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INFRARED EMISSION BY DUST IN NGC 1068 AND THREE PLANETARY NEBULAE

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ABSTRACT

Photometric observations of NGC 1068, NGC 7027, IC 418, and BD +30°3639 between 5 and 27 μ are reported. The observations are explained as thermal radiation from a form of dust that shows spectral features, but which has not yet been identified, and resembles that in the carbon-rich RV Tauri star AC Her. Arguments are deduced for its being a condensate from a carbon- and nitrogen-rich gas in an excited environment.

Subject headings: infrared sources — planetary nebulae — Seyfert galaxies

I. INTRODUCTION

A multifilter infrared photometer was prepared for use with the NASA 36-inch telescope on a CV 141 aircraft. The photometer was being tested on the 60-inch (91-cm) telescope of the University of Minnesota and UCSD at Mount Lemmon in exceptionally arid conditions even for this site. It was found that there was, for two nights, high infrared transmission through a 24- to 35-μ passband filter, and so observations were made of the Seyfert galaxy NGC 1068 and three planetary nebulae, NGC 7027, BD +30°3639, and IC 418.

The purpose of these observations was to find whether any evidence could be found concerning the nature of the solid particles in planetary nebulae (Gillett, Low, and Stein 1967; Woolf 1969; Gillett, Forrest, and Merrill 1973; Krishna Swamy and O'Dell 1968; Gürtler 1972), and to see whether any spectral features might appear in the Seyfert galaxy. Such spectral features might be evidence to suggest an origin for the large infrared radiation of these objects.

II. OBSERVATIONS

The airplane telescope photometer included a dielectric interference filter with transmission from 24 to 35 μ. During the two arid nights, 1973 October 30 to November 1, when it was tested at Mount Lemmon Infrared Observatory, the relative humidity was below 10 percent. Observations of some K stars were compared with measurements of a laboratory source, and it was inferred that the average transmission through the band was about 45 percent. Water vapor spectra show that most of this transmission will have been attained at the short-wavelength side of the filter passband. Accordingly, for ground use the effective wavelength has been taken to be 27 μ. The observed extinction was approximately 1 mag per air mass.

Observations using an additional BaF_2 window demonstrated that on K stars approximately 10 percent of the signal came from a short-wavelength leak of the filter, and further studies showed that indeed this dielectric interference filter had a transmission of approximately 1 part in 10^5 near a wavelength of 1 μ. However, for the observations made here, small corrections (0.1 mag) for spectra peaking at wavelengths beyond 1 μ have been applied.

Observations are intended to fit the *UBV* Arizona system where a set of A0 V stars define zero magnitude at all wavelengths. In this case K stars have been used to transfer the calibration from the 10-μ region out to the longer wavelengths under the assumption that in this region they will radiate at a color temperature not far from their effective temperature. We use the formula F_λ (0 mag) $= 1.26 \times 10^{-12}/\lambda^4$ W cm^{-2} μ^{-1}. In table 1, magnitudes are quoted for a few secondary standard stars.

The readings showed a high level of consistency comparable to that at 18 μ. For the 27-μ observations of NGC 1068, of 44 total differences of 10-s integrations, obtained in three separate runs, all but three differences were positive.

Observations have also been made using a 12-filter photometer constructed by Gehrz (1972), though attention has mainly been directed to the longer wavelengths. For both photometers the aperture has a diameter of 11 arc seconds and the throw is 15 seconds. For NGC 1068 and BD +30°3639 this caused no problems, but for NGC 7027 and IC 418, which are too large for the beam, the signal has been substantially diminished. For NGC 7027, the direct observations are given in table 1, then in figure 1 the absolute fluxes have all been scaled up to agree with earlier measures at five wavelengths using larger apertures.[1] The factor seems to be uniform at all wavelengths (2.2 μ–11.5 μ), indicating that there are no marked systematic variations of spectral with spatial features in the infrared. Figure 2 shows the observations of BD +30°3639, and figure 3 compares the energy distribution of NGC 1068 with other objects. The solid line for NGC 1068 in figure 3 is taken from Jameson *et al.* (1974). It includes results by other observers as well, and in consequence does not exactly follow the results in table 1.

The observations of IC 418 have not been plotted because they are not of high enough quality at the

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[1] For this we used data by Gillett, Merrill, and Stein (1972) and Willner, Becklin, and Visvanathan (1972).

