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16–38 MICRON SPECTROSCOPY OF NGC 7027

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ABSTRACT

Medium-resolution spectral observations of NGC 7027 from the Kuiper Airborne Observatory from 16 to 38 microns show a smooth continuum with a peak flux of 7×10^{-16} W cm^{-2} μm^{-1} between 20 and 25 μm. The absence of a predicted [O IV] fine-structure line at 25.91 μm implies an electron density greater than 2.5×10^4 cm^{-3} in the region where this ion exists. No evidence for a predicted carbonate resonance in the 22–35 μm range was observed. This result calls into question the carbonate identification for the 11.3 μm feature seen previously. One possible model consisting of small graphite grains at about 90 K which fits all the spectral observations longward of 20 μm is suggested. The large dust (2.5×10^{-2} $M_\odot$) and gas (1 $M_\odot$) masses which result imply that much of this radiation is from the molecular cloud surrounding the ionized region. Further observations which would test this model are proposed.

Subject headings: infrared: spectra — interstellar: matter — nebulae: individual — nebulae: planetary

I. INTRODUCTION

NGC 7027, the brightest planetary nebula at infrared wavelengths, has an interesting and complex spectrum. Numerous emission and forbidden lines from the ultraviolet out to the mid-infrared have been observed (Bohlin, Marionni, and Stecher 1975; Kaler *et al.* 1976; Treffers *et al.* 1976; Merrill, Soifer, and Russell 1975; Gillett, Forrest, and Merrill 1973). In the 1–3 μm region the continuum is dominated by thermal emission from the ionized gas, but at ~ 3 μm thermal emission by dust becomes important and dominates at longer wavelengths (Willner, Becklin, and Visvanathan 1972; Merrill, Soifer, and Russell 1975; Gillett, Forrest, and Merrill 1973). In the 2–4 μm and 8–13 μm bands several possible continuum features have been seen, in particular the 11.3 μm feature which has been tentatively identified as due to carbonate minerals in the dust grains (Gillett, Forrest, and Merrill 1973; Bregman and Rank 1975). Radio observations show a typical free-free emission spectrum (Scott 1973) plus ^{12}CO and ^{13}CO emission (Mufson, Lyon, and Marionni 1975). This paper reports on new medium-resolution spectroscopy from 16 to 38 μm.

Optical photographs of the nebula show an irregular form which is quite different from the symmetrical 10 μm and 5 GHz maps (Becklin, Neugebauer, and Wynn-Williams 1973; Scott 1973). This is interpreted as due to obscuration by patchy dust clouds, and Osterbrock (1974) has been able to show that most of the optical extinction occurs exterior to the H II region.

II. OBSERVATIONS

The observations were performed on the nights of 1976 May 18–19 and 20–21 with a dual-channel helium-cooled grating spectrometer attached to NASA's KAO 36 inch (91 cm) telescope. The short-wavelength channel (16–23 μm) has a $\Delta\lambda = 0.5$ μm and uses an arsenic-doped silicon photoconductor for a detector, while the other channel (20–38 μm), with a gallium-doped germanium photoconductor, has $\Delta\lambda = 1.2$ μm. The data were taken at a density of three points per resolution element. The beam had a diameter of 32″ and was centered on the visual object. Standard chopping and beam-switching techniques were used.

To determine the shape of the spectrum the data were divided by a lunar spectrum taken with the same equipment on the night of 1976 May 18–19. The beam was placed near the subsolar point, and the lunar spectrum was assumed to be a blackbody with $T =$ 375 K. The absolute flux calibration was achieved by normalizing to the 20 μm broad-band flux for NGC 7027 reported by Becklin, Neugebauer, and Wynn-Williams (1973). Finally, small air-mass corrections were applied for the extinction due to the 15 μm carbon dioxide band, which affected the data from 16 to 17 μm.

III. RESULTS

The spectrum obtained is shown in Figure 1. Where large enough to plot, the errors shown are standard deviations of the mean. Within the errors, the spectrum is smooth and has the shape of a dilute 130 K blackbody but falls below that curve at the longer wavelengths. Agreement with the broad-band results of Telesco and Harper (1977) at 36 μm is excellent. The dip shown in the broad-band observations from 18 to 27 μm by Jameson *et al.* (1974) is not consistent with our data. Their 27 μm point is about a factor of 2 lower, although their 18 μm and 22 μm points agree with our data within the errors.

