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Symbiotic stars: spectrophotometry at 3–4 and 8–13 μm

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Summary. We present infrared spectrophotometry of 20 symbiotic stars, mostly of the dust-rich variety. HDE 330036 is unique in showing an emission feature at 11.3 μm. The remainder combine a hot grey component and/or optically thin silicate emission. A model in which the grey component is due to optically thick silicate dust is not consistent with the spectra. We propose instead that iron-based grains, expected to form in the ejecta of cool stars, are heated by the ultraviolet radiation field of the hot companion.

1 Introduction

Symbiotic stars can be divided into two groups according to their 2–4 μm continua. About 25 per cent show colour temperatures of about 700–1500 K, whilst the remainder are typified by temperatures of 2500 K or more. The explanation generally accepted for this bimodality (e.g. Allen 1979) is that in the hotter objects we record primarily the photosphere of a star (usually a K–M giant) whilst in the cooler there is an an additional contribution from heated dust. Moreover, there are indications (Feast, Robertson & Catchpole 1977) that the dust-rich specimens are Mira variables, and field Miras are well known to generate circumstellar dust emission.

Data beyond 4 μm are generally sparse for symbiotic stars, and a number of outstanding questions remain to be answered, in particular:

(i) Mira variables and cool oxygen-rich giants release silicate grains (e.g. Woolf 1973). Do the dust-rich symbiotic stars exhibit the 10-μm emission peaks due to silicate grains?

(ii) Is there evidence for cool dust in those symbiotic systems which have no excess radiation at 4 μm. In particular, does optically thin silicate dust generate excess radiation only at 10 (and 18) μm in some systems?

(iii) Why is the dust generally hotter than in field Mira variables? (Feast *et al.* 1977).

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This paper reports spectroscopy of a number of symbiotic systems in the wavelength ranges 3–4 and 8–13 μm and addresses each of the three questions.

2 The observations

The observations were made on the 3.9-m Anglo-Australian telescope, with the exception of the 8–13 μm spectra of V1016 Cyg and CH Cyg which were taken on the 3.8-m UK Infrared telescope. The 8–13 μm spectra were mostly secured in 1981 July, using the cooled grating spectrometer of University College London. The instrument and observing protocol have been outlined in Aitken & Roche (1982). These data were supplemented in most cases by 3–4 μm spectroscopy taken at various times with the infrared photometer–spectrometer on the AAT. Additionally, broad-band infrared photometry exists in all cases and is listed in the compilation by Allen (1982). Because of the Mira-like variability of these stars it is not possible to relate observations made at different epochs to better than ~ 1 mag.

The principal interest in these data lies in the 8–13 μm spectra. The data at 3–4 μm are now briefly summarized. All but one of the observed continua are smooth and featureless showing a gradient in the 3–4 μm region consistent with the broad-band photometry though not always at the same flux level, because of source variations. Over the wavelength range 1–4 μm there is no evidence that the dust emission is anything but grey- (or black-) body, superimposed on the continuum of the cool star itself. The sole exception is HDE 330036, which shows narrow emission features between 3.2 and 3.6 μm. Its spectrum is reproduced in Allen *et al.* (1982).

Table 1. Stars observed.

