

SYMBIOTIC STARS AND DUST

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SUMMARY

New members of the class of very high excitation symbiotic stars, with relatively strong lines of [Fe VII], have been found. The strong unidentified emission band at 6830 Å has been detected in two of these and its identification is discussed. There is a subgroup of high excitation objects which also emit near-infrared thermal radiation from dust grains and are distinguished by the properties of their emission-line spectra. It is proposed that the dust exists in neutral gas and that the optical and infrared spectra of this subgroup of symbiotic stars arise because they are radiation bounded either at their perimeter or around condensations.

INTRODUCTION

Very high excitation, high density emission spectra, typified, for example, by lines of [Ne V], [Fe VI] and [Fe VII], occur in a rather small number of galactic stars. Since some of these objects also exhibit the molecular bands of late-type stars, all have been classed as symbiotic. In the course of our spectroscopic programs on emission-line objects we have found a further set of stars having the same general emission spectra. In addition, many of these stars have infrared excesses attributable to hot circumstellar dust clouds. Previous surveys of symbiotic stars had revealed dust emission (in the 1- to 3- μ m region) in only V1016 Cyg and RX Pup (Swings & Allen 1972) and He2-104 and He2-106 (Swings 1973). In all other symbiotic stars the near-infrared continua are those of the late-type components (Swings & Allen 1972; Glass & Webster 1973). 1 to 3 μ m dust emission is, by contrast, very common in peculiar Be stars with low-excitation spectra (Allen 1973). Moreover, in the hotter Be stars the dust is constrained to lower temperatures (Allen & Penston 1973) so that, by extrapolation, no dust emission should be detected even at 3.5 μ m in the high-excitation symbiotic stars. Dust emission at longer wavelengths has been found in the symbiotic star Z And (Woolf 1973) and the G-type 'yellow symbiotic stars' (see Glass & Webster 1973).

OBSERVATIONS

The relevant infrared observations at 1.2–3.5 μ m have already been given by Allen & Glass (1974, 1975). We use them now only to distinguish two types of star, those with circumstellar dust (D type) and those with cool stellar continua (S type). The spectroscopic observations were made with the Cassegrain image-tube spectrograph on the 1.88-m (74-in.) Radcliffe telescope. We used three detectors in the course of the programme: (A) a spectracon covering 3200–5400 Å with a dispersion of 155 Å mm⁻¹; (B) the same spectracon when suffering from

TABLE I

Object	PK	HJD 2440000 +	Detector	Approx. $N_1/H\beta$	Radial velocity	Infrared type	HJD (i.r.) 2440000 +	Refs
He2-38	280-2°1	2186.3	C	3	+156 ± 20	D	1807	SSa
He2-104	315+9°1	2193.2	B	3	-105 ± 25	D	1807	JPS, SSb
He2-106	312-2°1	2184.4	C	6	+8 ± 20	D	1806	JPS
He2-177	326-10°1	2183.4	C	<1	-120 ± 10	S	1426, 1472	W, CH, GW
He2-171	346+8°1	2185.4	C	4	-83 ± 25	D	1811	SSb
H2-4	352+3°1	1896.3	C	0.3	-14 ± 25	S	1807	SSb
Th3-20	357+2°3	1896.4	C	0.3	+29 ± 25	S	1811	
H1-36	353-4°1	1803.6	2 × A	>10	-125 ± 5	D	2170, 2171	
		2183.5	C		-128 ± 20			
		2186.6	C					
H2-28	6+2°2	2193.6	B	1	+221 ± 25	D	1809, (1141)	SSb, MB
Ap1-8	2-3°1	1813.4	C	0.3	-114 ± 30	S	2172	SSb
H2-38	2-3°4	1804.6	A	2	-51 ± 10	D (+S)	2171	SSb
		2185.5	C		-36 ± 25			
Ap1-9	3-4°2	1812.5	B	≤1	—	S	1806	H, SSb
Ap1-10	3-4°1	1812.5	B	≤1	—	S	1811	H, SSb, Hof
Ap1-11	3-4°6	1812.6	B	≤1	—	S	1806	SSb
He2-390	5-5°2	2186.6	C	1	-16 ± 25	D	1811, 2171	SSb, CSV
Pe2-16	29-2°1	1896.4	C	≤1	+52 ± 25	S	1813	
V1016 Cyg		2287.4	H	3	-55 ± 30	D	1140*	MC, F

Notes and references:

* Also Harvey (1974), Aug 1969 to Sept 1972.