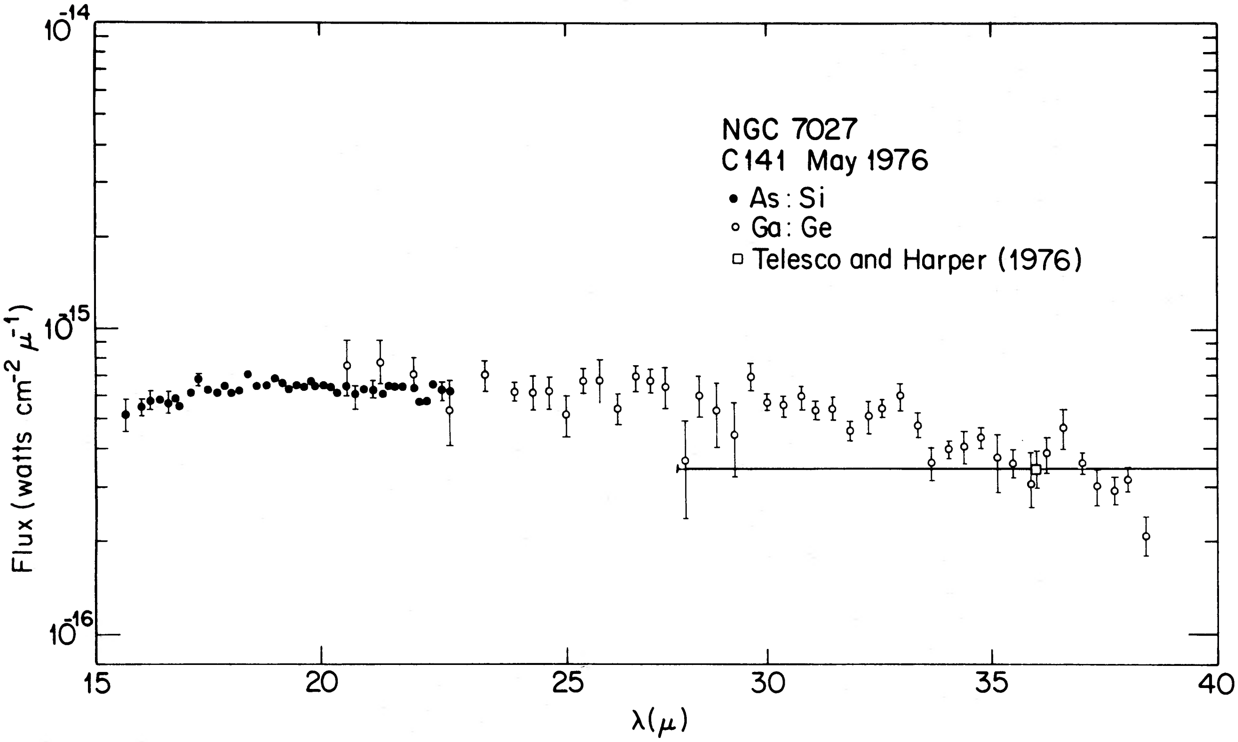

FIG. 1.—Spectrum of NGC 7027 from 16 to 38 microns. *Open and closed circles*, present observations; *open squares*, from Telesco and Harper (1977), whose bandwidth is indicated by the horizontal line.

Various theoretical models predict spectral features in the 16–40 μm band. Their absence from the data sets limits on the physical conditions within the nebula. The strongest predicted features are a fine-structure line of O IV at 25.91 μm, and a broad emission feature in the 22–35 μm region due to carbonate minerals. In the following sections the lack of these features is discussed, and a simple model of graphite grains is proposed to explain the observed featureless continuum.

a) *The* O IV *Line*

The emissivities of many infrared lines have been calculated by Simpson (1975), and, using these data and simple uniform models for planetary nebulae, she has made predictions of the intensities of these lines in several planetaries. In the case of the [O IV] fine-structure line at 25.91 μm, a total flux of 3.8×10^{-16} W cm^{-2} was predicted which, at our resolution, should appear as a bump with a height 60% above the continuum and about a micron wide. This is not seen, and an upper limit of half the prediction, or 1.9×10^{-16} W cm^{-2}, can be set.

