11.9	108
1750 NIII]	11.8	111*	10.3	40	6.5	58
1815 SiII	1.4:	13.7:	3.9	15.7	—	—
1892 SiIII]	6.5	73	14.7	64	7.8	83
1909 CIII]	39	455	62.4	280 ⁺	15.8	175
2325 CII]	—	—	7.7	40	—	—
2424 [NeIV]	2.6:	24:*	3.1	12.1	—	—
2783 [MgV]	14.8	55	23.2	52	5.9	21.4
2973 [NeV]	2.8:	8.1:*	2.8:	5.4:	—	—
3133 OIII	34	84	34	60	38	92
3203 HeII	12.0	28.1	11.8	19.9	15.8	36
3426 [NeV]	223	443	152	231 c	17.6	34
3444 OIII	18.1	36	15.9	24.0 c	12.7	24.6
3587 [FeVII]	9.4	17.0	9.0	12.9 c	4.0	7.1
3663 [FeVI]	2.0	3.5	0.94	1.3 c	—	—
3727 [OII],[SIII]	9.1	15.2 b	2.0	2.7 b	—	—
3760 [FeVII]	21.0	34 b	16.4	22.0 b	6.8	11.0
3771 H11	3.6	5.9 b	2.8	3.8 b	3.2	5.2
3798 H10	5.1	8.2	4.1	5.5	4.1	6.6
3835 H9	7.7	12.2	6.0	8.0	6.6	10.4
3869 [NeIII]	95	149	35	46	2.1	3.2
3889 H8, HeI	19.6	30	15.4	20.1	11	16.9
3969 H ϵ , [NeIII]	42	64	24.9	32	13.8	20.5
4026 HeI, HeII	2.0	2.9	1.6	2.0	2.8	4.1
4069 [SII]	13.2	18.9	5.3	6.6	2.0	2.8
4102 H δ , NIII	23.1	33	22.3	27.5	19.8	27.7
4200 HeII	1.5	2.0	1.5	1.8	2.6	3.5
4340 H γ	42	54	42	49	37	47
4363 [OIII]	66	85	26.8	31	1.4:	1.8: i
4471 HeI	3.2	3.9	2.4	2.7	3.9	4.7
4542 HeII	2.5	2.9	2.1	2.3	3.3	3.8
4634 NIII	2.5	2.8 b	2.1	2.2 b	5.3	5.9 b
4641 NIII	5.4	6.0 b	2.4	2.6 b	5.6	6.2 b
4658 CIV,[FeIII]	2.8	3.1 b	1.2	1.3 b	2.3	2.5
4686 HeII	62	68	51	53	67	73
4714 [NeIV]	5.5	5.9	2.7	2.8	—	—
4716 HeI	—	—	—	—	2.0	2.1
4724 [NeIV]	7.8	8.3	3.6	3.75	—	—
4740 [ArIV]	3.1	3.3	1.2	1.2	—	—
4861 H β	100	100	100	100	100	100
4893 [FeVII]	2.5	2.5 b	2.0	2.0	0.92:	0.91: i

Table 3 – continued

λ	HM Sge		V1016 Cyg		HBV 475	
	obs	der	obs	der	obs	der
4922 HeI, FeII-42	0.97:	0.94: b	1.10	1.08 b	7.8	7.6
4941 [FeVII],[CaVII]	6.0	5.8 b	5.1	5.0	3.0	2.9
4959 [OIII]	127	122	61	59	4.8	4.6
4989 FeVII	3.3	3.1 b	2.3	2.2	0.56:	0.53: i
5007 [OIII]	389	363	179	172	15.3	14.3
5017 HeI, FeII-42	—	— b	0.76	0.73 b	8.8	8.2
5146 [FeVI]	3.7	3.3	1.8	1.7	0.89:	0.79:
5158 [FeVII]	4.5	3.9	3.8	3.5	2.4	2.1 b
5169 FeII-42	—	— b	—	— b	4.4	3.9
5176 [FeVI]	7.4	6.4	3.4	3.1	0.81:	0.71:
5278 [FeVI],[FeVII]	5.6	4.7	4.2	3.8	3.4	2.9 b
5309 [CaV]	5.0	4.1	2.5	2.2	—	—
5319 FeII	—	—	1.5	1.3	5.1	4.2
5335 [FeVI]	1.4	1.1	1.1	0.97	1.2:	0.98: b
5412 HeII	8.0	6.3	5.2	4.5	7.2	5.7
5424 [FeVI]	1.9	1.5	0.81	0.70	1.4:	1.1: b
5631 [FeVI]	1.5	1.08	0.63	0.52	—	—
5677 [FeVI]	2.3	1.6	0.78	0.63	—	—
5721 [FeVII]	25.1	17.4	15.1	12.1	5.0	3.5
5755 [NII]	28.1	19.2	3.4	2.7	0.59:	0.41: i
5801 CIV	0.51	0.34	0.30	0.23	0.92:	0.62:
5812 CIV	0.14:	0.09:	0.12:	0.09:	0.45:	0.30:
5876 HeI	17.7	11.5	10.7	8.2	22.6	14.8
6087 [FeVII],[CaV]	43	25.9	24.4	18.0	7.8	4.8
6300 [OI]	19.4	11.0	6.4	4.5	1.6	0.92
6312 [SIII]	19.1	10.8	3.9	2.8	1.0	0.57 b
6364 [OI]	7.1	3.9	2.4	1.7	—	—
6435 [ArV]	7.4	4.0	2.1	1.5	2.2	1.2
6548 [NII]	14.1	7.4 b	4.0	2.7 b	—	— b
6563 H α	645	338	710	479	800	425
6583 [NII]	42	21.8 b	9.6	6.5 b	—	— b
6678 HeI	6.3	3.2	2.7	1.8	20.5	10.6
6731 [SII]	1.8	0.90	0.75	0.49	—	—
6825 OVI Raman scat.	—	—	8.4	5.4	33	16.3
6891 HeII	1.0	0.48	0.47	0.30	0.84	0.41
7006 [ArV]	17.5	8.2	4.0	2.5	1.2	0.57
7065 HeI	15.9	7.4	7.8	4.9	22.4	10.6
7082 OVI Raman scat.	—	—	0.99	0.62	3.4	1.6
7136 [ArIII]	45	20.4	7.0	4.3	—	—
7155 FeII-14F	1.2	0.55	0.90	0.56	1.1	0.51
H β abs. flux [erg/cm ² s]	$2.5 \cdot 10^{-11}$		$5.2 \cdot 10^{-11}$		$5.1 \cdot 10^{-12}$	
extinction c	0.87		0.53		0.85	

: weak line; b blend; c calibration problems; i identification uncertain; * variation more than 15 per cent between 1987 April and 1988 March (HM Sge); + flux from 1988 June (V1016 Cyg).

spectra, using the Balmer continuum and the Bowen lines as calibrators.

The UV observations will be discussed in more detail elsewhere (e.g. Nussbaumer & Vogel 1990). In Table 3, we only list the strongest UV lines and those used in the following analysis. Well-exposed UV emission lines can be measured with an accuracy of about 10 per cent. We denote

line fluxes for which errors more than 20 per cent must be expected with a colon or a letter. UV line fluxes of HM Sge for which variations of more than 15 per cent were observed between 1987 April and 1988 March are marked with an asterisk.

All three objects have been observed previously and show various degrees of variability in their emission-line fluxes. Optical observations of HM Sge dating from 1985 and 1986 have been reported recently by De Freitas Pacheco, Codina-Landaberry & Lopes (1989). Comparison with our data shows that the line fluxes relative to $H\beta$ of $H\text{I}$, He II , $[\text{N II}]$, $[\text{O I}]$, $[\text{O III}]$ and $[\text{Fe VII}]$ remained unchanged but the $\text{He I } \lambda 4471$, $\text{He I } \lambda 6678$ and $\text{Ne V } \lambda 3426$ lines increased whereas the $[\text{Ne III}] \lambda 3869$, $[\text{Ne IV}] \lambda 4720$ and $[\text{Fe VI}] \lambda 5176$, 5630 lines decreased. UV spectra show a well-defined evolution towards higher nebular excitation (Nussbaumer & Vogel 1990).

Ipatov & Yudin (1986) published a series of calibrated spectra of V1016 Cyg obtained between 1980 and 1984. Their last spectrum taken in 1984 October has consistently higher line ratios (relative to $H\beta$). It is, however, noteworthy that our data agree well with theirs taken between 1980 and 1982. Possibly V1016 Cyg has reverted into a stage in which it was before. A similar behaviour is reported for low-excitation UV lines in Nussbaumer & Schmid (1988).

