THE ASTROPHYSICAL JOURNAL, 270:645–653, 1983 July 15

DETERMINATIONS OF S III, O IV, AND Ne V ABUNDANCES IN PLANETARY NEBULAE FROM INFRARED LINES

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Received 1982 November 22; accepted 1982 December 28

ABSTRACT

Airborne observations of the infrared forbidden lines [S III] 18.71 μm, [Ne V] 24.28 μm, and [O IV] 25.87 μm have been made for 12 planetary nebulae. One or more of the lines were detected in seven of these nebulae, and ionic abundances were calculated. These results are insensitive to nebula temperatures, in contrast to the case for optical or UV lines. However, density estimates from optical and UV forbidden lines were required to obtain abundances.

The Ne V infrared line flux from NGC 7662 was combined with the 3426 Å flux to obtain a Ne V electron temperature of $11{,}200^{+2000}_{-1100}$ K, which overlaps O III temperature measurements. Since the ionization potential of Ne IV is much greater than that of O II, T_e (Ne V) would be expected to be much greater than T_e (O III). In fact, numerical models predict T_e (Ne V) $\approx (16\text{–}20)\times 10^3$ K. This discrepancy may indicate inaccuracies in currently available atomic parameters for Ne V.

Subject headings: infrared: spectra — nebulae: abundances — nebulae: planetary

I. INTRODUCTION

Planetary nebulae represent an important stage in the evolutionary life of many stars. It has been estimated that planetary nebulae contribute as much as 25% of the total mass return to the interstellar medium (Maciel 1981). If material processed in the interiors of planetary nebula precursors is mixed into their outer envelopes prior to the mass loss stage, planetary nebulae will be important contributors to the enrichment of the interstellar medium. Unfortunately, neither mixing nor mass loss processes are well understood at present (cf. Iben 1981; Kwok 1981; Peimbert 1981). It is therefore of interest to make elemental abundance measurements of planetary nebulae to obtain information about prenebular mixing and mass loss processes, as well as ISM enrichment.

In order to determine an ionic abundance relative to hydrogen, the ratio of the ionic line flux to either a hydrogen line flux or the radio continuum flux must be measured. For optical and UV line measurements, extinction and reddening often become very strong. The ionic emissivities and hence the derived abundances are also very sensitive to the electron temperature, further complicating abundance determinations. In contrast, infrared fine-structure line measurements are not as affected by extinction. Also, the emissivities of these lines are only weakly dependent on temperature over the temperature range found in typical planetary nebulae. Recently, there have been abundance studies of planetary nebulae which include measurements of infrared forbidden lines which are accessible from ground-based observatories: [Ar III] 8.99 μm, [S IV] 10.51 μm, and [Ne II] 12.81 μm (Beck *et al.* 1981; Rank 1978, and references therein). There are, however, important additional infrared lines which are observable from airborne telescopes. The current investigation presents observations of 12 planetary nebulae obtained with the NASA Kuiper Airborne Observatory (KAO) for three infrared lines: [S III] 18.71 μm, [Ne V] 24.28 μm, and [O IV] 25.87 μm. Observations of [S III] 18.71 μm in planetary nebulae have been reported previously for NGC 7027 and BD +30°3639 (Greenberg, Dyal, and Geballe 1977). The O IV and Ne V infrared lines have been detected in NGC 7027 (Forrest, McCarthy, and Houck 1980) and are reanalyzed here.

The main purpose of the present study is to compute ionic abundances for the seven nebulae in which one or more of the infrared lines were detected. The electron densities necessary in calculating ionic abundances were obtained from optical and UV forbidden line measurements. Emission of these lines is unfortunately weighted toward low-extinction and high-temperature regions of nebulae. Densities obtained from optical line fluxes integrated over the entire nebula were used when available, in an attempt to average over local variations in extinction and temperature. We have also combined our Ne V IR line flux from NGC 7662 with the [Ne V] 3426

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TABLE 1

SUMMARY OF OBSERVATIONS

Object	Observing Night	Spectral Region Scanned
NGC 2392	1980 Mar 4	S III, Ne V, O IV
NGC 6210	1979 Jul 16	S III, O IV
NGC 6543	1978 May 8	S III, O IV
NGC 6572	1980 Jul 22, 31	16–30 μm
NGC 6790	1980 Jul 22	S III, Ne V, O IV
NGC 6884	1979 Jul 18	O IV
NGC 7027	1979 Jul 10	16–30 μm
NGC 7354	1980 Jul 24	Ne V, O IV
NGC 7662	1980 Jul 24	Ne V, O IV
IC 418	1980 Mar 6	16–30 μm
IC 2003	1980 Mar 6	O IV
BD +30°3639 ...	1979 Jul 12	16–30 μm

Å flux to obtain an estimate of the nebular temperature. The unusually low temperature thus obtained probably indicates inaccuracies in the collision strengths presently available. If this is the case, some of the derived Ne V abundances will be in error as well.