This discrepancy can be interpreted as indicating that the electron density is higher than assumed. If one accepts the other parameters assumed by Simpson (electron temperature 15,000 K, electron-to-proton density ratio of 1.169, O IV–to–proton density ratio of 1.2×10^{-4}, and emission measure of 6.7×10^7 cm^{-6} pc), then the electron density will have a lower limit of 2.5×10^4 cm^{-3}, whereas Simpson had assumed 6300 cm^{-3}. Our lower limit is in agreement with results obtained by other methods. By fitting a 5 GHz high-resolution map to a cylindrical shell model, Scott (1973) derived $T_e = (13 \pm 2) \times 10^3$ K and $n_e = (5.0 \pm 0.5) \times 10^4$ cm^{-3} as average values in the nebula. Using observations of forbidden lines of five ions, Saraph and Seaton (1970) found that the derived electron density increased with ionization potential. These results are interpreted as evidence for large-scale density variations, and this idea is confirmed by Kaler *et al.* (1976). The densities deduced by Saraph and Seaton ranged from $n_e \approx 6 \times 10^3$ cm^{-3} for S II and O II up to $n_e \approx 1.5 \times 10^5$ cm^{-3} for Ar IV and K V. Since O III has an ionization potential intermediate between Ar III and K IV, it seems that O IV, like Ar IV and K V, should be found in a region of high electron density ($n_e \sim 10^5$ cm^{-3}), which would account for its absence from our spectrum.

b) *Carbonates*

First observed at moderate resolution by Gillett, Forrest, and Merrill (1973), the 11.3 μm feature has been attributed to carbonate grains, primarily $MgCO_3$, $CaCO_3$, and $FeCO_3$, since these species are expected to be dominant on the basis of abundance arguments. The existence of the feature was confirmed by Aitken and Jones (1973), although they claimed that the profile was "ragged," unlike the smooth shape expected from a grain resonance. Using higher resolution, Bregman and Rank (1975) fitted a combination of carbonate lab spectra to the 11.3 μm feature and concluded that $MgCO_3$ was about an order of magnitude more abundant than both $CaCO_3$ and $FeCO_3$.

The most recent measurements of the strength and location of carbonate bands have been performed by Penman (1976*a*, *b*), who covered the range 200–2000 cm^{-1} in both magnesite ($MgCO_3$) and calcite ($CaCO_3$). The reflectivity of bulk crystals was measured, and the optical constants were calculated using Kramers-Kronig analysis; then Mie theory was employed to derive the mass absorptivity.

Penman's results for small magnesite spheres show the 11.3 μm and 7 μm features familiar from the results of Hunt, Wisherd, and Bonham (1950). In addition, there is another feature found at 24.4 μm which is intermediate in strength between the 7 and 11.3 μm features. The two short-wavelength features (plus a weaker one in the 14–15 μm region whose peak wavelength is sensitive to the identity of the cation) are due to transitions between the various stretching and bending modes of the carbonate ion itself. In addition, the carbonate ion as a whole can vibrate and rotate with respect to the neighboring cations, giving rise to lattice modes (White 1974). Transitions between these states cause bands longward of 20 μm, e.g., the 24.4 μm feature of magnesite. The exact position of the resonances depends not only on the chemical composition but also on the crystal structure. For example, the calcite form of $CaCO_3$ has a peak at 30 μm, while aragonite peaks around 40 μm (Morandat, Lorenzelli, and Lecomte 1967).

Penman's results longward of 20 μm have been compared with studies of the transmission of suspensions of finely ground carbonate minerals by Angino (1967) and Morandat, Lorenzelli, and Lecomte (1967). These qualitative spectra are in fair agreement with each other and with Penman's derived spectra for small spheres. The correspondence is better when Penman's optical constants are used to calculate a spectrum for a mixture of shapes (equal parts by mass of spheres, needles, and disks) suggesting that the differences are due to varying shape distributions.

