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DETECTION OF [O IV] AND [Ne V] INFRARED EMISSION LINES FROM NGC 7027

W. J. FORREST, J. F. MCCARTHY, AND J. R. HOUCK
Center for Radiophysics and Space Research, Cornell University
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ABSTRACT

Medium-resolution ($\Delta\lambda \approx 0.16$ μm) spectroscopy of NGC 7027 in the wavelength range 16–30 μm using the NASA C-141 Kuiper Airborne Observatory has revealed the presence of two emission lines due to fine-structure transitions in Ne V and O IV superposed on a smooth continuum. The [Ne V] line is at a wavelength of 24.28 μm with a flux of 3.0×10^{-10} ergs cm^{-2} s^{-1}. The [O IV] line is at a wavelength of 25.87 μm with a flux of 5.8×10^{-10} ergs cm^{-2} s^{-1}. The line strengths are in good agreement with the model predictions of Péquignot, Aldrovani, and Stasinska. The abundance of these high-excitation ions appears to be quite high, comparable to the standard abundances of Ne and O. Since the formation of Ne V by photoionization requires at least 97 eV, the central star must be very hot. The continuum is shown to be very similar in shape to that observed for the galactic H II regions M17 and the Orion Nebula (using the NASA Lear Jet telescope). This indicates that the dust grains responsible for the far-infrared emission may be similar in these objects (i.e., silicates); however, alternative grain compositions are also discussed.
Subject headings: infrared: spectra — nebulae: planetary

I. INTRODUCTION

The planetary nebula NGC 7027 is a fascinating object with a complex and interesting spectrum and structure. In a previous paper (McCarthy, Forrest, and Houck 1978, hereafter Paper I), we presented a medium-resolution ($\Delta\lambda \approx 0.8$ μm) spectrum of NGC 7027 over the spectral range 16–38 μm. In this *Letter* we report higher-resolution observations ($\Delta\lambda \approx 0.16$ μm) in the range 16–30 μm. The new observations confirm the previously observed continuum results and, in addition, show two new emission lines centered at 24.28 and 25.87 μm. These lines are identified with fine-structure transitions in the ground states of Ne V (24.28 μm) and O IV (25.87 μm). In the following sections the line emission is discussed in terms of the physical conditions within the nebula, and the implications of the observed continuum emission are reassessed.

II. OBSERVATIONS

NGC 7027 was observed with the NASA C-141 91 cm telescope (Kiuper Airborne Observatory). A liquid helium–cooled Ebert-Fastie grating spectrometer with a 10 element Si:Sb detector array provided a resolution varying from $\Delta\lambda \sim 0.17$ μm at 16 μm to $\Delta\lambda \sim 0.14$ μm at 30 μm. The entrance aperture limited the field of view to a 30″ circle on the sky. Standard chopping (~80″ throw) and beam-switching techniques were used. The detector signals were demodulated by an Intel 8080-based microprocessor system. The microprocessor also controlled the telescope beam-switching, data storage, and display. The data system is described more fully in McCarthy, Forrest, and Houck (1979). The NEP of this system was measured in flight to be about 7×10^{-14} W Hz$^{-1/2}$ for each of the 10 detectors near 25 μm wavelength.

NGC 7027 was observed for 26 minutes on the night of 1979 July 10–11 from an altitude of 41,000 feet (12,500 m). The line-of-sight water vapor varied smoothly from 24 to 18 precipitable microns during the observations. The shape of the spectrum has been determined by comparison with observations of the Moon, which was assumed to radiate as a gray body at a temperature of 400 K (Geoffrion *et al.* 1960). Small additional corrections were necessary between 16 and 17 μm because of differing amounts of terrestrial CO_2 absorption in the lunar and NGC 7027 spectra. The absolute flux level has been determined by observations of several standard stars at 20 μm. The accuracy of the flux calibration is estimated to be about ±10%. The resulting spectrum is shown in Figure 1(*a*).