Calibrated optical spectra of HBV 475 are rather scarce and the last reported observations date from 1980 August (Blair *et al.* 1983). Comparison with our data shows that all recombination-line ratios either remain unchanged or have slightly increased. Some of the collisionally excited line ratios have markedly decreased (e.g. $[\text{O III}] \lambda 5007$ relative to $H\beta$). *IUE* observations show large line variations with a period of 960 d (Nussbaumer *et al.* 1986).

4.2 Diagnostic diagrams for HM Sge and V 1016 Cyg

The rich emission-line spectra of HM Sge and V1016 Cyg offer various possibilities for the determination of the nebular parameters T_e and N_e . The diagnostic line ratios used are listed in Table 4. We have grouped them according to the ionization energies of the ions involved. Interpreting the model calculations of Nussbaumer & Schild (1981), we distinguish between lines emitted in

Table 4. Dereddened line ratios for diagnostic diagrams.

line ratio	HM Sge	V1016 Cyg	HBV 475
(a) $\text{Si II } 1533/1815(3)$	—	0.36	—
$\text{S II } 4068,76/6716,31$	15	9.2	—
$\text{C II } 1335(2)/2325(5)$	—	0.14	—
(b) $\text{N II } 5755/6548,84$	0.66	0.29	—
$\text{Si III } 1206/1892$	—	0.20	—
$\text{He I } 5876/6678$	4.1	5.4	1.4
$\text{O III } 4363/4959,07$	0.17	0.13	0.094:
$\text{O III } 1661,66/4363$	1.2	2.7	61:
$\text{Ne IV } 1601(2)/2423,25$	2.1	1.6	—
(c) $\text{Fe VI } 5176/5678$	4.0	5.0	—
$\text{Fe VI } 3663/5146$	1.1	0.78	—
$\text{Fe VII } 3586/5721$	0.98	1.1	2.0
$\text{Fe VII } 5158/5721$	0.23	0.28	0.60
$\text{Ne V } 2975/3426$	0.018	0.023	—

- (a) the transition zone between the ionized and neutral region: S II , Si II and C II ;
- (b) the He^+ zone and the outer edge of the He^{+2} zone: He I , N II , Si III , O III and Ne IV ; and
- (c) the inner He^{+2} zone: Ne V , Fe VI and Fe VII .

Each emission-line ratio defines a curve in the T_e - $\log N_e$ diagram (Fig. 2a and b). For each ion, we computed the equilibrium populations of all low-lying levels. It was assumed that N_e and T_e are constant within the section of the nebula in which a given ion occurs. Almost all atomic data have been taken from the compilation of Mendoza (1983).

For the interpretation of the $\text{He I } \lambda 5876$ and $\lambda 6678$ lines, we used a code described by Schmid (1990, see also Section 5.2.2). In nebulae with $N_e \geq 10^4 \text{ cm}^{-3}$ the $\text{He I } 2^3\text{S}$

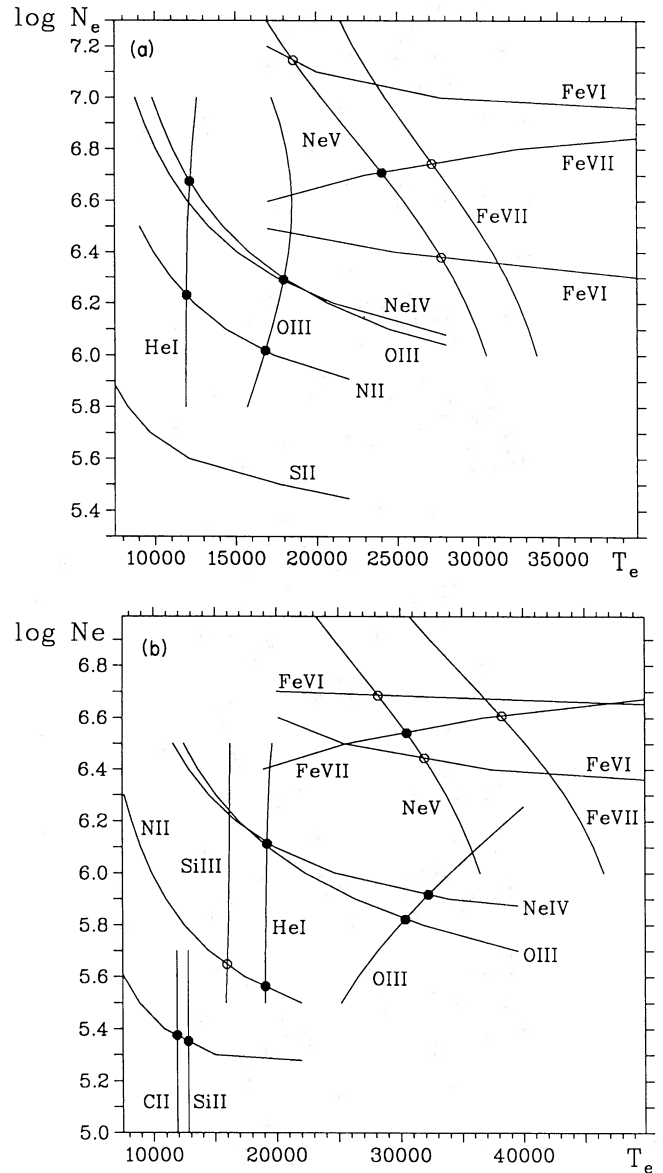


Figure 2. (a) Diagnostic diagram for HM Sge. Each line ratio in Table 4 is represented by a line along which the ratio has the observed value. Apart from He I , all lines are purely collisionally excited (see text). Filled circles denote intersections of higher reliability. (b) Same as (a) for V1016 Cyg.

level is highly populated due to its metastability, and collisional enhancement of He I recombination lines occurs. If collisional excitations contribute significantly to the emissivities, the line ratio $\lambda 5876/\lambda 6678$ becomes temperature sensitive. (Note that the He I line ratios in Table 4 are corrected for the He II $\lambda 6683$ contribution which contaminates He I $\lambda 6678$.)

Intersections in Fig. 2(a and b) between ions of the same group are qualified with filled and open circles. Filled circles are plotted for intersections of more reliable line ratios having a strong dependence on the nebular parameters N_e and/or T_e and which have been derived from strong emission lines. The open circles are less accurate because of potentially larger observational errors.

Figs 3 and 4 show the resulting density and temperature structure of V1016 Cyg and HM Sge as a function of the ionization energy. We find a steep gradient in N_e covering more than an order of magnitude from the highest to the lowest observed ionization stage in both symbiotic nebulae. Also T_e decreases with decreasing ionization as expected from model calculations. Both objects display a remarkably similar density pattern with the only difference that N_e is about 50 per cent higher and the temperature slightly lower in HM Sge.

For abundance analysis it must be kept in mind that N_e is highly variable across the nebulosity. Abundances must therefore be determined from emission-line ratios which are not density biased.

In V1016 Cyg there is a conspicuous difference in the electron temperature determined from the O III and the He I lines, $T_e(\text{O III})$ is even comparable to $T_e(\text{Ne V})$ although model calculations predict much higher temperatures in the Ne^{+4} region in the O^{+2} zone (Nussbaumer & Schild 1981). This discrepancy may be due to the fact that collisionally excited lines are weighted towards high temperatures and towards the critical density for collisional de-excitation while $T_e(\text{He I})$ reflects more the average temperature in the nebula. However, the temperature difference derived from O III and He I lines in V1016 Cyg seems to be too large to be attributed solely to temperature fluctuations in the nebula. Alternatively, it is possible that regions with different densities contribute to the O III line fluxes. For example, the observed O III line ratios can be reproduced when combining emission-line fluxes from two regions with electron densities $N_e \approx 3 \times 10^5$ and $5 \times 10^7 \text{ cm}^{-3}$ and both having $T_e = 25\,000 \text{ K}$. A similar effect is even more clearly seen in the O III lines of HBV 475 (see below).

