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THE 4 TO 8 MICRON SPECTRUM OF NGC 7027

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ABSTRACT

Spectrophotometric observations of NGC 7027 with $\Delta\lambda/\lambda \approx 0.015$ are reported. The continuum shows a strong, broad peak near 7.7 μm, but little or no evidence for the strong peak near 7.0 μm expected from previously postulated carbonate grains. A spectrally resolved feature at 6.2 μm is found and attributed to an increase in the emissivity of some as yet unidentified dust material.

Unresolved emission features are seen at 4.49 and 5.60 μm. These are attributed to [Mg IV] λ4.49, [Ar VI] λ4.52, and [Mg V] λ5.61. The flux in the [Mg V] line is used to derive a lower limit on the temperature of the central star of 1.3×10^5 K; a better estimate might be $T_* \approx 2 \times 10^5$ K. It is suggested that magnesium is overabundant.

Subject headings: infrared: spectra — nebulae: planetary

I. INTRODUCTION

Infrared observations of the planetary nebula NGC 7027 (Gillett, Low, and Stein 1967) revealed an infrared excess above the expected free-free continuum extrapolated from the radio observations. This excess is attributed (e.g., Krishna Swamy and O'Dell 1968) to thermal radiation by dust mixed with the nebular gas.

NGC 7027 has an extremely rich infrared spectrum (Merrill, Soifer, and Russell 1975, hereafter Paper I; Gillett, Forrest, and Merrill 1973, hereafter GFM) displaying broad peaks, atomic fine-structure lines, and recombination lines of hydrogen and helium. The broad peaks have, at best, been only tentatively identified as solid state emission bands. We report here airborne 4–8 μm spectroscopy of NGC 7027. The spectrum exhibits considerable structure. Two new broad emission peaks were found; these complicate the interpretation of the dust emission spectrum. In addition, at least two emission lines were observed.

II. OBSERVATIONS

The data were obtained with the UCSD spectrophotometer mounted at the bent Cassegrain focus of the 90 cm telescope on the Kuiper Airborne Observatory (KAO). The system utilized an arsenic-doped silicon detector, but otherwise remains as described by Russell and Soifer (1977). The beam size was 28″ and the two chopped beams were separated by ~2′.

The 4–8 μm spectrum of NGC 7027 is displayed in Figure 1. The data were obtained in 110 minutes of flight time on 1976 May 26 (U.T.), 50 minutes on 1976 May 28, and 15 minutes on 1976 November 5. Data reduction was accomplished by comparison with a standard star (α Boo or α Tau) also observed during each flight.

Figure 2 shows the 2–14 μm spectrum of NGC 7027; the 2–4 μm data are from Paper I. New data between 7.5 and 13.7 μm were obtained with the UCSD–University of Minnesota 1.5 m telescope on Mount Lemmon using a 17″ beam and standard techniques (Gillett and Forrest 1973). These data, obtained by A. Knutson, K. M. Merrill, and the authors and plotted in Figure 2, have more complete wavelength coverage and a better signal-to-noise ratio than the data of GFM. For Figure 2 no adjustment of the absolute levels of the three spectral regions was made; the slight difference in level is smaller than the uncertainty in the flux densities of the various standard stars used to calibrate the data.

III. RESOLVED FEATURES

a) Feature at 7.7 μm

The continuum flux, as shown in Figure 2, rises to a strong peak near 7.7 μm. This peak is significantly broader than the instrumental resolution, yet narrower than a blackbody distribution. If the infrared continuum is due to thermal emission from dust, as is generally accepted, the dominant character of this feature links it implicitly with the dust. If the temperature of the dust $T_D > 250$ K, as indicated by color-temperature estimates based on the data in Figure 2, the dust must have an optical depth $\tau < 10^{-2}$. Because the dust is optically thin, broad emission peaks may be attributed to peaks in the grain emissivity. Other resolved features are seen at 3.3/3.4, 6.2, 8.6, and 11.3 μm; neither these nor the 7.7 μm feature can reasonably be attributed to any blend of atomic lines.

