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DETECTION OF [S III] FINE-STRUCTURE EMISSION IN IONIZED NEBULAE*

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ABSTRACT

The $^3P_2$–$^3P_1$ fine-structure line of doubly ionized sulfur has been detected at 534.41 ± 0.03 cm^{-1} in the spectra of NGC 7027, BD +30°3639, and G333.6−0.2. The abundance of S^{++} and the electron density are discussed. The ionization of G333.6−0.2 is lower than expected from its luminosity.
Subject headings: nebulae: abundances — nebulae: general

I. INTRODUCTION

Optical forbidden lines have been for many years a useful tool for studying the ionic abundances, electron temperatures, and electron densities in gaseous nebulae. Lines between fine-structure levels lie in the infrared region and offer certain advantages over the optical lines as has been pointed out by Delmer, Gould, and Ramsay (1967) and Petrosian (1970), among others.

Fine-structure lines of the ions Ar^{++}, S^{+++}, Ne^{+}, and O^{++} have been previously detected in the infrared spectra of ionized nebulae. The line arising from the $^3P_2$–$^3P_1$ transition of S^{++} at 18.7 μm has been predicted (e.g., Simpson 1975) to be one of the strongest undetected fine-structure lines. This *Letter* reports the detection of this line for the first time in two planetary nebulae and one compact H II region. The observed fine-structure line intensities are used in combination with the optical forbidden lines and other fine-structure lines to investigate the physical conditions and ionic abundances in the observed nebulae.

II. OBSERVATIONS

The observations were made in 1975 June at the coudé focus of the 224 cm telescope on Mauna Kea, which was chosen for high atmospheric transmission in the 20 μm window. The detector was an Si:As photon-noise-limited photoconductor at the exit slit of a small liquid-helium-cooled grating monochromator with a bandpass of ~2.5 cm^{-1}. An ambient temperature Fabry-Perot interferometer (resolution = 0.20 cm^{-1}) was piezoelectrically scanned once every 10 s over a portion of the monochromator bandpass, and successive scans were digitally summed. As the transition frequency was uncertain, initially a scan of ~2.5 cm^{-1} was used. Once the line position was accurately known from the spectrum of G333.6−0.2, a shorter scan, ~1.3 cm^{-1}, was used. Standard two-beam sky chopping was done with a focal plane chopper operating near 19 Hz. The chopper throw was 10″, and the rectangular beam was 3″.7 by 4″.7 in size ($\Omega = 4.0 \times 10^{-10}$ sr).

The primary intensity calibration was taken from Mars which was assumed to emit as a gray body with an emissivity of 0.90. The brightness distribution of Mars at the time of observation was calculated using the temperature contours given by Morrison, Sagan, and Pollack (1969). Integration over the field of view gave an effective Martian brightness equal to that of a 270 K blackbody. The wavelength-dependent atmospheric extinction was determined from the zenith-angle dependence of both absorption spectra of astronomical sources and sky emission and from model calculations. Atmospheric water vapor lines and NH_3 lines from a heated gas cell were used for frequency calibration.

III. RESULTS

The observed spectrum of G333.6−0.2 at the position of peak [S III] intensity is shown in Figure 1. A spectrum of the Moon, taken at about half the zenith distance the same night, shows a number of telluric absorption lines in the scanned spectral region. All the telluric features, except the weak line at 535.19 cm^{-1}, have been identified in the AFCRL line compilation (McClatchey *et al.* 1973). The broad feature on the left is the pressure broadened wing of a strong H_2O line at 536.25 cm^{-1}. The [S III] line is unfortunately close to the moderately strong H_2O line at 534.26 cm^{-1} which is unresolved and is quite opaque near line center. The radial velocity of G333.6−0.2 at the time of observation, −41 km s^{-1}, is responsible for about a third of the separation between the [S III] line and the H_2O line. Detection of [S III] in several redshifted objects has been hampered by this near coincidence with an atmospheric absorption feature, indicating the need for observations from airplane or higher altitudes. The transition rest frequency determined by our observations is 534.41 cm^{-1} with an estimated uncertainty of ±.03 cm^{-1}. This agrees with an unpublished term difference of 534.45 ± .10 cm^{-1} determined by V. Kaufman at the National Bureau of Standards, but not with the tabulated value, 535.3 cm^{-1} (Moore 1971). A recent astronomical measurement by Baluteau *et al.* (1976) of 534.39 ± .01 cm^{-1} is in agreement with our frequency determination.