In § II we discuss the S III, O IV, and Ne V, line observations. Line fluxes are used to calculate ionic abundances in § III. In § IV, the Ne V line flux from NGC 7662 is combined with the [Ne V] 3426 Å flux integrated over the nebula to estimate the electron temperature in the Ne V emission region. A summary of our results is presented in § V.

II. OBSERVATIONS

Observations of 12 planetary nebulae were made between 1978 May and 1980 July using the 91 cm telescope of the KAO. Flight altitudes were in excess of 12.5 km for all observations. All nebulae were observed with a 10-channel liquid-helium–cooled Ebert-Fastie grating spectrometer (Forrest, McCarthy, and Houck 1980) with a resolution of $\Delta\lambda \approx 0.16$ μm (FWHM). Used in conjunction with the KAO, the spectrometer has a beam diameter on the sky of 30″. For a description of the calibration techniques, see Forrest, McCarthy, and Houck (1980). An observations log is presented in Table 1.

Line positions and the adjacent continua were sampled at up to three points per resolution element (FWHM), and the fluxes were obtained by fitting the observed data with a Gaussian instrumental response function plus a linear baseline. Line fluxes are given in Table 2. Statistical errors quoted are 1 σ, while upper limits are 3 σ. Additional overall flux calibration uncertainties are estimated to be $\lesssim 15\%$ (this uncertainty is not included in any of the fluxes or abundance results). The wavelength calibration is estimated to be accurate to ± 0.02 μm. Some line positions were scanned at less than one point per resolution element, as indicated in Table 2. Although such scans include only one point within the line, fluxes and upper limits were obtained from them since the flux was measured at a wavelength within $\pm 1/4 \times$FWHM (0.04 μm) of the expected line center position (except as noted below). Gaussian plus

TABLE 2

PLANETARY NEBULA SIZES AND FLUXES

Object	Size[a]	Radio Flux[b] (Jy)	$F_{\mathrm{S\,III}}$(18.71 μm) (10^{-18} W cm^{-2})	$F_{\mathrm{Ne\,V}}$(24.28 μm) (10^{-18} W cm^{-2})	$F_{\mathrm{O\,IV}}$(25.87 μm) (10^{-18} W cm^{-2})	$F_{\mathrm{continuum\ at\ 25.87\ \mu m}}$ (10^{-18} W cm^{-2} μm^{-1})
NGC 2392	~18″ (45″ outer region)	0.32 ± 0.06	≤ 9.2[c]	≤ 2.1[c]	8.3 ± 1.1	< 2.4
NGC 6210	8″ (13″×20″ fainter region)	0.39 ± 0.06	≤ 4.8[c]	≤ 2.5[c]	≤ 3.6[c]	10.3 ± 1.0
NGC 6543	16″×22″ (300″ faint shell)	0.77 ± 0.08	13.6 ± 2.0	...	≤ 6.6[c,d]	63.2 ± 2.1
NGC 6572	13″×16″	1.15 ± 0.25[e]	≤ 6.5	≤ 1.4[c]	≤ 1.3[c]	88.8 ± 0.9
NGC 6790	5″×10″	0.34 ± 0.06	≤ 7.7[c]	≤ 2.6[c]	≤ 2.3[c]	12.9 ± 0.9
NGC 6884	7″.5	0.22 ± 0.05	≤ 4.5[c]	≤ 2.1[c]	≤ 5.1[c]	4.9 ± 1.1
NGC 7027	10″×15″ at 8 GHz[f]	6.37 ± 0.48	≤ 23	33.1 ± 5.0	59.9 ± 6.2	535 ± 3
NGC 7354	18″×22″ (32″ fainter region)	0.39 ± 0.10	...	3.56 ± 0.91[c]	56.4 ± 1.7	8.7 ± 1.6
NGC 7662	25″	0.60 ± 0.09	...	3.58 ± 0.72[c]	51.4 ± 2.0	6.9 ± 1.0
IC 418	11″×14″	1.56 ± 0.14	≤ 11[c]	≤ 4.5[c,d]	≤ 4.5[c]	92.5 ± 5.5
IC 2003	6″×7″	0.020[g]	...	...	5.24 ± 0.48[c]	< 4.6
BD +30°3639	~6″	0.54 ± 0.07	4.9 ± 1.5	≤ 3.4	≤ 4.9	107 ± 3

[a] Optical diameters from Perek and Kohoutek 1967 and Curtis 1918.

[b] From Higgs 1971—all fluxes at 10.63 GHz unless noted otherwise.

[c] Line position scanned at less than one point per resolution element (see text).

[d] Based on signal measured at greater than 0.25 times (resolution element) from expected line center (see text).

[e] Flux at 9.6 GHz.

[f] From Terzian, Balick, and Bignell 1974.

[g] Flux at 6.63 GHz.

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linear baseline fits to lines thus observed were performed by fixing the instrumental response function at the expected line center. Observations of [O IV] in NGC 6543 and [Ne V] in IC 418 were made at 0.06 μm and 0.10 μm displacement from the expected line center, respectively, so that the resulting upper limits are less reliable.