The features are not likely to be molecular bands, because they have all been observed at the same wavelengths in the low-excitation objects HD 44179 (Russell, Soifer, and Willner 1978) and M82 (Willner *et al.* 1977), and molecular bands are usually quite temperature-dependent in their shape and wavelength of peak flux (Russell, Soifer, and Merrill 1977). However, only higher resolution observations can absolutely rule out molecular bands or atomic line combinations. The interpretation that appears most reasonable is that the

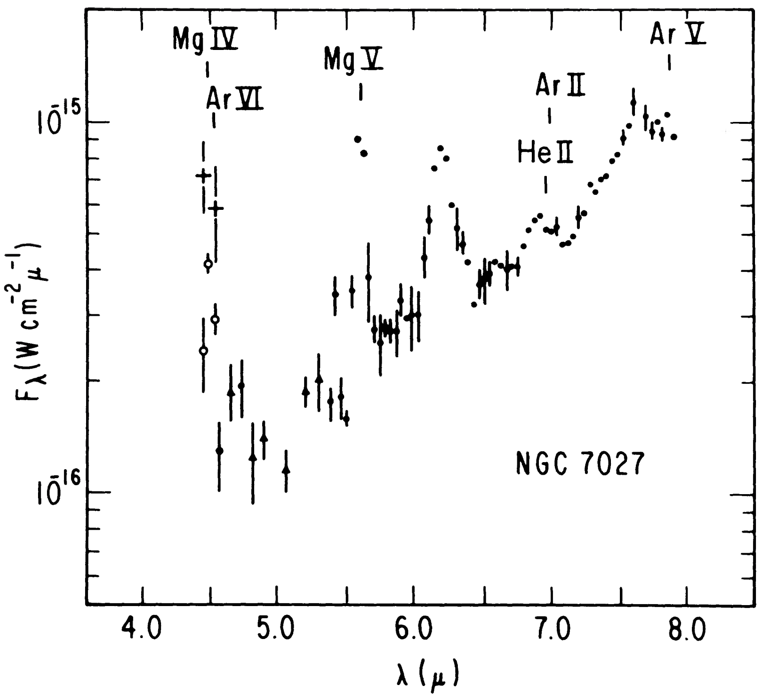

FIG. 1.—The 4–8 μm spectrum of NGC 7027. Wavelengths of fine structure lines are noted, along with the wavelength of the He II line discussed in the text. Open circles represent data obtained on 1976 November 4/5 only. Filled triangles are averages of adjacent wavelengths and have a resolution of 3%. Pluses are 1976 May data at the wavelength of [Mg IV] and [Ar VI]. Significant variations in the observed intensity were seen at these wavelengths, as discussed in the text. Statistical errors $\geq 5\%$ are shown.

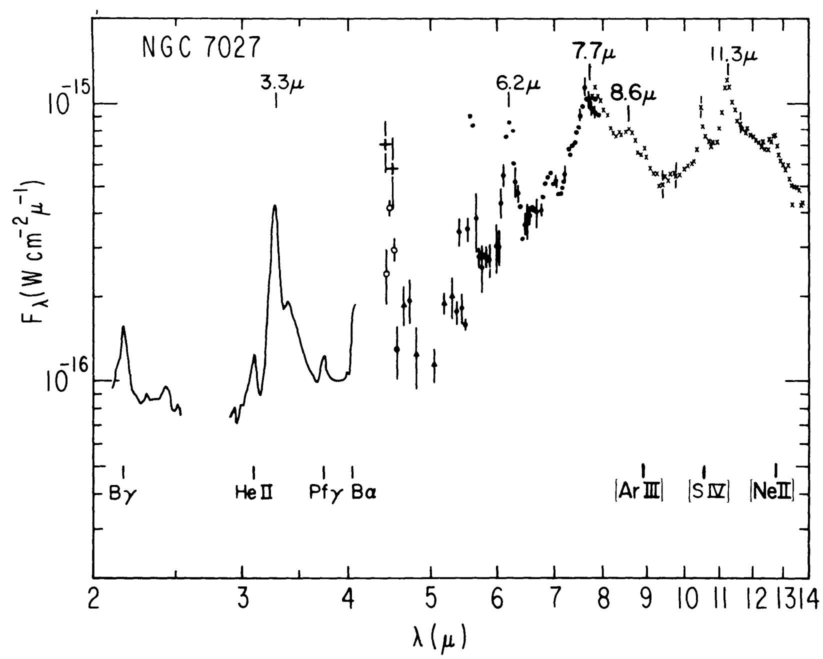

FIG. 2.—The 2–14 μm spectrum of NGC 7027. Symbols for airborne data are the same as for Fig. 1, and crosses represent ground-based data. Data for $\lambda \leq 4.0$ μm are from Paper I. Possible dust emission features and additional atomic transitions are noted.