Name	Spectral type	$(K-L)$	$[m_{10}]$	IP (eV)	2–13 μm spectrum	Silicate continuum	χ^2
AG Peg	M3	0.23	3.8	80	Photospheric	–	0.
V2416 Sgr	M5	0.35	3.9	90	Photospheric	–	0.
BI Cru	M	1.4	1.0	15	Smooth dust emission only	–	1.
He 2-104		2.1	1.8	50	Smooth dust emission only	–	2.
AS 210	G?		2.5	50	Smooth dust emission only	–	1.
He 2-390	M	2.2	3.1	60	Smooth dust emission only	–	1.
He 2-147	M8	0.12	2.3	30	Silicate + photospheric	1.9	2.
CH Cyg	M6	0.5	−2.8	20	Silicate + photospheric	1.3	1.
RX Pup	M5	1.4	−2.0	60	Silicate + smooth dust emission	1.4	2.
He 2-38	M	1.2	1.6	80	Silicate + smooth dust emission	0.5	1.
SS 38	M	2.0	1.9	100	Silicate + smooth dust emission	0.9	4.
He 2-106	M	2.1	0.2	100	Silicate + smooth dust emission	1.3	1.
He 2-127	M7	1.0	5.0	100	Silicate + smooth dust emission	0.4	0.
He 2-171	M	1.8	1.8	120	Silicate + smooth dust emission	2.1	2.
He 2-176	M7	0.6	3.1	70	Silicate + smooth dust emission	1.7	1.
H1-36	M	2.5	1.3	90	Silicate + smooth dust emission	2.6	2.
SS 122	M7		3.3	80	Silicate + smooth dust emission	1.0	0.
H2-38	M8	1.0	2.5	80	Silicate + smooth dust emission	3.7	2.
HM Sge	M	1.9	−1.2	80	Silicate + smooth dust emission	3.5	3.
RR Tel	M5	1.2	0.4	120	Silicate + smooth dust emission	1.2	2.
V1016 Cyg	M3	2.3	−0.1	100	Silicate + smooth dust emission	2.8	1.
HDE 330036	F–G	1.7	0.7	40	Narrow dust emission features	–	–

Notes
* Plus possible free–free excess.
† Fit with optically thick μ Cep curve.
‡ Fit with Trapezium silicate curve.

By contrast, the 8–13 μm spectra fall into three groups. Some are also smooth and grey; others show in addition the expected emission signature of silicate grains; and HDE 330036 is the sole member of a third group.

Table 1 lists the stars observed, some relevant parameters (from Allen 1982) and a summary of the present observational data. The 8–13 μm spectra were represented by the sum of a grey component and a standard silicate emissivity function from μ Cep (Russell, Soifer & Forrest 1975). Least-squares fits were made to the three parameters: temperature of the silicate dust, temperature of the grey body and relative proportions of the two. The latter is given in the form of silicate peak height to continuum ratio at 9.7 μm. A goodness-of-fit parameter, χ^2/n, is also given. The V1016 Cyg spectrum is new and of higher signal-to-noise ratio, but not substantially different from that given by Aitken, Roche & Spenser (1980).

For four stars (noted in Table 1), improved fits to the spectra are obtained either by adding a third parameter to the μ Cep component by allowing the emissivity curve to become optically thick ($\tau_{9.7} \sim 2$), or by substituting it with the emissivity function derived from the Trapezium in Orion (Gillett *et al.* 1975). Effects similar to increasing optical depths can be obtained by increasing the size of the emitting silicate grains (to a diameter of a few microns) which would then not require the large extinction implied by $\tau_{9.7} \sim 2$. Alternatively, it may be that the condensates are of a different chemical composition from those in μ Cep. For these four stars, the silicate/continuum ratio is not well related to the other stars.

The temperatures of the underlying grey continua obtained from the fits to the 8–13 μm spectra are very uncertain, both because of the latitude allowed in the fitting process and because the emissivity of the emitting grains may be wavelength-dependent. Replacement of the grey component with a λ^{-2} emissivity law, appropriate to optically thin emission from conducting grains, improves the fit to several objects somewhat and lowers the temperature of the smooth component considerably. In some objects, a steeper emissivity curve than the Rayleigh–Jeans tail of a blackbody appears to be required unless the λ^{-2} law is used. In V1016 Cyg, for instance, the λ^{-2} law improves the χ^2/n fit from 2.9 to 1.7 and allows the smooth dust component a reasonable temperature of 600 rather than > 2000 K.

The derived temperature of the silicate feature ranges from 200 to 600 K for the adopted value in μ Cep of 500 K. Thus the dust is generally cooler than in μ Cep and indeed than in most M giant systems.

3 Types of 8–13 μm spectra

3.1 HDE 330036

The 8–13 μm spectrum, reproduced in Fig. 1(a), shows the unidentified 11.3 μm feature in emission, together with a broad rise at the shorter end which can probably be identified with the 7.7-μm emission feature. Both are normally associated with carbon-rich dust (e.g. Aitken 1980), as indeed is the 3.2–3.6 μm emission seen in the shorter wavelength region. The underlying star is too hot to show TiO absorption and its C/O abundance ratio is currently indeterminate. The ultraviolet spectrum obtained by Allen & Penston (in preparation) shows abnormally intense [C III] and C IV emission lines relative to the other species and this suggests a high carbon abundance. HDE 330036 thus appears to be unique amongst dust-rich symbiotic stars in being carbon-rich. It would be of interest to analyse the C/O abundance ratio of the F–G component in HDE 330036 (assuming this to arise in a stellar photosphere rather than an accretion disc) in order to determine whether the carbon-rich material originates there or is donated by the second, hotter star in the system.

