THE ASTROPHYSICAL JOURNAL, Vol. 157, July 1969

INFRARED EMISSION FROM PLANETARY NEBULAE

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Received May 12, 1969

ABSTRACT

Broad-band 11.5-μ observations are reported for eight planetary nebulae, four W-R and Of stars, and three symbiotic stars. The largest infrared excess is found for BD+30°3639.

Infrared emission has now been observed for a total of five planetary nebulae. Two cases have been reported previously (Gillett, Low, and Stein 1967; Low and Kleinmann 1968; Gillett and Stein 1969; Low 1969), and three further cases of emission and four upper limits are reported in this Letter.

The infrared radiation from planetary nebulae could be thermal emission from dust or gas, or it could be a nonthermal process, perhaps associated with the flow of matter from the nucleus into the nebula. The emission could either give information about processes of stellar evolution and dust formation, or it might be related to the processes occurring in some Seyfert galaxies and quasi-stellar sources.

To attempt to find evidence for the nature of the emission process, broad-band 10–13.5-μ observations were made of eight planetary nebulae, four Wolf-Rayet and Of stars, and three symbiotic objects. The W-R stars were observed because their spectra resemble those of the nuclei of the nebulae. If the central stars of nebulae are directly responsible for the emission, one might expect the W-R and Of stars to be bright sources. The symbiotic stars were observed because of their supposed relationship to the early phases of some planetary nebulae.

The photometric observations were made with the 30-inch telescope of the O'Brien Observatory. The sky diaphragm was 26″ in diameter. Most observations were made in July, August, and September of 1968. Typical extinction for stars was 0.4 mag per air mass from 1 to 2 air masses. Uncertainties in the extinction appropriate for the nebulae leave doubt of about ± 20 percent in the interpretation of measured emission. The absolute-calibration procedure will be reported elsewhere (Woolf and Ney 1969*b*). This particular series of observations had a typical standard error for the results of $\pm 6 \times 10^{-26}$ W m^{-2} Hz^{-1}. The results are shown in Table 1.

In Table 1 the 11.5-μ flux from the last two objects is from observations reported by Gillett and Stein (1969) and by Ney and Allen (1969). The 6-cm radio observations are from Kaftan-Kassim (1969) and are consistent with a large number of other measures (Terzian 1968). The 11.5-μ free-free flux is assumed to be three times smaller than the radio flux because of the Gaunt factor. The values in Table 1 are somewhat smaller than estimates by Stein (1967). His values were extrapolated from Hβ fluxes and required uncertain corrections for interstellar extinction. The predicted line emission in the band is from Delmer, Gould, and Ramsay (1967). One further observation not reported in Table 1 is an upper limit of 0.33×10^{-26} W m^{-2} Hz^{-1} or 5×10^{-18} W cm^{-2} to the 3.5-μ flux from NGC 7662. This limit is close to the predicted free-free emission of the gas and a severe restriction on possible line emission within the 3.3–4.0-μ band.

On a first examination of Table 1 it is apparent that the W-R and Of stars are at most weak infrared sources. Since the nuclei of the nebulae are typically 4 visual magnitudes fainter than these objects, it is unlikely that the nuclei of the nebulae are strong sources of emission.

The observations of the symbiotic stars AG Peg, Z And, and R Aqr give a definite flux from R Aqr, a possible flux from AG Peg, and an upper limit to the flux from Z And. The observation of AG Peg is consistent with the thermal flux from an ionized gas cloud observed in the visible by Boyarchuk (1968). The visual emission from Z And is far fainter, and thus the failure to detect it in the infrared is not surprising. Neither of these objects has a large excess emission. The emission from R Aqr was detected independently by Stein *et al.* (1969). They have shown that the spectrum of this object is somewhat unusual in its circumstellar peak compared with the shape found for other M giants (Woolf and Ney 1969*a*). However, the planetary-nebula component of R Aqr is one of the faintest objects in Table 1, and the 11.5-μ emission is the largest; therefore, it seems unlikely that the planetary nebula is responsible for the emission. The ratio of emission peak to cool-star continuum is typical of the similar variables *o* Cet and χ Cyg. Thus, in summary, symbiotic objects seem to add little help in interpreting the nature of the emission from planetary nebulae.

