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THE 2–4 MICRON SPECTRUM OF NGC 7027

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ABSTRACT

Spectrophotometric observations of NGC 7027 from 2.1 to 4.1 μ with a resolution $\Delta\lambda/\lambda \sim 0.015$ are reported. The spectrum is rich in features, including three hydrogen recombination lines and several unidentified features. The 2-μ continuum level and the hydrogen recombination-line fluxes agree well with predictions based on the observed radio and Hβ fluxes.
Subject headings: infrared — planetary nebulae

I. INTRODUCTION

NGC 7027 is among the most studied of planetary nebulae. It was one of the first gaseous nebulae discovered to have a large infrared excess (Gillett, Low, and Stein 1967), and subsequent infrared studies have shown it to be an exceedingly useful object for investigating infrared emission mechanisms (see, e.g., Krishna Swamy and O'Dell 1968; Gillett, Forrest, and Merrill 1973, hereafter GFM).

In this *Letter* we report spectrophotometric observations of NGC 7027 from 2.1 to 4.1 μ with a spectral resolution of $\Delta\lambda/\lambda \sim 0.015$. The observations were made in 1974 November using a cooled circular variable filter-wheel spectrophotometer at the UCSD–University of Minnesota 152-cm infrared telescope on Mount Lemmon. The system and data-taking procedures are similar to those described previously (Gillett and Forrest 1973). The only differences are the wavelength coverage of the filter wheel and the infrared detector (an InSb photovoltaic detector was used in these observations).

II. THE DATA

The 2–4 μ spectrum of NGC 7027 is shown in Figure 1. The focal-plane aperture for the observations was 17″, larger than the ∼7″ diameter that recent radio and infrared observations (Balick, Bignell, and Terzian 1973; Becklin, Neugebauer, and Wynn-Williams 1973) indicate for the size of the source. The spectrum of Figure 1 is the average of several separate spectra. The statistical errors are less than 4 percent of the spectral flux where no error bars are shown. Where sensible identification of narrow emission features can be made, they are indicated.

III. DISCUSSION

There are six narrow spectral features in the 2–4 μ spectrum of NGC 7027, as well as a broad feature centered at 3.4 μ. Three of these can be identified with recombination lines of hydrogen at 2.16 μ (7 → 4; Brackett γ), 3.74 μ (8 → 5; Pfund γ) and 4.05 μ (5 → 4; Brackett α). Besides the hydrogen recombination lines, there are narrow emission features at 3.09 μ and 3.27 μ, and probably one at 2.43 μ. The line at 2.43 μ is fairly weak: although it appears in all five individual scans of the 2.4–2.5 μ region, further observations are needed to confirm its reality.

a) The Hydrogen Recombination Lines

The flux in the 5 → 4 hydrogen recombination line cannot be determined since the spectrometer can measure fluxes reproducibly only for $\lambda \lesssim 4.046$ μ. The

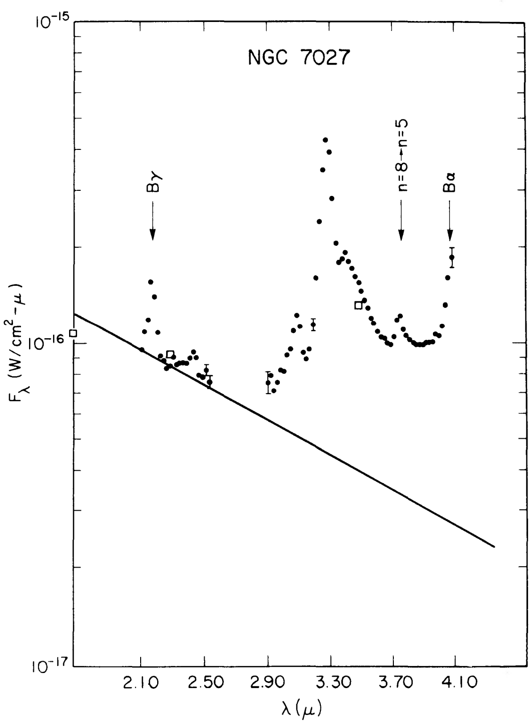

FIG. 1.—The spectrum of NGC 7027 from 2.1 to 4.1 μ, which is the average of several spectra. Where no error bars are shown, the statistical errors are less than 4% of the spectral flux. The solid line is the continuum from the ionized gas extrapolated from radio observations. The identified features, all hydrogen recombination lines, are noted in the figure. The open squares are broad-band fluxes obtained at the same time as the spectrum.

$8 \rightarrow 5$ transition is not resolved by the instrument, and the $7 \rightarrow 4$ line is probably not resolved (transitions of He I could contribute 10–20 percent of the flux attributed to this line and broaden it slightly). The measured fluxes in these lines are given in Table 1.

Also listed in Table 1 for comparison are the fluxes predicted for these lines on the basis of simple recombination theory (populations of the angular-momentum states within a given energy level n are assumed proportional to the statistical weights of the l states). The ratio of the $n \rightarrow n'$ transition to the $n \rightarrow 2$ transition is given by (e.g., Petrosian 1970)

$$\frac{I_{nn'}}{I_{n2}} = \frac{\nu_{nn'} A_{nn'}}{\nu_{n2} A_{n2}} . \quad (1)$$

The flux in the $n \rightarrow 2$ transition was related to Hβ using Brocklehurst's (1971) detailed calculations for the case $n_e = 10^4$ cm^{-3} and $T_e = 2 \times 10^4$ K. The absolute flux in Hβ was taken from Miller and Mathews (1972), and corrected for reddening using the extinction at Hβ (3.63 mag) derived by them on the basis of the measured radio flux.

