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FAR-INFRARED EMISSION-LINE AND CONTINUUM OBSERVATIONS OF NGC 7027

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ABSTRACT

We have obtained the first observation of a fine-structure transition in NGC 7027 at wavelengths greater than 30 μm. The flux in the 63.2 μm [O I] line is observed to be $\sim 10^{-16}$ W cm^{-2}. If NGC 7027 lies at 1 kpc, this corresponds to a luminosity, in the line, of $\sim 30\ L_\odot$.

The flux of the 88.35 μm [O III] line is less than 10^{-17} W cm^{-2}, and the upper limit to the line flux at 51.8 μm is 10^{-16} W cm^{-2}. These upper limits imply an electron density $n_e < 1.6 \times 10^5$ cm^{-3}.

The continuum measurements we obtain are in agreement with the results of Telesco and Harper and support a dust temperature of 90 K with an $\sim 1/\lambda^2$ emissivity. Our data exclude grain materials whose wavelength-dependent emissivity $(1/\lambda^n)$ requires n to be outside the range $1.6 < n < 2$, unless the temperature varies drastically across the dust cloud.

Subject headings: infrared: sources — nebulae: individual — nebulae: planetary

I. INTRODUCTION

NGC 7027 is the brightest, and consequently the best-studied, planetary nebula at infrared wavelengths. Thermal emission from dust grains dominates its continuum spectrum from 3 to 300 μm (Gillett, Low, and Stein 1967; Telesco and Harper 1977). In addition, a number of emission lines of molecular hydrogen, ionized hydrogen and helium, and forbidden lines covering a wide range of elements and ionization stages have been observed in the wavelength range from 1 to 30 μm (Treffers *et al.* 1976; Russell, Soifer, and Willner 1977; Greenberg, Dyal, and Geballe 1977; McCarthy, Forrest, and Houck 1978). While increased theoretical interest in the use of infrared fine-structure lines as probes of elemental abundance, electron density, and temperature of ionized regions has led to extensive observational efforts, only broad-passband photometric data of planetary nebulae have thus far been obtained at wavelengths beyond 30 μm (Telesco and Harper 1977; Mosley 1979). This paper presents the first medium-resolution spectroscopic results at wavelengths greater than 40 μm and reports the detection of the 63.2 μm [O I] line from NGC 7027—the first such detection for any planetary nebula.

During the past few years, studies of H II regions in the far-infrared (Dain *et al.* 1978; Melnick, Gull, and Harwit 1979*a*, *b*; Storey, Watson, and Townes 1979; Moorwood *et al.* 1979) have succeeded in detecting several prominent far-infrared fine-structure forbidden lines which could be useful in studies of planetary nebulae. The 63.2 μm [O I] line is central to studies of the cooling in postshock regions and ionization fronts (Aannestad 1973; Hill and Hollenbach 1978) and has been observed in several H II regions. Further, measurements of the 51.8 and 88.35 μm lines of [O III] have supplied estimates of the O^{++} abundance and the electron density in the central portions of H II regions. In addition to the detection of the 63.2 μm [O I] line, we report upper limits to the line strength of the 51.8 and 88.35 μm [O III] lines from the planetary nebula NGC 7027, which can be analyzed in a manner similar to that used for the H II regions.

With assumptions on source geometry and the extinction of the 6300 Å line of [O I], we can estimate both upper and lower limits for the temperature of the gas in the [O I]-emitting region. Further, upper limits to the line fluxes at 88.35 and 51.8 μm can be used to derive upper bounds on the electron density in the [O III]-emitting region. Finally, measurements of the continuum in the spectral vicinity of the 52, 63, and 88 μm lines can be compared with the earlier photometric results of Telesco and Harper (1977) and provide further data on grain temperature and emissivity at long wavelengths.

II. OBSERVATIONS

Observations were made on the nights of 1979 May 30–31, May 31–June 1, and June 4–5 with the 91 cm telescope of the NASA-operated Gerard P. Kuiper Airborne Observatory (KAO). On all 3 nights the observations were made from an altitude of 12.5 km. We employed the same dual-channel liquid-helium-cooled grating spectrometer used in earlier flights on the NASA Lear Jet (Houck and Ward 1979). Only minor modifications to the optics were necessary to accomodate the larger (f/17) focal ratio of the KAO telescope. Both the short-wavelength channel (40–70 μm), and the long-wavelength channel (70–120 μm) utilized gallium-doped germanium photoconductors.