† 2430000 +.

CH Carlson & Henize 1974; CSV CSV 4026?; F FitzGerald 1971; GW Glass & Webster 1973; H Herbig 1969; Hof Hoffleit 1970; JPS Swings 1973; MB Merrill & Burwell 1950; MC Mammano & Ciatti 1974; SSa, b Sanduleak & Stephenson 1972, 1973; W Webster 1973.

a varying electronic focus, in which case a wide slit was used and no radial velocity determinations were made; and (C) a Carnegie image-tube covering 3200–7100 Å at 140 Å mm⁻¹. A spectrum of V1016 Cyg was obtained on the Isaac Newton telescope with an EMI image-tube and covered the spectral region 3300–6600 Å with a dispersion of 210 Å mm⁻¹ (code H).

Because the symbiotic stars were discovered in two separate programmes, they either lie near the galactic centre or have infrared colours of type D. They do not, therefore, provide an unbiased sample; for example, the D objects tend to be brighter than the S objects. The galactic distribution and radial velocities of the objects are similar to those of members of the old disc population. The stars on our programme which have high-excitation emission spectra are listed in Table I, and Table II presents a summary of their spectroscopic features. He2-177 and V1016 Cyg are included for comparison. Representative spectrograms are illustrated in Plate I.

3. VARIATIONS

Since as a class symbiotic stars vary in both magnitude and spectrum, we can discuss the relation between different parts of the spectrum only if they have been observed at the same time. The infrared measurements and the spectra described in this paper were obtained a maximum period of one year apart, and usually much less than that. Known characteristic time scales for variation of symbiotic stars are usually of the order of months or years. The N₁/Hβ ratio in He2-38 has apparently increased since the observations of Sanduleak & Stephenson (1972), reverting to about its 1965 value. The other objects for which we obtained more than one spectrogram or were able to compare with the references given in Table I have not changed in character. We shall therefore assume that no major changes occurred between the spectroscopic and infrared measurements. This assumption cannot be made in the case of symbiotic stars not observed by us and for which the literature contains no recent spectroscopic descriptions.

RX Puppis is an example of a star which has undergone a major spectral change. Published spectra, mostly taken in the 1940's, record very strong [Fe VII] and other high excitation emission lines (see Swings 1970). This situation had apparently changed radically by 1968 when Sanduleak & Stephenson (1973) recorded no He II and only very weak [O III]. Our recent spectrograms in the blue show the Balmer lines (with wide wings and absorption edges) and Fe II to be the strongest emission lines and offer no evidence of high excitation features.

4. LINE INTENSITIES

The He II λ4686 line is strong in all the objects, being comparable in strength to Hβ. From Table II it is seen that all also contain emission lines arising from ions with ionization potentials up to about 100 eV. If the mode of ionization of the gas is radiative, and there is no evidence from the line intensities to the contrary, it is clear that a very hot object is responsible for the ionization, e.g. a black body of about 2 × 10⁵ K.

A comparison between columns 5 and 7 of Table I indicates that the N₁/Hβ ratio is greater than 1 in those high excitation stars with dust (D) and less than 1 in those showing only a cool star in the infrared (S). We cannot reliably check this relation for stars outside the present sample because of the variability factor

TABLE II

The occurrence of ions represented in the spectrograms. A cross indicates that lines from the ion are present. The maximum ionization potential (I.P.) is quoted for the permitted lines and the minimum one for the forbidden lines

	Ion	I.P.	He2- 38	He2- 104	He2- 106	He2- 177	He2- 171	H2- 4	Th3- 20	H1- 36	H2- 28	Ap1- 8	H2- 38	Ap1- 9	Ap1- 10	Ap1- 11	He2- 390	Pe2- 16	V1016 Cyg
Permitted lines	H	13.6	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Fe II	16.2	x	?		x	x	x		?		x	x				x		x
	Si II	16.3	?			x						x					?		
	He I	24.6	x	x	x	x	x	x	x	x	x	x	x	x			x		x
	N III	47.4	x	x	?	x	x	x	x	x	Broad ?	x	x	x			x		x
	He II	54.4	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x
	O III	54.9	x	x		x	x	x	x	x			x	x			x		x
	C IV	64.5	Broad																x
	N IV	77.5					??										?		
	Forbidden lines	O I	0	x	?	x	x	x			x			x				x	
Fe II		7.9	x		x	x	x			x	x		x				?		x
S II		10.4	x	x	?	x	x			x	x		x	?			x		x
O II		13.6	x	x	x	x	x	x		x			x				x		x
N II		14.5	x	x	x		x	x		x				x			x		x
Fe III		16.1				x	x	x	?	x							x		x
F II		17.4								x									x
S III		23.3	x	x	x	x	x			x			x				x		x
Ar III		27.6	x							x							?		x