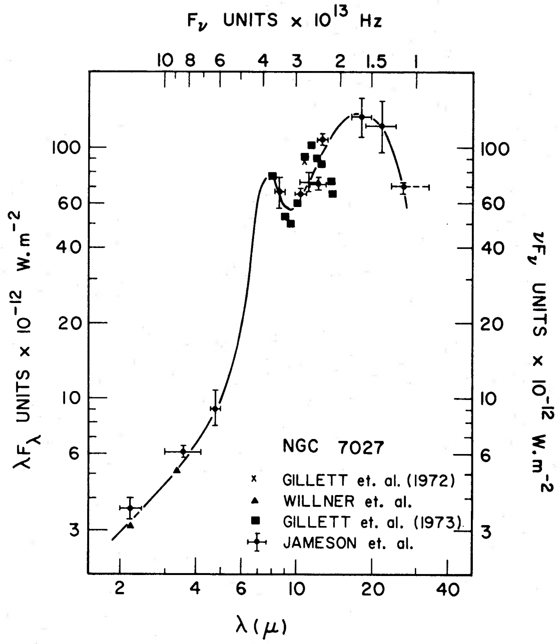

FIG. 1.—Infrared spectrum of planetary nebula NGC 7027. The wavelength error bars mark the half-transmission points of the filter.

shorter wavelengths to define the spectrum well. Clearly this planetary nebula is relatively faint at 8.6 μ compared with the other two, but despite this the emission seems to be concentrated into the 8- to 20-μ region as with the other nebulae.

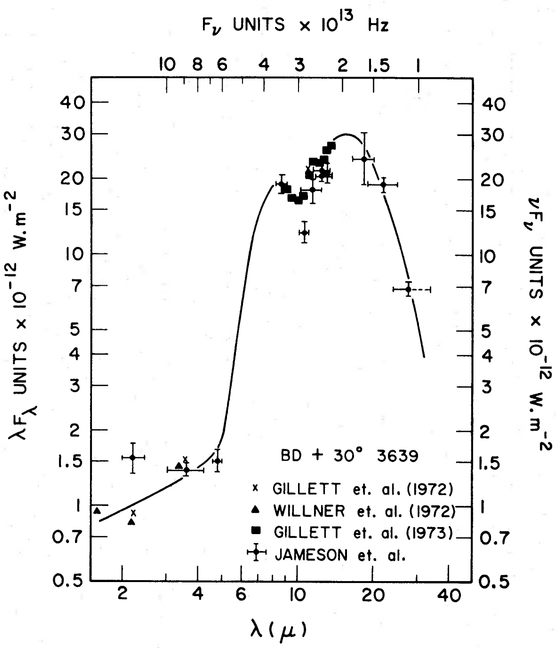

FIG. 2.—Infrared spectrum of planetary nebula BD + 30°3639. The wavelength error bars mark the half-transmission points of the filters.

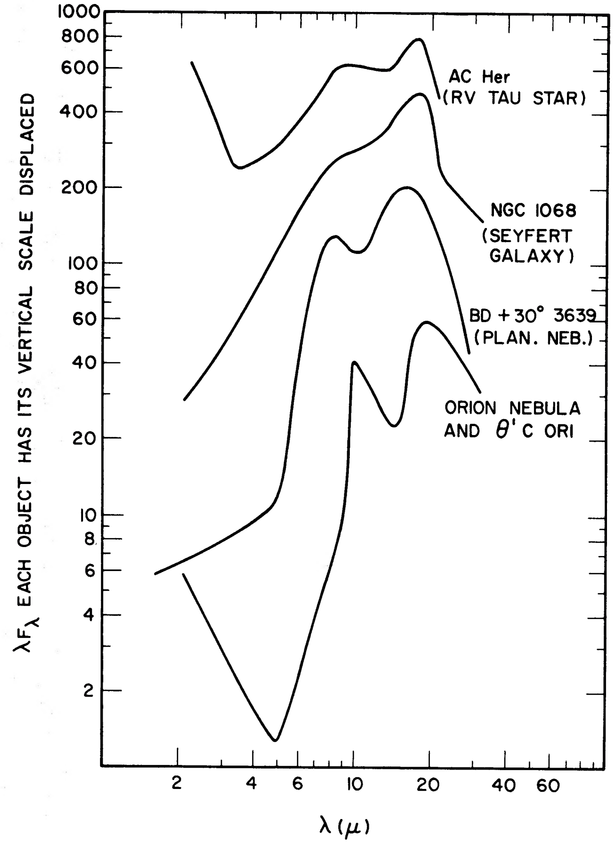

FIG. 3.—Comparative infrared distributions of three objects with the unusual dust spectrum and the Orion Nebula + θ^1 C Ori, a typical strong silicate dust spectrum. Each object has its absolute vertical scale displaced for clarity of presentation.