peaks represent the structure in the emissivity curve of the grains.

b) *Nondetection of Carbonates*

GFM proposed mineral carbonates as a possible constituent of the dust, based on the wavelength and shape of the 11.3 μm feature. Higher resolution observations (Bregman and Rank 1975) supported this identification. However, terrestrial carbonates studied in absorption (e.g., Hunt, Wisherd, and Bonham 1950) and recently in emission in our laboratory show a peak in their emissivity near 7 μm even larger than that at 11.3 μm. When only the ground-based data were available, it was reasonable to suppose (GFM) that the flux level would peak at 7 μm. The airborne data show that this does not happen; rather, the major peak lies near 7.7 μm.

Four reasons why the 7.0 μm feature is not observed at the expected strength are considered here. First, carbonates may not be present. Second, the wavelength of peak emission may be shifted from 7.0 to 7.7 μm, where NGC 7027 has a feature close in relative strength and half-width to that expected for the 7 μm carbonate feature. The idea of such a large wavelength shift is barely tenable, because the feature can only appear within the wavelength range where the real part of the dielectric constant is negative (Huffman 1977). For terrestrial $MgCO_3$, which exhibits an 11.3 μm feature most like that seen in NGC 7027, the peak emission cannot be shifted to a wavelength longer than 7.05 μm (Huffman 1977).

A third explanation for the smaller peak at 7.0 μm relative to that at 11.3 μm is that the intrinsic strength of the 7 μm feature is weaker in astrophysical grains than in terrestrial samples. This is unlikely because both of these peaks are due to molecular resonances in the CO_3 radical, and the relative strength should be moderately insensitive to the composition or size of the particles. The 11.3 μm feature could possibly be enhanced if it is excited by fluorescence, the mechanism suggested by Gillett (1977) for exciting the strong feature at 3.3 μm.

The fourth alternative is that the carbonate grains have a temperature sufficiently low that the ratio of the strengths of the 7 and 11.3 μm features is reduced. There is a small rise above the adjacent continuum at 7.0 μm. The strength of this rise cannot be completely explained by a blend of He II and [Ar II] atomic lines expected at this wavelength, and the rise is broader than would be expected even for a blend of two lines. If one assumes that carbonates are responsible for the 7 μm rise and the 11.3 μm feature, the relative flux levels place an upper limit of ~150 K on the temperature of the carbonate dust. On the other hand, Penman (1976) found a peak in carbonate spectra near 25 μm. No such peak was observed in NGC 7027 by McCarthy, Forrest, and Houck (1977). Their upper limit, combined with the flux in the 11.3 μm feature, places a lower limit on the temperature of 325 K. The absence of a 25 μm feature might be due to the disruption of long-range order in the carbonate crystal by radiation damage, which would be expected to leave the shorter wavelength carbonate features intact (Day 1977). This explanation still requires that the carbonate grain temperature be very low. Until some explanation for the absence of the 7 and 25 μm features is substantiated, the identification of carbonates in NGC 7027 must be regarded as doubtful.

c) *Feature at 6.2 μm*

The 6.2 μm feature is characterized both by its strength and comparatively narrow width. The band is slightly broader than the instrumental resolution, having an apparent full width at half-maximum intensity of $\Delta\lambda \approx 0.15$ μm. No atomic fine-structure lines of reasonably abundant elements are known to occur at this wavelength. Moreover, the observation of this band in the low-excitation nebulae M82 (Willner *et al.* 1977) and HD 44179 (Russell, Soifer, and Willner 1977) makes the identification of this band with a combination of several atomic fine-structure lines highly doubtful. The wide variety of excitation conditions under which this band is observed also makes it extremely unlikely that this band is due to a collisionally excited molecular band.

