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THE INFRARED SPECTRA OF CRL 618 AND HD 44179 (CRL 915)

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ABSTRACT

Spectrophotometry from 4 to 8 μm is reported for the infrared sources CRL 618 and HD 44179 (CRL 915). In addition, 2–4 μm spectrophotometry of CRL 618 is reported. Except for marginal detection of emission lines at 2.1 and 2.45 μm, the spectrum of CRL 618 is featureless, consistent with graphite being the major constituent of the circumstellar dust cloud. Strong emission bands at 6.2 μm and 7.7 μm are found in the spectrum of HD 44179. These bands have been observed previously in NGC 7027 and M82. No positive identification of these bands is made.

While both objects probably represent advanced stages of stellar evolution, the substantial differences between CRL 618 and HD 44179 suggest that they are members of different evolutionary sequences.

Subject headings: infrared: sources — infrared: spectra — stars: individual

I. INTRODUCTION

Recent infrared, optical, and radio observations (see Zuckerman *et al.* 1976 for a review) have suggested that many bright infrared sources are at intermediate stages of stellar evolution between red giants and planetary nebulae. The distinguishing feature of these sources is their association with a visible reflection nebula. The usual model for such objects consists of a central evolved star surrounded by a disk of gas and dust that often obscures the star from view. Scattering of light from an extensive halo of circumstellar material produces the reflection nebula. If correct, this model has interesting applications for this stage of stellar evolution and for the resulting chemical abundances of interstellar matter. We report here infrared spectroscopy of two of these sources, CRL 618 and CRL 915 = HD 44179. Both were originally discovered in the AFCRL sky survey (Walker and Price 1975) and may belong to the evolutionary sequence suggested by Zuckerman *et al.* (1976).

CRL 618 was observed in detail by Westbrook *et al.* (1976), who found the infrared source to be located between two optical nebulosities. The spectra of the optical nebulae indicated that they are reflection nebulae; the central illuminating star was estimated (Westbrook *et al.*) to be of spectral type ~B0. The infrared source was interpreted as a dust cloud that obscures the exciting star from direct view. From the size of the infrared source and the apparent color temperature, Westbrook *et al.* estimated the 10 μm optical depth to be ~0.3; however, the errors in the source size allow $\tau \gtrsim 1$. The 8–13 μm spectrum of CRL 618 was found to be featureless and to fit a 275 K blackbody comparatively well.

CRL 915/HD 44179 was investigated in detail by Cohen *et al.* (1975, hereafter CAZ), who named it the "Red Rectangle." Further optical observations of this object were reported by Greenstein and Oke (1977). Morphologically, this is extremely similar to CRL 618—an infrared source centrally located in a biconical reflection nebula. CAZ suggest that the spectrum of the nebulosity indicates that the spectral type of the central star is B9–A0. However, Greenstein and Oke point out that the spectral type is not easily evaluated and could range from late B to F. The color temperature of the infrared source is ~500 K, and there is no size information on the infrared source except that the diameter $\theta \lesssim 4''$. The appearance in the infrared spectra of several strong emission bands, interpreted by CAZ as being due to resonance bands in dust particles, suggests that the emission is not optically thick. Greenstein and Oke report a remarkably strong emission band at 0.658 μm in the spectrum of the reflection nebula. They interpret this as being due to a strong peak in the reflectivity of the dust in the nebula.

The data reported here are spectrophotometric observations from 4 to 8 μm of these two interesting infrared sources. These observations were made in 1976 November using the 0.9 m telescope of the Kuiper Airborne Observatory flying at ~12.5 km altitude. In addition, we report a 2–4 μm spectrum of CRL 618 obtained at the Mount Lemmon Observatory.

II. THE OBSERVATIONS

The 4–8 μm observations used the filter-wheel system described by Russell and Soifer (1977) with a Si:As detector. The spectral resolution was $\Delta\lambda/\lambda \approx 0.015$, the observing aperture for these observations was 28″, and the chopper amplitude was ~42″. The star α Tau, observed as a calibration standard, was assumed to have a blackbody spectrum at the temperature of 3800 K, except that allowance was made for CO absorption near 5 μm determined from broadband measurements (Forrest 1974).