4.3 Nebular parameters for HBV 475

The optical spectrum of HBV 475 shows, besides the usual recombination lines of hydrogen and helium, numerous weak Fe II lines, but only a few of the diagnostic lines observed in HM Sge and V1016 Cyg can be detected (Table 4). We can, however, use the [Ne V] $\lambda 3426$, [Fe VII] $\lambda 6087$ and [Mg V] $\lambda 2783$ lines for an estimate of N_e . The critical densities for these lines are

$$\begin{aligned} N_e &= 2 \times 10^7 \text{ cm}^{-3} \text{ for } [\text{Ne V}] \lambda 3426; \\ N_e &= 4 \times 10^7 \text{ cm}^{-3} \text{ for } [\text{Fe VII}] \lambda 6087; \\ N_e &= 2 \times 10^8 \text{ cm}^{-3} \text{ for } [\text{Mg V}] \lambda 2783. \end{aligned}$$

The dereddened respective fluxes in HBV 475 amount to only 15, 27 and 42 per cent of those observed in V1016 Cyg (Table 3). The resonance lines C IV, N V, or the Raman-scattered O VI features at $\lambda\lambda 6825, 7082$ (see Schmid 1989), which are not affected by collisional de-excitation, are, however, the same strengths or even stronger in HBV 475. We conclude therefore that in HBV 475 at least [Ne V] and [Fe VII] are collisionally de-excited, pointing to an electron density of $N_e \gtrsim 10^8 \text{ cm}^{-3}$ in the highly ionized region.

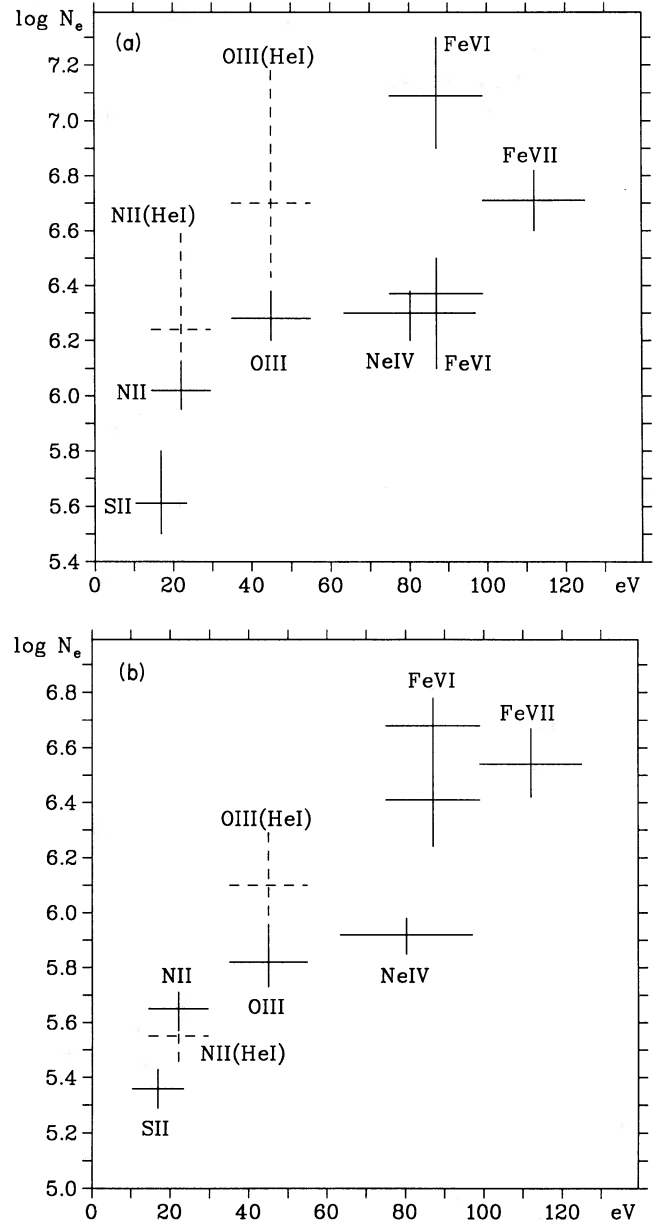


Figure 3. Electron density N_e versus ionization potential IP for (a) HM Sge and (b) V1016 Cyg. The electron densities are from the intersections in Fig. 2. The vertical error bars reflect the resulting variation if the underlying observed line ratios are varied by 10 per cent. The horizontal bars cover the range in IP of the line emitting and the next lower ionization stage. Solid crosses are based on electron temperatures from purely collisionally excited lines whereas dashed crosses are based on electron temperatures from the He I 5876/6678 ratio.

Lines formed by dielectronic recombination (Storey 1981) can be used for a temperature estimate in HBV 475. The recombination line of an ion X^{+m} originates in the same region as a collisionally excited line from X^{+m+1} . Because in HBV 475 no dielectronic recombination lines are visible, only lower limits for the line ratios, and with the recombination coefficients of Nussbaumer & Storey (1984), lower limits for the temperatures can be given:

$$\begin{aligned} F(\text{N v } \lambda 1240)/F(\text{N iv } \lambda 1718) &> 20, & T_e &> 13\,000 \text{ K}, \\ F(\text{C iv } \lambda 1549)/F(\text{C iii } \lambda 2297) &> 20, & T_e &> 10\,500 \text{ K}, \\ F(\text{C iii } \lambda 1909)/F(\text{C ii } \lambda 1335) &> 5, & T_e &> 10\,000 \text{ K}. \end{aligned}$$

Applying the same diagnostic analysis as described in the previous section to the O III line ratios in HBV 475 (Table 4) leads to the formal solution $T_e = 6500 \text{ K}$, $N_e = 3 \times 10^{10} \text{ cm}^{-3}$. This temperature is, however, in conflict with the absence of

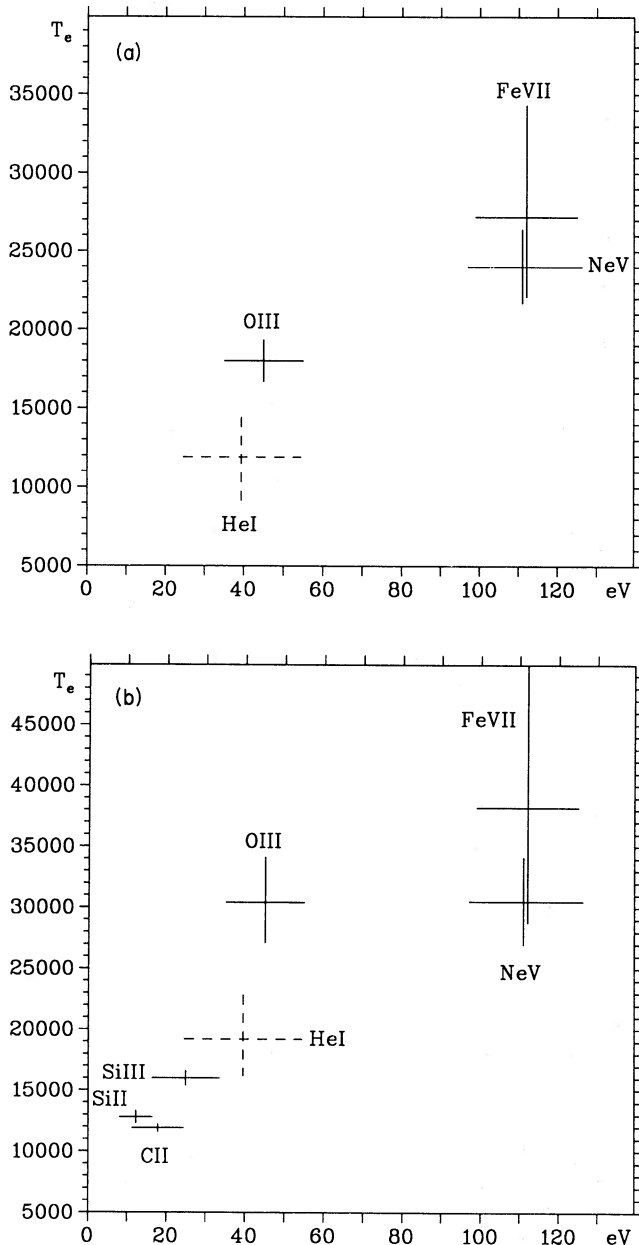


Figure 4. Same as Fig. 3 for the electron temperature T_e for (a) H M Sge and (b) V1016 Cyg.

lines arising from dielectronic recombination. For such a low T_e the recombination lines C III $\lambda 2297$ or C II $\lambda 1335$ are expected to have approximately the same intensities as the collisionally excited lines C IV $\lambda 1549$ or C III $\lambda 1909$ respectively. Changing the reddening parameter to $c = 0.5$ as indicated by the observed 2200 Å feature only lowers the density by about a factor of 3. A possible solution to this O III problem is suggested in Fig. 5 where emissivity ratios for O III lines are plotted as a function of density. We see that in the low-density limit $F(\lambda 4363) \approx F(\lambda 1661 + \lambda 1666)$ whereas in the high-density case $F(\lambda 4363) \approx F(\lambda 4959 + \lambda 5007)$. It follows from Fig. 5 that [O III] $\lambda\lambda 4959, 5007$ is mainly formed in a plasma with $N_e \lesssim 3 \times 10^6 \text{ cm}^{-3}$ whereas [O III] $\lambda\lambda 1661, 1666$ comes from a region with $N_e \gtrsim 10^9 \text{ cm}^{-3}$. Considerable contributions to the observed O III lines cannot originate from a zone with intermediate density because this would produce a much stronger [O III] $\lambda 4363$ emission. From the observed fluxes we infer that [O III] ($\lambda 4959 + \lambda 5007$) comes from a much more extended region (by about a factor of 10^4) than the [O III] ($\lambda 1661 + \lambda 1666$) emission. The nebular mass in the extended low-density region is larger than in the high-density component.