Also given in Table 2 are the continuum fluxes or 3 σ upper limits at 25.87 μm. It should be kept in mind that these fluxes are integrated over a 30″ diameter beam. This continuum emission is probably due to dust in or surrounding the nebulae. For some of the larger nebulae there may be considerable emission outside the beam. The complete 16–30 μm spectrum has been previously published for three of the nebulae: NGC 7027 (Forrest, McCarthy, and Houck 1980) and IC 418 and NGC 6572 (Forrest, Houck, and McCarthy 1981).

III. IONIC ABUNDANCES

The ground-state fine-structure energy levels for S III, O IV, and Ne V are shown in Figures 1, 2, and 3. Ionic abundances are calculated by using the line emissivity per ion density per electron density, $j/n^i_X n_e$, of the ith ionization state of element X evaluated at a temperature and density characteristic of the emitting region (Simpson 1975). Comparing the observed line flux with the appropriate optically thin free-free radio flux yields the ionic abundance (cf. Herter *et al.* 1981),

$$\frac{n^i_X}{n_H} = 2.95\times 10^{-6}\left(\frac{F_l}{10^{-18}\ \mathrm{W\ cm^{-2}}}\right) \times\left(\frac{S_\nu}{1\ \mathrm{Jy}}\right)^{-1}\left(\frac{T_e}{10^4\ \mathrm{K}}\right)^{-0.35}\left(\frac{\nu}{10\ \mathrm{GHz}}\right)^{-0.1} \times\left(\frac{j/n^i_X n_e}{10^{-22}\ \mathrm{ergs\ cm^3\ s^{-1}\ sr^{-1}}}\right)^{-1}, \tag{1}$$

where we have assumed an effective positive ion density of $1.16 n_H$; F_l is the measured line flux, S_ν is the radio flux (measured at a frequency ν), and T_e is the electron temperature. The radio fluxes are listed in Table 2. The quantity $j/n^i_X n_e$ is evaluated as a function of density and temperature by solving the two-level atom for O IV and the five-level atom for Ne V and S III using the transition probabilities and collision strengths compiled by Mendoza (1983). The references are listed in Table 3. The emissivities are shown in Figures 1, 2, and 3 for S III, O IV, and Ne V, respectively.

Densities in planetary nebulae are often quite high, on the order of 10^4 cm^{-3} or greater (cf. Osterbrock 1974). For collisionally excited lines, a critical density may be defined at which the rate of collisional de-excitation out of an ionic level equals that of spontaneous emission. For O IV, S III, and Ne V the critical densities are approximately 10,000, 15,000, and 57,000 cm^{-3}, respectively, for an assumed electron temperature of 10,000 K. At densities below the critical density, $j/n^i_X n_e$ becomes independent of electron density, and therefore, the resulting abundance determinations are independent of the assumed density. However, at densities above the critical density, $j/n^i_X n_e$ decreases linearly with increasing electron density, and so the derived abundances increase linearly with assumed density (see eq. [1]). Densities were determined through the use of optical and UV forbidden line ratios. In the presence of density variations, the densities derived from high-excitation ions should be more appropriate for the regions occupied by O IV and Ne V. The choice of electron temperature is not critical since the line emissivities are nearly independent of temperature over the range of interest here (see Figs. 1–3). The values adopted in our analysis are given in Table 4.

Sources for the adopted electron densities and temperatures are given below. The data of Barker (1978, 1979) have the advantage of being from observations with entrance apertures covering the entire nebula, except for NGC 6543, 7027, and 7662. Barker (1979) used a 12″×125″ slit to obtain fluxes from NGC 6543. In the case of NGC 7027, Barker (1978) used the line intensities of Peimbert and Torres-Peimbert (1971) obtained with a 21″ diaphragm in addition to his own measurements (obtained with a 8″×200″ slit). For NGC 7662, he used only the results of Peimbert and Torres-Peimbert (1971) from 21″ and 30″ diaphragm intensities. Therefore, he derives densities and temperatures averaged over the nebulae. However, as noted before, since optical forbidden lines were used, the results will be weighted toward regions of higher temperature and lower extinction.

1. *NGC 2392.*—This nebula shows a very inhomogeneous distribution of optical forbidden line emission (Aller 1956; Aller and Walker 1970). Using line fluxes integrated over the entire nebula, Zipoy (1976) obtained electron densities of 1800 cm^{-3} from the [S II] line ratio and 1000 and 4000 cm^{-3} from [O II] line ratios. We will adopt the mean of these values, 2300 cm^{-3}. An electron temperature of 14,000 K was determined by Zipoy from [O III] lines.

