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INFRARED LINE EMISSION FROM PLANETARY NEBULAE*

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ABSTRACT

A number of planetary nebulae with large Hβ fluxes have been examined for the infrared fine-structure lines of Ne II (12.8 μ), Cl IV (11.5 μ), S IV (10.5 μ), and Ar III (8.9 μ). Emission from S IV (10.5 μ) has been detected in NGC 6572, NGC 7009, and NGC 7027. The intensities of the infrared lines due to Ne II and S IV are generally much lower than theoretical considerations have indicated.

I. INTRODUCTION

The recent detection of line emission due to S IV in NGC 7027 (Rank *et al.* 1970) has prompted a broader survey of planetary nebulae for infrared fine-structure line radiation in the 8–13-μ region. Four lines were available for study: Ne II (12.8 μ), Cl IV (11.5 μ), S IV (10.5 μ), and Ar III (8.9 μ). Line intensities derived from the theoretical estimates of Delmer, Gould, and Ramsay (1967) and Flower (1970) indicated that the Ne II, S IV, and Ar III lines should be of sufficient intensity to be detected with our spectrometer, which has a practical sensitivity limit of $\sim 10^{-18}$ W cm^{-2} peak-to-peak noise after suitable integration time. The 120-inch Lick telescope was used with a 6″ beam, and spectral resolution of 0.3–0.5 cm^{-1} was obtained with a scanning Fabry-Perot interferometer.

II. RESULTS

Figure 1 shows the spectra of NGC 7027, NGC 6572, and NGC 7009 near the frequency of the S IV fine-structure transition. The Doppler shift due to the Earth's orbital motion has been removed from the data so that all frequencies are given with respect to the Sun. The value of V_s shown for each nebula is the radial velocity with respect to the Sun derived from the Doppler shifts of optical lines (Perek and Kohoutek 1967). The position of the small arrow indicates the expected position of the S IV line with a rest frequency of 951.5 cm^{-1}. The agreement between line centers and Doppler velocities of the nebulae is consistent within the limits imposed by the signal-to-noise ratio of the data, which is indicated by $\pm\sigma$ error bars. The variation of σ among the nebulae is due to differences in integration times, which were 1300 seconds for NGC 7027, 6000 seconds for NGC 6572, and 1920 seconds for NGC 7009.

Table 1 lists the results of this survey for the seven planetary nebulae NGC 7027, IC 418, NGC 6572, NGC 7662, NGC 7009, NGC 6210, and BD+30°3639. The flux measured in a 6″ beam in units of 10^{-18} W cm^{-2} is shown in the first row of Table 1 for each ion. Except for the S IV lines in NGC 7027, NGC 7009, and NGC 6572, all values are limits for line intensities set at 3 times the probable error. Flux measurements were calibrated against several standard reference stars, and the values quoted in Table 1 are thought to be accurate to ± 50 percent. The estimated total infrared line intensity from each nebula is given in the second row of Table 1 for each ion. These values were derived by multiplying the measured intensity within the 6″ beam by the square of the ratio of the nebular diameter in optical O III radiation to our beam diameter. The

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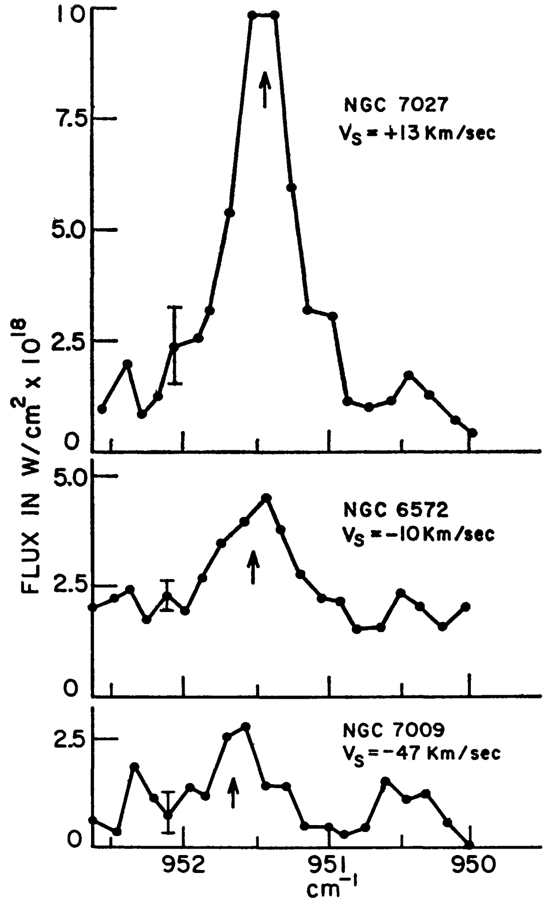

FIG. 1.—Spectra of NGC 7027, NGC 6572, and NGC 7009 at the frequency of the S IV fine-structure transition.