5 HELIUM ABUNDANCES IN HM SGE, V1016 CYG AND HBV 475

The determination of He abundances in low-density gaseous nebulae like H II regions is fairly straightforward because pure recombination case B theory applies. But already at the slightly higher densities occurring in planetary nebulae, a complication in the form of collisional excitation from the $\text{He}^0(2s^3S)$ state has to be taken into account (Ferland 1986; Peimbert & Torres-Peimbert 1987; Clegg 1987). At the even higher densities in our objects, a variety of other atomic processes may influence the H I, He I and He II recombination spectra.

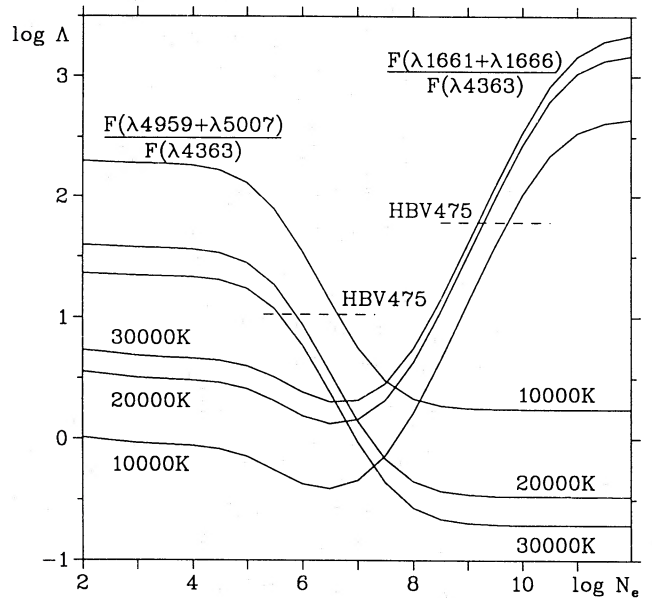


Figure 5. Theoretical emissivities of [O III] line ratios as a function of the electron density and temperature. Observed values for HBV 475 are plotted as dashed lines. The observations indicate that two distinct regions are responsible for the [O III] emission.

5.1 Optical depth effects

The metastability of the 2S levels in H I, He I and He II potentially gives rise to optical depth effects which in turn can change the recombination cascade routes.

5.1.1 Hydrogen

Line profiles of H α in symbiotic stars often show central absorption features pointing to line absorption effects in some Balmer lines (Oliversen & Anderson 1982; Tamura 1988). There is ample additional evidence that the Balmer lines deviate from pure case B recombination: the dereddened H α /H β ratios clearly disagree with case B recombination in V1016 Cyg and HBV 475 and to a lesser extent also in HM Sge. A further indication comes from the H β /P δ ratios: from the near-IR spectra we get the line ratios $F(\text{H I } \lambda 10049)/F(\text{He II } \lambda 10125)$ 0.49 for HM Sge, 0.70 for V1016 Cyg and 0.96 for HBV 475 (Fig. 6). Using the ratios $F(\text{H}\beta)/F(\text{He II } \lambda 4686)$ (the H β flux is corrected for the He II 8–4 contribution) and assuming that the He II lines are emitted according to recombination theory (see below), we obtain the hydrogen-line ratios $F(\text{H}\beta)/F(\text{H I } \lambda 10049)$ of 11.6 for HM Sge, 10.6 for V1016 Cyg and 5.9 for HBV 475. We note that this procedure is reddening independent. The observed line ratios are substantially lower than the theoretical case B ratio $R_B = 19.7$ for $N_e = 10^6 \text{ cm}^{-3}$ and $T_e = 20\,000 \text{ K}$ (Hummer & Storey 1987). R_B is only 5 per cent lower for densities appropriate for HBV 475. We conclude that the H β intensity in the observed symbiotic stars is considerably degraded by optical depth effects and therefore should not be used as a reference line for abundance determinations.

We can estimate the central line optical depth $\tau(\text{H}\beta)$ that is needed to produce the measured H β /P δ line ratios in HM Sge and V1016 Cyg. For a simple estimation, the tables on Balmer line redistribution and Paschen line generation probabilities of Capriotti (1964) can be used. The opacities $\tau(\text{H}\beta) \approx 4$ [or $\tau(\text{H}\alpha) \approx 30$] are obtained for the line ratios observed in HM Sge and V1016 Cyg. In this case H β is weakened by about 35 per cent and P δ increased by about 5 per cent relative to the pure recombination emissivities. The resulting ratio $F(\text{H}\alpha)/F(\text{H}\beta) = 4.82$ lies above the value observed in HM Sge but agrees well in V1016 Cyg.

For densities $N_e > 10^7 \text{ cm}^{-3}$ even the population of 2P can become important if Ly α photons undergo a large number of scatterings before escape or destruction. According to Capriotti (1964) the population ratio $N(2P)/N(2S)$ is proportional to the nebular density ($N_e \approx N_p$) and the average number of scatterings of Ly α photons Q :

$$\frac{N(2P)}{N(2S)} = \frac{3q_{2S,2P}QN_e}{A_{2P,1S}} \approx 1.5 \times 10^{-12} Z^{-6} QN_e (\text{cm}^3).$$

The value for the ratio between l -changing collisional transitions 2S–2P and relative decay $q_{2S,2P}/A_{2P,1S} \approx 5 \times 10^{-13} Z^{-6}$ is from Hummer & Storey (1987, equation 23; see also the correction in Storey & Hummer 1988, equation 2). For the nebular densities $N_e \approx 10^6 \text{ cm}^{-3}$ observed in HM Sge and V1016 Cyg the average number of Ly α scatterings Q must be $\geq 10^6$ to give a significant population of 2P. In radiation-bounded nebulae the central optical

depth in Ly α is typically $\tau_0(\text{Ly}\alpha) \approx 10^4$ and $Q \approx \tau_0 \ln(\tau_0) \approx 10^5$. A more realistic treatment would also include destruction processes for Ly α photons like absorption by dust or ionization of metals. This would lower the average number of scatterings Q . For HM Sge and V1016 Cyg we therefore assume that $N(2S) \gg N(2P)$ and only optical depth effects due to the population of 2S occur. In HBV 475, self-absorption due to both levels may, however, be present.

In summary, we conclude that the lower Balmer lines are affected by self-absorption in all our objects and should not be used for abundance analyses. Since, however, self-absorption is proportional to the oscillator strength, it may be possible to use higher lines of the Balmer series, where the effect is reduced.

5.1.2 Helium

The He II $\lambda 1640$ profile shows no self-absorption features in our objects. We conclude that the observed He II lines are not, or only very weakly, affected by self-absorption. This is also supported by the observed He II line ratios, which are consistent with pure case B recombination theory. He II $\lambda 4686$ would be one of the most enhanced lines if the $n-2$ series in He II were optically thick. Also perturbations by H I Ly α –He II 4–2 fluorescence, if present, could be detected.

In He I the transitions $n^3P^0-2^3S$ are optically thick, due to the high population of the lower metastable level. This leads to line enhancements in other cascade routes. The He I lines $\lambda 5876$, $\lambda 6678$ and $\lambda 4471$ will not be changed by this effect (Robbins 1968).

5.2 Collisional excitation

5.2.1 Hydrogen

In order to assess whether 1→2, 3 and 2→3 collisional transitions are important, we consult the tables of Hummer

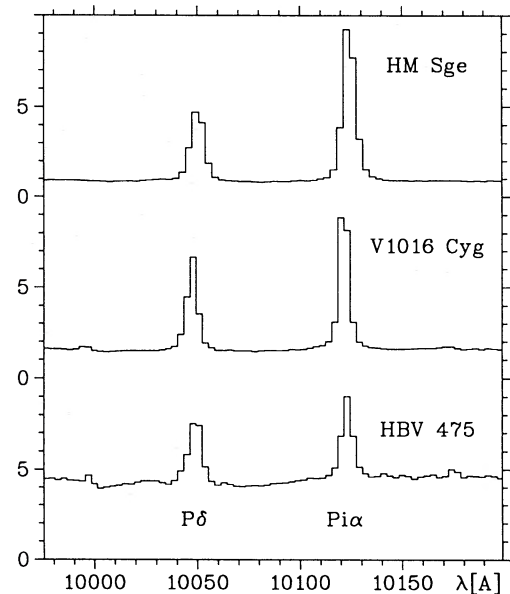


Figure 6. Near-infrared INT spectra showing the P δ and He II Pi α lines.

