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DETECTION OF 10.5-MICRON LINE EMISSION FROM THE PLANETARY NEBULA NGC 7027*

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ABSTRACT

Spectra of several planetary nebulae have been obtained, with a resolution of 0.3 cm^{-1}, at 950 and 1112 cm^{-1}, corresponding to the fine-structure transition frequencies from the ground states of S IV and Ar III, respectively. The S IV line has been detected in NGC 7027 at 951.5 cm^{-1}. Detection of the Ar III line in NGC 7027 is also indicated, though not certain. Upper limits for line intensities in other planetary nebulae are given, as well as continuum intensities in these spectral regions.

Emission of 951.5-cm^{-1} radiation due to the $^2P_{3/2}$–$^2P_{1/2}$ transition in the ground state of S IV has been detected from the planetary nebula NGC 7027. This spectral line has a spectral intensity about 10 times that of the continuum infrared radiation from the nebula at the same frequency and about 30 times the rms noise of the detection system. Several other planetary nebulae (NGC 7662, NGC 6210, and BD+30°3639) were examined for S IV emission with negative results. Line emission from Ar III at 1112 cm^{-1} was also searched for in NGC 7027 and NGC 6210, with a possible detection of the line in the former and negative results in the latter.

The observations were carried out with a scanning Fabry-Perot interferometer mounted at the coudé focus of the 120-inch telescope at Lick Observatory. Two beams approximately 6″ in diameter and separated by about 30″ were used to alternate between the sky and the nebula at 20 Hz. An Infrared Laboratories bolometer served as the detector, and a filter wheel with 1 percent bandpass was used to isolate individual orders from the Fabry-Perot. Typically, the interferometer was used with an order number of about 200 and a finesse of 15 so that the spectral resolution was about 0.3 cm^{-1}. A signal-averaging computer was used to accumulate data over a long period of time and to cancel sky signals appropriately.

Figure 1 shows spectra of four nebulae centered around the frequency of the S IV fine-structure line. The spectrum of NGC 7027 was recorded at two positions in the nebula. Results from the first position, corresponding to near the "bright knot," are shown in Figure 1. The second position was centered on the "dark lane." Both positions showed roughly equivalent line-emission intensity and ratios of line emission to continuum. Hence the line emission presumably is present throughout most of the visible nebula.

The best estimate of the transition frequency, obtained from differences between ultraviolet transitions, is 950.2 cm^{-1} (Bowen 1932; Moore 1949). The S IV line in NGC 7027 was detected at a rest frequency of 951.5 ± 0.1 cm^{-1}, which agrees reasonably with the above value from ultraviolet measurements (Bowen 1970). The wavelength was calibrated by ammonia lines in the 10-μ region, and by Ne and Hg visible lines. Since Fabry-Perot orders were separated by about 5 cm^{-1}, two orders were passed by the filter wheel. The ambiguity of overlapping orders was removed by observations with appropriate filter-wheel settings on either side of the S IV line. The line is not substantially broader than the instrumental resolution. Known Doppler shifts in the nebula would

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produce a breadth of about 0.1 cm^{-1}, as compared with the instrumental resolution of about 0.3 cm^{-1}. The spectra of NGC 7662, NGC 6210, and BD+30°3639 show no features larger than the peak-to-peak noise at the S IV line frequency. Fluctuations, which are seen in Figures 1 and 2, are consistent with the system noise and the total integration time.

Figure 2 shows the spectra of NGC 7027 and NGC 6210 in the region of 1112 cm^{-1}, which is the expected frequency of the fine-structure line in Ar III. There is a statistically significant feature at 1112.1 cm^{-1} in the spectrum of NGC 7027 which is in good agree-

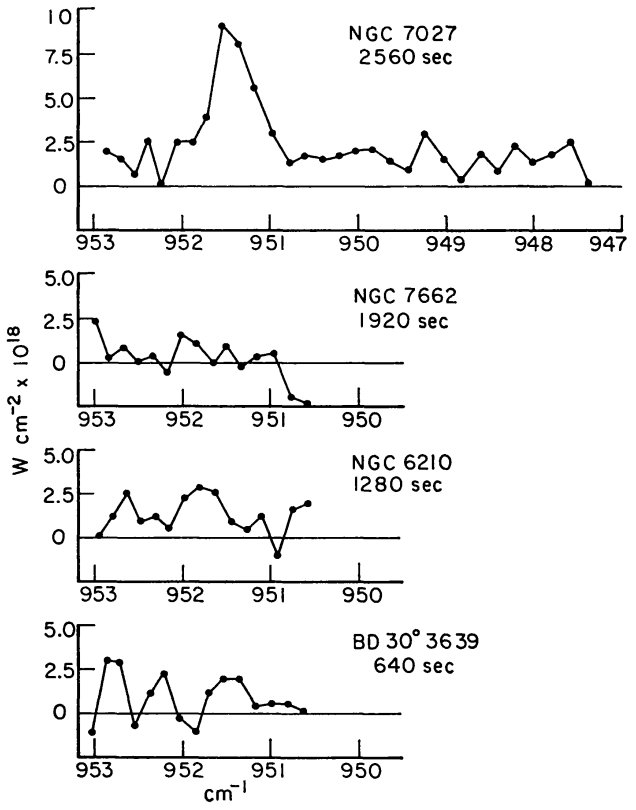

FIG. 1.—Spectra of four planetary nebulae near 950 cm^{-1}, showing power within the frequency range of 0.3 cm^{-1}. Note that for the spectrum of NGC 7027 the interferometer was scanned a full order, while a scan of one-half an order was used for the other nebulae. The length of time during which signals were averaged is shown for each case. The frequency scale corresponds to the wavenumbers in vacuo and with zero Doppler shift.