A possible mechanism for producing this feature is emission in a resonance band of the dust associated with this region. If the emission is strictly thermal and the 7.7 μm and 6.2 μm bands are in the same material and have intrinsically equal strengths, the required dust temperature is ~340 K. Water of hydration in a variety of host materials has a strong narrow resonance at ~6.2 μm (Nyquist and Kagel 1971); however, for temperatures $\gtrsim$300 K, most hydrates would lose several, if not all, of their water molecules. Thus, this identification must be regarded as extremely doubtful, and this band must be regarded as unidentified.

IV. UNRESOLVED FEATURES—ATOMIC LINES

No hydrogen or helium recombination lines were clearly detected from 4 to 8 μm, but the upper limits are consistent with observed recombination line strengths (Paper I; Brocklehurst 1971).

Several ions have forbidden lines between 4 and 8 μm. Possible forbidden-line identifications, based on the wavelengths of the observed narrow features and on the observations of related lines in the optical (Kaler *et al.* 1976, hereafter KACE), are indicated in the figures. These include [Mg V] at 5.61 μm and a blend (if both are present) of [Mg IV] at 4.49 μm and [Ar VI] at 4.52 μm. [Ar II] at 6.98 μm and [Ar V] at 7.89 μm might also be present.

The line at 5.60 ± 0.02 μm, identified with [Mg V], is an important one because of the high (109.3 eV) ionization potential of Mg IV. At the same time, this high ionization potential, compared to the more prevalent states of ionization indicated by other ionic species (discussed originally by Aller and Menzel 1945), casts some doubt upon the identification.

A strong, narrow band at 5.6 μm has been seen in several minerals studied in our laboratory. These all have an XYO_3 composition, suggesting that the feature may be associated with the O_3 structure. While the 5.60 μm feature might be attributed to such minerals in NGC 7027, we regard this as unlikely for two reasons. First, stronger, broader bands at other wavelengths observed in the laboratory spectra remain inconsistent with the astronomical data. Second, if the material that produces the 5.60 μm feature is responsible for other resonances that appear in the NGC 7027 spectrum, the feature should appear in the spectra of M82 and HD 44179, where all the broad spectral features are seen in common. Because the feature at 5.60 μm is not present in the other two sources, we regard it as more likely that this feature is an atomic line uniquely associated with the high excitation in NGC 7027. Higher spectral resolution observations are clearly needed to confirm this assumption.

The line wavelength derived from our observations is in excellent agreement with that tabulated for [Mg v] (Johannesson, Lundstrom, and Minnhagen 1972), and we were unable to find any other atom or ion through iron which had a likely transition near this wavelength. The Mg v ion has two additional forbidden transitions at 2783 Å and 13.54 μm (Johannesson, Lundstrom, and Minnhagen 1972), neither of which has been observed (Bohlin, Marionni, and Stecher 1975; Fig. 2). However, the upper limits are consistent with the expected fluxes of 1.7×10^{-12} ergs cm^{-2} s^{-1} for the UV line and 5.2×10^{-11} ergs cm^{-2} s^{-1} for the IR line; atomic and nebular parameters used to calculate these expected line fluxes were taken from KACE; Bohlin, Marionni, and Stecher (1975); Saraph, Seaton, and Shemming (1969); and Wiese, Smith, and Miles (1969). Observations of both of these lines should be possible with higher resolution in the IR and with the improved sensitivity in the UV reported by Bohlin, Marionni, and Stecher (1975).

If the [Mg iv] line at 4.488 μm (Johannesson, Lundstrom, and Minnhagen 1972) is present, it might be considered a confirmation of the identification of the 5.60 μm feature with the [Mg v] line. Although there is an emission feature at 4.49 μm, it may be partly due to [Ar vi]; furthermore, the total observed strength of this feature is weaker than would be expected for the [Mg iv] line alone, based on the 5.60 μm line strength and a reasonable ionic abundance distribution (Aller and Menzel 1945). One possible explanation for the apparent weakness of the [Mg iv] line is a wavelength coincidence with, and thus absorption by, a telluric line. Both N_2O and $^{13}CO_2$ have lines in this general part of the spectrum, but only an N_2O line is both close enough in wavelength and a strong enough absorber to reduce the strength of the line to that observed (Greenberg 1977). Observational support for at least some telluric absorption is provided by the fact that the observed 4.49 μm flux varied by a factor of 2 between the spring and fall, as shown in Figure 1. This variation was presumably due to the changing relative wavelengths of the celestial and telluric lines caused by the Earth's motion. Depending on the exact wavelengths and on the strength of the telluric line, the total absorption could easily be a factor of 3 (Greenberg 1977). Observations with higher spectral resolution are necessary to confirm the identification and to determine the exact amount of absorption.

