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UNUSUAL FEATURES OF THE 1–4 MICRON SPECTRUM OF HR 4049

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ABSTRACT

Moderate resolution spectra from 1.05 to 3.65 μm of the post–AGN star HR 4049 show a number of features indicative of intense mass loss and unusual circumstellar chemistry. These are deep Brackett series absorption lines to rather high n states, emission in the 3.29 and 3.40 μm "dust" features, and the rarely occurring emission features near 3.5 μm. HR 4049 is only the third star in which the 3.5 μm features have been reported; the other two stars are pre–main-sequence objects. The physical and chemical conditions for the production of the (unknown) molecule responsible for this emission appear to be highly constrained.
Subject headings: infrared: spectra — interstellar: grains — molecular processes — stars: individual (HR 4049) — stars: mass loss

I. INTRODUCTION

The high-latitude star HR 4049 (B9.5 Ib) has come under considerable scrutiny during the last few years because of its peculiar abundances, as derived from optical and near-infrared spectroscopy (Abt 1984; Waelkens, Lamers, and Waters 1987) and because of its large infrared excess (Lamers *et al.* 1986). It is now generally thought that HR 4049 is a low-mass star, undergoing a high and variable rate of mass loss and evolving into a planetary nebula. In the extended stellar atmosphere the products of He-burning (particularly C, O, and N) are exposed (Lamers *et al.* 1986; Lambert, Hinckle, and Luck 1988). Although the ratio C/O is not known reliably, the high dust temperature is suggestive of carbonaceous dust.

II. OBSERVATIONS

Reports that HR 4049 possesses some of the well-known infrared "dust" emission features (Waters *et al.* 1988) stimulated us to observe its 3 μm spectrum from the United Kingdom 3.8 m Infrared Telescope, with its common-user seven-channel grating spectrometer, on 1988 April 7. Our initial spectrum revealed, in addition to the 3.29 μm feature, a somewhat weaker emission peaking at 3.53 μm. Subsequent L-band spectra, obtained on 1988 April 23 and 24, have been combined with the original spectrum; the result is shown in Figure 1. Further spectra, in the J, H, and K bands, were obtained on 1988 April 25, also with the grating spectrometer. The H-band spectrum is shown in Figure 2. Spectra in the H, K, and L bands were repeated on 1989 January 26 and 27. The J-band (1.02–1.50 μm) and K-band (2.0–2.5 μm) spectra, obtained at resolving powers of ~300 and ~700, respectively, are featureless to within the noise level (~1% of the flux in a resolution element) and are not shown here.

All spectra were obtained in a 5″ aperture and with chopper throws of 30″–45″ (EW). They were divided by spectra of the stars BS 3871, SAO 179514, and SAO 179668. For flux calibration in Figures 1 and 2, BS 3871 was assumed to have a temperature of 6200 K and broad-band fluxes given by Bailey *et al.* (1981). Flux calibration is thought to be accurate to ±10%.

III. DESCRIPTION OF SPECTRA

The strongest emission in the 3 μm spectrum (Fig. 1) is from the familiar 3.29 μm feature. Its peak wavelength agrees to within the uncertainties with those of brighter features seen in many UV-excited nebulae. Its deconvolved width (FWHM = 0.030 μm) may be somewhat narrower than "normal" (as in HD 44179; see Tokunaga *et al.* 1988). A narrow emission feature at 3.40 μm, which usually is associated with 3.29 μm emission, is also present. The profile of the 3.53 μm emission feature in HR 4049 (Fig. 1), with its distinctive shoulder extending to short wavelength, resembles the 3.53 μm feature in the two other objects in which it has been detected (e.g., Baas *et al.* 1983). The weak satellite feature, at ~3.43 μm, is also discernible in HR 4049, when a linear baseline is fitted to the L-band spectrum (Fig. 1).

In the H-band spectrum, at least seven absorption lines from the Brackett series are detected; these range from 13–4 at 1.611 μm to 19–4 at 1.526 μm. Presumably these lines are considerably deeper than observed here, at a resolution of ~600 km s^{-1}. Other features shortward and longward of these lines (in particular, in the 1.49–1.52 μm and 1.62–1.75 μm intervals) may also be present but are difficult to identify because of limitations of spectral resolution, low equivalent width, and signal-to-noise ratio. High-resolution spectra of Hα in HR 4049 by Waelkens, Lamers, and Waters (1987) reveal a complicated and variable line profile, with absorption partially filled in by emission. Spectra of the Brackett lines at similar