By combining the observed 11.3 μm flux, an upper limit to the 22–33 μm carbonate resonance flux, and Penman's mass absorption coefficients, a lower limit to the grain temperature and the flux in the strongest band at 7 μm can be estimated. If the dust is optically thin, then the flux in a band is

$$F_\lambda = B_\lambda(T_d)\kappa_\lambda \frac{M_d}{D^2}, \quad (1)$$

where $B_\lambda(T_d)$ is the blackbody intensity for the grain temperature T_d, κ_λ is the mass absorption coefficient, M_d is the mass of dust, and D is the distance to the nebula. After subtracting the continuum, we obtain 4.5×10^{-16} W cm^{-2} μm^{-1} as the flux in the 11.3 μm feature (Gillett, Forrest, and Merrill 1973), and we will use 2×10^{-16} W cm^{-2} μm^{-1} (approximately 30% of the observed continuum) as an upper limit to the flux in any feature in the 22–33 μm region. If we consider particles of pure $MgCO_3$, as suggested by the results of Bregman and Rank (1975), and use Penman's mass absorption coefficients for small spherical particles (with the neighboring continuum subtracted out), then we find $T_d \gtrsim 540$ K and we predict $F_{7\,\mu m} \gtrsim 66 \times 10^{-16}$ W cm^{-2} μm^{-1}, where $F_{7\,\mu m}$ is the flux in the feature alone. The total observed flux at 7 μm is $\sim 5.5 \times 10^{-16}$ W cm^{-2} μm^{-1} (Russell, Soifer, and Willner 1977), so clearly there is a substantial disagreement.

The assumption of spherical grains may not hold in the case of NGC 7027. As an approximation to a continuous distribution of shapes, we have used Penman's (1976*b*) optical constants for magnesite to compute mass absorption spectra for a mix of shapes consisting of equal mass fractions of spheres, infinitely thin needles, and infinitely flat disks. (Spectra of more nearly continuous distributions of shapes have been calculated. The primary effect is to smooth and flatten the 22–33 μm resonance, but the predicted 7 μm flux is nearly the same as below.) Compared with the spectrum of spheres, this distribution has a broadened and truncated 7 μm feature extending from 6.4 μm to 7.1 μm, bifurcated and shifted lattice mode band in the 25 μm region, a slightly stronger 11.3 μm resonance, and a generally enhanced continuum. These spectra are compared with the data in Figure 2. Employing the same procedure as before yields considerably different results: $T_d \gtrsim 280$ K and $F_{7\,\mu m} \gtrsim 9.6 \times 10^{-16}$ W cm^{-2} μm^{-1}. The flat top of the broadened 7 μm feature now has a relatively minor bump at 7.04 μm. Quantitatively, however, the predicted 7 μm flux in this feature is still considerably higher than the observed 7 μm flux. If the dust were instead made out of calcite ($CaCO_3$) but with the same shape distribution, the upper limit on the dust temperature would be lowered to ~ 250 K, but because of differences in the mass absorption spectrum the flux in the 7 μm feature would reach a slightly higher peak flux of 10.3×10^{-16} W cm^{-2} μm^{-1} at a wavelength of 7.1 μm. This again is more than the total observed flux. These calculations are summarized in Table 1.

How can this disagreement be understood? Optical depth effects could act to round off the spectral features. To test this, one can calculate values of the carbonate mass column density by assuming a solid angle for the source; for this purpose $\Omega = 1.5 \times 10^{-9}$ sr was used, corresponding to an $8'' \times 8''$ rectangle (Becklin, Neugebauer, and Wynn-Williams 1973). The derived column densities can be converted into 7 μm optical depths, and in all cases $\tau_{7\,\mu m} \ll 1$ (see Table 1). Since the 7 μm resonance is the strongest one in the carbonate infrared spectrum, this indicates that the carbonate dust is optically thin in all bands. However, there is still the possibility that individual particles may be large enough to be optically thick. If we model a grain as having a cross section s, thickness b, and density ρ, then we reach $\tau = 1$ for a thickness $b = 1/\kappa_\lambda \rho$. Terrestrial $MgCO_3$ crystals have $\rho = 3.0$ g cm^{-3} and calcite has $\rho = 2.7$ g cm^{-3}, which for the 7 μm feature yields $\tau = 1$ thickness of 0.7 μm and 0.4 μm, respectively. These sizes are at the upper bound of those normally quoted for interstellar