& Storey (1987). Let us first consider collisions originating from the ground state. Critical values of $N(1S)/N(H^+)$ such that collisional excitation amounts to 10 per cent of the total population rate of the 2 or 3 levels are $\approx 5 \times 10^{-5}$ for the physical conditions occurring in HM Sge and V1016 Cyg. Our previous (unpublished) model calculations suggest that $N(H^0)/N(H^+) \lesssim 10^{-6}$. Collisional transitions from the ground state therefore seem unlikely to populate significantly the $n=2$ or 3 levels.

Similarly, the critical electron density for which collisional transitions $2 \rightarrow 3$ account for 10 per cent of the level 3 population rate is $2 \times 10^6 \text{ cm}^{-3}$ (Hummer & Storey 1987). This applies if the Ly α loss probability $\beta=0$. In our objects $\beta=1/Q \approx 10^{-5}$ (see Section 5.1.1) and the above critical electron density has to be multiplied by a correction factor $1 + 2.310^8 \beta \approx 10^3$ leading to $N_e^{\text{crit}} \approx 10^9 \text{ cm}^{-3}$. If there is Ly α destruction, e.g. by dust absorption the correction factor would be even larger. We therefore assume that at least in HM Sge and V1016 Cyg collisional $2 \rightarrow 3$ transitions are negligible.

5.2.2 Helium

Collisional enhancement of He I lines has been recognized to be important under physical conditions occurring in planetary nebulae (see Clegg 1987). The $2s^3S$ state is highly metastable and collisional excitation enhances the $\lambda 4471$, $\lambda 5876$ and $\lambda 6678$ recombination lines. Clearly, at the even higher densities and temperatures occurring in symbiotic nebulae, this process is bound to be even more important.

Clegg (1987) has given formulae for the ratio of collisionally excited to recombination contributions C/R as a function of N_e and T_e for all three transitions. The collisional contributions can therefore be evaluated if the physical conditions are known. The He I $\lambda 4471$ line may be somewhat problematic for abundance determination because no accurate collision strength Ω for the transition $2^3S - 4^3D$ exists. But for He I $\lambda 5876$ and $\lambda 6678$, accurate atomic data are fortunately available (Berrington & Kingston 1987). We used Clegg's formula for the evaluation of $(C/R)_{\lambda 4471}$ (Table 5). For the $\lambda 5876$ and $\lambda 6678$ transitions, we adopted a different and more empirical approach. The upper levels 3^3D and 3^1D of the lines $\lambda 5876$ and $\lambda 6678$ have almost exactly the same excitation energy. Therefore the collisional excitation rates C from 2^3S have a similar temperature dependence and the collisional contribution to the line ratio is given by the collision strengths only:

$$C_{\lambda 5876}/C_{\lambda 6678} \approx \Omega(2^3S - 3^3D)/\Omega(2^3S - 3^1D).$$

The collisional contributions to these He I lines can therefore be determined from the observed ratio $F(\lambda 5876)/F(\lambda 6678)$, which changes from the pure recombination value of 3.5 to higher values proportional to the amount of collisional enhancement from 2^3S . If $N_e \lesssim 10^7 \text{ cm}^{-3}$, collisions from other levels can be neglected (Schmid 1990), and the relation

$$(C/R)_{\lambda 5876} \approx 3(C/R)_{\lambda 6678}$$

is valid. This relation depends only very weakly on T_e (as outlined above) and is independent of the population of the metastable level 2^3S . This relation is therefore also correct, if

photoionization or another process depopulates 2^3S as described in Clegg & Harrington (1989). From the observed $F(\lambda 5876)/F(\lambda 6678)$ line ratios 4.1 in HM Sge and 5.4 in V1016 Cyg we derive the remaining C/R ratios in Table 5. It is reassuring that our procedure leads roughly to the same result as Clegg's formulae.

At the densities observed in HBV 475, the He I lines are also influenced by radiation-transfer effects (e.g. Feldman & MacAlpine 1978; Schmid 1990). Such processes depend strongly on the population of the metastable levels, which are linked to the population of the He I ground state. Without detailed calculations of the He I level population and optical depths in the He I Lyman lines, it is even difficult to decide whether the emissivity in $\lambda 4471$ is enhanced or degraded. An interpretation of other observable He I lines seems even more difficult. At present these large uncertainties render an accurate determination of the He abundance in HBV 475 impossible.

5.3 He/H abundances

Contrary to previous attempts to determine the He abundance in symbiotic stars, we adopt an approach that takes into account collisions from the He I $2s^3S$ state and also minimizes the effects of self-absorption in hydrogen lines. As outlined in Section 5.1.1, the use of low-lying Balmer lines may lead to erroneous results. As an illustration, we list in Table 6 ratios $y^{++} = N(\text{He}^{+2})/N(H^+)$ resulting from He II $\lambda 4686$ relative to various Balmer lines and He II $\lambda 10125$ (Pi α) relative to P δ . The Balmer lines were corrected for the corresponding He II contributions (amounting to about 3 per cent). The recombination emissivities for H I and He II were taken from Hummer & Storey (1987) whereas those for He I are from Brocklehurst (1972). We see that in HM Sge and HBV 475 a noticeable decrease of y^{++} occurs with increasing Balmer lines as is expected in the presence of self-absorption. In HM Sge, the $N(\text{He}^{+2})/N(H^+)$ ratio from the H9 Balmer line agrees well with the ratio obtained from He II Pi α and P δ .

The results for V1016 Cyg are more ambiguous. All Balmer lines yield the same ratio $N(\text{He}^{+2})/N(H^+) = 0.05$ but the He II Pi α /P δ ratio leads to a lower value of 0.027. An additional spectrum of V1016 Cyg taken by Ian Griffin (UCL) with the INT yields the same lower value for all measurable Paschen lines. The same type of discrepancy occurs in HBV 475. With respect to the high-excitation class of these two nebulae the low $N(\text{He}^{+2})/N(H^+)$ ratio from the IR lines is surprising. Using these ionic ratios would lead to He/H abundances which are far below the solar value. It therefore seems that either the He II Pi α lines are degraded or the Paschen lines are enhanced by some unknown process. A further investigation into the near-IR recombination lines in

Table 5. Empirical C/R ratios of excitation by collision and recombination for He I lines.

He I line	HM Sge	V1016 Cyg
$\lambda 4471$	0.14	0.56
$\lambda 5876$	0.27	1.11
$\lambda 6678$	0.093	0.37

symbiotic stars is in progress. In the following we use the $N(\text{He}^{+2})/N(\text{H}^+)$ ratios from the Balmer line H9 but we emphasize that this choice is somewhat arbitrary as long as the IR line fluxes are not understood.

The $y^+ = N(\text{He}^+)/N(\text{H}^+)$ ratio could be obtained from the He I $\lambda\lambda 4471, \lambda 5876$ and $\lambda 6678$ lines and H9 as hydrogen reference. We prefer, however, to use He II $\lambda 4686$ and calculate the $y' = N(\text{He}^+)/N(\text{He}^{+2})$ ratio. The resulting abundances are listed in Table 6. Corrections for collisional contributions to the He I lines in HM Sge and V1016 Cyg were made as outlined in Section 5.2.2. For HBV 475 it is not possible to calculate reliable y' ratios, due to the unsolved problems mentioned in Section 5.2.2.

6 ABUNDANCE OF HEAVY ELEMENTS

Relative elemental abundances between heavier elements can be obtained from emission lines which originate in a common region. In dense nebulae, the ionization structure of helium is particularly well defined by the Strömberg radii of He^{+2} and H^+ . It is therefore appropriate to compare ions which coincide with either the He^{+2} or He^+ regions.