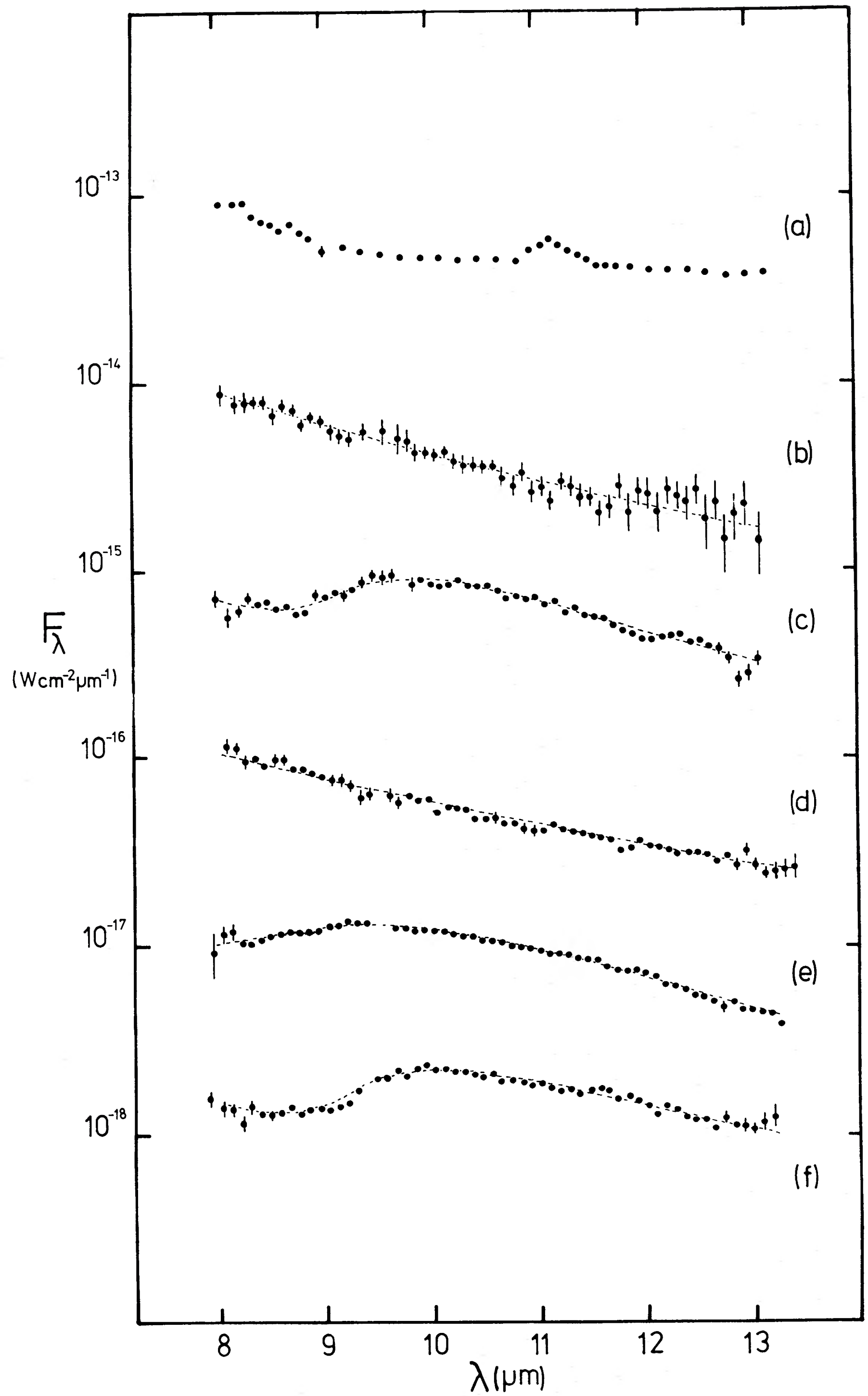

Figure 1. 8–13 μm spectra of some symbiotic stars: (a) HDE 330036 ×1000; (b) AG Peg ×1000; (c) He 2-147 × 50; (d) BI Cru; (e) He 2-106 ÷ 10; (f) H 1-36 ÷ 20. The dashed lines are the fits to the spectra (see text and Table 1). Error bars are one standard deviation of the mean and are shown where they exceed 5 per cent of the flux.