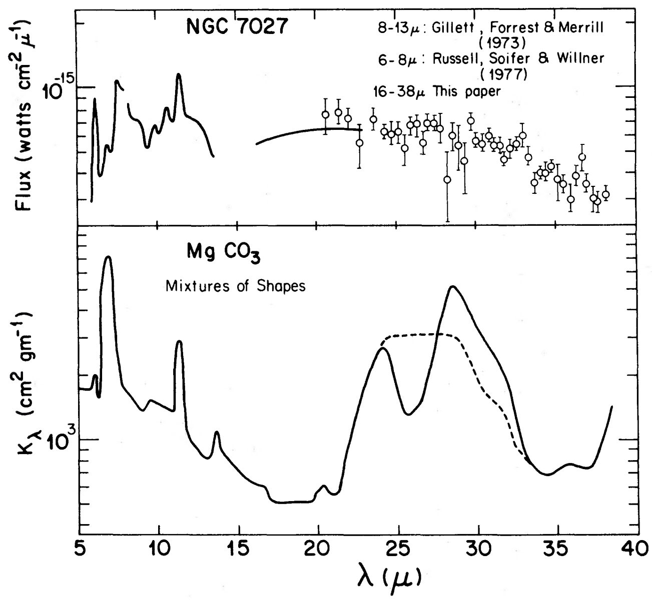

FIG. 2.—*Top:* Observed spectrum of NGC 7027 from 8 to 38 microns. *Bottom:* Calculated mass absorption coefficient for small particles of $MgCO_3$, based upon the optical constants of Penman (1976*b*). *Solid line*, a mixture of particle shapes consisting of equal mass fractions of spheres, thin needles, and flat disks, all randomly oriented; *dotted line*, a more nearly continuous distribution of shapes.

grains (Aannestad and Purcell 1973), so it seems unlikely that the individual grains are becoming optically thick.

Other explanations of the discrepancy between the predicted and observed 7 μm fluxes are more speculative. Since the long-wavelength resonances are due to lattice vibration and rotation modes, one might expect that amorphous forms of carbonates (similar to the amorphous silicates studied by Day 1974) might not exhibit these bands. Since no spectra of these materials exist, one simply cannot say whether this is true. The presence of impurities in the carbonate lattice would have a similar effect. Water of hydration has been observed to change the location and strength of the long-wavelength features (Angino 1967). Another possible effect is a temperature-dependent variation in the spectrum analogous to those seen by Day (1976) in silicates. Nonetheless, the identification of the 11.3 μm feature with ordinary crystalline carbonates similar to those studied by Penman does seem to be in doubt.

c) *Graphite Model*

In § III*b* it was shown that carbonates are probably not a major contributor to the observed smooth continuum in the 16–38 μm range (Fig. 1). In particular, all the measurements of carbonates available to us indicate a small emissivity from 16–20 μm (cf. Fig. 2), which is not observed in NGC 7027. Further, the observed spectrum is unlike the emission from the Trapezium (Forrest, Houck, and Reed 1976; Forrest and Soifer 1976) and from oxygen-rich stars (Treffers and Cohen 1974). This indicates that silicates are probably not the predominant grain constituent. A possible grain material which will explain the observed continuum in the 16–38 μm region is graphite. At infrared wavelengths the emissivity of small graphite grains goes as $\kappa_\lambda \sim 1/\lambda^2$ (Werner and Salpeter 1969); a comparison of the observed 8–100 μm data with the expected emission from 95 K grains with emissivity proportional to $1/\lambda^2$ is shown in Figure 1 of Telesco and Harper (1977). A similar comparison for the