Figure 2 shows spectra of NGC 7027 and BD +30°3639 taken with the short scan. The first row in Table 1 gives the observed surface brightness values, S[S III], corrected

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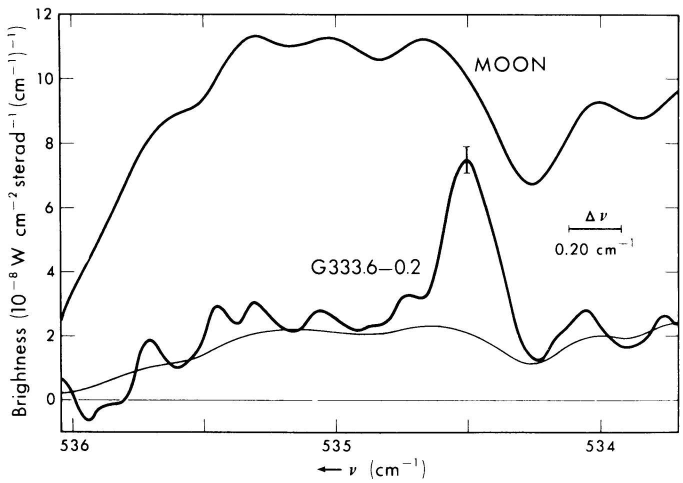

FIG. 1.—Spectra of G333.6−0.2 and the Moon in the region of the [S III] 18.7 μm fine-structure line. The vertical scale is apparent brightness through the Earth's atmosphere. The light line is a continuum fit to the spectrum of G333.6−0.2. The data have been smoothed over an interval of 0.1 cm^{-1}; the error bars, $\pm 1\ \sigma$, are for this smoothing interval and at the center of the scan. The effective noise level at the ends is larger because of removal of the instrumental transmission function. The lunar signal has been reduced greatly and has negligible noise. The resolution is indicated by the horizontal bracket.

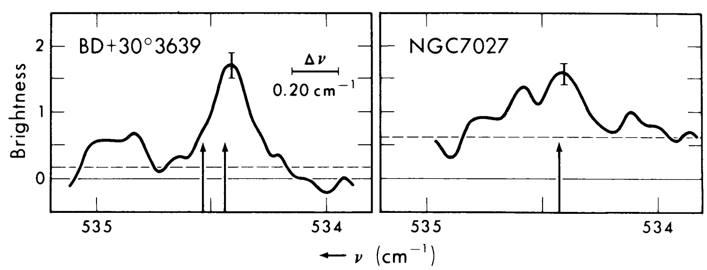

FIG. 2.—Spectra of BD +30°3639 and NGC 7027 taken with a shorter scan. The brightness unit, smoothing, and error bars are as in Fig. 1, but the noise level is constant over the spectral region. The arrows indicate the expected positions of [S III] 18.7μm. The [S III] line in BD+30°3639 agrees more closely in frequency with the red component of the split optical lines. The dashed lines indicate the level of the detected continuum.

TABLE 1

FINE-STRUCTURE LINE COMPARISON

Parameter	NGC 7027	BD +30°3639	G333.6 −0.2
S([S III] 18.7 μm) (10^{-9} W cm^{-2} sr^{-1})......	3.8±0.6	6.7±0.9	33±2
$I(\lambda18.7)$ (10^{-18} W cm^{-2})...	7.7	4.0	...
$\lambda(9069)/\lambda(18.7)$...........	5.2	2.5*	...
S([Ne II])/$S(\lambda18.7)$........	2.1	5.5†	9.0
S([S IV])/$S(\lambda18.7)$.........	3.8	<0.4‡	<0.15
$\int n(S^{++})dl$ (cm^{-2}).........	4.2×10^{16}	7.3×10^{16}	...

* λ9069 from O'Dell 1963.
† [Ne II] from Gillett *et al.* 1973.
‡ [S IV] from Holtz *et al.* 1971.

for atmospheric attenuation. The indicated uncertainty is the noise contribution; the systematic error in the absolute intensity should be less than 40%.

IV. DISCUSSION

a) *NGC 7027*

Extensive optical, infrared, and radio observations are already available for this planetary nebula, including measurements of the fine-structure lines of S^{+++}, Ar^{++}, and Ne^{+}. The optical image is irregular due to an intervening dust cloud, while the 10μm infrared emission and the thermal radio emission have similar bilaterally symmetric distributions (Becklin, Neugebauer, and Wynn-Williams 1973). The field of view used in our observations was smaller than the entire nebula and centered on the visible "bright knot." The ratio of the total [S III] flux to the observed flux may be estimated from the known distributions of [S IV] 10.5μm, [Ne II] 12.8μm (Bregman and Rank 1975), the radio continuum and the infrared continuum by assuming that the intensity of [S III] relative to anyone of these is constant. Similar numbers are obtained in each case; the resulting estimate of the total flux is 7.6×10^{-18} W cm^{-2}. This flux agrees extremely well with that predicted by Simpson (1975).