Table 6. Helium abundances derived from various recombination-line ratios.

line ratio	HM Sge	V1016 Cyg	HBV 475
$y^{++} = N(\text{He}^{+2})/N(\text{H}^+)$			
HeII 4686/H β	0.064	0.050	0.073
HeII 4686/H γ	0.056	0.048	0.074
HeII 4686/H δ	0.051	0.048	0.069
HeII 4686/H9	0.041	0.049	0.057
H ρ /HeII ρ	0.039	0.029	0.021
adopted y^{++}	0.041	(0.049)	(0.057)
$y' = N(\text{He}^+)/N(\text{He}^{+2})$			
HeI 4471/HeII 4686	1.17	0.77	—
HeI 5876/HeII 4686	1.14	0.67	—
HeI 6678/HeII 4686	1.16	0.73	—
adopted y'	1.16	0.72	—
$N(\text{He})/N(\text{H})$	0.089	(0.084)	—

Because the studied objects show large gradients in their nebular parameters, it is desirable that the emission lines should additionally have the same dependence on density and temperature. We therefore should avoid ratios involving collisionally excited and recombination lines and only use ratios of collisionally excited lines having similar excitation energies and critical densities well above the N_e s observed in the nebula.

6.1 Carbon, nitrogen, oxygen

Nussbaumer *et al.* (1988) have examined the C/N and O/N ratios of 24 symbiotic stars by using the strong UV lines of C III $\lambda 1909$, C IV $\lambda 1550$, N III $\lambda 1750$, N IV $\lambda 1486$ and O III $\lambda 1664$. They argued that the emissivities of these lines have a very similar dependence on the nebular parameters. But in the more statistical approach of Nussbaumer *et al.*, the parameters $T_e = 12\,000$ K and $N_e = 10^9 \text{ cm}^{-3}$ were used for all symbiotic systems. We calculate here new values for HM Sge and V1016 Cyg with nebular parameters from Figs 3 and 4 ($N_e = 10^6 \text{ cm}^{-3}$ and $T_e = 20\,000$ K). Using the same computer code and atomic data as in Nussbaumer *et al.* (1988), we obtain the abundance ratios C/N and O/N for HM Sge and V1016 Cyg given in Table 7. For HBV 475 we used the line fluxes from Table 3, but retained the nebular parameters of Nussbaumer *et al.* (1988). The new values differ by about 30 per cent or less from those in Nussbaumer *et al.* (1988) and are consistent with the expected errors quoted there.

We determine abundance ratios between elements with $Z > 2$ and helium from recombination lines only in order to minimize the impact of temperature inhomogeneities in the nebulae. In our spectra the recombination lines C IV $\lambda\lambda 5801, 5812$, C IV $\lambda 4658$ and O V $\lambda 1371$ can be identified. Considering ionization structure calculations for symbiotic stars (Nussbaumer & Schild 1981; Hayes & Nussbaumer 1986) the following relations between the emitting ions can be made for the He^{+2} region:

$$\frac{N(\text{C}^{+4})}{N(\text{C})} \approx \frac{N(\text{He}^{+2})}{N(\text{He})} \approx 1$$

and

$$\frac{N(\text{O}^{+5})}{N(\text{O})} < \frac{N(\text{He}^{+2})}{N(\text{He})}.$$

Table 7. Abundance ratios (by number) in symbiotic novae. The solar values are from Grevesse (1984).

	HM Sge	V1016 Cyg	HBV 475	solar	remarks
He/H	0.089	0.084:	—	0.10	
C/N	0.74	1.46	0.67	5.0	
O/N	1.00	2.08	1.55	8.3	
O/He	>5.6–3	>5.5–3	>8.6–3		OV $\lambda 1371$
C/He	>2.7–3	>1.8–3	>3.6–3		CIV $\lambda 5801, 12$
	<14–3	<8.2–3	<14–3		CIV $\lambda 4658$
C/O · O/He	>4.1–3	>3.9–3	>3.7–3		
C/He adopted	8.0–3:	6.0–3	8.0–3	4.9–3	
Ne/O	0.22	0.19	0.23:	0.12	
Ar/O	0.014:	0.010:	—	4.7–3	
Fe/Ne	0.11	0.18	—	0.47	
Si/C	0.12:	0.16:	—	0.072	

From the C iv lines $\lambda\lambda 5801, 5812$ and $\lambda 4658$, the He II $\lambda 4686$ and recombination coefficients of P. Storey (personal communication), the relative abundance C/He can be derived (Table 7). For $\lambda\lambda 5801, 5812$ we used the case B coefficients assuming the transitions to the ground state of C iv to be optically thick. Of course it is not clear how well the case B assumption is fulfilled. Because the nebular density is highest for HBV 475 the situation may be closest to case B there. The resulting C/He abundances can in any case be used as a lower limit.

Unfortunately the C iv $\lambda 4658$ line is blended with [Fe III] $\lambda 4658$ in HM Sge and V1016 Cyg. The Fe III contribution, however, can be estimated from the weak nearby [Fe III] $\lambda 4755$ line, originating from the same upper level as [Fe III] $\lambda 4658$. According to Garstang, Robb & Rountree (1978) the theoretical [Fe III] line ratio is $\lambda 4658/\lambda 4755 = 5.6$. From our spectra we estimate the Fe III contribution to $\lambda 4658$ as at least 30 per cent in HM Sge and V1016 Cyg. In HBV 475 the line C iv $\lambda 4658$ seems to be blended with other nearby emission lines. Because we rather underestimated the Fe III contribution (and other weak lines in HBV 475) the values given in Table 7 can be used as upper limits for the relative C/He abundances.

The O v $\lambda 1371$ line is formed by dielectronic recombination and can be compared with the He II $\lambda 1640$ line. Because also O^{+3} and O^{+4} ions are expected to coexist in the He^{+2} zone, only lower limits for the O/He ratio can be determined. The atomic data were taken from Nussbaumer & Storey (1981). Using the relative C/O abundances, additional lower limits for the C/He abundance ratios can be obtained (Table 7).

For V1016 Cyg the recombination lines of C iv and O v define a tight range for the C/He abundance ratios around the solar value. We adopt the value $C/He = 6 \times 10^{-3}$ for V1016 Cyg. For HM Sge and HBV 475 the possible range for the C/He abundance ratio is larger and we adopt the mean value $C/He = 8 \times 10^{-3}$ for both objects.

6.2 Neon, argon, silicon, iron

Additional relative abundances between metals can be obtained from forbidden and intercombination lines. Whenever possible we have chosen line ratios which depend only little on the nebular parameters but some line ratios do not fulfil these criteria and the derived abundances are less accurate. We have denoted the ratios for which an error of about a factor 2 must be expected with a colon in Table 7. For the other values the accuracy should be about 30 per cent.

In the He^{+} region, ionization structure calculations suggest the following relations:

$$\frac{N(O^{+2})}{N(O)} \approx \frac{N(Ne^{+2})}{N(Ne)} \approx \frac{N(Ar^{+2}) + N(Ar^{+3})}{N(Ar)} \approx 1.$$

For the Ne/O abundances in HM Sge and V1016 Cyg we use the line fluxes of [O III] $\lambda 5007$, [O III] $\lambda 4363$ and [Ne III] $\lambda 3869$. The critical densities for these lines are $N_c = 7 \times 10^5 \text{ cm}^{-3}$ ($\lambda 5007$), $N_c = 3 \times 10^7 \text{ cm}^{-3}$ ($\lambda 4363$) and $N_c = 1 \times 10^7 \text{ cm}^{-3}$ ($\lambda 3869$). The N_c are rather low as compared with the nebular densities, introducing a considerable N_c dependence for the derived Ne^{+2}/O^{+2} ionic abundances. But the

collisional de-excitation effects can be minimized for $N_e < 3 \times 10^7 \text{ cm}^{-3}$ if we use the ratio

$$[F([O \text{ III}] \lambda 5007) + 7F([O \text{ III}] \lambda 4363)]/F([Ne \text{ III}] \lambda 3869).$$

In HBV 475, we take the lines [O III] $\lambda 5007$ and [Ne III] $\lambda 3869$ and assume that they are emitted in a low-density region $N_e \approx 10^6 \text{ cm}^{-3}$ (see Section 4.3).

The [Ar III] $\lambda 7136$ and [Ar IV] $\lambda 4740$ lines are seen in HM Sge and V1016 Cyg and have been used together with [O III] $\lambda 5007$ for the determination of the Ar/O abundance ratio. Note that the new collision strengths for Ar IV of Zeippen, Butler & Le Bourlot (1987) are about a factor 2 higher than those given in the compilation of Mendoza (1983).

We determine the Si/C abundance ratio for HM Sge and V1016 Cyg from the UV lines C III] $\lambda 1909$, Si III] $\lambda 1892$ and Si IV $\lambda\lambda 1394, 1403$. The following relation is valid for the ionic abundances of C and Si in the outer parts of the He^{+} zone:

$$\frac{N(C^{+2})}{N(C)} \approx \frac{N(Si^{+2}) + N(Si^{+3})}{N(Si)}.$$

According to the ionization structure calculation of Nussbaumer & Schild (1981), silicon is slightly overestimated by this approximation. But the similar ionization potentials $IP(Si^{+3}) = 45.1 \text{ eV}$ and $IP(C^{+2}) = 48.9 \text{ eV}$ justify the inclusion of the Si^{+3} ion. Due to the larger excitation energy of the Si IV doublet, the derived abundance ratios given in Table 7 depend on the temperature. In V1016 Cyg $T_e(Si \text{ III})$ is slightly lower than $T_e(He \text{ I})$. We take the values from $T_e(He \text{ I})$ for both objects as mean temperatures representing the Si^{+2} and Si^{+3} regions.