III. DISCUSSION

As shown in Figure 1*a*, the 16–30 μm spectrum of NGC 7027 consists of a nearly flat, smooth continuum with a peak flux of avout 6×10^{-16} W cm^{-2} μm^{-1}. In addition are two unresolved emission lines near 24.3 and 25.9 μm. (The [S III] line at 18.7 μm observed by Greenberg *et al.* 1978 is below our detection limit.) The continuum and line emission will be discussed separately below.

a) The Emission Lines

Infrared emission lines from fine-structure transitions in the ground state are important probes of the ionized gas, as discussed by Delmer, Gould, and Ramsay (1967); Petrosian (1970); and Simpson (1975). Since the extinction in the infrared is many times less than at visual wavelengths, large extinction corrections are

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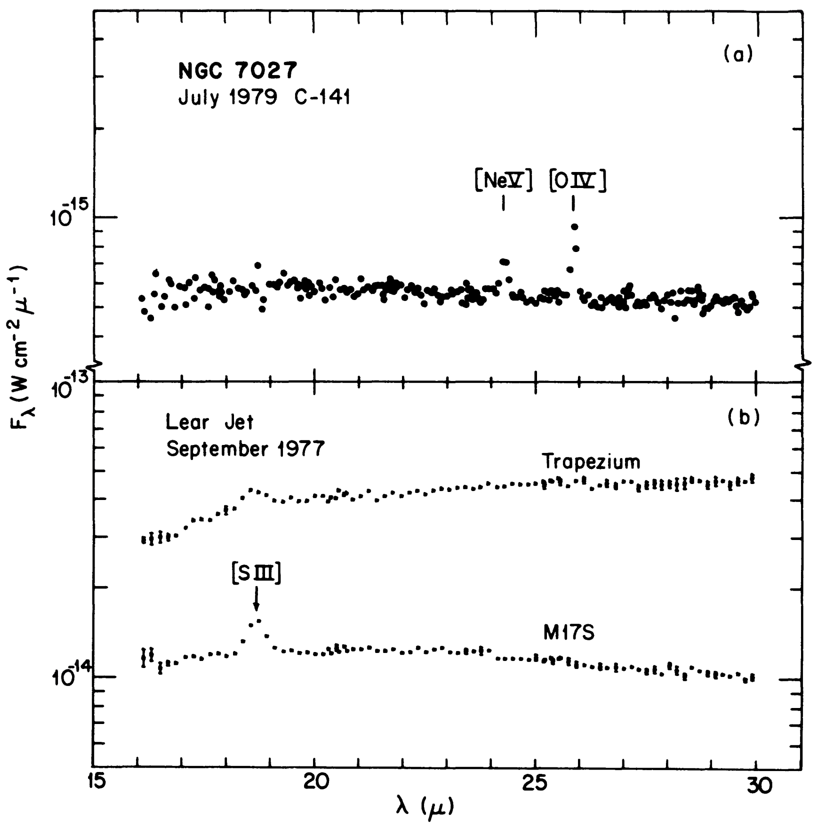

FIG. 1.—(*a*) The 16–30 μm spectrum of NGC 7027. The data have been taken at a density of two points per resolution element, so the errors may be estimated by the scatter in adjacent points. The predicted positions of the [Ne v] and [O IV] emission lines discussed in the text are noted. In the region of the spectrum between 24 and 27 μm the statistical errors were approximately ±3% on each point. (*b*) The 16–30 μm spectrum of the Trapezium region of the Orion nebula and the southern radio peak in M17. The spectral resolution is 0.5 μm, and the beam size was 2'.7. One-sigma error bars are shown where the statistical error is larger then the size of the points. An arrow marks the predicted position of the 18.7 μm [S III] emission line.

avoided. For NGC 7027 the extinction is quite patchy and the corrections at visual wavelengths are correspondingly less certain. The observed emission results from radiative decay of the ionic fine-structure levels which have been populated through collisions with the ambient electrons. The observed line strength depends mainly on the ionic abundance and the electron density within the nebula. The dependence on electron temperature is very weak for temperatures near 10^4 K, which are typical of H II regions and planetary nebulae. If the electron density can be determined independently, the observed line strengths give a good estimate of the ionic abundances. From this information, the excitation within the nebula and the atomic abundances may be derived. The ionic abundance ratios provide information on the spectrum of the exciting star at extreme ultraviolet wavelengths which cannot be observed directly. For NGC 7027, neither the total atomic abundances nor the stellar spectrum is well known.