2. *NGC 7027.*—For this nebula, electron densities obtained from ions with a range of ionization potentials yield much higher values for the higher potential ions, suggesting higher densities in the high-excitation regions (Saraph and Seaton 1970; Kaler *et al.* 1976). From the results of Kaler *et al.* these densities range from 3.5×10^4 cm^{-3} for O II to 2.4×10^5 cm^{-3} for Ar IV and 3.4×10^5 cm^{-3} for K V, assuming their value of $T_e = 11{,}500$ K. Although the atomic parameters for Ar IV and K V are suspect (Kaler *et al.* 1976; Czyzak *et al.* 1980; Mendoza 1983), the hydrogen and helium decrements obtained by Kaler *et al.* indicate even higher densities than do these lines (as high as 10^7 cm^{-3}). Therefore, high densities are

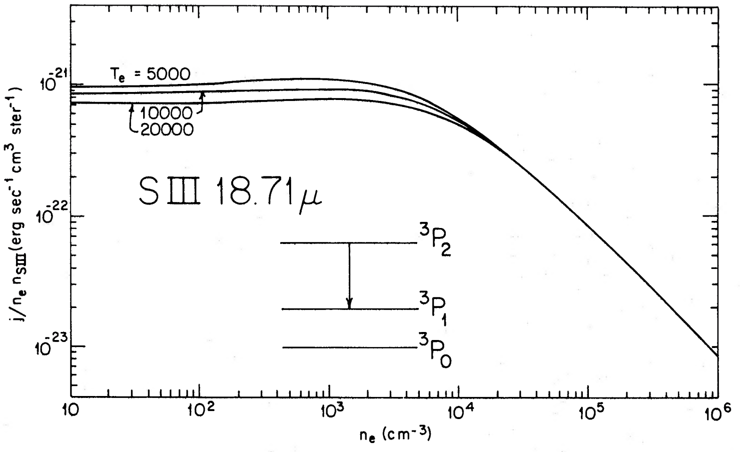

FIG. 1.—S III level diagram (to scale) and emissivity per electron density per ion density vs. electron density. The higher $^1D_2$ and $^1S_0$ levels are omitted.

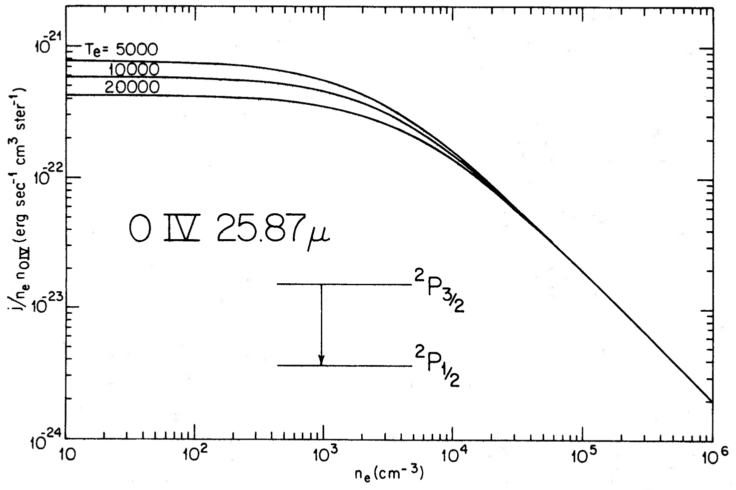

FIG. 2.—O IV level diagram and emissivity per electron density per ion density vs. electron density

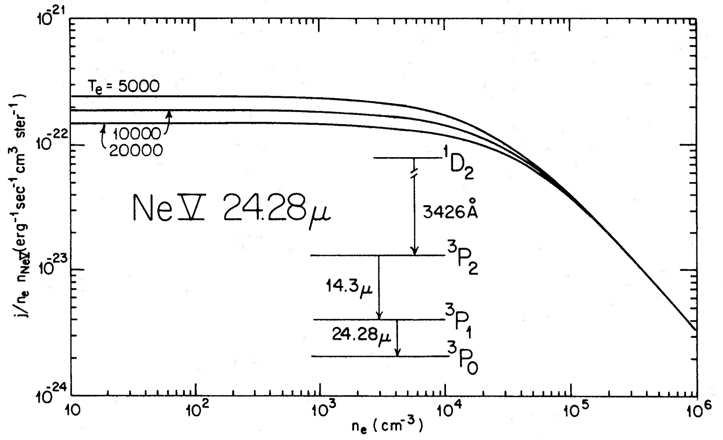

FIG. 3.—Ne V level diagram (to scale except for $^1D_2$ level) and emissivity per electron density per ion density vs. electron density. The higher $^1S_0$ level is omitted.

TABLE 3

REFERENCES FOR TRANSITION PROBABILITIES AND COLLISION STRENGTHS USED IN LINE EMISSION CALCULATIONS

Ion	Transition(s)	A	Ω
S III	all among $^3P_J, {}^1D_2, {}^1S_0$	Mendoza and Zeippen 1982	Mendoza 1982
O IV ...	$^3P_{1/2}-{}^3P_{3/2}$	Garstang 1968	Hayes 1982
Ne V ...	$^3P_J-{}^3P_{J'}$	Nussbaumer and Rusca 1979	Saraph, Seaton, and Shemming 1969
Ne V ...	others among $^3P, {}^1D_2, {}^1S_0$	Nussbaumer and Rusca 1979	Baluja, Burke, and Kingston 1980