The agreement between the calculated and observed fluxes is excellent for both the $7 \rightarrow 4$ and the $8 \rightarrow 5$ lines, indicating that there is little or no extinction at either wavelength. Since the calculated $b(n, l)$ coefficients describing the departure of the l states from the LTE values are somewhat uncertain, more detailed calculations of the fluxes in the lines were not attempted. Such detailed calculations are needed for these transitions, since these hydrogen lines can be used to determine accurately the extinction at these wavelengths to highly obscured regions of ionized hydrogen (*independent* of the relative contributions of free-free and dust emission to the continuum flux, or any assumed wavelength dependence of the extinction).

b) The Continuum from 2 to 4 μ

Figure 1 shows the free-free/bound-free continuum extrapolated from radio observations to the 2–4 μ region (*solid line*). The extrapolation simply scaled the observed radio flux at 8 GHz where $\tau_{ff} \approx 0.2$ (Balick *et al.* 1973) by the ratio of the infrared to radio emissivities in the ionized gas. (There is some scatter in the measured radio fluxes indicating that a realistic error in the overall level of the extrapolation is 10%). The infrared emissivity was taken from the calculations of Sibille, Lunel, and Bergeat (1974) for $T_e = 17{,}000$ K (the best-fit T_e from Miller and Mathews) and the radio free-free emissivity from the expression in Pacholczyk (1970).

TABLE 1

H I transition............	7→4(Bγ)	8→5
λ(μ)....................	2.16	3.74
Measured flux (ergs cm^{-2} s^{-1})..................	$3.4\pm0.5\times10^{-11}$	$1.5\pm0.3\times10^{-11}$
Predicted flux (ergs cm^{-2} s^{-1})..................	3.6×10^{-11}	1.2×10^{-11}

Within the calibration and measurement errors at 8 GHz and the infrared, the observed flux agrees well in both level and slope with the predicted flux from 2.1 to 2.5 μ. This gives further evidence for the conclusion that there is little or no extinction to NGC 7027 at 2 μ.

The continuum level for $\lambda > 2.9$ μ is significantly above the extrapolated radio free-free continuum; the excess is normally attributed to thermal emission by hot dust within the ionized gas. The excess flux at 3.5 μ is $\sim 7 \times 10^{-17}$ W cm^{-2} μ^{-1}; this is not large compared with the 10-μ excess (6×10^{-16} W cm^{-2} μ^{-1} [GFM]) and does not require exceptionally hot ($T >$ 350 K) grains. Thus simple materials could account for the 3-μ excess radiation. Mineral carbonates, identified by their characteristic signature at 11.2 μ (GFM; Bregman and Rank 1975) are already known to be present in NGC 7027.

c) The Unidentified Spectral Features

Besides the hydrogen recombination lines, there are unidentified lines at 2.43, 3.09, and 3.27 μ, and a broad feature peaking at 3.4 μ. The surprising strengths of these features make them particularly interesting, since they are not readily identifiable with any obvious transitions of cosmically abundant atoms or ions. We have also searched infrared spectra of minerals and solid inorganic materials and can find no material that could reasonably produce the broad 3.4-μ feature without producing another stronger feature somewhere between 8 and 13 μ; such additional features are not seen in the 8–13 μ spectrum of NGC 7027 (GFM).

The line at 3.27 μ and the broad emission feature at 3.40 μ are most interesting, since there is a significant amount of energy emitted in these features. The "line" at 3.27 μ is marginally resolved at the instrumental resolution; however, this requires higher spectral resolution for confirmation.

A feature similar to that at 3.27 μ has also been found in a preliminary spectrum of the nuclear region of the galaxy NGC 253 (Soifer and Russell, unpublished), suggesting that the conditions which give rise to this feature are not uncommon. In this context, it is interesting to note that there are also similarities in the 8–13 μ spectra of NGC 253, NGC 7027, and BD +30°3639 (Gillett *et al.* 1975).

The 3.27-μ feature is close to the wavelength of the $9 \rightarrow 5$ transition in H I (3.29 μ) and also close to the $n \rightarrow$ 6 series limit (3.28 μ) in H I. It is possible that this is more than coincidental, but this is doubtful since the strengths of these features would be significantly larger than predicted by recombination theory. If there were abnormally strong transitions to the $n = 5$ or $n = 6$ levels in hydrogen, the enhanced populations in these levels could be expected to appear in the appropriate Balmer and Paschen lines, a result not observed (Miller and Mathews; Pipher and Terzian 1969).

An intriguing alternate possibility is that these features are molecular in origin. The patchy nature of the extinction to NGC 7027 suggests that most of the extinction is local to the object, so that ultraviolet radiation could be sufficiently attenuated near the planetary to allow molecules to exist, if this ultraviolet shielding were necessary. (Recent observations of planetary nebulae suggest that dust and hence the supposed molecular precursors *can* form within the ionized gas [Cohen and Barlow 1974; Stein; 1975]).

IV. CONCLUSIONS

The 2–4 μ spectrum of the planetary nebulae NGC 7027 has been found to be rich in strong features, half of which can be identified with hydrogen recombination lines, and half being unidentified at this time. The hydrogen lines and the 2-μ continuum agree well with predicted strengths, indicating that there is little or no extinction to NGC 7027 for $\lambda \geq 2$ μ. The 3-μ excess is small, and so does not require hot ($T > 350$ K) dust. The unidentified spectral features are most interesting; there is no evidence as to whether they come from the ionized or surrounding neutral gas.

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Note added in proof.—Subsequent observations of a variety of other sources has shown that the 3.3–3.4 μ emission features appear in objects that also have an emission feature near 11.3 μ which has been attributed to the carbonate radical in solid carbonates (GFM). In most sources where both features have been found, the strengths of the two features are comparable (to within a factor of 2).

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