The Ne/Fe abundance ratio can be derived from Ne^{+3} , Ne^{+4} and Fe^{+5} , Fe^{+6} , because the ionization potential of these ions are nearly identical ($IP: 97 \text{ eV } Ne^{+3}$, $99 \text{ eV } Fe^{+5}$ and $126 \text{ eV } Ne^{+4}$, $125 \text{ eV } Fe^{+6}$). Support for this assumption comes from the ionic abundance ratios Ne^{+4}/Ne^{+3} and Fe^{+6}/Fe^{+5} , which agree well in both stars. Both ratios are 4.7 in HM Sge and 10.0 for neon and 8.5 for iron in V1016 Cyg. These ionic abundances are derived for both elements from nearby lines in order to minimize the temperature and reddening dependence. We use the lines [Ne V] $\lambda 1575$, [Ne IV] $\lambda 1602$ and [Fe VII] $\lambda 3587$, [Fe VI] $\lambda 3663$. The relative abundances Ne/Fe given in Table 7 were calculated from the lines [Ne V] $\lambda 3426$ and [Fe VII] $\lambda 3587$.

7 DISCUSSION

A prerequisite for any reliable abundance determination is the detailed knowledge of the physical conditions under which line radiation is emitted. We have found a steep gradient of N_e in both HM Sge and V1016 Cyg and a smaller gradient in T_e . The physical conditions in HBV 475 remain less well determined. The best clue coming from the O III lines indicates that the nebula is made up of two distinct components with densities $N_e \approx 10^6 \text{ cm}^{-3}$ and $N_e \approx 10^9 \text{ cm}^{-3}$.

By careful selection of emission lines it is possible to minimize the impact of density and temperature gradients and fluctuations on abundance ratios. Because of the existing gradients, it is important to use only emission lines from

elements with similar ionization potentials. In this work, we obtained C/He and O/He ratios from recombination lines and the further abundance ratios C/N, O/N, Ne/O, Ar/O, Fe/Ne and Si/C from collisionally excited lines. We believe that the abundance ratios in Table 7 are accurate to within 30 per cent unless they are listed with a colon. The ratios relative to hydrogen in Table 8 on the other hand suffer possibly from propagating errors and are only accurate to within a factor of ≈ 2 .

In relation to the He/H abundance, we stress that in symbiotic stars the Balmer lines should only be used with caution as a hydrogen reference. Clearly, the direct application of case B theory to low Balmer lines can lead to erroneous results. It is also important to take into account the contribution of collisions from the metastable $\text{He}^0 2s^3S$ state. The use of self-absorbed Balmer lines as well as neglect of collisional contributions to He I lines will both lead to an overestimation of the He abundance. Previous work was mainly focused on HM Sge and considerable helium overabundances were indeed reported (see De Freitas Pacheco *et al.* 1989 and references therein). We attribute the discrepancies between the previous results and ours to the different corrections made by us. In fact, when using the dereddened $H\beta$, $\text{He II } \lambda 4686$ and $\text{He I } \lambda 4471$ line fluxes without taking into account $H\beta$ self-absorption and collisional enhancement of the He I lines, we would also obtain a higher He/H ratio of 0.15 for HM Sge.

In the case of V1016 Cyg and HBV 475 some uncertainty remains in relation to the near-IR recombination lines. In both symbiotics, the He/H ratio is, however, unlikely to be above solar.

7.1 Comparison with abundances in other objects

The most outstanding feature in the abundances of HM Sge, V1016 Cyg and HBV 475 is the clear overabundance of N in all objects. The other abundances are basically solar with the possible exception of neon in HM Sge which also seems slightly increased. The derived Ne/O ratio, however, agrees very well with the mean value $\text{Ne/O} = 0.21$ found in 170 planetary nebulae (Henry 1989).

In the following we will concentrate on HM Sge and V1016 Cyg because in these objects abundances relative to hydrogen can be reasonably well determined. We first compare the abundances found in symbiotic stars with those observed in novae (for a summary about abundances in novae, see Truran 1985; Williams 1985). Although there seem to be large variations in chemical composition for different nova events, all of them have one common feature: the He and/or metal mass fraction is strongly increased at the expense of the H mass fraction. None of the novae listed by Truran (1985) has a hydrogen mass fraction larger than 0.53, the remainder being either locked into helium as in HR Del or metals as in Aql 1982. By contrast, the H and He mass fractions in HM Sge and V1016 Cyg are 0.72 and 0.25, which are very close to the solar values. Clearly, the overall chemical composition in HM Sge and V1016 Cyg is quite different from those hitherto observed in any nova ejecta. We therefore conclude that the gas presently ionized in HM Sge and V1016 Cyg is very unlikely to have experienced any ordinary nova processing.

Let us now compare the abundances in the two symbiotic stars with those observed in red giants. We see from Table 8 that the C, N, O abundances in V1016 Cyg are almost identical to the mean abundances found in 21 M or S giants (Smith & Lambert 1985, 1986). According to model calculations (Iben & Renzini 1983) a low-mass star is converting carbon into nitrogen, due to the C–N cycle and the products are mixed into the atmosphere during the first dredge-up phase to form the well-known C, N, O abundance ratios of red giants.

In HM Sge, the N abundance and to a lesser extent also the C abundance is larger than observed in normal-field red giants with masses $M \lesssim 5 M_{\odot}$. The abundances in HM Sge must therefore be attributed to a more advanced nuclear burning stage. HM Sge may be in the third dredge-up phase (Iben & Renzini 1983) such that the products of He burning are seen. In this respect it is interesting to note that HM Sge contains a Mira with a period of 580 d as compared to V1016 Cyg with a period of only 450 d.

The C, N, O abundances of HM Sge are also comparable with Type I planetary nebulae (Peimbert & Torres-Peimbert 1983) but the He abundance is considerably lower in the symbiotic star.

In summary, we find that the symbiotic novae HM Sge, V1016 Cyg and HBV 475 show abundances similar to M giants in accordance with Nussbaumer *et al.* (1988). If the outburst seen in these objects was caused by a thermonuclear runaway on the hot component, then there was either no material ejected or the ejecta have been swept away in the meantime by the red giant wind. We suggest therefore that, in symbiotic stars, it is in principle possible to derive abundances of red giant stars with the diagnostic tools used for gaseous nebulae. This provides an independent check of abundance determinations from photospheric lines and offers the unique possibility to determine the abundances of otherwise unobservable elements such as He.

7.2 Dust and the geometrical configuration

With the abundances derived for HM Sge and V1016 Cyg, we can determine if depletion of some elements due to dust

Table 8. Elemental abundances in units of $[12 + \log(A/H)]$ for the symbiotic nebulae HM Sge and V1016 Cyg. Values for the Sun, M giants and planetary nebulae are also listed.

	HM Sge	V1016 Cyg	solar ¹	M giants ²	PN ³
He	10.94	10.9:	11.0	?	11.0
C	8.85	8.7	8.69	8.55	8.89
N	9.0	8.55	7.99	8.45	8.26
O	9.0	8.85	8.91	8.88	8.64
C+N+O	9.4	9.2	9.15	9.14	9.14
Ne	8.3	8.15	8.0	?	8.03
Si	7.95:	7.9:	7.55	?	6.5
Ar	7.1:	6.85:	6.58	?	6.43
Fe	7.35	7.4	7.67	7.6	6.32

¹Grevesse (1984).

²Smith & Lambert (1985, 1986).

³Aller & Czyzak (1983), Shields (1978).

condensation is present. Of significance are the abundance ratios between the typical dust components Si, Fe and the inert gases Ne and Ar. The Fe/Ne ratio especially can be reliably determined in HM Sge and V1016 Cyg. In planetary nebulae the characteristic depletion of Si and Fe is one or two orders of magnitude. In HM Sge and V1016 Cyg the Fe/Ne ratios are slightly lower than the solar value, which itself is, however, rather uncertain. Comparing the Fe and O abundances via $\text{Fe}/\text{Ne} \times \text{Ne}/\text{O}$ gives much better agreement. We conclude that in both symbiotics only a small, if any, depletion of Fe is present. However, both objects are classified as D-types and are therefore known to contain dust grains. If these grains are constituted from Fe, they must be located outside the highly ionized region. Similarly the Si/C abundance ratios show no signs of grain depletion although we determined these values from ions occurring at the outer edge of the ionized region. However, both symbiotic stars show silicate-emission features at $10\ \mu\text{m}$ (Roche, Allen & Aitken 1983) but unlike in PNs, there is neither Fe nor Si depletion in symbiotic stars indicating that grains were broken up in the ionized nebulosity.