Kaler *et al.* (1976) estimated the electron density in the region where S^{++} is abundant from the optical forbidden line ratios of Cl^{++}, which is of similar ionization excitation and would be expected to coexist with S^{++}, and obtained a value of $n_e = 1.8 \times 10^5$ cm^{-3}. The density in the S^{++} region may be more directly determined from a comparison of the 18.7 μm line with the optical forbidden lines of S^{++}. The relative intensities of the optical [S III] lines to Hβ given by Kaler *et al.* (1976) were corrected for reddening and combined with the Hβ photometry of Miller and Mathews (1972) to yield the intensity ratios $\lambda 9069/\lambda 18.7\ \mu$m = 5.2 and $\lambda 9069/\lambda 6312 = 6.65$. Comparison line ratios were predicted as a function of temperature and density by solving the steady-state rate equations using collision strengths and radiative transition rates due to Czyzak and Krueger (1963; Krueger and Czyzak 1970). The electron density and temperature of a homogeneous S^{++} region required to fit the observed ratios are $n_e = 1.0 \times 10^5$ cm^{-3} and $T_e = 13{,}000$ K. These values and those of Kaler *et al.* (1976) agree within the uncertainties in either determination. The sensitivity of our values to the 18.7 μm intensity is such that a $\pm 20\%$ uncertainty results in a variation of $\mp 40\%$ in n_e and ± 500 K in T_e.

Because of collisional saturation, the population of the $^3P_2$ level of S^{++} is very insensitive to the electron temperature and density if the density exceeds 5×10^4 cm^{-3}, having the value $n(^3P_2) = 0.45 \pm 0.05\ n(S^{++})$. Although the values of n_e and T_e given above are sensitive to inhomogeneity and the reddening correction, the high ratio $\lambda 9069/\lambda 18.7\ \mu$m guarantees that $n(^3P_2) = 0.45\ n(S^{++})$ is a good approximation. Therefore, from the observed surface brightness at the "bright knot" we calculate a column density of S^{++} ions equal to 4.2×10^{15} cm^{-2}.

This is apparently the only direct measurement of an ionic column density in ionized nebulae. Comparison with other measurable quantities, which are weighted in various ways with the electron density and temperature, is inappropriate without a detailed model of the nebular structure including fluctuations. However, collisional saturation of the fine-structure levels will generally occur for all fine-structure lines lower in frequency than [S III], so their future measurements will allow excellent direct comparisons of ionic column densities. Collisional saturation will not commonly occur in ions with higher-frequency fine-structure lines; however, relative ion abundances determined from fine-structure line ratios are still likely to be more accurate than those provided by other methods. The ionization potentials of S^{++}, S^{+++}, Ar^{++}, and Ne^+ are close enough to reasonably assume a common value for the electron density and temperature. If one uses the [S IV] and [Ne II] intensities of Bregman and Rank (1975) and the [Ar III] 9.0 μm intensity of Geballe and Rank (1973), the relative ion abundances at the position of the "bright knot" are $S^{+++}/S^{++} = 0.86$, $Ne^+/S^{++} = 3.0$, and $Ar^{++}/S^{++} = 0.30$ assuming $n_e = 1.0 \times 10^5$ and $T_e = 13{,}000$ K. The rather unrealistic assumption of a homogeneous nebula would also give the abundance of S^{++} relative to H^+ as

$$\frac{n(S^{++})}{n(H^+)} = \frac{n_e \int n(S^{++}) dl}{\mathrm{EM}} = 1.4 \times 10^{-6}\,, \qquad (1)$$

where EM is the average emission measure in our field of view and equals 1×10^8 pc cm^{-6} from the 15 GHz contours of Harris and Scott (1976). It is interesting to note the equal abundance of S^{++} and S^{+++} in this high-excitation nebula.

b) BD +30°3639

The low-excitation planetary nebula BD +30°3639 is approximately the same size as our beam, and the detected flux represents an uncertain fraction of the total, in the range $\frac{1}{2}$ to 1. The estimated total intensity given in Table 1 assumes that two-thirds of the flux is detected. At the electron density, 5×10^4 cm^{-3}, and temperature, 8150 K, derived by Peimbert (1971), the predicted ratio $\lambda 9069/18.7\ \mu$m is 2.0, which is in good agreement with the observed value of 2.5. The intensity of $\lambda 6312$ is not presently available; its observation would be very useful in determining both the electron temperature and density in the higher-excitation regions of BD +30°3639. The [Ne II] $\lambda 12.8\ \mu$m/[S III] $\lambda 18.7\ \mu$m ratio (Table 1) implies that Ne^+ is about 10 times as abundant as S^{++}. Since S^+ and S^{++} are roughly equal in abundance in BD +30°3639, the neon-to-sulfur ratio is near the cosmic value of 5.2 (Allen 1973) if neon is ionized in the S^+ zone.

c) G333.6−0.2

The visually obscured compact H II region G333.6−0.2 is the most intense source of [Ne II] 12.8 μm emission known. It is not surprising that it is also a strong emitter of [S III] 18.7 μm. We have made a partial exploration of the distribution of [S III] emission and find a slightly extended central condensation similar to the distribution of [Ne II] measured by Aitken, Griffiths, and Jones (1976). A small beam separation and the standard technique of beam switching greatly reduce our sensitivity to the extended "halo" observed in [Ne II] by Wollman *et al.* (1975). Although we cannot confidently derive a total [S III] flux from our data, it is not expected that the extended emission will strongly affect the observed central surface brightness. The tentative detection of [S III] by Aitken, Griffiths, and Jones (1976) using a 13″ beam is consistent with the condensed nature of the [S III] emission.