These photoconductors were prepared using a new technique designed to reduce contact noise. Doped with Ga to a density of 2×10^{14}/cm^3, these detectors were then boron implanted at energies of 70 and 100 keV at the National Research and Resource Facility for Submicron Structures at Cornell. They appear to be 2–3 times better than unimplanted detectors previously used, although variations in the raw material used could also account for the difference. Our in-flight system NEP was $\sim 3 \times 10^{-13}$ W $Hz^{-1/2}$ in the short-wavelength channel and $\sim 10^{-12}$ W $Hz^{-1/2}$ in the long-wavelength channel. Our beam size was 30″ × 50″ on the sky. We operated the oscillating secondary mirror at 35 Hz with a beam separation of ~2′.2.

The spectrometer resolution, $\lambda/\Delta\lambda$, was ~300 during this flight series, and the data were sampled at three points per resolution element at 52 and 88 μm and 2.5 points per resolution element at 63 μm. A typical spectral run consisted of either seven or eight data points centered about the nominal line position. The points were chosen to include atmospheric H_2O features for wavelength calibration. Each spectral run on NGC 7027 lasted approximately 5 minutes (40 s of integration/point) and was repeated as often as time permitted. In total, six runs were completed at 63 μm, four were obtained at 88 μm, and two were made at 52 μm.

The Moon was the only calibration source available to us for this flight series. On the 3 nights of our observations the Moon was 5, 6, and 10 days old, respectively. Knowledge of our beam location on the Moon permitted use of the detailed thermal maps of Saari and Shorthill (1967). We estimate the lunar temperatures in our beam as 310, 330, and 360 K on the 3 nights. Errors in the temperatures are ~(−30, +15) K the first night and ±15 K on the second and third nights. Both the spectral shape and the absolute flux of our data are obtained assuming the lunar spectrum to be a blackbody at these temperatures.

In the course of postflight data analysis we discovered that some loss of signal had occurred at the beginning of our second flight while observing the Moon. As the effect decreased with time (to no detectable loss after 40 minutes), and the telescope cavity had been kept cold between flights 1 and 2, we attribute this to a thin film of ice on the telescope optics which sublimated at the beginning of the flight. Evidence for rapidly sublimating ice films has been found on other KAO flights when the telescope has been kept cold between successive flights (Gillespie 1979). This circumstance has led to some uncertainties in the absolute flux levels of data obtained on our second flight. Comparison of lunar spectra from the first and second flights shows an overall reduction in the apparent brightness of the Moon the second night, but introduced no new spectral features in the wavelength regions we examined.

III. RESULTS AND DISCUSSION

a) 63.2 Microns [O I]

The calibrated spectrum of NGC 7027 in the spectral region about the 63.2 μm [O I] line is shown in Figure 1. This spectrum represents the result of averaging the six runs taken during the first two observing nights. In order to correct for the diminished lunar signals on our second night, the flight 2 lunar spectra were normalized to the flight 1 lunar data taking into account the slightly higher temperature of the Moon on the second night. The errors