Two emission lines are observed in the present spectrum. Data in and near the lines have been fitted with a Gaussian line profile and a linear baseline by minimizing χ^2. The resultant wavelengths and fluxes are given in Table 1. The estimated accuracy is ±0.02 μm in wavelength and ±15% in flux. Also included in Table 1 are the fluxes predicted by the best-fit model of Péquignot, Aldrovani, and Stasinska (1978, assuming an Hβ flux of 1.6×10^{-9} ergs cm^{-2} s^{-1}), the range of energies necessary to produce the ion in question (Allen 1973), and the derived ionic abundance (see next section).

In the following sections the significance of these new emission lines will be discussed further. The emissivity

TABLE 1

INFRARED FINE-STRUCTURE EMISSION LINES

Ion	Observed Flux[a] (10^{-17} W cm^{-2})	Model Flux[b] (10^{-17} W cm^{-2})	Energy Required to Form Observed Ion (eV)[c]	Derived Ionic Abundance[a] n(ion)/n(H)
O IV λ25.87......	5.8	4.8	55–77	3.9×10^{-4}
Ne V λ24.28.....	3.0	3.1	97–126	1.0×10^{-4}

[a] This *Letter*, see text.
[b] Péquignot *et al.* 1978, see text.
[c] Allen 1973.

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of the ions has been calculated by solving for the equilibrium of the five-level Ne V atom and the two-level O IV atom as a function of electron density and temperature. The transition rates given by Osterbrock (1974) and the collision cross sections calculated by Saraph, Seaton, and Shemming (1969)[1] have been assumed. In the comparison with the radio flux, an abundance ratio n(positive ions)/n(H) = 1.12 has been assumed. As will be shown later, the energy levels responsible for the [Ne V] and [O IV] lines observed here will be close to their values in thermal equilibrium for the densities appropriate for NGC 7027. Under these conditions, the ionic emissivity is independent of electron density and depends only weakly on electron temperature.

i) [Ne V], *24.28* μm

The newly observed emission line at 24.28 μm is most probably the $^3P_1 \rightarrow {}^3P_0$ transition in the ground state of Ne V. The identification is primarily based on the close coincidence with the wavelength of 24.25 μm predicted for this transition by Greenberg (1978). The Ne V ion is known to be abundant in NGC 7027 through its strong forbidden lines in the UV discovered by Wright (1918) and identified by Swings and Edlén (1934) and Bowen (1934). We are not aware of any other lines near this wavelength which are predicted to be strong in this nebula. The data of Traub and Stier (1976) show no significant telluric absorption features near the observed wavelength. In fact, the Ne V line occurs in a narrow window and could be observed from the ground at a very dry site ($\lesssim 1$ mm precipitable H_2O). The observed flux in this line is in close agreement in flux with the model predictions of Péquignot, Aldrovani, and Stasinska (1978; see Table 1). Because the ionization of Ne IV to Ne V requires 97 eV photons, the presence of Ne V requires a high temperature for the exciting star. This supports the identification of the 5.6 μm line with the Mg V as suggested by Russell, Soifer, and Willner (1977). Those authors estimated a temperature of $T \sim 2 \times 10^5$ K for the central star. Péquignot *et al.* used a temperature of 1.7×10^5 K.

For the [Ne V] line the critical density at which the rates for collisional de-excitation and spontaneous emission are equal is about $n_e \sim 4 \times 10^4$ cm^{-3} for an electron temperature of 12,500 K (Péquignot *et al.* 1978). As discussed in Paper I, the higher ionization states appear to occur in higher density regions in NGC 7027. The electron density appropriate for the Ne V ion (and the O IV ion discussed later) is about 2.5×10^5 cm^{-3}, based on the densities Kaler *et al.* (1976) found for ions with similar excitation potentials. By comparing the flux in the infrared line to the flux in the UV line at 3426 Å (Kaler *et al.* 1976) it is found that the electron temperatures and densities must satisfy $(T_e/12{,}500\ \mathrm{K})^3\ (n_e/2.5 \times 10^5\ \mathrm{cm}^{-3})^{1.1} = 0.93$ in the Ne V zone. Within the uncertainty in extinction, this agrees with the above estimates of 12,500 K and 2.5×10^5 cm^{-3} for the electron temperature and density.