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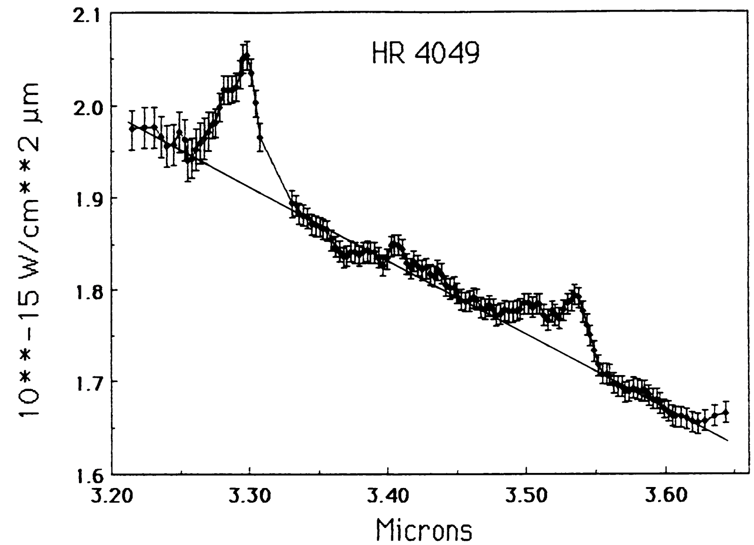

FIG. 1.—Spectrum of HR 4049 from 3.20 to 3.65 μm. The spectrum has been Hanning-smoothed to a resolution of $\sim$0.009 μm. Error bars are $\pm 1\ \sigma$. The straight line denotes the assumed continuum level.

resolution are probably needed in order to understand them. Waelkens, Lamers and Waters (1987) find that the Balmer absorption lines in HR 4049 are formed in an extended atmosphere, and hence we suspect that the Brackett lines in the *H*-band spectrum originate from the same region.

In the spectra of the *H* and *L* bands obtained in 1989 January, all of the features mentioned above appeared at approximately the same strengths as in 1988 April and no new features were seen.

IV. DISCUSSION: THE 3 MICRON EMISSION FEATURES

HR 4049 is only the third star in which the 3.5 μm emission features have been detected. Previously, they have been seen in HD 97048 and Elias 1 (Taurus Dark Cloud) (Blades and Whittet 1980; Whittet *et al.* 1983; Whittet, McFadzean, and Geballe 1984). Comets Halley and Wilson also exhibited emission peaks near 3.5 μm (Baas, Geballe, and Walther 1986; Brooke *et al.* 1989), although the overall shapes of their emissions were different.

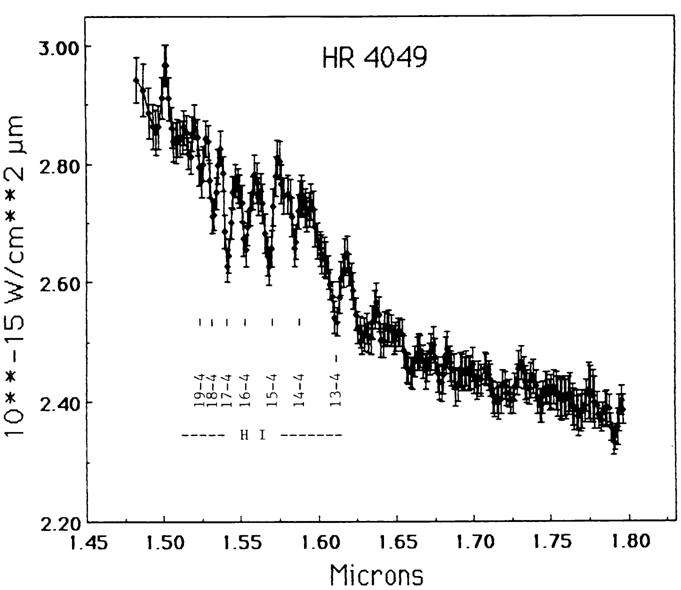

FIG. 2.—Hanning-smoothed spectrum of HR 4049 from 1.48 to 1.80 μm. Resolution is $\sim$0.0040 μm. Brackett series lines are indicated.

HD 97048 and Elias 1 have similarities with HR 4049, namely spectral types close to A0, and infrared continuum emission from circumstellar dust grains at characteristic temperatures 1200–1500 K. However, a fundamental difference is the fact that HD 97048 and Elias 1 are both young (classified as Herbig Be/Ae stars—see, e.g. Finkenzeller and Mundt 1984), whereas HR 4049 is evolved. Speckle interferometry by Roche, Allen, and Bailey (1986) has demonstrated that, at least in the case of HD 97048, the 3.5 μm feature–emitting material is refractory, surviving at temperatures >1000 K, and cannot be a volatile product of the molecular cloud out of which the star formed. That the same (or very similar) material is also detected in an object which is highly evolved strongly suggests that the material is manufactured in the circumstellar environments, not only of HR 4049, but of the two young objects as well.