It is worth noting that the spectral region between the two observed peaks—i.e., around 9–10 μ—is the most difficult to measure due to the strong atmospheric ozone band centered at 9.6 μ. Therefore, possibly there is less difference between the objects under discussion, in this wavelength range, than appears in the figures shown.

III. DISCUSSION

The first result clearly visible from figures 1, 2, and 3 is that two of the planetary nebulae and the Seyfert galaxy have remarkably similar infrared energy distributions. The optical emission line spectra of NGC 7027 and the Seyfert galaxy are also similar. Therefore, it seems unreasonable to ask for different physical processes to give the emission from these objects, and at least in the Seyfert galaxy there is evidence of large extinction by dust (Wampler 1971). Consequently we believe that the most straightforward hypothesis would be to assume that the emission for these objects is thermal emission by some kind of dust that is common to each object. This does not exclude the possibility that some of the mid-infrared emission from NGC 1068 is nonthermal; but if so, it cannot dominate the spectral distribution.

TABLE 1

MAGNITUDES OF INFRARED OBJECTS

OBJECT	Filter (Bandwidth) 2.2 μ (0.5)	3.6 μ (1.2)	4.8 μ (0.4)	8.6 μ (0.8)	10.3 μ (0.9)	11.3 μ (2.0)	12.4 μ (2.0)	12.8 μ (1.2)	18 μ (3.4)	22 μ (6)	27μ (11)
NGC 1068, Seyfert Galaxy........	...	5.5 ± 0.2 (1)	3.6 ± 0.2 (1)	1.0 ± 0.1 (3)	0.7 ± 0.1 (3)	0.4 ± 0.2 (1)	−0.2 ± 0.1 (1)	−0.6 ± 0.1 (2)	−1.8 ± 0.1 (3)	−1.7 ± 0.1 (1)	−2.0 ± 0.1 (2)
NGC 7027, Planetary nebula.......	7.1 ± 0.1 (2)	4.9 ± 0.1 (2)	3.6 ± 0.2 (2)	−0.5 ± 0.1 (3)	−1.1 ± 0.1 (1)	−1.5 ± 0.1 (2)	−1.8 ± 0.1 (2)	−2.3 ± 0.1 (1)	−3.8 ± 0.1 (3)	−4.2 ± 0.2 (2)	−4.3 ± 0.1 (1)
BD +30°3639, Planetary nebula.......	7.2 ± 0.1 (1)	5.8 ± 0.1 (1)	4.7 ± 0.1 (1)	0.0 ± 0.1 (3)	0.0 ± 0.1 (1)	−0.8 ± 0.1 (2)	−1.3 ± 0.1 (2)	−1.3 ± 0.1 (1)	−2.7 ± 0.1 (3)	−3.0 ± 0.1 (3)	−2.8 ± 0.1 (1)
IC 418, Planetary nebula.......	...	...	...	2.0 ± 0.1 (3)	1.0 ± 0.1 (2)	0.5 ± 0.1 (1)	0.4 ± 0.1 (1)	−0.6 ± 0.1 (3)	−1.1 ± 0.1 (2)	−1.4 ± 0.2 (1)	−1.8 ± 0.1 (2)
α Tau, K5 III............	−2.9	−3.0	−2.8	−3.0	−3.0	−3.0	−3.0	−3.0	−3.0	−3.0	−3.0
β Peg, M2 II–III.........	−2.2	−2.4	−2.2	−2.4	−2.5	−2.5	−2.5	−2.5	−2.5	−2.5	−2.5
α Ari, K2 III............	−0.6	−0.7	−0.6	−0.7	−0.7	−0.7	−0.7	−0.7	−0.7	−0.7	−0.7

NOTES.—(1) Numbers in parentheses indicate number of independent observations. (2) Magnitudes for NGC 7027 and IC 418 have not been corrected for beam size (see text). (3) Data plotted for AC Her in figure 3 were taken from Gehrz 1972. (4) Data plotted for θ^1 C Ori in figure 3 were taken from Ney *et al.* 1973, supplemented by additional observations at 22 μ.