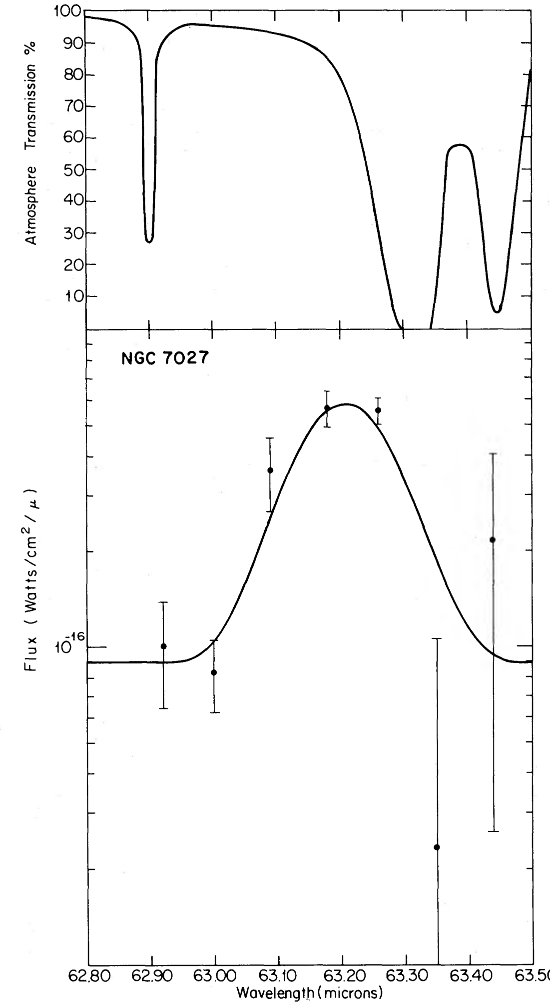

FIG. 1.—Profile of the atmospheric transmission (Traub and Stier 1976) (*top curve*) and the 63.2 μm [O I] emission line in NGC 7027 (*bottom curve*) corrected for atmospheric water vapor absorption. Data points closest to the water vapor absorption features are most strongly affected by fluctuations in the water vapor along the line of sight. This is evident in the relatively large uncertainties in the data points at 63.35 and 63.44 μm. The best-fit Gaussian curve (*solid line*) has a FWHM corresponding to our instrument resolution of 300.

shown are the standard deviations of the mean obtained as a result of averaging and may be viewed as a measure of agreement between the contributing spectra. The uncertainties in the lunar temperature in our beam each night results in an additional ~20% uncertainty in the absolute level of our spectrum. The large fluctuations evident in the last two points are due to their proximity to strong telluric water vapor features at 63.31 and 63.44 μm (Traub and Stier 1976). Changing water vapor content along the line of sight can lead to appreciable variability at these wavelengths.

The 63.2 μm [O I] line is not resolved at a system resolution of 300. Our laboratory system response to an unresolved line that fills our beam is found to be well fitted by a Gaussian curve. For an unresolved line that occupies a fraction of our beam, we would expect a slightly flattened spectral profile. Although recent electronographic observations of NGC 7027 by Atherton *et al.* (1979) in the 6300 Å [O I] line measure a nebular size of 14″ × 11″ (major and minor axes, respectively)—small compared to our beam—the errors in our present data are too great to allow us to obtain any information about the spacial extent of the 63 μm line emission.

The 63.2 μm [O I] flux we detect is $\sim 1 \times 10^{-16}$ W cm^{-2}, which, at a distance of 1 kpc (Churchwell, Terzian, and Walmsley 1976), amounts to $\sim 30\ L_{\odot}$ in the line. Uncertainty in the assumed blackbody temperature of the Moon and our inability to correct entirely for the effects of ice on the KAO optics on our second night dominate our sources of error and limit our accuracy for this value to $\sim 50\%$.

The origin of the observed 63 μm [O I] emission in NGC 7027 is uncertain. This is primarily because it is not currently known whether collisional excitation due to atomic hydrogen, protons and electrons, or a charge exchange reaction is the dominant process responsible for populating the $^3P_1$ level of neutral oxygen in planetary nebulae. However, when coupled with what is known of the strength and distribution of the 6300 Å [O I] emission, we believe that it is possible to narrow the range of likely regions from which most of the 63 μm [O I] emission occurs.

As mentioned earlier, Atherton *et al.* (1979) have obtained monochromatic maps of NGC 7027 in the optical lines of several atoms and ions including [O I] 6300 Å. Their measured size of 14″ × 11″ in [O I] 6300 Å is in agreement with the size of a radio map at 6 cm obtained by Scott (1973), with the size derived from the 10 μm map made by Becklin, Neugebauer, and Wynn-Williams (1973), and is consistent with the upper limits on the size of the far-infrared continuum source (Telesco and Harper 1977; Moseley 1979). It is of interest to note that the maps made in the lines of several ionic species show no contrast to the map at 6300 Å.

Whether the 63 μm and the 6300 Å radiation are emitted within one and the same portion of the nebula can only be judged by calculating the expected flux at each wavelength for different portions of the nebula. It is difficult to account for the full amount of 6300 Å emission observed (Williams 1973), but it is also likely, if collisional excitation is responsible for this emission, that a high ambient temperature is required to produce the high observed flux. This is necessary because the excitation temperature of the ^1D level from which the 6300 Å line flux originates is $\sim 22{,}700$ K. However, at such high temperatures the relative 63 μm flux produced would be too low to account for the observed 6300 Å—63 μm flux ratio.