ment with the value 1112.4 cm^{-1} determined from laboratory measurements (Moore 1949). However, the signal-to-noise ratio for this feature is low, and hence there is some doubt about its identification as the Ar III line rather than a noise fluctuation. The spectrum of NGC 6210 shows no statistically significant feature in this region.

Intensities and upper limits for S IV line emission from the nebulae examined are shown in Table 1; those for Ar III are similarly listed in Table 2. Column (2) gives the intensities actually measured within the 6″ beam centered on the nebula. Intensity calibrations were obtained by continuum measurements of α Her, in which the flux used was that given by Gillett, Low and Stein (1968). Columns (3) of Tables 1 and 2 give the estimates of total intensities, on the assumption that the three larger planetaries have an effective size of 12″, and the smaller planetary, BD+30°3639, falls entirely within the 6″ beam of the apparatus.

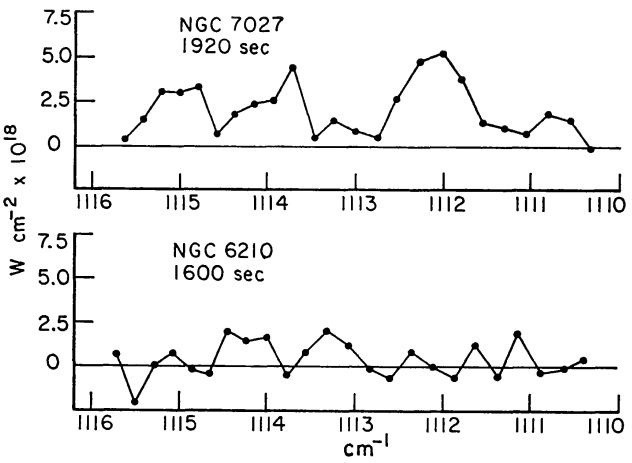

FIG. 2.—Spectra of NGC 7027 and NGC 6210 near 1113 cm^{-1}, showing power within the frequency range of 0.3 cm^{-1}. The length of time during which signals were averaged is shown for each case. The frequency scale corresponds to the wavenumbers in vacuo and with zero Doppler shift.

TABLE 1

INTENSITIES OF S IV $^2P_{3/2} \rightarrow {}^2P_{1/2}$ LINE AT 951.5 CM^{-1} AND OF NEARBY CONTINUUM

Planetary Nebula (1)	Observed Intensity of 951.5 cm^{-1} Line within 6″ Beam (W cm^{-2}) (2)	Total Line Intensity (W cm^{-2}) (3)	S IV Intensity Predicted from Delmer *et al.* (1967) (W cm^{-2}) (4)	S IV Intensity Predicted from Flower (1970) (W cm^{-2}) (5)	Infrared-Continuum Intensity within 6″ Beam (W cm^{-2} μ^{-1} at 950 cm^{-1}) (6)	Total Infrared-Continuum Intensity (W cm^{-2} μ^{-1} at 950 cm^{-1}) (7)
NGC 7027	1.0×10^{-17}	4×10^{-17}	1×10^{-16}	(7×10^{-18})	2.0×10^{-16}	8×10^{-16}
NGC 7662	$<1.5\times10^{-18}$	$<6\times10^{-18}$	1×10^{-16}	5.5×10^{-19}	$<3\times10^{-17}$	$<1.2\times10^{-16}$
NGC 6210	$<2.0\times10^{-18}$	$<8\times10^{-18}$	1×10^{-16}	(7×10^{-19})	1.0×10^{-16}	4×10^{-16}
BD+30°3639	$<2.5\times10^{-18}$	$<2.5\times10^{-18}$	(1×10^{-17})	(7×10^{-19})	1.0×10^{-16}	1.0×10^{-16}

NOTE.—Total intensities are based on the somewhat arbitrary assumption of equal intensity over a disk 12″ in diameter except for BD+30°3639, where all intensity is assumed to be within the 6″ beam used. Predicted values in parentheses are not given directly by authors referred to. Such predictions from Flower (1970) are obtained by using the average ratio of S IV to Hβ line intensity given by him for three planetary nebulae. The BD+30°3639 prediction from Delmer *et al.* (1967) assumes Hβ values from O'Dell and Terzian (1970) and the same ratio of S IV to Hβ as Delmer *et al.* give for NGC 7027.