TABLE 1

PARAMETERS OF CARBONATE MODELS

Case	T_d	$F_{7\,\mu m}$*	$\tau_{7\,\mu m}$†
		($W\ cm^{-2}\ \mu m^{-1}$)	
$MgCO_3$ spheres	$\gtrsim$540 K	$\gtrsim 66 \times 10^{-16}$	$\lesssim 3.3 \times 10^{-4}$
$MgCO_3$ mixture of shapes	$\gtrsim$280 K	$\gtrsim 9.6 \times 10^{-16}$	$\lesssim 1.8 \times 10^{-3}$
$CaCO_3$ (calcite) mixture of shapes	$\gtrsim$250 K	$\gtrsim 10.3 \times 10^{-16}$	$\lesssim 4.1 \times 10^{-3}$

* Flux in feature only. Continuum plus feature is, respectively, 1.19, 1.26, and 1.18 times $F_{7\,\mu m}$.
† Assuming $\Omega = 1.5 \times 10^{-9}$ sr.

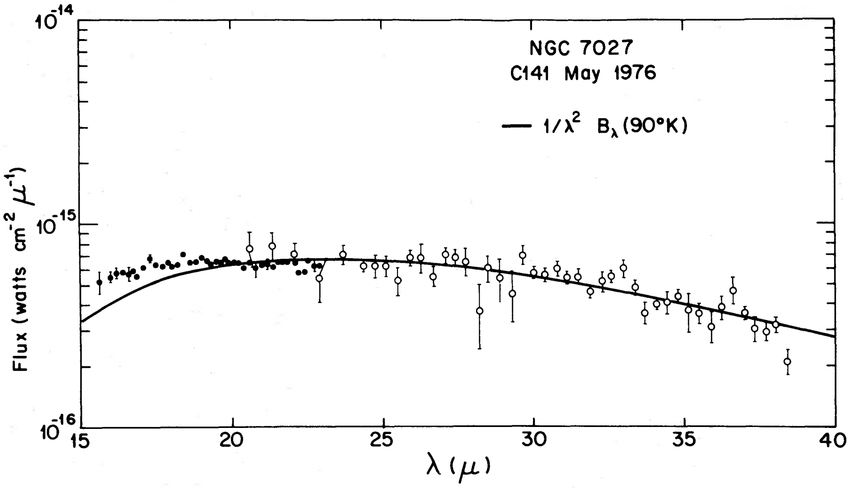

FIG. 3.—Theoretical fit (*solid line*) to the NGC 7027 spectrum as described in the text

present 16–38 μm data is shown in Figure 3; it was found that a 90 K grain temperature provided a slightly better fit than the 95 K adopted by Telesco and Harper (1977). It is seen that this model fits all the spectral observations longward of 20 μm. The excess at shorter wavelengths could be due to a component of hotter dust in this source.

Several recent determinations (Torres-Peimbert and Peimbert 1977; Panagia, Bussoletti, and Blanco 1977; Péquignot, Aldrovandi, and Stasinska 1977; Shields 1978) indicate that carbon is significantly overabundant in NGC 7027, which suggests that graphite is a likely grain material. If the grains are small (radius $\lesssim 0.1$ μm), spherical graphite grains, the mass in dust required to give the observed flux (eq. [1]) is approximately $2.5 \times 10^{-2} M_\odot$ (assuming a distance of 1 kpc), and the corresponding total mass is approximately 1 $M_\odot$ (assuming the carbon abundance given by Torres-Peimbert and Peimbert 1977). This mass is much larger than the mass in ionized gas but is comparable to the mass of the recently discovered molecular cloud surrounding NGC 7027 (Mufson, Lyon, and Marionni 1975).