At this density, the relative population in the energy level responsible for the 24.3 μm [Ne V] line is close to its thermal equilibrium value, so the flux depends only on the ionic column density. Then, using a radio flux of 6 Jy at 10 GHz (Higgs 1971) and the observed Ne V line strength (Table 1), we find an abundance of n(Ne V)/n(H) $\approx 1.0 \times 10^{-4}$. This is close to the standard abundance of Ne of 8×10^{-5} (Allen 1973) and a major fraction of the total Ne abundance found by Péquignot *et al.* of 2.2×10^{-4}. As is the case for the Mg V ion (Russell, Soiffer, and Willner 1977), we find a surprisingly large abundance of this very high ionization state of neon, Ne V.

ii) [O IV], *25.87* μm

The identification of the stronger line in Figure 1*a* with the $^2P_{3/2} \rightarrow {}^2P_{1/2}$ transition of O IV is based on the close correspondence with the prediction by Greenberg (1978) of 25.91 μm for its wavelength. The observed flux of 5.8×10^{-10} ergs cm^{-2} s^{-1} is in good agreement with the model prediction of Péquignot *et al.* (1978, see Table 1). For this [O IV] line there is some possibility of absorption by a strong terrestrial H_2O line centered at 25.94 μm (Traub and Stier 1976). However, our measurements of the line strength through 17 and 22 μm of water vapor were the same within the statistical uncertainty ($\pm 3\%$), and we conclude that atmospheric absorption could decrease the observed line strength by at most 15%. The strength of the [O IV] line observed here is consistent with the upper limit of 1.9×10^{-9} ergs cm^{-2} s^{-1} given in Paper I.

As is the case for the Ne V ion discussed earlier, the electron density in the region where O IV exists is high enough to saturate collisionally the energy levels. We estimate the critical density to be about 1.4×10^4 cm^{-3} for an electron temperature of 12,500 K. As discussed earlier, the density appropriate for the O IV ion is about 2.5×10^5. Then the present data and a radio flux of 6 Jy at 10 GHz (Higgs 1971) lead to an estimate of n(O IV)/n(H) $\sim 3.9 \times 10^{-4}$. The standard abundance of oxygen is about 6.6×10^{-4} (Allen 1973), while Péquignot *et al.* assumed an abundance of 7×10^{-4}. Thus a major fraction of the oxygen in NGC 7027 appears to be in the O^{+++} state.

b) The Continuum

From Figure 1*a* it is seen that the 16–30 μm continuum emission is very smooth. This makes the identification of the radiating material quite difficult. In Paper I it was shown that radiation from dust at a temperature of 90 K and with an emissivity $\epsilon_\lambda \propto 1/\lambda^2$ will fit the observed spectrum beyond 20 μm. It was suggested that small graphite grains in the molecular cloud surrounding NGC 7027 might be responsible for this radiation. However, a recent determination of the far-infrared optical constants of graphite by Philipp (1977) weakens this argument considerably. Applying the Mie theory for small grains with his data shows that $\epsilon_\lambda \propto 1/\lambda^3$ beyond 20 μm, with a bump around

[1] The averaged collision strengths tabulated by Osterbrock (1974) systematically assume $z = 1$ even for ions with $z \neq 1$.

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95 μm. In addition, the opacity per unit mass is about 20 $cm^2 g^{-1}$ at 31 μm, which is about half that assumed in Paper I. Since the emissivity is steeper than $1/\lambda^2$, the grain temperatures would have to be lower than 90 K to explain the observed emission. Taken together, the estimate of the dust mass in Paper I would have to be increased by more than a factor of 4 to $>0.1\ M_\odot$, which seems unreasonably large. In addition, the equilibrium temperature for grains at the edge of the H II region would be higher than the 115 K derived in Paper I, making the temperature discrepancy noted there even larger. It appears that small graphite grains are not a good candidate for the far-infrared emitters in NGC 7027.

