THE ASTROPHYSICAL JOURNAL, **182**:503–507, 1973 June 1

INFRARED PHOTOMETRY OF PLANETARY NEBULAE

S. ERIC PERSSON* AND JAY A. FROGEL†
Harvard College Observatory, Cambridge, Massachusetts
Received 1972 December 15

ABSTRACT

Photometric observations from 1.6 to 3.5 μ of 28 planetary nebulae are presented. Most of these emit 3.5-μ radiation in excess of that expected from thermal emission by ionized gas. When combined with the measurements of Willner, Becklin, and Visvanathan, the data show that the nebulae with relatively high densities are the more likely to emit excess 3.5-μ radiation. This trend supports a model in which the excess radiation arises from dust particles that cool off as the nebulae evolve.
Subject headings: infrared sources — planetary nebulae

I. INTRODUCTION

Since the discovery of a large infrared flux from NGC 7027 at 10 μ by Gillett, Low, and Stein (1967), further infrared photometric observations of planetary nebulae have been reported. The 11-μ magnitudes of brighter northern planetaries have been compiled and the observations extended by Gillett, Merrill, and Stein (1972). These authors concluded that in several objects the excess emission in this wavelength region can be attributed to thermal radiation by dust particles. Willner, Becklin, and Visvanathan (1972) have reported observations of several bright planetaries at 1.65, 2.2, and 3.5 μ, and have shown conclusively that the 3.5-μ fluxes from NGC 7027, BD+30°3639, and IC 418 are substantially greater than expected.

This paper presents broad-band photometry at 1.6, 2.2, and 3.5 μ of additional planetary nebulae generally selected on the basis of compactness, high density, or high surface brightness. In these nebulae the grains might be expected to have higher temperatures and thus produce an excess at 3.5 μ.

II. OBSERVATIONS AND RESULTS

The observations were made with the 60-inch (152-cm) Tillinghast reflector of Mount Hopkins Observatory, the Kitt Peak National Observatory 50-inch (127-cm), the Cerro Tololo Inter-American Observatory 36-inch (91-cm), and the 40-inch (102-cm) telescope of the Carnegie Institution at Las Campanas Observatory, Chile. Observations at CTIO were made in collaboration with Dr. D. E. Kleinmann. The measurements were made with a PbS detector mounted behind cooled filters and focal plane apertures. These apertures were usually chosen to be substantially larger than the optical size of the objects.

The absolute fluxes from the nebulae were determined by observing a number of standard stars and by adopting the absolute calibration of Wilson *et al.* (1972). Nebulae were selected on the basis of one or more of the following criteria: large radio or Hβ flux, high surface brightness, small angular size, or high value of N_e as estimated by Kaler (1970).

* Guest Investigator, Carnegie Institution of Washington.

† Visiting Astronomer, Cerro Tololo Inter-American Observatory and Kitt Peak National Observatory, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 1