TABLE 4

DERIVED ABUNDANCES

Object	$\frac{n_{\text{S III}}}{n_{\text{H}}}$	$\frac{n_{\text{O IV}}}{n_{\text{H}}}$	$\frac{n_{\text{Ne V}}}{n_{\text{H}}}$ [a]	n_e (cm^{-3})	T_e (K)
NGC 2392	...	$(2.1\pm0.5)\times10^{-5}$	...	2300[b]	14,000[c]
NGC 7027	...	$(4.1\pm0.5)\times10^{-4}$	$(1.2\pm0.2)\times10^{-4}$	3.5×10^5 [b]	16,000 ± 1500[d]
NGC 7354	...	$(1.8\pm0.5)\times10^{-4}$	$(1.7\pm0.6)\times10^{-5}$	5600[e]	13,500[e]
NGC 7662	...	$(7.3\pm1.1)\times10^{-5}$	$(1.0\pm0.3)\times10^{-5}$	2650 ± 1350[f]	13,500 ± 800[d]
IC 2003...........	...	$(1.5\pm0.7)\times10^{-4}$	...	5500 ± 3000[d]	14,200 ± 1000[d]
NGC 6543	$(8.6\pm1.5)\times10^{-6}$	...	...	7080[g]	8250 ± 450[b]
BD +30°3639 ...	$(5.1\pm1.7)\times10^{-6}$	...	...	10,000 ± 5000[d]	9500 ± 1000[d]
Cosmic elemental abundance[h]	$\frac{n_{\text{S}}}{n_{\text{H}}}=1.6\times10^{-5}$	$\frac{n_{\text{O}}}{n_{\text{H}}}=6.6\times10^{-4}$	$\frac{n_{\text{Ne}}}{n_{\text{H}}}=8.3\times10^{-5}$		

[a] Ne V abundances for NGC 7354 and 7662 subject to question because of uncertainty in atomic parameters (see text).

[b] See text.

[c] Zipoy 1976.

[d] Barker 1978.

[e] Kaler 1978.

[f] Flower, Penn, and Seaton 1982.

[g] Saraph and Seaton 1970.

[h] Allen 1981.

confirmed, and we have adopted $n_e = 3.5\times10^5$ cm^{-3} for the density in the O IV– and Ne V–emitting regions. This is slightly higher than the value 2.5×10^5 cm^{-3} used in the previous analysis by Forrest, McCarthy, and Houck (1980). Clearly, the density in the high-excitation regions is still open to question. Barker (1978) obtained an electron temperature of 16,000 ± 1500 K from [O III] and [N II] line ratios.

3. *NGC 7354.*—Very little information is available for this nebula. The electron density and temperature are from Kaler (1978).

4. *NGC 7662.*—Recent measurements of the Ne IV UV line ratio yield $1300 \leq n_e \leq 4000$ cm^{-3} (Flower, Penn, and Seaton 1982). We therefore adopt an electron density of 2650 ± 1350 cm^{-3}. The electron temperature of 13,500 ± 800 K was obtained by Barker (1978) from [O II], [O III], and [S II] line ratios.

5. *IC 2003.*—The electron density and temperature were both determined by Barker (1978) using [O II], [O III], [N II], and [S II] line ratios.

6. *NGC 6543.*—The electron density is taken from the [Cl III] determination of Saraph and Seaton (1970). The electron temperature is an average of the results of Barker (1979), 8000 ± 200 and 8500 ± 700 K, obtained from [O III] and [N II] lines, respectively.

7. *BD + 30°3639.*—The electron density and temperature are those of Barker (1978), who used the [O II] and [N II] line ratios.

Figures 4, 5, and 6 show the sensitivity of the ionic abundances to assumed electron density. In addition, the likely density limits outlined above are shown for each object. Because of the higher critical densities of S III and Ne V, those derived abundances are less sensitive to density uncertainties than those of O IV. The