In the past several years, charge exchange models involving O^+ and H have been invoked in order to account for the higher expected 6300 Å flux observed in many planetary nebulae. Because of the near equivalence of the ionization potentials of neutral oxygen and hydrogen, the charge exchange reaction

$$O^+ + H \rightleftharpoons H^+ + O$$

is very nearly a resonance process, and the cross section for this reaction is consequently relatively large. In most planetary nebulae the photoionization and recombination rates for ions are substantially greater than the rates for charge exchange reactions at all points in the gas except near the edge of the nebula (Williams 1973), implying that ionization fronts are the primary regions giving rise to emission due to charge exchange. Recently, Péquignot, Aldrovandi, and Stasinka (1978) have modeled NGC 7027 and have included the effects of charge exchange. With charge exchange their model is able to account for the observed flux of 6300 + 6363 Å and 5577 Å [O I] emission to within 10%. The observed strength of the 63 μm [O I] line, however, is ~ 20 times greater than that predicted by their model. It may therefore be possible that much of the optical [O I] emission is due to charge exchange, while the infrared [O I] emission is the result of a different process.

Two possible models to produce the observed flux are considered here. The first involves shocks; the second the heating of the gas by near-ultraviolet radiation.

Theoretical studies of shock-induced transitions by Aannestad (1973) and, more recently, by Hill and Hollenbach (1978) indicate that atomic hydrogen excitation of neutral oxygen is capable of producing significant amounts of [O I] 63 μm flux in the postshock regions. Recent molecular hydrogen observations of NGC 7027 (Beckwith *et al.* 1980) in fact suggest that shock fronts around the nebula may be responsible for exciting the H_2. If this is the case, and we assume that NGC 7027 is surrounded by a spherical shock front moving into the neutral gas, then we can estimate the energy available for emission in the 63 μm [O I] line. If the shock front is at a radius R, moving at a velocity v_s into a preshock region with a hydrogen number density n_H, then the total number of hydrogen atoms flowing across the surface per second is $4\pi R^2 n_H v_s$. If the heat produced in the shock is dissipated totally through 63 μm radiation, the total luminosity in the 63.2 μm line is then

$$L(63) \approx 2\pi R^2 n_H m_H v_s^3 \quad \text{ergs s}^{-1}, \qquad (1)$$

where m_H is the mass of the hydrogen atom. If we let R equal the radius of the visible nebula, the total 63 μm flux received at Earth becomes

$$F(63) \approx \tfrac{1}{2}\theta^2 n_H m_H v_s^3 \quad \text{ergs cm}^{-2}\ \text{s}^{-1}, \qquad (2)$$

where θ is the angular radius of the optical emission region. For an angular radius of 7″, $n_H \approx 10^5$ cm^{-3} (the density found in the ionized gas [Kaler *et al.* 1976]) and a shock velocity of 22 km s^{-1} (Wilson 1950), this produces a flux of 10^{-16} W cm^{-2}, in agreement with what we observe.

In the alternate mechanism that could be responsible for the observed 63 μm flux, a shell of neutral gas surrounding the nebula is heated by near-ultraviolet radiation emanating from the central star. We estimate the thickness of the shell to be $\sim 10^{16}$ cm, based in part on the optical depth of $\sim 6 \times 10^{20} n_H^{-1}$ cm that Hollenbach and Shull (1977) use in their computation of radiation absorbed into the Lyman and Werner bands at the interface of an ionized and neutral region. The gas in this layer appears to be heated through the action of 912–1100 Å radiation, although the exact mechanism is not understood. For stars associated with planetary nebulae, about one-tenth of the luminosity is found in the 912–1100 Å band. Thus, it can be assumed that ϵL ergs s^{-1} go into heating a layer of gas $\sim 10^{16}$ cm thick surrounding the ionized region, where L is the luminosity of the star in the 912–1100 Å band, and ϵ is the fraction of this radiation that heats the gas. Although ϵ is not well known, if the gas is heated by radiation in the 912–1100 Å wavelength range, either through photoelectron ejection from grains, or through absorption by hydrogen molecules followed by collisional de-excitation, the value of ϵ is likely to be of the order of 0.01 (cf. Watson 1975). The remainder of the stellar radiation is largely absorbed by the dust. Correspondingly, we may expect that ϵF ergs cm^{-2} s^{-1} is the cooling radiation that can be expected at Earth from this layer, where F is the total infrared flux. The measured infrared flux at Earth is $F \approx 2 \times 10^{-7}$ ergs cm^{-2} s^{-1} (Telesco and Harper 1977), so that cooling of the order $\sim 2 \times 10^{-9}$ ergs cm^{-2} s^{-1} might be expected from such a layer. This is comparable to our observed 63 μm flux.