INFRARED PHOTOMETRY OF PLANETARY NEBULAE

Object	Aperture Diameter (arc seconds)	c*	Flux Density $\pm 1\ \sigma$ (10^{-26} W m^{-2} Hz^{-1}) 1.65 μ	2.2 μ	3.5 μ	Predicted† Flux Density 2.2 μ	Notes
VV8..........	15, 27	0.42	0.093 ± 0.010	0.080 ± 0.009	0.148 ± 0.027	< 0.010	2, 6
IC 2149.......	20	0.90	0.105 ± 0.012	0.095 ± 0.010	0.070 ± 0.038	0.072 ± 0.007	2
IC 2165.......	20	0.81	0.045 ± 0.011	0.061 ± 0.006	< 0.120	0.059 ± 0.003	1
NGC 2438.....	55	1.14	...	0.028 ± 0.014	...	0.022 ± 0.003	1
NGC 2440.....	27	0.66	0.065 ± 0.040	0.115 ± 0.010	0.250 ± 0.080	0.105 ± 0.003	1, 3
NGC 2818.....	59	0.82	...	0.035 ± 0.030	...	0.010 ± 0.010	1
NGC 2867.....	23	0.17	0.086 ± 0.017	0.079 ± 0.016	0.160 ± 0.100	0.076 ± 0.008	2
IC 2501.......	23	1.09	0.091 ± 0.030	0.135 ± 0.022	0.240 ± 0.110	0.092 ± 0.030	2
NGC 3132.....	59	0.44	0.260 ± 0.050	0.300 ± 0.030	< 2.300	0.066 ± 0.006	1
IC 2553.......	16	1.10	...	0.036 ± 0.020	...	0.040 ± 0.010	1, 5
NGC 3242.....	27	0.23	...	0.170 ± 0.010	0.180 ± 0.040	0.240 ± 0.070	1, 3
NGC 3918.....	23	0.80	0.200 ± 0.020	0.220 ± 0.020	0.320 ± 0.040	0.250 ± 0.020	1
NGC 5315.....	23	1.49	0.225 ± 0.029	0.270 ± 0.023	0.525 ± 0.085	1.0	2, 5, 7
NGC 5882.....	23	0.66	0.070 ± 0.010	0.115 ± 0.012	< 0.400	0.110 ± 0.010	1
He 2-131......	16	0.49	0.150 ± 0.020	0.150 ± 0.010	0.270 ± 0.080	0.180 ± 0.030	2, 5
IC 4593.......	27	0.27	0.043 ± 0.011	0.048 ± 0.006	...	0.032 ± 0.004	1
NGC 6153.....	29	1.31	0.120 ± 0.026	0.139 ± 0.025	0.175 ± 0.065	0.171 ± 0.017	1
NGC 6210.....	27	0.16	0.070 ± 0.014	0.098 ± 0.017	0.191 ± 0.120	0.090 ± 0.005	1
M3-27.........	20, 27	0.84	0.035 ± 0.010	0.014 ± 0.004	0.067 ± 0.020	0.016 ± 0.005	2, 4
Hu 2-1........	27	0.66	0.015 ± 0.010	0.043 ± 0.009	0.080 ± 0.070	0.048 ± 0.008	2
NGC 6790.....	15	0.33	0.089 ± 0.010	0.123 ± 0.010	0.230 ± 0.035	0.110 ± 0.010	2
NGC 6833.....	27	0.60	...	0.010 ± 0.006	0.070 ± 0.070	< 0.030	2, 6
NGC 6886.....	15	1.38	0.031 ± 0.018	0.035 ± 0.006	0.070 ± 0.043	0.045 ± 0.010	1
NGC 6891.....	27	0.50	0.024 ± 0.009	0.045 ± 0.005	0.115 ± 0.130	0.029 ± 0.003	1
IC 4997.......	15	0.54	0.090 ± 0.009	0.115 ± 0.010	...	0.031 ± 0.003	2
NGC 7026.....	27	0.99	...	0.095 ± 0.010	0.105 ± 0.050	0.076 ± 0.003	1
IC 5117.......	22	1.66	0.120 ± 0.012	0.170 ± 0.016	0.380 ± 0.038	0.066 ± 0.010	2
Hb 12.........	15	1.93	0.200 ± 0.016	0.310 ± 0.025	0.830 ± 0.070	< 0.070	2, 6

* $c = \Delta \log H\beta$.

† The predicted fluxes for thermal emission from ionized gas at 1.65 and 3.5 μ are ~15 percent lower than that at 2.2 μ.

NOTES.—(1) $N_e < 10^4$ cm^{-3}. (2) $N_e > 10^4$ cm^{-3}. (3) Measuring aperture does not include entire object. (4) Predicted 2.2 μ flux density estimated from optical data given by Kohoutek (1968). (5) Predicted 2.2 μ flux density estimated from optical data given by Cahn and Kaler (1971) and Webster (1969). (6) Radio flux very uncertain. (7) Reddening constant uncertain.

The fluxes given in table 1 are corrected for interstellar absorption by adopting Kaler's (1970) absorption coefficients, $c = \Delta \log \mathrm{H}\beta$, and the same reddening law used by Willner *et al.* (1972), i.e., $\Delta \log F_\nu$ ($1.65\ \mu$, $2.2\ \mu$, $3.5\ \mu$) = (0.123, 0.075, 0.039) $\times$ $\Delta \log \mathrm{H}\beta$, respectively. These corrections are small and do not affect the following discussion.