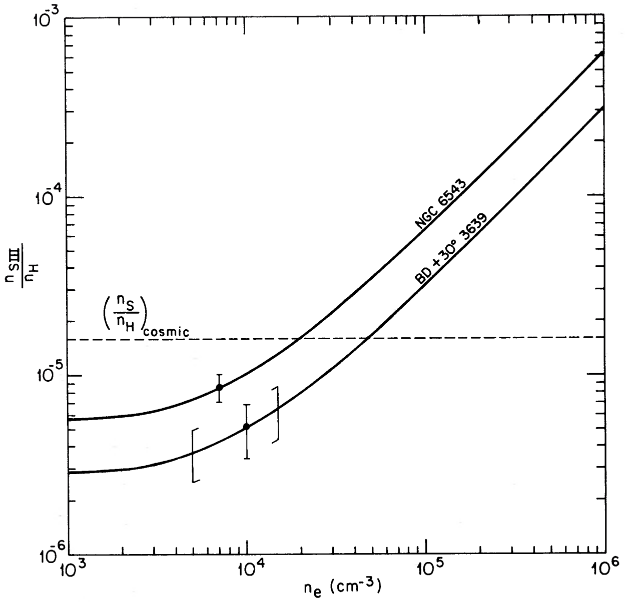

FIG. 4

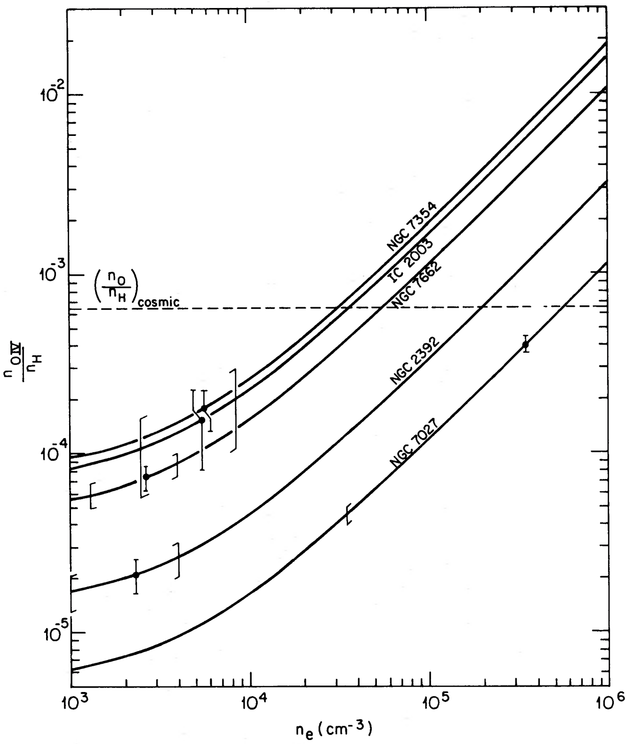

FIG. 5

FIG. 4.—S III ionic abundance vs. assumed electron density. The plotted points indicate abundances for the best estimates of electron density given in Table 4. The error bars on the points denote the range resulting from uncertainties in line and radio fluxes (given in Table 2) being used in eq. (1). The brackets indicate the range in assumed electron densities, where available.

FIG. 5.—Same as Fig. 4 for O IV

ionic abundances obtained from the plotted points in Figures 4, 5, and 6 are given in Table 4.

Ignoring faint ansae (43″ apart) in the case of NGC 6210 and a 5′ diameter, very faint shell around NGC 6543, all of the nebulae were totally within our beam except NGC 7354 and 2392. Curtis (1918) described NGC 7354 as an "irregular oval ring" 18″×22″ in size surrounded by "a ring or disk of much fainter matter, rather more circular in form and 32 arsec across." Since our beam diameter was 30″ and this outer disk was so faint, we did not make any corrections to the observed line fluxes. In addition, only the O IV and Ne V line positions were scanned, and these ions would be expected to be concentrated near the center of the nebula. Slitless spectra of NGC 2392 show that all of the λ3426 [Ne V] and most of the λ5007 [O III] emission is restricted to the inner shell of 18″ diameter (Wright 1918; Wilson 1950; Aller 1956). This implies that the Ne V and O IV infrared line emission is also confined mainly to the inner region of the nebula, well within our 30″ beam. Thus, our measurements yield estimates of the ionic abundance for the entire nebula for all of the nebulae we observed.

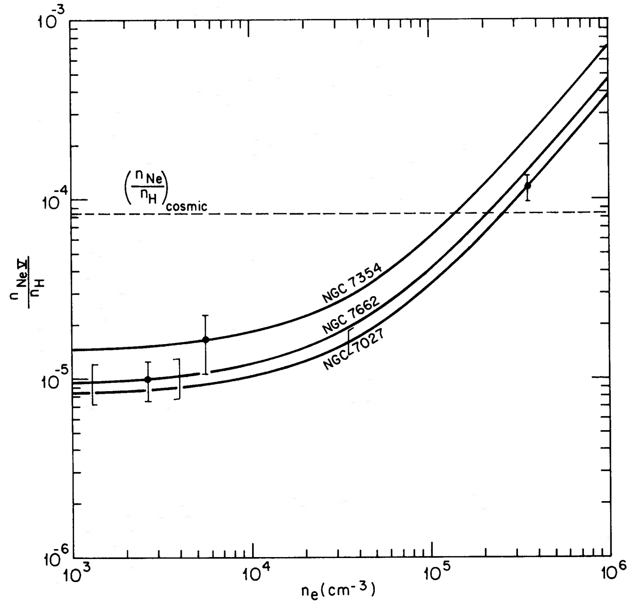

FIG. 6.—Same as Fig. 4 for Ne V. As discussed in § IV, these abundances are possibly overestimates for NGC 7354 and 7662.

Because of uncertainties in the collision strengths for Ne V (see discussion in § IV), the Ne V abundances are

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possibly overestimates for NGC 7354 and 7662. More accurate results for these nebulae must await more accurate calculations of the atomic parameters. The derived abundance for NGC 7027, however, is independent of collision strengths since $n_e \gg n_{\rm crit}$, and the infrared level is statistically populated. Figure 6 implies that the Ne V abundance in NGC 7027 is greater than the cosmic Ne abundance. This result was discussed in Forrest, McCarthy, and Houck (1980).