TABLE 2

INTENSITIES OF Ar III $^3P_1 \rightarrow {}^3P_2$ LINE AT APPROXIMATELY 1112.1 CM^{-1} AND OF NEARBY CONTINUUM

Planetary Nebula (1)	Observed Intensity of Possible 1112.1 cm^{-1} Line within 6″ Beam (W cm^{-2}) (2)	Total Line Intensity (W cm^{-2}) (3)	Ar III Intensity Predicted from Delmer *et al.* (1967) (W cm^{-2}) (4)	Ar III Intensity Predicted from Flower (1970) (W cm^{-2}) (5)	Infrared-Continuum Intensity within 6″ Beam (W cm^{-2} μ^{-1} at 1113 cm^{-1}) (6)	Total Infrared-Continuum Intensity (W cm^{-2} μ^{-1} at 1113 cm^{-1}) (7)
NGC 7027	$\leq5\times10^{-18}$	$\leq2\times10^{-17}$	7×10^{-17}	(7×10^{-19})	2×10^{-16}	8×10^{-16}
NGC 6210	$<3\times10^{-18}$	$<1.2\times10^{-17}$	8×10^{-18}	(7×10^{-20})	0.5×10^{-16}	2.0×10^{-16}

NOTE.—Total intensities are based on the somewhat arbitrary assumption of equal intensity over a disk 12″ in diameter. Predicted values from Flower (1970) are in parentheses because they were not given directly by him but are obtained by using the average ratio of Ar III to Hβ line intensity that he obtains for three planetary nebulae.

The deflection of the spectra of NGC 7027, NGC 6210, and BD+30°3639 above the zero line in Figures 1 and 2 indicates that broad-band continuum radiation from these nebulae was detected. No continuum was detected from NGC 7662. Since there were two overlapping orders in the filter-wheel bandpass, the effective bandwidth of the system for continuum radiation was 0.7 cm^{-1}. Hence the spectral intensity shown is twice the actual continuum spectral intensity. If the continuum emission originates from an object as large as the visible nebula, then the continuum-flux measurement from NGC 7027 at 950 cm^{-1} is approximately 8×10^{-16} W cm^{-2} μ^{-1}, or twice that measured by Gillett, Low, and Stein (1967) and more consistent with the observations of Woolf (1969).

The continuum spectra obtained at high resolution ($\sim$0.3 cm^{-1}) in these planetary nebulae seem to rule out the interesting possibility suggested by Goldberg (1968) that continua previously reported in the 8–14-μ region might be due to a collection of weak lines. This would require, for example, a half-dozen or more lines of approximately equal intensity within the very small 5-cm^{-1} region over which the Fabry-Perot was swept.

Columns (4) and (5) of Tables 1 and 2 list results of calculations for the strengths of infrared fine-structure lines which have appeared in the literature recently. Delmer, Gould, and Ramsay (1967) have calculated the total flux in the fine-structure lines of Ar III and S IV for three of the nebulae observed. Their predictions are in reasonable agreement with present observations for NGC 7027, although about a factor of 2 too high (if one assumes that approximately one-quarter of the flux from the nebula is received in the 6″ beam). NGC 7662 and NGC 6210 are observed to be less than one-tenth their predicted intensities. Flower (1970) has also calculated the intensity of Ar III and S IV lines in NGC 7662. His intensity for the S IV line is about one-tenth the observed lower limit for NGC 7662, and hence is consistent with this observation. However, he indicates that NGC 7027 can be treated much like NGC 7662, from which one would predict a S IV intensity considerably less than what is actually observed.

Disagreements between observations and theoretical calculations for some fine-structure infrared lines have already been noted by Gillett and Stein (1969) from observations with a filter-wheel photometer of several nebulae. In the case of the Ne II line in IC 418 which they observed, the discrepancy has been attributed largely to lack of information on the abundance of neon (Flower 1970). Since the abundance of sulfur is somewhat better known from visible lines of S III, there are evidently other sources of discrepancies, perhaps particularly associated with density and temperature nonuniformities. Clearly, NGC 7027 must be rather more different from NGC 7662 and BD+30°3639 than one might otherwise assume.

The first and only other spectral line so far reported in the 10-μ region from a source outside the solar system is the 12.8-μ line of Ne II from a planetary nebula reported by Gillett and Stein (1969), who used a filter-wheel spectrometer with a resolution of about 15 cm^{-1}. The same type of spectrometer has also been used to obtain an indication, although an uncertain one, of the S IV line in NGC 7027 (Gillett *et al.* 1967). The considerably improved resolution and sensitivity of the present spectrometer appear to allow detection of a number of other interesting lines. More observational data for Ar III, S IV, and other infrared-emitting ions in a larger sample of planetary nebulae are clearly needed, along with refinement of theoretical calculations.

We have benefited from help in a number of forms during the development and use of the spectrometer. We particularly appreciate discussions with Professor Frank Low, the helpful collaboration of Dr. Alistair Gebbie in experimentation with Fourier spectroscopy and related techniques, assistance from Dr. Roger Knacke in our initial infrared observations on the 120-inch telescope, and generous help from staff members of the Lick Observatory. The filter wheel was made available by Professor George Pimentel. Mr. George Hammond and Lynn Urry gave important assistance with particular problems.

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