[illegible]

Notes to Table II

He2-38 Possibly appears non-stellar at the telescope.

The [O II] $\lambda\lambda 3726, 3729$ lines are in their high density ratio. HI-36

API-8 TiO bandheads are seen in absorption in the red and visible.

ApI-9 Strong blue continuum. The spectrum is consistent with Herbig's (1969) description if his spectrogram is weaker, as he does not mention the forbidden lines.

Apr-10 Strong blue continuum.

Pe2-16 The only line present apart from H and He II lines is a definite feature at 6083 Å which may be the [Fe VII] + [Ca V] blend at 6085.9 Å.

mentioned above, but we find no evidence of exceptions. The [O III] $\lambda 4363$ line is masked by the Hg $\lambda 4358$ sky line in many of the fainter S objects, but in general it appears to be weaker relative to H γ in the S objects than in the D ones.

This correlation leads us to think that the infrared excess is associated with the nebula rather than one or other star. Thus we do not favour an explanation of the infrared continuum based on free-free emission from the cool star's atmosphere as proposed for the NML Tauri stars by Gilman (1974).

Lines from low ionization states appear in most of the spectra. They are in general fainter than the high excitation lines and weak exposure of the spectrogram is apparently responsible for their absence in some of the spectra. The [O I] $\lambda 6300$ line is stronger than [Fe VII] $\lambda 6087$ in three D objects, and less than it in five D and five S objects.

[Ne V] $\lambda 3426$ has appreciable strength in nearly all the objects and the reddening is therefore unlikely to be extremely high.

5. THE 6830 BAND

A strong unidentified band at about 6830 Å is known in He2-177 (Webster 1973) and RR Tel (Thackeray & Webster 1974) and a strong emission line or pair of lines appears at times in the novae RS Oph (Dufay *et al.* 1964) and RT Ser (Swings 1970). Inspection of spectral tracings by Mammano & Ciatti (1974) shows that a feature at about 6830 Å appeared in V1016 Cyg in 1974 (and 1973?) and in HBV 475 in 1973. (A feature at 6825 Å in HBV 475 in 1972, together with conflicting wavelength measurements in novae may mean that we are dealing with more than one feature or with a varying emission mechanism.) A similar band is seen in our spectrograms of He2-38 and H2-38 and this allows us to discuss further the systematics of the band.

The band occurs only when the [Fe VII] lines are strong and, in addition, may be correlated with the presence of Fe II and [Fe II] lines. In He2-38 and H2-38 all these lines are seen. Whilst several of the other stars of our sample simultaneously contain Fe II and [Fe VII] without 6830, the [Fe II] lines are seen less frequently in them. Since the spectra of the two stars with 6830 are by a small amount the deepest of the series, and since the [Fe II] lines are very weak in all the stars, we cannot be certain whether this apparent correlation is merely an exposure effect. In the case of the slowly changing systems RR Tel and RS Oph, in which the evolution with time has been followed spectroscopically, the feature develops about the time that Fe II reappears in addition to [Fe VII]. The Fe II and [Fe II] lines apparently did not strengthen with 6830 in V1016 Cyg. The band is present in both stars with and stars without hot dust.