IV. NEBULAR TEMPERATURES

Determinations of electron temperatures within the very high excitation regions of planetary nebulae are relatively scarce. A common temperature determinant is the λ4363/(λ4959 + λ5007) line ratio of O III. To ionize O II, 35 eV photons are required. In contrast, Ne IV requires 97 eV photons to be ionized, and so Ne V probes regions much closer to the central star.

Nussbaumer (1972) suggested using the [Ne V] 14.3 μm to [Ne V] 3426 Å line ratio to determine electron temperatures. The 14.3 μm line is situated in a strong atmospheric CO_2 feature and so is unobservable, even from airborne altitudes. However, the 24.28 μm line also originates in the ^3P multiplet (see Fig. 3), and the 24.28 μm to 3426 Å ratio is also sensitive to temperature and nearly independent of density for $n_e < n_{\rm crit} \approx 57{,}000$ cm^{-3}. Contours for this ratio versus n_e and T_e are given in Figure 7.

Since the infrared line flux has been obtained as an integration over the entire emitting region, any comparison should be made with the 3426 Å line flux similarly integrated over the nebula. Such results have been published for NGC 7027 and 7662 from microdensitometer traces over photographic slitless spectra (Aller 1941). Because of differential extinction over the face of NGC 7027 (cf. symmetric 8 GHz map versus irregular optical image in Terzian, Balick, and Bignell 1974) and the high density [$n_e \approx 3.5 \times 10^5$ cm$^{-3} \gg n_{\rm crit}$], we will not attempt to use the Ne V line ratio to derive a temperature for this nebula. The integrated 3426 Å flux relative to Hβ for NGC 7662 was combined with the integrated Hβ flux as measured by Capriotti and Daub (1960) and corrected for extinction and reddening using an extinction constant of $c = 0.19 \pm 0.08$ from Cahn (1976) and the Whitford reddening curve as tabulated in Kaler (1976). The resulting [Ne V] 3426 Å flux is $(2.3 \pm 0.9) \times 10^{-18}$ W cm^{-2}. [A possible blend with the O III 3429 Å line was suggested by the slit spectra of Aller and Czyzak 1979, who found $I(3429)/I(3426) \approx 0.4$. However, examination of O. C. Wilson's slitless spectrum (Aller 1956) shows that the 3429 Å image is just barely visible, and so blending in Aller's integrated 3426 Å flux is ignored. Since the 3426 Å image is not uniformly bright, Aller and Czyzak's entrance slit might have been placed on a dim portion of the [Ne V] image.]

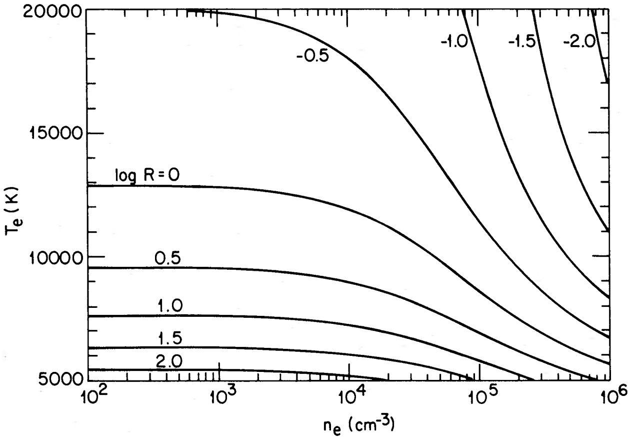

FIG. 7.—Contours of the ratio R of [Ne V] 24.28 μm to 3426 Å emissivity for a range of nebular temperatures and densities.

The flux ratio $R = F(24.28\ \mu{\rm m})/F(3426\ \text{Å})$ was found to be 1.52 ± 0.64. The range of densities and temperatures capable of generating the observed ratio is shown in Figure 8, along with the 1 σ uncertainty limits. Between these uncertainty limits and within the density range of 2650 ± 1350 cm^{-3}, the implied temperature is $11{,}200^{+2000}_{-1100}$ K. This is within the uncertainties of the value $13{,}500 \pm 800$ K obtained by Barker (1978) from [O II], [O III], and [S II] line ratios. Barker's value is probably a slight overestimate due to weighting toward high-temperature regions. An [O III] temperature contour map of this nebula (Reay and Worswick 1982) indicates a median temperature (defined as the temperature of the contour above which half the nebula is covered) of ≈ 12,000 K and includes contours of up to 13,500 K near the center. Using their measurements of the O IV] 1402 Å and He II 1640 Å lines, Harrington,

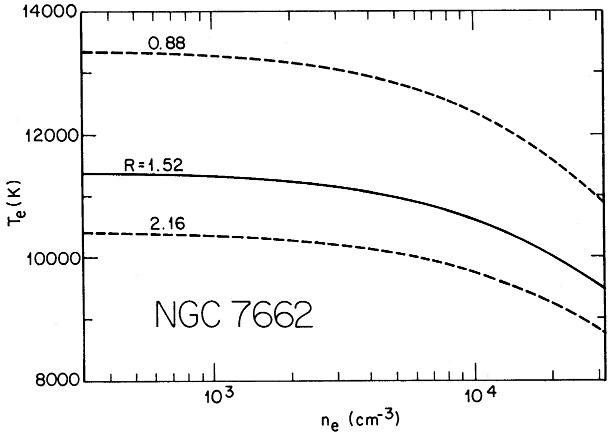

FIG. 8.—Ranges of temperature and density consistent with [Ne V] 24.28 μm to 3426 Å flux ratio in NGC 7662 (dashed curves denote 1 σ uncertainty limits).