Accurate determination of the relative ion abundances in G333.6−0.2 is hampered by uncertainty in the dust extinction at the different fine-structure line wavelengths. Aitken and Jones (1974) have observed a 9.7 μm silicate absorption feature, similar to that seen in a number of compact H II regions, with an optical depth at 10.4 μm equal to 1.5. The extinction at 18.7 μm is dominated by a second silicate resonance of which the strength and spectral shape are uncertain. It is expected that $\tau_{12.8\mu m} < \tau_{18.7\mu m} < \tau_{9.7\mu m}$ (Knacke and Thomson 1973), although there is a recent indication (Forrest, Houck, and Reed 1976) that the interstellar silicate material has a stronger 19 μm absorption than those materials studied in the laboratory.

The abundance ratio S^{++}/S^{+++} is valuable as a direct indicator of the degree of ionization. We may write

$$\frac{n(S^{++})}{n(S^{+++})} = \frac{S[\mathrm{S\ III}]}{S[\mathrm{S\ IV}]} f(x) \exp\left(\tau_{18.7\mu m} - \tau_{10.5\mu m}\right),$$

where $x = n_e T_e^{-1/2}$. At $T_e = 10^4$ K, $f(x)$ is ~ 2 for $n_e < 10^4$ cm^{-3} and slowly increases with density to ~ 4 at $n_e = 10^5$ cm^{-3}. The exponential correction factor is probably not less than 0.5. The [S IV] surface brightness used in Table 1 was calculated from the upper limit of Aitken and Jones (1974) on the assumption that the relative brightness of [S IV] to [Ne II] is constant over the central region of G333.6−0.2. Thus S[S IV]/S[S III] may be slightly underestimated since S^{+++} is likely to be more centrally concentrated than either Ne^+ or S^{++}. However, it is still reasonably certain that S^{++} is several times more abundant than S^{+++} in the core of G333.6−0.2.

If the excitation of G333.6−0.2 is provided by a single star, as suggested by its compact symmetrical structure, then the required number of ionizing photons and the total luminosity imply a star of very early spectral type. Model calculations (e.g., Balick and Sneden 1976) then predict that S^{+++} is more abundant tha S^{++}, in contrast to the observed situation. The weak He I 109α recombination line in G333.6−0.2 observed by McGee, Newton, and Batchelor (1975) is a further indication of a relatively cool ionization source. Dust in the ionized region can lower the ionization of sulfur, and helium to a lesser degree (Balick 1975), but the attendant reduction in the radio luminosity makes this explanation unappealing.

Consistent with its low excitation, G333.6−0.2 is one of the few H II regions where the intensity of [Ne II] is as strong as would be expected if neon were cosmically abundant and all singly ionized (Gillett *et al.* 1975; Wollman 1976). An equation similar to equation (2) may be written for $n(S^{++})/n(Ne^+)$, where $f(x)$ now ranges from $\sim$0.2 to $\sim$0.8 and the dust correction factor is greater than one. There exists considerable flexibility in the choice of parameters that are consistent with a cosmic neon-to-sulfur abundance ratio. For example, if one assumes that roughly half of the sulfur is double ionized (Balick and Sneden 1976) and also assumes a density of 2.8×10^4 as suggested by Aitken, Griffiths, and Jones (1976), the observations can be fitted with $\tau_{18.7\mu m} - \tau_{12.8\mu m} = 0.9$, a reasonable value considering the uncertainty in the behavior of the extinction law. This implies $(\tau_{18.7} - \tau_{10.5}) \sim 0$ in equation (2).

V. CONCLUSIONS

1. The [S III] 18.7 μm fine-structure line is a useful probe of ionized nebulae, but its frequency has been found to be so close to an atmospheric H_2O line that airborne observations are desirable.

2. The fine-structure line intensities agree well with existing optical data on NGC 7027 and BD +30°3639. The column densities of S^{++} ions have been directly measured in NGC 7027 and BD +30°3639 by taking advantage of the collisional saturation of the fine-structure levels.

3. The sulfur abundance in G333.6−0.2 is apparently normal. However, it is difficult to reconcile the high radio and infrared luminosity of this source with its low state of ionization excitation.

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