TABLE 1

INFRARED FINE-STRUCTURE LINE INTENSITIES

Ion	NGC 7027	IC 418	NGC 6572	NGC 7662	NGC 7009	NGC 6210	BD +30°3639
S IV (10.5 μ).....	10	<1	3	<2	2	<4	<1.5
	36	<1.5	4	<36	22	<8.8	<1.5
Ne II (12.8 μ)....	<5	<6	<10	<10	...	...	<15
	<18	<7.0	<15	<180	...	...	<15
Ar III (8.9 μ)....	<5	<4	<3	<5	<4	<6	<5
	<18	<4.6	<4	<90	<44	<13	<5
Cl IV (11.5 μ)....	<4	<8	<5	...	...	...	<4
	<14	<9.3	<7	...	...	...	<4

NOTE.—Intensity of infrared fine-structure lines in 10^{-18} W cm^{-2}. The first row of figures for each ion gives the measured intensity in a 6″ beam; the second row gives the estimated intensity from the entire nebula.

O III diameter was selected since O III has an ionization energy typical of the ions under consideration in this paper.

III. DISCUSSION

A comparison of the intensity of an ionic fine-structure line I_i with the intensity of the hydrogen Hβ line, $I(\mathrm{H}\beta)$, from the same region may be used to derive the ratio of the ionic abundance to the abundance of hydrogen. The abundance ratio R_i derived in this manner is not very sensitive to electron temperature T_e or to electron density, and is given by

$$R_i = \frac{I_i}{I(\mathrm{H}\beta)(13.8 \times 10^4)K_i} \left\langle \frac{T_e}{10^4\,^\circ\,\mathrm{K}} \right\rangle^{-0.36} , \quad (1)$$

where K_i is a constant for each infrared line which depends on the collision strengths and degeneracies of the fine-structure levels (Petrosian 1970). Equation (1) assumes that the radiation lifetime of the fine-structure level is small compared with the time between collisions, so that each collisional excitation gives rise to one infrared fine-structure photon. For all ions considered here this assumption is reasonably well satisfied for $n_e < 5 \times 10^4$. To calculate R_i from equation (1) it is necessary to determine $I(\mathrm{H}\beta)$ for the central region of the nebula, where I_i was measured. Intensities of the total hydrogen Hβ radiation given by Terzian (1968) along with isophotes of hydrogen recombination radiation given by Aller (1956) were used to determine the Hβ flux for the region of the nebula within the infrared beam. For the case of NGC 7027, where isophotes were not available, the Hβ radius of the nebula (Perek and Kohoutek 1967) was used to estimate the Hβ flux within the infrared beam. Hence for a nebula larger than the 6″ beam the value of R_i calculated from the "reduced" Hβ flux and the value of I_i given in the first row of Table 1 represents a spatial average over its central region.

The value of R_i, when multiplied by the fractional abundance of the element with respect to hydrogen, yields a value for $\eta(i)$, the fractional ionization, where

$$\eta(i) \equiv \frac{\text{number density of the ion } i}{\text{number density of the atom in all stages of ionization}} .$$

If standard abundance ratios of Aller (1956) are used to calculate the apparent fractional ionizations, the results shown in Table 2 for each of the nebulae are obtained.

Fractional ionizations on the order of 1 percent should be detectable for S IV and Ne II due to the relatively high collision strengths and cosmological abundances of their respective neutral atoms. These ions are also of considerable interest since they possess no forbidden optical lines and hence are undetectable by conventional techniques. The ionization potential of S III (35 eV) implies that S IV should be one of the more abundant