3.2 AG PEG AND V2416 SGR

These two stars have no hot-dust emission, and no evidence for optically thin silicate emission is seen in our spectra. The spectrum of AG Peg is shown in Fig. 1(b). The foma fit reveals a very cool silicate component in V2416 Sgr and a surprisingly low greybody temperature in AG Peg. Both of these reflect the presence of a weak excess at the longer wavelengths.

We attribute these excesses to free–free emission rather than to very cool dust. We are able to justify this in the case of AG Peg for which both Hβ intensities and radio data are available. By assuming a flux density of 10 mJy at 2 cm (Wright & Allen 1978) and a spectrum $F_\nu \propto \nu^{0.6}$ (Wright & Barlow 1975), we derive a contribution of a few per cent at 10 μm for the free–free emission. Using an equivalent width of 130 Å for Hβ (Allen 1979) and $V = 8.5$, we expect a 10–15 per cent contribution at 10 μm for optically thin free–free emission.

3.3 CH Cyg and He 2-147

He 2-147 was classified as dust-rich by Allen (1979, 1982) on the basis of a $K-L$ colour of 0.89 measured by Allen & Glass (1974), but a recent measurement of $K-L'$ gave 0.12 ± 0.04. Observations at J, H and K show no variations in excess of about 0.1 mag, so the 2–10 μm colour derived from the spectrum is thought to be reliable. Given the very late spectral type of the star and the likelihood of a little interstellar reddening, the 2–10 μm colour leaves no room for an additional grey dust component. The earlier $K-L$ value must either be a measurement error or indicate the intermittent presence of a dust shell.

The 8–13 μm spectrum shows a strong silicate emission feature (Fig. 1c). Thus He 2-147 is evidence that optically thin silicate dust can be found without the hotter grey component. The low-excitation symbiotic-like system CH Cygni is a second such example, as suggested by Bopp (1981).

3.4 BI Cru, AS 210, He 2-104 and He 2-390

These four stars show hot grey continua from dust without an additional silicate component. BI Cru (Fig. 1d) and He 2-390 certainly contain visible M stars, so the absence of silicate features is surprising. When a silicate dust shell becomes optically thick and radiates significantly at wavelengths as shorts as 3 μm, the silicate feature is transformed from emission to absorption (Jones & Merrill 1976) and structure in the 8–13 μm region can be weak. We have, however, been unable to fit these spectra with any absorption optical depth and acceptable fits are only obtained with a dominant contribution from featureless material. A more likely source for the hot grey component is iron, shown by Lewis & Ney (1979) to be an important condensate in the environment of the M star.

In AS 210 the underlying star appears to be of type G. This is a very early type to shed an optically thick shell of dust. We cannot rule out the existence of an obscured, cooler star in this system, in which case the G-type spectrum may originate in a disc or wind surrounding the companion.

3.5 The remainder

Silicate emission features are clearly seen in the remaining 13 objects observed (Fig. 1e, f). In all, however, there is an additional hot, grey component. The silicate dust shell models of Jones & Merrill (1976) do not simultaneously predict a 10-μm silicate emission peak and a cool continuum at wavelengths as short as 2–3 μm. Since we find evidence that a continuum component can exist in the absence of silicate emission, and vice versa, we seem forced to accept that the dust lies in two components or domains.

The intensity of the silicate emission feature might be expected to correlate with some other parameter in symbiotic stars. We have found no correlation with any of the following observables:

$H-K$ or $K-L$ colour index
Type or range of optical variability
2-cm flux density
Electron density
Intensity of the unidentified λ 6830 band
Equivalent width of Hβ.

If any correlation exists with the spectral type of the M star, it is masked by the large uncertainty of most spectral types.