A major uncertainty in this estimate of the nebular mass is the mass opacity coefficient κ_λ appropriate for the grains in this object. Other solid forms of carbon which could approximate the $1/\lambda^2$ opacity dependence which is indicated by the present data and the observations of Telesco and Harper (1977) are amorphous carbon, highly elongated graphite grains, and very large spherical graphite grains. For amorphous carbon, $\kappa_{31\,\mu m}$ is approximately 4 times larger than for graphite (Hagemann, Gudat, and Kunz 1974). For very elongated (length/width $\gtrsim 7$) or very large (radius ≈ 1 μm) graphite grains, the 30 μm emissivity per unit mass would be approximately 10 times that of the small, spherical grains considered here. Several observational tests might be able to distinguish between these various possible grain materials. If the grains are small and the mass, therefore, large, much of the grain mass responsible for the far-infrared emission must be exterior to the H II region. A scan through the center of NGC 7027 at 20 μm with 2".5 resolution by Becklin, Neugebauer, and Wynn-Williams (1973) shows no evidence for a component broader than the 10 μm emission which in turn is closely similar to the distribution of ionized gas. This is a major problem for the present model but is not sufficient to rule out the existence of a broader component at long wavelengths. High-spatial-resolution measurements in the 34 μm atmospheric window might be able to resolve this component, though the possibility of a thin shell of material surrounding the H II region may be hard to distinguish from dust mixed in the region. The alternative grain types will have different short-wavelength absorption and scattering properties than the small spherical graphite grains considered here. Therefore a study of the extinction and polarization caused by the dust in and around NGC 7027 may be able to distinguish between various grain models. As an example, for large grains, the extinction will be nearly neutral and polarization upon scattering small at visual wavelengths. Thus observations of reddening or polarization due to the dust in and around NGC 7027 would support the small-grain dust model.

Two further questions regarding the viability of this model for the far-infrared emission from NGC 7027 have been considered. First, Telesco and Harper (1977) have shown that there is probably sufficient energy in the form of diffuse nebular radiation (other than Lα) at optical and shorter wavelengths to power the far-infrared emission. Thus the model of far-infrared emission from grains surrounding the H II region is energetically allowed. Second, the temperature of a single 0.1 μm radius graphite grain bathed in this radiation field at an angular distance θ_r arcsec from the ionized region is estimated from energy balance to be $T_d \approx 250\ \mathrm{K}/\theta_r^{1/3}$. This calculation assumes spherical symmetry, a heating flux corresponding to the 1.6×10^{-14} W cm^{-2} of far-infrared emission observed at the Earth (Telesco and Harper 1977), grain absorption efficiency $Q_{abs} = 1$ for the short-wavelength photons, and $Q_{abs} = 1.5 \times 10^{-3}(30\ \mu m/\lambda)^2$ appropriate for graphite in the far-infrared. Thus at a distance of 10″ from the center, such a grain is expected to reach a temperature of about 115 K, which is somewhat higher than the 90–95 K indicated by the infrared spectra. For a finite optical depth in the shell the predicted temperature would be reduced. However, this is a very gradual process, because for a $1/\lambda^2$ emissivity dependence the luminosity from a grain goes as T_d^6 (cf. eq. [2] of Telesco and Harper 1977). More detailed modeling of this source is necessary to evaluate the significance of this temperature discrepancy.

IV. CONCLUSIONS

The 16–38 μm spectrum of NGC 7027 has been found to be quite smooth with a peak flux of 7×10^{-16} W cm^{-2} μm^{-1} between 20 and 25 μm. The absence of a predicted [O IV] fine-structure line at 25.91 μm is consistent with an electron density $n_e > 2.5 \times 10^4$ cm^{-3} which is reasonable for this nebula. The absence of any isolated emission features in the 22–35 μm region where carbonate minerals are expected to resonate implies that the carbonate identification for the 11.3 μm feature suggested by Gillett, Forrest, and Merrill (1973) may not be correct. A model of small graphite grains at around 90 K which does reproduce the observed spectrum longward of 20 μm is suggested. The very large dust ($\sim 2.5 \times 10^{-2}\ M_\odot$) and gas ($\sim 1\ M_\odot$) masses which result imply that most of this mass is associated with the molecular cloud surrounding the ionized region. High-spatial-resolution far-infrared scans and observations of short-wavelength extinction and polarization in and around the nebula may be able to distinguish between alternative grain models.

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Note added in proof.—In our spectrum there are two high points at 33.0 μm and 36.6 μm. Russell (private communication) has tentatively suggested identifying them with [S III] and [Ne III] lines, respectively. Greenberg (private communication) gives the wavelengths of these lines as 33.44 and 36.02 μm which would put the line center one point to the right of the 33.0 μm point and the [Ne III] line two points to the left of the 33.6 μm point. Furthermore, both of these points were measured in only one of the four spectra which were averaged into our final result. Therefore we are reluctant to identify these high points with line emission.

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