Clearly, it is important to understand how the physical and chemical conditions of these three objects differ from the vast majority of circumstellar environments, which, in the presence

TABLE 1

WAVELENGTHS (μm) OF 3 MICRON FEATURES

HR 4049	HD 97048	Comet Halley
3.300 ± 0.005	3.28 ± 0.01	3.285 ± 0.005
		3.36 ± 0.01
3.405 ± 0.005	3.413 ± 0.005	3.405 ± 0.005
3.435 ± 0.010	3.435 ± 0.005	3.44 ± 0.01
3.50 ± 0.01	3.50 ± 0.01	...
3.535 ± 0.005	3.534 ± 0.005	3.52 ± 0.01

NOTE.—Wavelengths are from spectra published by Blades and Whittet 1980; Baas *et al.* 1983; Baas, Geballe, and Walther 1986; and this *Letter*.

of sufficient ultraviolet radiation, produce detectable levels of emission by the 3.29 μm feature and its family, but no hint of the 3.53 μm feature. The 3.29 μm feature, which is due to the fundamental CH stretching vibration, and its family, are widely attributed to emissions from polycyclic aromatic hydrocarbons and related molecules, either as free molecules or in clusters (grains), that are produced in carbon-rich (i.e., $C/O > 1$) environments (Duley and Williams 1981; Leger and Puget 1984; Sakata *et al.* 1984; Allamandola, Tielens, and Barker 1985). In the case of HR 4049, this material must be produced *in situ*, as the star is located at a high Galactic latitude and has very little foreground extinction. The fact that the 3.29 μm feature is also observed in oxygen-rich environments, such as compact H II regions, implies that these molecules are all-pervasive in the interstellar medium, as has been proposed by many authors, but it also might indicate that they can form to some extent in oxygen-rich regions. The presence of weak 3.29 μm emission in Elias 1 and HD 97048 also suggests that the latter may be true. However, Frenklach and Feigelson (1989) argue that PAH production requires a highly specialized circumstellar environment, in terms of both physical conditions and chemical composition, and conclude that the carriers of the 3.29 μm feature and its family may originate in a relatively small fraction of carbon-rich red giants. Thus, it may be that the 3.29 μm features in HD 97048 and Elias 1 arise in ambient interstellar material distributed around these stars, while their 3.5 μm features are due to material that was either formed or reprocessed in their circumstellar shells. An important test would be provided by high angular resolution observations of both features in these stars (see Roche, Allen, and Bailey 1986), to investigate whether they are similarly distributed.

As HD 97048 and Elias 1 are young stars, the carrier of the 3.5 μm features in them presumably forms in oxygen-rich environments. In HR 4049, C/O is unknown, but probably is close to unity (Lambert, Hinckle, and Luck 1988). We note that no molecular spectral features characteristic of carbon stars (e.g., the C_2 band head at 1.78 μm) appear in our spectra. However, in view of the strong UV radiation field close to the star, this negative result does not necessarily imply $C/O < 1$, as such molecules may be nearly completely dissociated. In addition, based on the three objects in which the 3.53 μm feature is detected, it appears that a spectral type very close to A0 is necessary for the presence of the 3.5 μm features. Thus, there may be an environmental link between HR 4049 and the two pre–main-sequence stars (regardless of evolutionary status). In contrast, the Red Rectangle, which in evolutionary terms is more similar to HR 4049 and is also powered by a star of spectral type close to A0, has a strong 3.29 μm feature but no trace of the 3.53 μm feature (e.g., Geballe *et al.* 1989). The Red Rectangle probably has $C/O \gg 1$ (e.g., based on the correlation between intensity of its 7.7 μm feature and its total far-infrared luminosity; Cohen *et al.* 1986). Thus it may be that only the simultaneous presence of an intense, but relatively soft, UV field, coupled with a high-density oxygen-rich (or at least not overly carbon-rich) environment, leads to the kind of photochemistry which produces the 3.5 μm feature–emitting molecules in detectable numbers. Van der Zwet *et al.* (1985) suggest that the 3.53 and 3.43 μm features may arise from aldehydic (CHO) groups, attached to aromatic rings. Because of the relative intensities of the 3.53 and 3.29 μm features, this would imply in the cases of HR 4049 and Elias 1 that roughly equal numbers of aldehydic groups and bare H atoms are attached to the carbon rings, and in HD 97048 that the aldehydic groups are dominant.

It also is worth speculating about a possible connection between the chemistry occurring in mass-loss objects such as HR 4049, HD 97048, and Elias 1, and the organic grains that are present in comets. The several spectral coincidences listed in Table 1 suggest that at least some of the 3 μm emission features from comets are from molecules that are similar in nature to those being formed around these stars. Additional 3 μm features, most notably the 3.4 μm absorption seen toward the galactic center (e.g., Butchart *et al.* 1986) are also at least superficially similar to some of those seen in comets. Whether these comparisons provide evidence that comet grains are an averaged remnant of interstellar grains formed in a variety of circumstellar and interstellar environments is open to debate and further investigation.

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