The strong N_e gradients found in HM Sge and V1016 Cyg can be used to derive some basic parameters of the geometrical configuration if we assume that the heavy wind of a red giant star is illuminated by a companion object. Both symbiotics are of the Mira-type variety with fairly long periods. Mass-loss rates for such variables are typically $\approx 10^{-5}\ M_{\odot}\ \text{yr}^{-1}$. With the electron density derived from the highest ionized species from e.g. Fig. 3 and a typical expansion velocity of $20\ \text{km}\ \text{s}^{-1}$, we find for the binary separation 115 AU in V1016 Cyg and 75 AU in HM Sge.

We can compare this to the characteristic dust radii of 150 AU for V1016 Cyg and 125 AU for HM Sge which were deduced from IRAS colours by Kenyon, Fernandez-Castro & Stencel (1988). In view of the different model assumptions made and the totally different observational input, the agreement between the two sets of radii is remarkable.

We suggest that in both systems the dust extends to approximately the orbit of the hot companion. A large fraction of the radiation of the hot companion emitted towards the Mira is absorbed by dust thereby heating it and eventually breaking it up. Most of the ionized gas will be localized outside the companion's orbit, consistent with the observed N_e gradient and the fact that grain-forming elements are not depleted in the gas.

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REFERENCES

- Allen, D. A., 1981. *Mon. Not. R. astr. Soc.*, **197**, 739.
 Aller, L. H. & Czyzak, S. J., 1983. *Astrophys. J. Suppl.*, **51**, 211.
 Berrington, K. A. & Kingston, A. E., 1987. *J. Phys. B*, **20**, 6631.
 Blair, W. P., Stencel, R. E., Feibelman, W. A. & Michalitsianos, A. G., 1983. *Astrophys. J. Suppl.*, **53**, 573.
 Brocklehurst, M., 1972. *Mon. Not. R. astr. Soc.*, **157**, 211.
 Capriotti, E. R., 1964. *Astrophys. J.*, **140**, 632.
 Clegg, R. E. S., 1987. *Mon. Not. R. astr. Soc.*, **229**, 31p.
 Clegg, R. E. S. & Harrington, J. P., 1989. *Mon. Not. R. astr. Soc.*, **239**, 869.
 De Freitas Pacheco, J. A., Codina-Landaberry, S. J. & Lopes, D. F., 1989. *Astrophys. J.*, **337**, 520.
 Feldman, F. R. & MacAlpine, G. M., 1978. *Astrophys. J.*, **221**, 486.
 Ferland, G. J., 1986. *Astrophys. J.*, **310**, L67.
 Garstang, R. H., Robb, W. D. & Rountree, S. P., 1978. *Astrophys. J.*, **222**, 384.
 Grevesse, N., 1984. *Phys. Scr.*, **T8**, 49.
 Hayes, M. A. & Nussbaumer, H., 1986. *Astr. Astrophys.*, **161**, 287.
 Henry, R. B. C., 1989. *Rev. Mex. Astr. Astrofis.*, **18**, 81.
 Hummer, D. G. & Storey, P. J., 1987. *Mon. Not. R. astr. Soc.*, **224**, 801.
 Iben, I. & Renzini, A., 1983. *Ann. Rev. Astr. Astrophys.*, **21**, 271.
 Ipatov, A. P. & Yudin, B. F., 1986. *Astr. Astrophys. Suppl.*, **65**, 51.
 Kenyon, S. J., Fernandez-Castro, T. & Stencel, R. E., 1988. *Astr. J.*, **95**, 1817.
 Mendoza, C., 1983. In: *Planetary Nebulae, IAU Symp. No. 103*, p. 143, ed. Flower, D. R., Reidel, Dordrecht.
 Mueller, B. E. A. & Nussbaumer, H., 1985. *Astr. Astrophys.*, **145**, 144.
 Nussbaumer, H. & Schild, H., 1981. *Astr. Astrophys.*, **101**, 118.
 Nussbaumer, H. & Storey, P. J., 1981. *Astr. Astrophys.*, **99**, 177.
 Nussbaumer, H. & Schmutz, W., 1983. *Astr. Astrophys.*, **126**, 59.
 Nussbaumer, H. & Storey, P. J., 1984. *Astr. Astrophys. Suppl.*, **56**, 293.
 Nussbaumer, H. & Schmid, H. M., 1988. *Astr. Astrophys.*, **192**, L10.
 Nussbaumer, H. & Vogel, M., 1990. *Astr. Astrophys.*, in press.
 Nussbaumer, H., Schmutz, W. & Vogel, M., 1986. *Astr. Astrophys.*, **169**, 154.
 Nussbaumer, H., Schild, H., Schmid, H. M. & Vogel, M., 1988. *Astr. Astrophys.*, **198**, 179.
 Olliversen, N. A. & Anderson, C. M., 1982. In: *The Nature of Symbiotic Stars, IAU Colloq. No. 70*, p. 71, eds Friedjung, M. & Viotti, R., Reidel, Dordrecht.
 Peimbert, M. & Torres-Peimbert, S., 1983. In: *Planetary Nebulae, IAU Symp. No. 103*, p. 233, ed. Flower, D. R., Reidel, Dordrecht.
 Peimbert, M. & Torres-Peimbert, S., 1987. *Rev. Mex. Astr. Astrofis.*, **14**, 540.
 Robbins, R. R., 1968. *Astrophys. J.*, **151**, 511.
 Roche, P. F., Allen, D. A. & Aitken, D. K., 1983. *Mon. Not. R. astr. Soc.*, **204**, 1009.
 Schild, H., 1989. *Mon. Not. R. astr. Soc.*, **240**, 63.
 Schmid, H. M., 1989. *Astr. Astrophys.*, **211**, L31.
 Schmid, H. M., 1990. In: *The Physics of Classical Novae, IAU Colloq. No. 122*, eds Cassatella, A. & Viotti, R., Springer-Verlag.
 Seagquist, E. R., 1988. In: *The Symbiotic Phenomenon, IAU Colloq. No. 103*, p. 69, eds Mikolajewska, J. et al., Kluwer, Dordrecht.
 Seaton, M. J., 1979. *Mon. Not. R. astr. Soc.*, **187**, 73p.
 Shields, G. A., 1978. *Astrophys. J.*, **219**, 559.
 Smith, V. V. & Lambert, D. L., 1985. *Astrophys. J.*, **294**, 326.
 Smith, V. V. & Lambert, D. L., 1986. *Astrophys. J.*, **311**, 843.
 Storey, P. J., 1981. *Mon. Not. R. astr. Soc.*, **195**, 27p.
 Storey, P. J. & Hummer, D. G., 1988. *Mon. Not. R. astr. Soc.*, **231**, 1139.
 Tamura, S., 1988. In: *The Symbiotic Phenomenon, IAU Colloq. No. 103*, p. 285, eds Mikolajewska, J. et al., Kluwer, Dordrecht.
 Taranova, O. G. & Yudin, B. F., 1983. *Astr. Astrophys.*, **117**, 209.
 Taylor, A. R., 1988. In: *The Symbiotic Phenomenon, IAU Colloq. No. 103*, p. 77, eds Mikolajewska, J. et al., Kluwer, Dordrecht.

- Truran, J. W., 1985. *Proc. of the ESO Workshop on Production and Distribution of C, N, O Elements*, p. 211, eds Danziger, I. J. *et al.*, ESO conference and workshop proceedings No. 21.
- Viotti, R., 1988. In: *The Symbiotic Phenomenon, IAU Colloq. No. 103*, p. 269, eds Mikolajewska, J. *et al.*, Kluwer, Dordrecht.
- Webbink, R. F., 1988. In: *The Symbiotic Phenomenon, IAU Colloq. No. 103*, p. 311, eds Mikolajewska, J. *et al.*, Kluwer, Dordrecht.
- Williams, R. E., 1985. *Proc. of the ESO Workshop on Production and Distribution of C, N, O Elements*, p. 255, eds Danziger, I. J. *et al.*, ESO conference and workshop proceedings No. 21.
- Zeppen, C. J., Butler, K. & Le Bourlot, J., 1987. *Astr. Astrophys.*, **188**, 251.