The Mg v abundance can be estimated by a comparison of the intensity of the 5.60 μm line with the radio flux (Higgs 1971), provided the identification of the 5.60 μm line is correct. The observed ratio n(Mg v)/n(H ii) is $\sim 1.7 \times 10^{-5}$, or about one-half the solar Mg abundance of 2.6×10^{-5} (Allen 1973); the collision strengths were taken from Saraph, Seaton, and Shemming (1969) and the electron temperature from KACE. As indicated by Aller and Menzel (1945), there should be more Mg iv than Mg v; thus magnesium appears to be overabundant in NGC 7027. If the deduced fractional abundance of magnesium in the gas phase of NGC 7027 is typical of planetary nebulae, then either the observed depletion of magnesium in the interstellar medium (Field 1974) is due to processes occurring at a later stage than that evidenced by NGC 7027, or else planetary nebulae produce no more than 10% of interstellar matter.

The flux of the [Mg v] line sets a lower limit on the rate of emission by the central star of photons capable of ionizing Mg iv. This emission rate sets a lower limit on the temperature T_* of the central star, provided the luminosity can be determined. If the infrared luminosity of the nebula (Telesco and Harper 1977) represents the total luminosity of the central star and if all photons capable of ionizing Mg iv do so, then $T_* > 1.3 \times 10^5$ K. The limit is independent of the distance to NGC 7027 but is based on the assumption that the central star radiates like a blackbody. Probably other ions, notably oxygen ions, are important competitors for the UV photons. If the fraction of UV photons absorbed by Mg iv ions is really 1/25, the solar abundance ratio by number of Mg to O (Allen 1973), then $T_* \approx 2 \times 10^5$ K.

V. SUMMARY

Spectroscopy of NGC 7027 from 4 to 8 μm has revealed two resolved features at 6.2 and 7.7 μm, assumed to be due to characteristics of the dust grains responsible for the infrared continuum emission. A large peak near 7.0 μm, expected on the basis of the previous identification of the 11.3 μm feature with mineral carbonates, does not exist in NGC 7027. The emission peak at 6.2 μm is probably due to another resonance band of the dust associated with the nebula.

Two unresolved emission features at 4.49 and 5.60 μm have been observed. The feature at 5.60 μm is best identified as a fine-structure line of [Mg v]. The line intensity implies a lower limit on the temperature of the central star of NGC 7027 of $T_* > 1.3 \times 10^5$ K; a better estimate might be $T_* \approx 2 \times 10^5$ K. Also, the Mg abundance is probably greater than the solar value.

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Note added in proof.—There is a wavelength coincidence between the $v = 0$, $J = 7 \rightarrow 5$ line (6.91 μm) of H_2 and the 7 μm rise in our data. However, if the H_2 is in thermal equilibrium at a temperature comparable to the excitation temperature of the observed $v = 1$, $J = 3 \rightarrow 1$ line at 2.12 μm (Treffers, Fink, Larson, and Gautier, *Ap. J.*, **209**, 793 [1976]), molecular hydrogen emission should not contribute significantly to the flux (1×10^{-17} W cm^{-2}) in the 7 μm rise in our data. (These calculations are based on the molecular data of Fink, Wiggins, and Rank [*J. Molec. Spectrosc.*, **18**, 384 (1965)]; Gautier, Fink, Treffers, and Larson [*Ap. J.* (*Letters*), **207**, L129 (1976)]; Aannestad [*Ap. J. Suppl.*, **25**, 223 (1973)].) Nonthermal excitation mechanisms are still possible; higher resolution observations are necessary to clarify the identification of the 7 μm feature.

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