The 2–4 μm observations of CRL 618 were obtained in 1976 March and September with the system described by Merrill, Soifer, and Russell (1975). The spectral resolution was $\Delta\lambda/\lambda \approx 0.02$. A 17″ focal plane aperture and a 30″ chopper amplitude were used.

a) *CRL 618*

The 2–13 μm spectrum of CRL 618 is shown in Figure 1. The spectrum of CRL 618 is remarkably featureless, following quite closely the 275 K blackbody curve estimated by Westbrook *et al.* (1975) from their spectral and broad-band observations. There is an excess over the blackbody emission at shorter wavelengths, suggesting that a range of temperatures is present.

The only spectral features of apparent significance are possible emission lines at 2.12 and 2.45 μm. Both lines appear as roughly 3 σ deviations from the continuum and cannot be claimed to be positive detections. Further observations to confirm these lines are essential. If these are real lines, the best identifications are with vibration-rotation lines of H_2 that have been previously detected in the BN source (Gautier *et al.* 1976) and NGC 7027 (Treffers *et al.* 1976). A molecular cloud is known to be associated with this source (Lo and Bechis 1976). No discussion of H_2 is warranted, pending confirmation of its detection.

b) *HD 44179*

The 2–13 μm spectrum of HD 44179 is shown in Figure 2. The 8–13 μm data are taken from CAZ and