The identification of the feature has been a puzzle for some decades. In a previous paper (Thackeray & Webster 1974) we gave reasons for believing that Ca X (Dufay *et al.* 1964) was a likely origin for it. In discussions with Mrs J. E. Sinclair it was brought to our attention that a possible alternative, based on wavelength, is the A band of CaH which is present in absorption in M dwarfs. Since the CaH band is several hundred Angstroms wide, it would be necessary to invoke some mechanism which selects the 6830 Å region. Selection effects due to pre-dissociation are present in the emission spectrum of AlH in χ Cygni (Herbig 1956) and were seen in one spectrogram of V1016 Cyg (FitzGerald 1971). In support of the CaH identification is the occurrence of the band close to the time when the

S

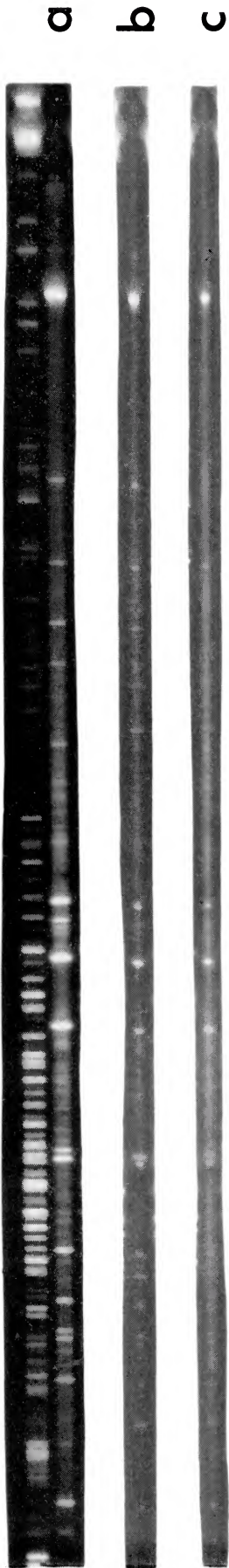


PLATE I. Representative spectrograms (Carnegie image-tube) of type S and type D symbiotic stars. The stars are (a) He2-177, (b) H2-4, (c) Ap1-8. (d) He2-38, (e) H1-36, (f) H2-38, (g) He2-390. The comparison arc flanking the outside spectra is copper-argon. Some of the emission features discussed in the text are marked.

[facing page 176]

low ionization features reappear. The much weaker B band of CaH is at 6385 Å. This wavelength region is confused by Fe II $\lambda 6383$ emission, but in H2-38, where the 6830 band is particularly strong, a weak, broad emission feature, stronger than we would expect Fe II to be, is possibly present at the right wavelength.

6. THE LOCATION OF THE DUST

Our main new result is the identification of a group of objects displaying strong [Fe VII] and other high-excitation lines together with infrared radiation between 1.2 and 3.5 μm which we presume to come from dust. Furthermore, that this group differs from the group of high-excitation stars without dust emission in the details of its spectral line strengths, in particular of the $N_1/H\beta$ ratio. It would be interesting to know why some objects have dust and not others, where the dust is located and when it is formed. We shall base our discussion of these questions chiefly on the following facts. First, the $N_1/H\beta$ ratio is greater than 1 in D objects and less than 1 in S objects. Second, the dust emission from one of the D objects, V1016 Cyg, varies with a period of 450 days as if it is heated by the variable star that was observed before the outburst (Harvey 1974).

In what follows we shall assume that all our symbiotic stars are binary systems, containing a cool giant star and a hot, subluminoous companion star which ionizes a surrounding nebula. This model is probable for several reasons. There is at least one symbiotic star in an eclipsing system, namely AR Pav (Mayall 1937; Thackeray 1954), and possibly a second, HBV 475 (Stienon, Chartrand & Shao 1974), and the binary nature of an eclipsing star is beyond doubt. Periodic radial velocity variations for many systems are indicative of binary motion (Boyarchuk 1969). Finally, an indirect line of argument concerns the similarity of symbiotic stars and slow novae to novae, which are accepted to be binaries (Kraft 1963). The possibility that some symbiotic stars are single systems cannot be excluded and Wood (1974) puts forward a plausible process for forming such systems, but there are no clear candidates for them.

The nature of its variation tells us that the heating of the dust emitting between 1 and 3 μm in V1016 Cyg is mainly by the cool star and not merely by direct radiation from the hot star or by Lyman α . Since the ionized gas has a high electron density and since heating by Lyman α is proportional to the square root of the electron density (Cohen & Barlow 1974), and also because the hot star has a luminosity comparable with that of the M star, the dust would be appreciably heated by the hot star and nebula if it were situated in ionized gas. The dust must therefore be located in neutral gas either as neutral condensations within the otherwise ionized region or outside the 'Strömgren sphere'.