An explanation in terms of dust is consistent with a report by Becklin *et al.* (1973) that NGC 1068 can be resolved at 10 μ and has a diameter of about 1 arc sec. Compared with BD $+30°3639$, where the visual diameter is about 5 arc sec, NGC 1068 has an infrared surface brightness 10 times higher, and it is about a factor of 25 higher than for NGC 7027. However, the depth of the NGC 1068 emitting region is about 10^3 times as great as for the planetary nebulae, so that its volume emissivity is about 100 times lower than for the planetary nebulae.

The infrared radiation can be described as a broad emission from 8 to 20 μ, that either has two peaks or has a central absorption. It is not like the silicate emission seen, for example, in the Orion Nebula. The short-wavelength peak is at a distinctly shorter wavelength, perhaps near 8 μ as opposed to 9.7 μ for the silicates. However, the emission does seem similar to the formerly unique emission for carbon-rich RV Tauri stars—e.g., AC Her (Gehrz 1972; Gehrz and Ney 1973), whose emission spectrum is also unexplained. In contrast, normal composition RV Tauri stars show silicate-like spectra, or in some cases, perhaps featureless continua. As Gillett *et al.* have shown, the emission lines in NGC 7027 and BD $+30°3639$ do not appreciably affect the appearance of the unusual peaking of the continuum near 8 μ.

The explanation of the spectral features of the emitting material, and the understanding of its chemical composition presents some problems. As Gillett *et al.* (1973) have pointed out, it is possible to explain the depression between the 8-μ and the 18-μ emissions of the planetary nebulae as a silicate absorption band. However, for this interpretation, as they show, the amount of silicates required does not seem compatible with the optical extinction. If we were, despite this, to adopt the hypothesis that this is an interstellar absorption feature, then the emitting material in the nebula could be a substance like iron or graphite, which is spectrally featureless in the infrared. If instead we assume that the spectrum is intrinsic to the source, then we note that the peaks occur at typical lattice vibration frequencies for dielectric solids, and that these solids have a high emissivity at these frequencies.

The most commonly observed solid emitter of this kind is silicate material (Woolf 1973), but clearly in NGC 1068, NGC 7027, and BD $+30°3639$ this material does not match. Nor does it seem to be SiC, which is the second commonest material (Treffers and Cohen 1973; Hackwell 1972), and even a self-reversed SiC feature does not seem to match the detailed energy distribution in the 10-μ region. Nor does the proposal by Gillett *et al.* (1973) that the material is carbonates adequately account for the observations, because carbonates are not very strong emitters near 18 μ. However, if two materials are present, one of them could be carbonates.

IV. THE NATURE OF THE DUST

We shall explore two hypotheses about the dust. In the first hypothesis, the material was originally silicate dust produced in cool M stars but has been subsequently modified by the ultraviolet and particle bombardment in the nebula. In the second hypothesis we shall assume that the chemical composition of the gas from which the dust condensed was unusual, and that possibly also the condensation conditions were unusual.

An example of potential processing of the first kind occurs in the Orion nebula. However, as the spectrum shows (Woolf 1973), near the O star θ^1 C Orionis there is unmodified silicate emission. The nebula near θ^1 C Ori has very similar excitation to that of BD $+30°3639$, being slightly higher than for IC 418. The latter is Aller excitation class 2 (Aller 1956), whereas the two former are between classes 2 and 3. The published densities for these sources show scatter, but cover the same density range for all objects. The lifetime for potential bombardment is the dynamical lifetime of these regions, and in all cases is about 10^4 years. We conclude that the differences in infrared spectra are not due to the modification of the dust, since if this were so, the Orion dust would be modified too.

Next we consider whether the condensation conditions might be unusual, but still maintaining a normal composition. There the evidence of the RV Tauri stars seems to dispose of this option. The ejection process in these stars appears to involve shock waves in their outer regions, but normal-composition RV Tauri stars such as U Mon and RV Tau itself do manage to produce silicates, and only the abnormal-composition RV Tauri stars AC Her and RU Cen appear to have produced the unexplained condensate.