In view of these considerations, we will assume there is emission of 63 μm radiation from a layer thickness of 10^{16} cm, at a density $n_H \approx 10^5$ cm^{-3} and an oxygen abundance of 7.4×10^{-4} n_H (Torres-Peimbert and Peimbert 1977).

Launay and Roueff (1977) have given a collision cross section for atomic oxygen and hydrogen for excitation of the $^3P_1$ state that levels off around 4.5×10^{-16} cm^2 at 1000 K. The corresponding rate coefficients for 63 μm radiation also tend to level off at 1000 K, where a value of $L_H(O, T) \approx 10^{-23}$ ergs cm^3 s^{-1} characterizes the cooling function.

If we take the emitting shell to lie just outside an H II region of radius R, say at $1.1R$ from the star, and adopt a layer thickness of $0.1R$ (which roughly corresponds to 10^{16} cm at a source distance of $D = 1$ kpc), then a 2000 K cloud (Beckwith *et al.* 1980) will produce a 63 μm luminosity of

$$L(63) \approx 4\pi(1.1R)^2 10^{16} L_H(O, T)(n_O/n_H)n_H^2 \quad \text{ergs s}^{-1} . \tag{3}$$

The corresponding flux $F(63)$ is

$$L(63)/4\pi D^2 \approx 1.2 \times 10^{16} L_H(O, T)(n_O/n_H)n_H^2\theta^2 ,$$

or

$$F(63) \approx 10^{-16} \text{ W cm}^{-2} . \tag{4}$$

This corresponds to our observed flux. Collisional de-excitation is not yet appreciable at the densities cited here, though it might become significant in the higher density shocks. Electrons produced through the ionization of carbon will also collide with the atoms, but the atomic collisions effectively dominate the cooling function of interest here. The 2000 K temperature which suffices to produce the observed 63 μm line flux is not sufficient to lead to 6300 Å emission since the Boltzmann factor in the cooling function for 6300 Å emission is exp $[-(22{,}700/T)] \approx 10^{-5}$. Even if shock temperatures of the order of 3000 K were considered, the Boltzmann factor 5×10^{-4} would still be too small to permit appreciable 6300 Å emission.

It is conceivable, however, that a heated H I region at 5000 K, just beyond the ionization front, could account for part of the 63 μm flux and contribute to the 6300 Å radiation as well. A more detailed calculation would be required to examine the transition region between neutral and ionized gas at the edge of the nebula and is beyond the scope of this paper.

b) 51.8 and 88.35 Microns [O III]

All of our 52 and 88 μm data were obtained on the first and third observing nights and were therefore unaffected by the icing problem encountered on the second night. The upper limits we set to the strengths of the 51.8 and 88.35 μm [O III] lines are $\sim 10^{-16}$ W cm^{-2} and 10^{-17} W cm^{-2}, respectively.

The upper limit on the line fluxes at 51.8 μm and 88.35 μm can yield information about the electron density in the [O III] emitting region. We can write an expression for the estimated flux in the form

$$F(^3P_k \rightarrow {}^3P_i) = \frac{hc}{4\pi\lambda} A(k, i) f_k(n_e, T) \frac{n(O^{++})}{n_e} n_e l\Omega , \tag{5}$$