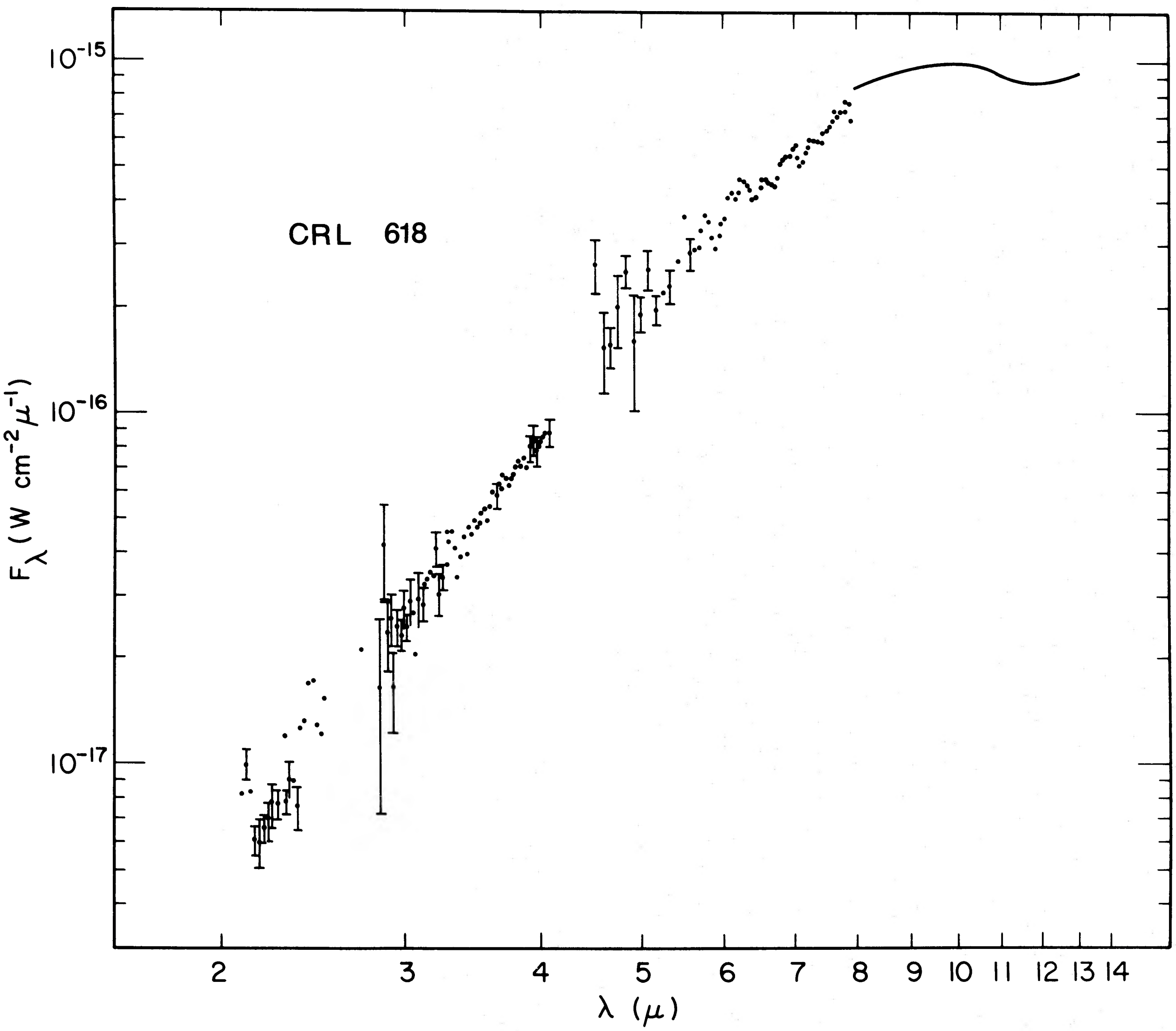

FIG. 1.—The 2–13 μm spectrum of CRL 618. The 2–4 μm data were obtained from Mount Lemmon and the 4–8 μm data from the KAO. Data from 8–13 μm were taken from Westbrook *et al.* (1975), who used a 22″ aperture for their observations. Statistical uncertainties ($\geq$ 8%) are plotted in the figure.

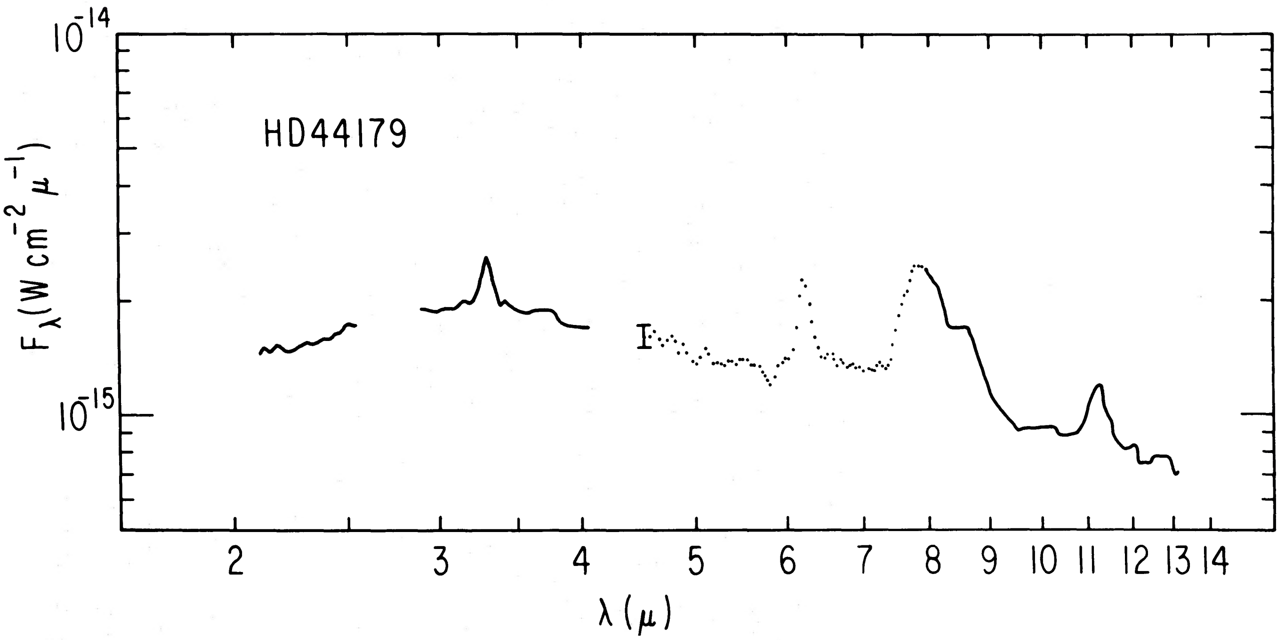

FIG. 2.—The 2–13 μm spectrum of HD 44179 (CRL 915). The 4–8 μm data were smoothed by averaging adjacent points—a typical statistical error is shown on the first data point. The shape of the 2–4 μm data, obtained with a 17″ aperture, was taken from Russell, Soifer, and Merrill (1977), and the level was normalized to the 2.28 μm broad-band flux level measured from the KAO. The ~20% lower level of the airborne data compared with the ground-based data may have been due to the presence of a faint star in one reference beam during the airborne observations. The 8–13 μm data, obtained with a 22″ aperture, were taken from Cohen *et al.* (1975), with no adjustment of the level.

the 2–4 μm spectrum is taken from Russell, Soifer, and Merrill (1977). The 4–8 μm portion of the spectrum shows a very strong continuum and two emission features that are well above the continuum at 6.2 and 7.7 μm. Both of these bands have been observed in the 4–8 μm spectra of NGC 7027 (Russell, Soifer, and Willner 1977) and M82 (Willner *et al.* 1977). The origin of these bands is discussed below.