The infrared fluxes may be compared with those expected from thermal emission by ionized gas alone by extrapolating published radio fluxes (Higgs 1971) measured at frequencies where the nebulae are optically thin. Table 1 shows that there is general agreement between the observed and predicted 1.65- and 2.2-μ fluxes for these nebulae, consistent with the conclusions of Willner *et al.* (1972). Interesting exceptions are NGC 3132, IC 4997, IC 5117, and Hb 12, for which the 1.65- and 2.2-μ fluxes are three to four times greater than expected. The errors in the infrared data are small for these objects but the radio data are unambiguous only for the first two. Less extreme excesses at 1.65 and 2.2 μ were also found by Willner *et al.* (1972) in NGC 40, BD+30°3639, and IC 418. NGC 3132 is similar to NGC 40 in that both have relatively low electron densities.

Since the radio turnover frequency is proportional to N_e, the high-density nebulae must be measured at very high frequencies ($\sim$15 GHz) to ensure that the predicted fluxes at 2.2 μ are not underestimated. Thus, in order to interpret the infrared data for all the nebulae regardless of the quality of the radio data, it is necessary to consider the infrared colors. The [1.65 μ] $-$ [2.2 μ] and [1.65 μ] $-$ [3.5 μ] colors for each object were plotted against $\log N_e$ (from Kaler 1970) by Persson and Frogel (1972). (Hereafter the magnitude at a particular wavelength λ is denoted by [$\lambda\mu$].) In figure 1 the [1.65 μ] $-$ [2.2 μ] and [2.2 μ] $-$ [3.5 μ] colors are grouped into two density regimes. Both figures incorporate the data of Willner *et al.* (1972), as well as those presented here.

Figure 1*a* shows that the [1.65 μ] $-$ [2.2 μ] colors agree reasonably well with that expected from recombination theory. Note that the objects with excess flux at 1.65 and 2.2 μ have apparently normal [1.65 μ] $-$ [2.2 μ] colors. Figure 1*b* shows that most of the nebulae appear to emit excess radiation at 3.5 μ. Since the color scale is logarithmic, the large [2.2 μ] $-$ [3.5 μ] colors indicate that substantially more excess radiation at 3.5 μ is emitted by nebulae of higher density. Similar results are obtained when the surface brightness or inverse radius is used instead of the density.

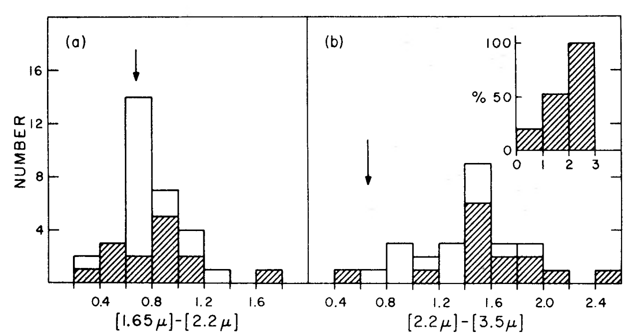

FIG. 1.—Histogram of the number of planetary nebulae versus (*a*) [1.65 μ] $-$ [2.2 μ] color and (*b*) [2.2 μ] $-$ [3.5 μ] color. In each case the upper line represents the total number of planetaries and the hatched area indicates those nebulae having $N_e > 10^4\ \mathrm{cm}^{-3}$. The arrows indicate the colors expected for the emission from ionized gas for $T_e = 10^4$ °K. The insert in (*b*) gives the percentage of planetaries with $N_e > 10^4\ \mathrm{cm}^{-3}$ versus [2.2 μ] $-$ [3.5 μ] color interval. Although the uncertainties in the 3.5 μ fluxes may be large, a consideration of the errors shows that the separation in [2.2 μ] $-$ [3.5 μ] colors between the two density regimes would not change if the fluxes were known to higher precision. This figure includes the data of Willner *et al.* (1972).

III. DISCUSSION

In order to interpret the above results, three sources of radiation which may contribute to the infrared flux in the 1.65- to 3.5-μ region should be considered: (1) Continuous radiation from the central stars of planetary nebulae is expected to be very weak at infrared wavelengths, and in any case a correction for the emission from a blue star will increase the net color. (2) The 2.06-μ line of He I (not included in calculating the predicted colors plotted in figs. 1*a* and *b*) contributes to the flux in the 2.2-μ bandpass. Since one-third to one-half the strength of this line results from the collisional transition He I $2\,^3S \rightarrow 2\,^1P$, its intensity relative to that of Hβ (or the 2.2-μ atomic flux) increases slightly with both temperature and density. For $N(\mathrm{He}^+) = 0.1N(\mathrm{H}^+)$ this line should provide $\sim$20 percent of the flux in the 2.2-μ band. However, the line lies in the center of a terrestrial CO_2 absorption band, and thus it is unlikely that the observed colors will be appreciably affected by it. (3) There are no recombination lines of H or He in the 3.5-μ band, but the 3.21-μ fine-structure line of [Ca IV] may be important. Petrosian (1970) has given formulae for estimating the strength of this line relative to Hβ. The degree of ionization of Ca can be inferred from $N(\mathrm{He}^{2+})$, since He^+ and Ca^{2+} have similar ionization potentials. Assuming a solar abundance of Ca leads to the prediction that in all cases the 3.21-μ line contributes <30 percent of the expected flux.