Lutz, and Seaton (1979) obtained an O IV temperature of 14,100 K. This was found to be a lower limit to the O IV temperature by Harrington *et al.* (1982). Since O III ions require 55 eV to be ionized and Ne IV requires 97 eV, this provides us with a lower limit to the Ne V temperature.

The [O III] line originates in lower excitation regions than the Ne V emission. It is therefore surprising that our results should indicate such low temperatures. A recent comprehensive model constructed for NGC 7662 by Harrington *et al.* (1982), utilizing observed optical and UV line fluxes, predicts a temperature of 16,000 K in the Ne V zone. Earlier numerical models predict temperatures of $\approx 20,000$ K in the Ne V zone (Flower 1969*a*, *b*; Kirkpatrick 1972). Since the density we are assuming for this nebula is much less than $n_{\rm crit}$, we are already near the asymptotic low-density limit in Figure 8, and we cannot explain away this temperature discrepancy as due to an inaccurate density estimate. Even for a density as low as 300 $\rm cm^{-3}$, the upper bound on the temperature has only reached 13,300 K. It should be noted that at 2650 $\rm cm^{-3}$, the flux ratio R is only 1.6 σ away from a value which implies 16,000 K in Figure 8.

Before any clear conclusions may be drawn from the Ne V line ratios, it is important that more detailed atomic calculations be made. From Table 3 it is seen that the transition probabilities and the intermultiplet collision strengths for Ne V have been calculated fairly recently. The $^3P_J - {}^3P_{J'}$ collision strengths, however, have not been updated and may be somewhat questionable (Mendoza 1983). They are the most likely candidates for revision. Changing only the $^3P_J - {}^3P_{J'}$ collision strengths to bring the Ne V line ratio into agreement with a temperature of 16,000 K at 2650 $\rm cm^{-3}$ requires an increase in the sum $[\Omega(^3P_0 - {}^3P_1) + \Omega(^3P_0 - {}^3P_2)]$ of ≈ 3.1, where Ω is the collision strength between the indicated levels. Such a change would also decrease the derived ionic abundances of Ne V by the same factor for $n_e \ll n_{\rm crit}$ (see § III). We therefore suspect that the sum $[\Omega(^3P_0 - {}^3P_1) + \Omega(^3P_0 - {}^3P_2)]$ may be larger than presently believed and hope that these results prompt new calculations of the $^3P_J - {}^3P_{J'}$ collision strengths.

V. SUMMARY

We have derived ionic abundances for a low-excitation ion (S III) and two high-excitation ions (O IV and Ne V) in a number of planetary nebulae. The measured infrared line fluxes are insensitive to extinction and temperature variations in the nebula. However, the electron densities necessary to obtain ionic abundances were determined from optical and UV line fluxes weighted toward low-extinction and high–electron temperature regions. In our analysis, we assume a constant density throughout the relevant ion's emission region, choosing, where available, densities determined from ionic states of similar ionization potential. For nebular densities much less than the collisional critical density, the abundance determination becomes density independent. This is the case only for Ne V in NGC 7354 and 7662.

By combining our [Ne V] 24.28 μm observation in NGC 7662 with an integrated [Ne V] 3426 Å line flux, we were able to estimate the electron temperature for the Ne V–emitting regions of NGC 7662. We found the Ne V temperature to be equal within uncertainties to the temperature from lower excitation ions. We would expect Ne V to be found in high-excitation regions with higher temperatures, in agreement with numerical models of NGC 7662. Our Ne V electron temperature can be made to agree with the model result of Harrington *et al.* (1982) by increasing $[\Omega(^3P_0 - {}^3P_1) + \Omega(^3P_0 - {}^3P_2)]$ by a factor of 3.1. Any increase in these collision strengths would result in a corresponding decrease in the Ne V abundances derived for NGC 7354 and 7662. We suggest new calculations be carried out for the Ne V $^3P_J - {}^3P_{J'}$ collision strengths. Also, a new measurement of the integrated [Ne V] 3426 Å flux for NGC 7662, to compare with the photographic result used here, would be useful.

We thank the staff of the Kuiper Airborne Observatory for their excellent support. We wish to thank M. A. Hayes for helpful discussions of her O IV collision strength calculations. One of the authors (M. S.) also thanks Terrance Gaetz for useful discussions. This work was supported by NASA grant 33-010-081.

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