The strong continuum emission of HD 44179 is most easily interpreted as thermal emission by circumstellar dust (CAZ). This emission is broader than that from a single temperature blackbody and suggests a significant range of temperatures in the dust cloud. The fact that this range of temperatures is detectable requires either that the dust cloud be optically thin throughout the infrared, or that an optically thick disk be viewed nearly face-on. CAZ interpret the polarization observations as requiring that the dust disk be viewed nearly edge-on, which seems to rule out the optically thick cloud. Further support for the optically thin estimate comes from the appearance of the spectral features. The line-to-continuum ratio for these bands is much less in HD 44179 than in M82 or NGC 7027, and yet the shapes are so similar as to be indistinguishable at our resolution. This is most easily understood if the emission in HD 44179 is optically thin.

The angular size of the cloud can be estimated from the assumption that the brightness temperature is no higher than the color temperature $T_c \approx 500$ K. This requires that the angular diameter be greater than 0.1″. The diameter of the cloud should be larger than this, because the geometry is highly nonspherical and the cloud appears to be optically thin. Indeed, the size of the infrared source should be extremely wavelength-dependent, because the heat source is the central star. Angular size measurements of HD 44179 at 2 μm and 10 μm with spatial resolution less than 1″ would be extremely valuable in determining the characteristics of the dust cloud.

III. DISCUSSION

a) *Spectral Features*

The spectral features found in HD 44179 at 6.2 μm and 7.7 μm have previously been found in the spectra of NGC 7027 and M82. These bands, along with those at 3.3, 8.7, and 11.3 μm are common to all three objects. Many other sources, such as CRL 437 (Kleinmann *et al.* 1977), NGC 253 (Gillett *et al.* 1975), and CRL 3053 (Gillett, Joyce, and Merrill 1978), have been found to possess the 3.3 μm, 8.7 μm, and 11.3 μm bands and a spectrum sharply rising to short wavelengths at 8 μm, suggestive of the peak at 7.7 μm. It is therefore likely that the 6.2 μm and 7.7 μm bands are common to these objects as well.

Russell, Soifer, and Willner (1977) and Willner *et al.* (1977) have suggested that the wide range of temperature, density, and excitation conditions under which these bands are observed argue for resonances of some sort in the dust that is present in these objects. The hypothesis of solid-state bands has the drawback that the materials that produce the bands are unknown. Gillett, Forrest, and Merrill (1973) suggested that the 11.3 μm band is produced by thermal emission from small carbonate dust grains. This identification predicts a much stronger band centered at about 7.0 μm. From the relative strengths of the 7.0 μm and 11.3 μm bands in laboratory carbonates and the upper limit of 2×10^{-16} W cm^{-2} μm^{-1} on any 7 μm feature in HD 44179, the upper limit on the temperature for such grains would be $T_{\text{carbonates}} <$ 200 K, a result that seems to be in substantial disagreement with the color temperature of this source. Although the observed 7.7 μm band has the correct strength to be the predicted carbonate 7.0 μm band, the substantially longer wavelength is extremely difficult to reconcile with this identification.

The 6.2 μm band could be the sought-after shorter wavelength resonance of carbonate grains, produced by a population of extremely oblate grains (Gilra 1977; Huffman 1977). Such a uniform population of purely oblate grains in the wide variety of astrophysical environments represented by HD 44179, NGC 7027, and M82 is very difficult to understand. We therefore regard the previous identification of the 11.3 μm feature with carbonate grains as unconfirmed.

Nitrates have a strong band, with a shape similar to that of the carbonate 7.0 μm band, centered at about 7.5 μm. Nitrates also have a strong, narrow band at 11.95 μm. There is little or no evidence for such a feature in the 10 μm spectrum of HD 44179, and no evidence for such a band in NGC 7027. We therefore regard the identification of the 7.7 μm feature with nitrates as unlikely.