TABLE 2

FRACTIONAL IONIC ABUNDANCE, $\eta(i)$

Ion	NGC 7027	IC 418	NGC 6572	NGC 7662	NGC 7009	NGC 6210	BD +30°3639
S IV	$=\frac{1}{100}$	$<\frac{1}{500}$	$=\frac{1}{200}$	$<\frac{1}{15}$	$=\frac{1}{15}$	$<\frac{1}{25}$	$<\frac{1}{100}$
Ne II	$<\frac{1}{60}$	$<\frac{1}{25}$	$<\frac{1}{15}$	<5	...	...	$<\frac{1}{3}$
Ar III	$<\frac{1}{5}$	$<\frac{1}{8}$	$<\frac{1}{10}$	<3	<3	<1	$<\frac{1}{2}$
Cl IV	<1	<5	<5	...	...	...	<2

NOTE.—Apparent fraction of atoms in each ionic state. These are derived from infrared fine-structure line intensities, Hβ intensities, and normal stellar abundance ratios for the elements.

forms of sulfur in high-excitation planetary nebulae, while the much lower ionization potential of Ne I (22 eV) implies that Ne II should be one of the dominant forms of neon in low-excitation nebulae. Hence, one would expect values of η(S IV) $\gtrsim 0.2$ in high-excitation nebulae and values of η(Ne II) $\gtrsim 0.2$ in low-excitation nebulae. The small values derived for η(S IV) in the high-excitation nebulae NGC 7027 and NGC 6572 and the small value derived for η(Ne II) in the low-excitation nebula IC 418 are therefore particularly interesting and warrant further comment. There are a number of possible effects which might tend to produce these low values of η(S IV) and η(Ne II), such as intensity-calibration errors, overestimates of collision strengths, and mechanisms of selective ionic destruction. However, the low values of the apparent fractional ionizations of Ne II and S IV given in Table 2 are most probably due to (1) collisional de-excitation of the fine-structure levels or (2) an underabundance of the atomic species in the nebula with respect to standard abundances.

Collisional de-excitation of the fine-structure level of S IV is important for electron densities greater than about 5×10^4 cm^{-3}. The average electron densities for planetary nebulae are generally lower than this value, but in nebulae with large density fluctuations the effect of collisional de-excitation may be significant. Although nonuniformities are common in planetary nebulae, a reduction of the intensity of S IV line emission by one order of magnitude requires electron densities in excess of 5×10^6. Such densities are higher than are generally expected, and although collisional de-excitation may be an important effect for S IV, it is unlikely that this effect alone would account for the small value of η(S IV) derived for either NGC 7027 or NGC 6572.

In planetary nebulae, evidence for the deviation of heavy elements from normal stellar abundance is available from data on optical forbidden lines. In the high-excitation nebula NGC 7027, for which there are extensive optical data, Aller and Czyzak (1968) have calculated sulfur to be overabundant by a factor of 4. However, in planetary nebulae sulfur is observed optically only as S II and S III. Thus, in high-excitation nebulae, where most of the sulfur atoms must exist in more highly ionized states, the sulfur-abundance measurement by optical lines is necessarily uncertain. Hence, an underabundance of sulfur in NGC 7027 and NGC 6572 is not unreasonable, but it is unlikely that the abundance of sulfur is so low that it would account entirely for the small values of η(S IV) in Table 2. Thus, these low values of η(S IV) are difficult to reconcile with theoretical predictions, and agreement between the S IV infrared observations and the theoretical calculations for NGC 6572 and NGC 7027 requires some unusual physical conditions for these objects.

Collisional de-excitation should be relatively less important for Ne II ions than for S IV ions, because of the much lower electron-collision cross-section for Ne II. The small value of η(Ne II) in Table 2 for IC 418 is most probably due to an underabundance of Ne in this object. Optical data from forbidden lines of Ne in various stages of ionization imply a general underabundance of Ne in planetary nebulae by about a factor of 6 (Aller and Czyzak 1968) and tend to support this hypothesis.

It should be noted that the upper limit listed in Table 1 for the intensity of Ne II radiation in IC 418 at 12.8 μ is about 3 times less than the intensity of 2×10^{-17} W cm^{-2} for the 12.8-μ feature reported by Gillett and Stein (1969) who used 1 percent spectral resolution. This apparent discrepancy may possibly be due to differences in parameters used in the two experiments, such as differences in the solid angles and spectral resolutions.

Both Cl IV and Ar III have optical forbidden lines from which their abundances can be estimated. Due to relatively lower cosmological abundances and smaller collision strengths these ions are more difficult to detect in the infrared than S IV and Ne II. At present the values of η in Table 2 may be considered to be in complete agreement with the optical data in the case of Cl IV and in reasonable agreement in the case of Ar III, since in all cases the limit to the fractional ionization is of the order of 10 percent or more.

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