TABLE 1

OBJECTS OBSERVED AT 11.5 μ

Object	Type	Nucleus		6-Cm Flux $\times 10^{-26}$	11.5-μ Flux $\times 10^{-26}$	Pred. Lines*/ 7×10^{12} Hz	11.5-μ Flux	
		Type	M_v				÷ Free-Free	÷ Pred. Lines
HD 192103	WC7	....	7.9	....	<12	....	......	....
HD 192163	WN6	....	7.4	....	<12	....	......	....
HD 193793	WC6+06	....	6.8	....	<12	....	......	....
λ Cep	O6f	....	5.0	....	5::	....	......	....
R Aqr	M7 IIIe	....	6	....	1860	....	......	....
AG Peg	M3+WN6	....	8	....	15::	....	......	....
Z And	M2e	....	11	....	<12	....	......	....
NGC 6543	Planetary	W6–O7f	11.2	0.96	54	15	170	3.6
NGC 6572	Planetary	WN6	12.0	1.20	19	5.7	47	3.3
NGC 6826	Planetary	O6f	10.7	0.43	<12	8.3	< 84	<1.5
NGC 7009	Planetary	Con	11.9	0.76	<12	13	< 47	<1
NGC 7027	Planetary	....	>18	5.80	310	18	160	17
NGC 7662	Planetary	Con	12.6	0.66	<12	15	< 55	<0.8
BD+30°3639	Planetary	WC8	10.1	0.53	91	....	510	....
IC 4997	Planetary	W7	....	0.10	<12	....	<360	....
IC 418	Planetary	O7f	10.9	1.76	27	43	46	[0.6]†
NGC 1976	Diff. neb.	O6p	5.1	....	350‡	....	480	....

* The band width of the 11.5-μ filter is 7×10^{12} Hz; thus total predicted line fluxes have been divided by this for comparison with the observations.

† The line assumed responsible does not supply the observed flux.

‡ Brightest region at 11.5 μ in 13″-diameter beam.

If the emission from planetary nebulae is due to the thermal-line radiation of gas from many lines, one might expect that the ratio of observed total fluxes to predicted emission-line fluxes would be reasonably constant. Table 1 shows that there are nebulae for which the observations are already severe limits on possible line emission, while the flux from NGC 7027 is seventeen times larger than expected. Thus the observations do not encourage hypotheses that the infrared radiation could be the sum of many weak lines (Goldberg 1968).

Next we consider the hypothesis of nonthermal radiation associated with outflow from the nucleus. Here we note that those planetary nebulae with Wolf-Rayet nuclei tend to have a larger ratio of observed flux to predicted free-free emission. This result is highly uncertain because of the limited data. One might assume that the broad, bright emission lines of W-R stars indicate large mass outflow, and this might support a hypothesis of nonthermal emission.

Finally, we consider the possibility discussed by Gillett *et al.* (1967) and Krishna Swamy and O'Dell (1968) that the emission is caused by dust. In NGC 1976 the emission from near the Trapezium is spectrally similar to the emission peak of cool stars (Stein and Gillett 1969). This is probably silicate dust in emission. Thus it is remarkable that the ratio of free-free to dust emission for the brightest part of this nebula is equal to the extreme value found for any other nebula. Since ultraviolet heating of dust apparently causes the Orion Nebula emission, it could cause the emission of the planetary nebulae.

A further interesting feature is that the two objects in Table 1 with the greatest ratio of 11.5-μ flux to predicted free-free flux are BD+30°3639 and the Trapezium region of NGC 1976. The most unusual feature of BD+30°3639 is that, if one takes the observed visual emission and reddening (Terzian 1968; Pipher and Terzian 1969), one predicts a radio flux a factor of 10 smaller than is observed. If the radio flux is really free-free emission, one finds a ratio of total to selective absorption $\Delta V/\Delta(B-V) \sim 9$.

Following the submission of this article the optical flux from BD+30°3639 was redetermined by Dr. O'Dell (private communication). The new value of the logarithm of the Hβ flux is -10.01 ± 0.03 cgs units. It is believed that the published result of -11.5 either is an error in reduction or refers to some other object and does not mean that the nebula has changed. With this new value, the ratio of total to selective absorption for BD+30°3639 reverts to a value $\simeq 3$, and the object ceases to appear anomalous in this way.

There have long been suggestions of anomalous reddening for the Trapezium stars in NGC 1976 (e.g., Johnson 1967). If one considers the entire area of the Trapezium, the ratio of infrared emission to free-free emission would be substantially less than that for BD+30°3639. If anomalous extinction is caused by the evaporation of small particles, or by their ejection from the nebula by radiation pressure, one might expect the ratio of dust to gas emission to be linked to the amount of anomalous extinction. Since the most extreme object of Table 1, BD+30°3639, now fails to show anomalous extinction, it may be appropriate to query either the existence of the anomaly in NGC 1976 or the identity of the emitting material in the diffuse and planetary nebulae.

No observations have been found that are inconsistent with the dust hypothesis, and it retains its current status as the most probable explanation of the excess emission. The possibility of nonthermal emission is not yet excluded, and radio and infrared spectral studies should be useful in choosing between these hypotheses.

Mr. P. Kintner assisted with many of the observations. I am indebted to Drs. F. Gillett, W. Stein, and Y. Terzian for discussions. This research was supported by NASA grants NGL-24-005-008 and NGL-24-005-063.

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