The 6.2 μm feature is another strong, partially resolved band that appears in the spectrum of HD 44179, NGC 7027, and M82. The agreement in wavelength of this feature among the three sources is better than 1%. The variety of physical conditions under which it is found argues for a solid-state resonance. There is wavelength agreement with a narrow water-of-hydration band (Hunt, Wisherd, and Bonham 1950; Nyquist and Kagel 1971); however, we regard this as an unlikely identification because thermal dust temperatures in HD 44179 are high enough that hydrated material should not exist. The 6.2 μm feature must therefore join the other bands heretofore discussed as being currently unidentified.

There are now five infrared bands at 3.3 μm, 6.2 μm, 7.7 μm, 8.7 μm, and 11.3 μm that appear in emission in a variety of celestial sources, but are not identified with bands of terrestrial minerals. In addition, the strong band at 0.658 μm in HD 44179 (CAZ; Greenstein and Oke 1977) is probably associated with the dust and further complicates the understanding of the material. Current work in our laboratory (Russell 1978) indicates that the emissivities of small particles are reasonably represented by previous laboratory data on larger particles. Thus particle size effects alone appear not to be responsible for the lack of identification to date.

The infrared bands seem to appear together in sources where an ultraviolet radiation field is present. Tests of fluorescence emission, suggested by Gillett (1977) as a possible explanation of some of these bands, are under way and may permit a more positive statement about whether this effect can produce bands at the observed wavelengths.

Knacke (1977) and Field (1977) have suggested that these bands might be produced in carbon-rich materials; in particular, carbonaceous chondrites seem to have infrared bands near 3.3 and 11.3 μm (Knacke 1977). However, the presence of these bands as dominant emission bands in apparently oxygen-rich regions such as M82 (Willner *et al.* 1977) and Orion (Gillett, Joyce, and Merrill 1978) makes this suggestion difficult to understand. Moreover, the 4–14 μm data of Knacke (1977) show additional features not seen in Figure 2, in the spectra of the oxygen-rich regions mentioned above, or indeed in the spectrum of any celestial object showing the five emission bands discussed earlier.

b) The Evolutionary State of CRL 618 and HD 44179

Westbrook *et al.* (1975) presented convincing evidence for the post–main-sequence evolutionary stage of CRL 618. The high galactic latitude (12°) and lack of evidence of associated young stellar objects strongly suggest that HD 44179 also is in a post–main-sequence state (Zuckerman *et al.* 1976). While this seems to be a reasonably secure conclusion, the placement of CRL 618 and HD 44179 into an evolutionary sequence is far more difficult.

CRL 618 is probably near the end point of the carbon-rich sequence of stellar evolution into planetary nebulae. The lack of spectral features in the thermal emission argues for graphite's being the dominant dust component in the circumstellar shell. The continuous spectrum is common in post–main-sequence carbon-rich objects such as IRC +10216, CRL 2688, etc. The end point of this evolutionary sequence could be represented by a planetary nebula, such as IC 418, that has evidence for SiC emission from 10 to 12 μm (Willner *et al.* 1978) and lacks the strong unidentified bands found in HD 44179 (except possibly for the 3.3 μm band [Russell, Soifer, and Merrill 1977]).

HD 44179 is difficult to fit into an evolutionary sequence that includes CRL 618. The later spectral type of the star and higher infrared color temperature imply that HD 44179 is less evolved than CRL 618, but the infrared spectral features present in HD 44179 suggest that the dust cloud is optically thin and therefore at a later evolutionary stage than CRL 618, if the compositions are the same. Alternatively, the distinct differences in the infrared spectra of CRL 618 and HD 44179 could suggest real compositional differences in the circumstellar shells. The ratio of ^{12}CO antenna temperature (Lo and Bechis 1976) to infrared flux is substantially less for HD 44179 compared with CRL 618, again suggesting a compositional difference (Zuckerman *et al.* 1977).

Since the infrared spectra of HD 44179 and NGC 7027 are so similar, we would expect that these objects have similar dust compositions, and they might therefore be part of an evolutionary sequence distinct from the carbon-rich sequence. Whether this is the case, or whether we are seeing different forms of carbon-rich material in these two different objects, will ultimately be decided with the identification of the many strong infrared bands in the spectra of objects such as HD 44179.

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Note added in proof.—Recent ground-based observations at 2.28 μm ($\Delta\lambda = 0.5$ μm) of the field near HD 44179 failed to reveal any source strong enough to account for the level difference noted in Fig. 2. Short-wavelength variability of the source may account for the difference in levels.

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