There is some evidence that planetary nebulae may have unusual chemical compositions. Peimbert and Torres-Peimbert (1971) have produced evidence for an overabundance of nitrogen in a number of planetary nebulae. Although there have also been reports of carbon overabundances in planetary nebulae, caution in the interpretation of abundances obtained from weak permitted lines has been urged by Seaton (1968), based on overabundances of oxygen calculated from permitted recombination lines compared with forbidden lines. The error occurs because the permitted lines may also be caused by radiative excitation. In his paper, he shows that oxygen abundances from permitted lines seems to be overestimated by a factor of 13, and that the carbon abundance estimates are a factor of 25 higher than normal cosmic abundances. In the absence of any further information, we might divide the latter number by the former, and estimate a real overabundance of carbon by a factor of 2. Clearly it is wrong to assume that the ratio of radiative to collisional excitation is the same for oxygen and carbon, but the result is suggestive.

As an alternative approach, we may compare the C II $\lambda4267$ and He I $\lambda5876$ as published for the Orion Nebula and for these planetary nebulae, since these species have similar ionization potentials and there should be no C I inside an H II region. The result here is that the carbon abundances in the planetary nebulae seem to be high by factors between 2 and 4 compared with the Orion Nebula. There seems to be no obvious reason why the radiative excitation should be higher in the planetary nebulae.

In the center of BD $+30°3639$ there is a Wolf-Rayet star of class WC8. In this star it would seem that any nitrogen excess must be less than the carbon excess. Since we do not know how a star decides what to eject and what to retain, the assumption of the same relative N to C abundance in the surrounding nebula would be minimal. Finally we may refer to the fact that at least one carbon star, UV Aur, is associated with a planetary nebula. We do not know how this carbon star will die; but if it ejects an envelope and leaves a hot core, we would describe it as a planetary nebula. The assumption that the two components of UV Aur follow a single evolutionary path is again a minimal one.

In summary, there seems to be some observational evidence suggesting higher than usual nitrogen and carbon abundances in some planetary nebulae, and no evidence that we know to contradict this.

The contrast between our own Galaxy and NGC 1068 then becomes very interesting. Near the center of our Galaxy is an infrared sources which is surrounded by a cool cloud of silicate dust (Woolf 1973), whereas the dust that is heated in NGC 1068 seems to be of the strange unknown material that apparently condenses out of a nitrogen- and carbon-rich mixture.

Again there is evidence, although less substantial than in the planetary nebulae, for an overabundance of nitrogen in the nucleus of this Seyfert galaxy (Williams and Weymann 1968). Using data by Wampler (1971), we have attempted to compare [N II] and [O II] ionic abundances, and have also concluded that nitrogen is overabundant.

The chemical composition of solid condensates is one of the most sensitive indicators that we have in astrophysics of chemical composition of the initial medium. Because the bulk of C and O are used in forming CO, only the more abundant of these species is used for forming solids (Gilman 1969), and it may be for this reason that the querying of the interstellar matter composition has waited for an infrared study. It is tempting to infer that the Seyfert galaxy phenomenon may be related to the composition of the gas because the total amount of ionized gas in NGC 1068 is probably between $10^5\ M_\odot$ (with condensations) and $10^7\ M_\odot$ (without condensations), and the nuclear processing of such a large amount of matter must be a phenomenon substantially different from that in the center of normal galaxies.

Finally, as we already have infrared spectra and narrow-band photometry of many cool carbon stars (Treffers and Cohen 1973; Hackwell 1972), it could be asked why these do not exhibit the same spectral features as the objects discussed here. This might be explained in terms of the solids of the former condensing under conditions in which relatively low-temperature thermal radiation is predominant and the latter in more highly excited and ionized conditions. We are currently exploring this topic.

V. CONCLUSION

We have observed an 18-μ infrared spectral turnover in three planetary nebulae and a Seyfert galaxy.

It is inferred that the mid-infrared radiation from both NGC 1068 and the planetary nebulae is thermal emission by dust. The exact nature of the dust is still unknown, but it appears to be surprisingly similar in the galaxy and two of the nebulae, and similar to that in the unusual-composition RV Tauri stars AC Her and RU Cen. It is suggested that this particular infrared distribution may be the signature of a type of condensate forming in carbon- and nitrogen-enriched nebulae containing ionized gas. We show reasons for suspecting that matter of this composition occurs in the envelopes of some planetary nebulae.

If this interpretation is correct, and assuming that the original elemental abundances in the matter were normal, we conclude that the nebular material has undergone nuclear processing, probably associated with the CNO cycle. Hence, and more significantly, it may be that the Seyfert galaxy infrared phenomenon includes a remarkable processing mechanism to account for the mass of material of the proposed chemical composition.

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