where k and i equal 2 and 1, respectively for the 51.8 μm transition and 1 and 0, respectively, for the 88.35 μm transition. $A(k, i)$ is the transition probability (Garstang 1968), $f_k(n_e, T)$ is the fraction of all doubly ionized oxygen atoms in the ^3P_k state, $n(O^{++})/n_e$ is the fractional abundance of O^{++} and l and Ω are the line-of-sight length and solid angle, respectively, of the [O III] emitting regions. Atherton *et al.* (1979) have measured a size of $14'' \times 10''$ for this region on the basis of the 5007 + 4959 Å lines of [O III]. Peimbert and Torres-Peimbert (1971) have determined an ionic abundance, $n(O^{++})/n(H^+)$ of 2×10^{-4} in NGC 7027 and, taking $n_e/n(H^+) \approx 1.1$, we have $n(O^{++})/n_e = 1.8 \times 10^{-4}$. Assuming a distance to NGC 7027 of 1 kpc, the electron densities implied by the upper limits to the 51.8 and 88.35 μm line fluxes are $n_e < 1.5 \times 10^5$ cm^{-3} and $n_e < 1.6 \times 10^5$ cm^{-3}, respectively. These densities are in agreement with those of Kaler *et al.* (1976) who used the optical lines of [O III] to obtain $8 \times 10^4 < n_e < 2 \times 10^5$ cm^{-3}. This agreement may be viewed as a confirmation of our assumed ionic abundance. However, uncertainties in our measured upper limits, as well as in the l and Ω values appropriate to the [O III] region, are probably large enough to prevent us from discriminating between different published values.

c) The Continuum

During the course of our line measurements, continuum fluxes were measured on both sides of each line position. These are displayed in Figure 2. Although we have limited wavelength coverage, the relatively narrow passband provides us with greater certainty about the wavelength at which the continuum has been observed, compared to earlier photometric measurements, and warrants further discussion of these data.

A fit to the continuum values shown in Figure 2 forms a smooth connection to the 16–38 μm spectrum obtained

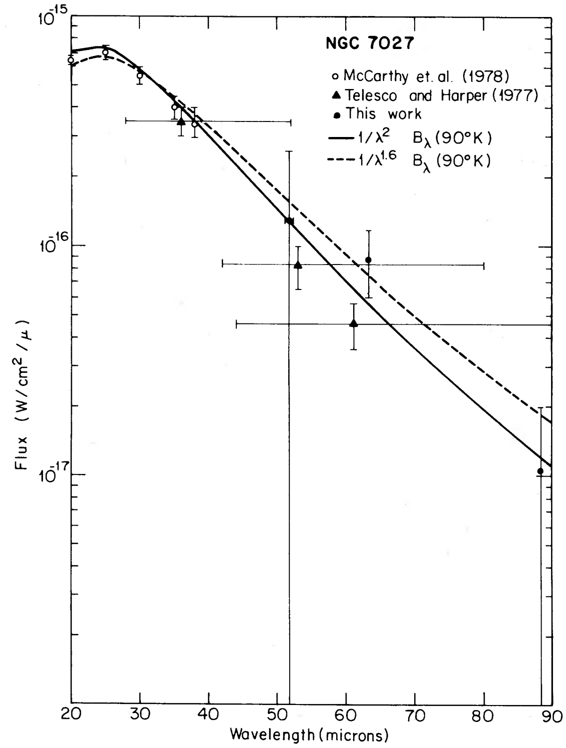

FIG. 2.—Mid- and far-infrared continuum spectrum of NGC 7027. Continuum fluxes from this work are averages of the continuum points measured in the spectral vicinity of the emission lines we sought. Where large enough to plot, the horizontal error bars reflect the bandpass of each value. Only a representative number of data points have been used from the work of McCarthy, Forrest, and Houck (1978).

by McCarthy, Forrest, and Houck (1978) and is in agreement with the broad-passband results of Telesco and Harper (1977). Data obtained from these previous studies were well fitted by a 90($\pm$5) K blackbody with a $1/\lambda^2$ emissivity. Our data can also be fitted with a 90 K blackbody with a $1/\lambda^2$ emissivity. More generally, if it is assumed that the grains are characterized by the single temperature of 90 K and that their emissivities vary as $1/\lambda^n$, then the spectral points between 16 and 88 μm (McCarthy *et al.* and ours) indicate that $1.6 < n < 2$, and the absolute emissivity at 25 μm is $\sim 10\%$ if all the dust is contained in an $11'' \times 14''$ field of view.

IV. CONCLUSION

Our main finding is that NGC 7027 emits about 30 $L_\odot$ in the 63 μm [O I] line if the planetary nebula lies at a distance of 1 kpc. Observations at the [O III] line positions (88 and 52 μm) set an upper limit on the electron density of $n_e \lesssim 1.6 \times 10^5$ cm^{-3}. The continuum flux, which we are able to measure at more precisely determined wavelengths, is in good agreement with the broad-band photometric values of Telesco and Harper (1977).

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