Other possible grain materials which could produce the observed emission are amorphous carbon, large graphite grains, or very elongated graphite grains (see Paper I; Panagia, Bussoletti, and Blanco 1977). In addition, Draine (1978) has suggested that the Mie theory may not apply when the mean free path of the conduction electrons is greater than the size of the grain. For graphite, this occurs when the grain radius $a < 0.1\ \mu$m. For such small grains, the opacity per unit mass could be larger than that given by Mie theory (Draine 1978). This possibility deserves further investigation. However, as suggested by N. J. Woolf (1977, private communication), it is also possible that the grain material could be silicates. The 19 μm emission feature of silicates (Forrest, Houck, and Reed 1976; Forrest and Soifer 1976; Forrest, McCarthy, and Houck 1979) might be masked by a combination of absorption from colder material and emission from different temperature grains. This would be interesting because silicates are characteristic of oxygen-rich material, while the ionized part of NGC 7027 is believed to be carbon-rich (cf. Péquignot *et al.*). It would imply that chemical changes had occurred in the evolution of the preplanetary nebula star. If featureless 16–30 μm spectra are observed in objects which are independently known to contain silicate grains, then it becomes more plausible that the far-infrared emission of NGC 7027 could be due to silicates.

In Figure 1*b* are shown spectra of the Orion Nebula and M17, which were obtained with a big-beam system (2'.7 aperture) using the NASA Lear Jet. As shown by Forrest, Houck, and Reed (1976) and Forrest and Soifer (1976), the Trapezium region of the Orion Nebula exhibits a 19 μm emission feature attributed to silicates, while the nearby KL nebula has a weak absorption feature at 19 μm. The spectrum shown in Figure 1*b* was taken with a beam large enough to include both these objects. It can be seen that the resulting spectrum is quite smooth, with no indication of silicate features around 19 μm. The character of this spectrum is similar to NGC 7027. The bump at 18.7 μm here and in M17 is due to [S III] emission (McCarthy, Forrest, and Houck 1979). Even more striking is the spectrum of M17 shown in Figure 1*b*; the shape of the continuum radiation is nearly identical to that of NGC 7027 at these wavelengths. Since the bulk of the dust in M17 is probably silicates, this shows that under certain conditions the 19 μm silicate feature is suppressed. At longer wavelengths, M17 and the Orion Nebula radiate much more relative to NGC 7027, but this could be due to a larger population of cooler grains in those objects.

In conclusion, it appears that the identification of the grain material responsible for the far-infrared emission from NGC 7027 will not be easy. This is unfortunate because those grains represent the bulk of the dust mass in NGC 7027.

IV. CONCLUSIONS

Emission lines have been discovered in the spectrum of NGC 7027 at 24.28 and 25.87 μm and are identified with fine-structure transitions of Ne V and O IV, respectively. The observed wavelengths are in good agreement with the predictions of Greenberg (1978). The observed intensities are in good agreement with the model predictions of Péquignot, Aldrovani, and Stasinska (1978). The abundances of these high-excitation ions appear to be quite high, with $n(\text{Ne V})/n(p) \sim 1.0 \times 10^{-4}$ and $n(\text{O IV})/n(p) \sim 3.9 \times 10^{-4}$, assuming $n_e = 2.5 \times 10^5$ cm^{-3}. The large abundance and high excitation of the Ne V ion supports the identification of Mg V by Russell, Soifer, and Willner (1977), and indicates that the temperature of the central star is very high, $\sim 2 \times 10^5$ K. O IV appears to be the dominant ionization state of oxygen in NGC 7027.

The continuum emission from NGC 7027 is similar in shape to the emission from the galactic H II regions M17 and the Orion Nebula in the 16–30 μm region. This suggests that silicate grains could be responsible for the far-infrared emission from NGC 7027. A positive identification of the dust composition does not appear possible at the present time.

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W. J. Forrest and J. R. Houck: Department of Astronomy, Cornell University, Space Sciences Building, Ithaca, NY 14853

J. F. McCarthy: Hughes Aircraft Co., Space and Communication Group, P.O. Box 92919, Airport Station, Los Angeles, CA 90009

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