Two main mechanisms exist for weakening the [O III] lines, collisional de-excitation in high density gas or ionization of O^{++} to other states. A low oxygen abundance does not alone generally weaken the lines since, as long as some O^{++} is present, the N_1 and N_2 lines are the main cooling agents and their strength is determined by the heating of the gas.

The density and temperature-dependent [O III] $N_1/\lambda 4363$ ratio indicates some collisional de-excitation in all the stars, but with no systematic difference between the S and D objects. In the S object He2-177 the $N_1/H\beta$ ratio dropped by a factor of two between 1965 and 1974, but the $N_1/\lambda 4363$ ratio remained

essentially unchanged. Other forbidden lines with low transition probabilities, [Ne v] for example, occur in both S and D objects, but they are very sensitive to the level of ionization. These facts indicate that a difference in electron density in the O^{++} zone is not likely to be responsible for the difference between the $N_1/H\beta$ ratio in S and D objects.

We may also consider a two-phase model in which a low density nebula produces forbidden lines and some Balmer emission, while a high density region has only H, He I, He II and other permitted lines. The $N_1/H\beta$ may then lie anywhere between its low-density value and zero. Such a model has been discussed for AR Pav (Thackeray & Hutchings 1974) and there is some indication that it applies to He2-177 (Webster 1973). However, by considering line ratios such as [O III] to [Ne v] and [Fe VII] it is clear that conditions in the low density region still differ from those in the dusty stars.

The ionization of oxygen to O^{+3} and higher states provides the natural explanation for the relative weakening of the [O III] lines in the S objects. Calculations of the ionization structure of a nebula around a blackbody star at about 2×10^5 K show that the O^{++} zone occupies only the outer 20% of its Strömgren radius. Thus if the nebula is density bounded the [O III] radiation will probably be weak. If neutral gas exists, so that the nebula is radiation bounded either around condensations or at the outer boundary, then O^{++} will occur near the neutral region and the [O III] lines will be enhanced. Comparable situations are seen in planetary nebulae except that the level of ionization is lower and the [O II] lines are enhanced in the outer regions and around condensations (Williams 1970).

It is thus clear that we can explain the correlation between the presence of [O III] lines and dust by the existence of neutral gas. The S objects can be identified with the homogeneous density-bounded situation whereas the D objects either have condensations or contain more material and are radiation bounded.

Several facts point to the presence of neutral condensations in the D objects. [O I] lines are seen in all of their spectra and rather more strongly than in the S objects (see Section 4). The best studied S object, He2-177, has weak [O I], [O II] and [O III], so it probably has some condensations. The characteristics of the dust radiation are consistent with the dust being contained in small regions. Nassau & Cameron (1954) and Mammano & Ciatti (1974) have shown that the M star in V1016 Cyg is oxygen-rich and not a carbon star so, if Gilman's (1969) model of dust formation is appropriate, the dust is likely to be silicates. Silicates emit at 10 and 20 μ m, but not in the 1–3 μ m region unless the dust is optically thick or the grains particularly large. If the dust exists in small condensations it can be optically thick without causing significant extinction in the visible region. We would expect a muted silicate feature in the 10–20 μ m spectra of the class D symbiotic stars.

Mammano & Ciatti (1974) and Baratta, Cassatella & Viotti (1974) have suggested that the dust was present in V1016 Cyg before its 1965 outburst and, indeed, H α has been observed before 1950 (Merrill & Burwell 1950) and may have arisen in a gas-dust cloud. One of the proposed mechanisms for forming condensations requires dust as a first stage (Capriotti 1971), so one might argue that the D objects are those in which the binary had ejected a pre-outburst gas cloud in which dust had condensed. On the other hand it is observed that dust forms in nova shells some time after visual maximum (Geisel, Kleinmann & Low 1970).

7. RELATION TO X-RAY SOURCES

Elliot & Liller (1972) have listed several reasons for believing that the nova phenomenon is related to X-ray emission from some galactic objects. The symbiotic stars are similar to the novae in so many respects that it is natural that we should consider whether they too are X-ray sources. The objects discussed in this paper, together with other very high excitation symbiotic stars, are the most likely candidates. In particular, the [Fe x] $\lambda 6374$ line is seen in He2-171 and possibly in H1-36, and this implies that a coronal-like temperature ($\sim 10^6$ K) exists somewhere in these systems. Two of the objects, He2-177 and H1-36 (Webster 1972, 1974), have already been suggested as weak X-ray emitters.

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