The uncertainties inherent in estimates of type (3) above preclude any attempt to specify the values of the nonatomic 3.5-μ excess for particular nebulae. The general features that have been noted remain, however, for the following reasons: several nebulae with large 3.5-μ excesses have no He II lines (and hence very little Ca^{3+}) and, in a statistical sense, corrections for 3.21-μ line emission will enhance the infrared color contrast between objects of high and low N_e. This occurs because the higher-excitation objects expected to have [Ca IV] emission tend to have lower densities and smaller infrared colors, and hence corrections are relatively more important for them.

Thus we conclude, in agreement with Willner *et al.* (1972), that the large infrared excesses at 3.5 μ are most easily accounted for by thermal radiation of hot dust particles located in or near the ionized regions of the nebulae. The variations in the infrared colors imply differences in temperature or concentration of the particles, but in general a high electron density appears to be required for a large 3.5-μ excess. Similarly, the 11-μ data of Gillett *et al.* (1972) show that for the nebulae that have well-determined radio fluxes, a density greater than $\sim 0.5 \times 10^4$ cm^{-3} appears to be required for the 11-μ flux to be greater than 40 times that expected. For the limited number of objects that have been measured at both 3.5 and 11 μ, the data show that *a large 3.5-μ flux excess guarantees a large 11-μ flux excess. However, a large 11-μ flux excess does not guarantee a 3.5-μ flux excess*, as is the case for NGC 6572, 7009, and 7026.

If it is accepted that planetary nebulae generally evolve from conditions of higher to lower mean density, then the features noted above may be interpreted as indicating a progressive loss of the 3.5-μ excesses with time. The possible contribution of the fluxes from line emission renders the residual continuum excesses uncertain, but the observed trend is certainly in qualitative agreement with a model in which dust grains cool off as the nebula expands. This cooling is due to a decreasing energy input to dust grains from both the central star and the resonantly trapped Lα radiation field.

In summary, the interpretation that the infrared excesses of planetary nebulae are due to thermal radiation from dust particles appears to be consistent with the available data and with a schematic evolutionary picture.

We thank the staffs of KPNO, CTIO, and the Las Campanas Observatory for their continuing interest and support. We thank our colleague Dr. D. E. Kleinmann for his interest and collaboration in this program. Mr. R. Baldwin assisted in making some of the observations and in the data reduction. Mr. B. van't Sant of Mount Hopkins Observatory provided valuable technical assistance. We also thank Señores Zúñiga and Papič at Las Campanas for assistance.

REFERENCES

Cahn, J. H., and Kaler, J. B. 1971, *Ap. J. Suppl.*, **22**, 319.
Gillett, F. C., Low, F. J., and Stein, W. A. 1967, *Ap. J.* (*Letters*), **149**, L97.
Gillett, F. C., Merrill, K. M., and Stein, W. A. 1972. *Ap. J.*, **172**, 367.
Higgs, L. A. 1971, National Research Council of Canada, *Pub. Ap. Branch*, **1**, 1.
Kaler, J. B. 1970, *Ap. J.*, **160**, 887.
Kohoutek, L. 1968, *Bull. Astr. Inst. Czechoslovakia*, **19**, 371.
Persson, S. E., and Frogel, J. A. 1972, *Proceedings 18th Liège International Astrophysical Symposium* (in press).
Petrosian, V. 1970, *Ap. J.*, **159**, 883.
Webster, B. L. 1969, *M.N.R.A.S.*, **143**, 79.
Willner, S. P., Becklin, E. E., and Visvanathan, N. 1972, *Ap. J.*, **175**, 699.
Wilson, W. J., Schwartz, P. R., Neugebauer, G., Harvey, P. M., and Becklin, E. E. 1972, *Ap. J.*, **177**, 523.