Although no quantitative correlation exists betwwen silicate strength and degree of ionization of the optical emission spectrum, it is apparent that the combination of silicate emission and a grey component is restricted to those dust-rich symbiotic stars of higher excitation. Specifically, for an ionization potential (as defined by Allen 1979) $\lesssim 60$ eV at the time of observation, only single-component dust emission is seen. This probably indicates a weakening of the silicate intensity at lower excitation, so that the silicate feature is seen only when the grey component is absent.

4 Discussion

In view of the hostile environment of the hot component in symbiotic stars, we expect the genesis of dust to occur near the cool component. In these systems the cool component is normally oxygen-rich; we do not therefore expect graphite grains to form.

Observations of late-type O-rich giants (Merrill & Stein 1976), and in particular μ Cep (Russell *et al.* 1975), demonstrate that the silicate grains formed in their circumstellar shells radiate very little at wavelengths less than 8 μm. The problem that presents itself in the symbiotic stars is the combination of silicate emission with a featureless, hot-dust emission component. Either the dust grain composition or the dust heating must differ in symbiotic systems from M giants.

In this respect the symbiotic stars parallel those O-rich H II regions and planetary nebulae (e.g. Aitken & Roche 1982) wherein a cool, grey continuum accompanies the silicate emission. Such emission systems usually exhibit a Trapezium-like silicate feature. The symbiotic stars appear to be an intermediate population in which the majority show silicates of the variety found in O-rich giants, whilst a few are Trapezium-like. Moreover, the grey dust component is somewhat warmer, so that typical $K-N$ values are about 2 mag smaller than in planetary nebulae.

Symbiotic stars differ from M giants and planetary nebulae in the presence of an extremely hot ($\gtrsim 10^5$ K) companion star emitting an intense ultraviolet radiation field. Small conducting grains, with absorption efficiencies $Q \propto \lambda^{-2}$, will attain higher temperatures in this field than will silicate grains (*cf.* Dwek *et al.* 1980). Suppose that conducting grains are a minority component of the dust. Close to the M star, emission from silicate grains would dominate, whilst in a more extended region heated by the hot companion, only the conducting grains would reach temperatures high enough to emit significantly in the near infrared. Grains of iron-based materials are suitably conducting, and are expected to condense (Lewis & Ney 1979). The non-appearance of the hot grey component in isolated M stars is readily explained by the absence of a source of ultraviolet radiation. The presence of a cooler grey component in planetary nebulae requires only a relatively weak ultraviolet field, and the stronger grey continuum in symbiotic stars is a natural result of the presence of the hot star.

Further evidence that the influence of the hot star extends into the giant's circumstellar envelope is afforded by the fact (noted above) that the balance between the two components of the dust is a function of the excitation of the hot star. We presume that the condensation equilibrium for the grains is influenced by the ultraviolet radiation field. Naively we expect an intense ultraviolet field to decrease the likelihood of formation of conducting grains compared to silicate grains. This action might explain the increased prominence of silicate emission at high excitation. The situation is further complicated, however, if the ultraviolet flux itself is dictated by the mass-transfer rate from the cool to the hot star, which in turn will have some dependence on the mass-loss characteristics of the cool star.

In RR Tel, studies of the infrared variability (Feast *et al.* 1983) provide independent evidence that some heating of the dust is caused by the hot companion.

An alternative model that we have considered involves only silicate grains. If the M giant were to produce an optically thick shell of silicates, that could provide the grey component to the dust. Heating of the outer parts of that shell by the hot companion star might then generate the silicate emission. Attempts at modelling the 8–13 μm spectra by the addition of optically thick absorption and optically thin emission do not yield satisfactory fits. We therefore reject this model.

The symbiotic stars appear to be intermediate between M giants and O-rich planetary nebulae in a second respect, namely the non-detection of fine-structure transitions in the 8–13 μm spectra ([Ne II], [Ar III], [S IV]). Suitable ionization stages are always present in the optical spectra to favour at least one of these lines, and one or more of these lines are invariably seen in the 8–13 μm spectra of planetary nebulae (Aitken & Roche 1982). Their absence is almost certainly due to the high electron densities present in these stars (e.g. Allen 1979).

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