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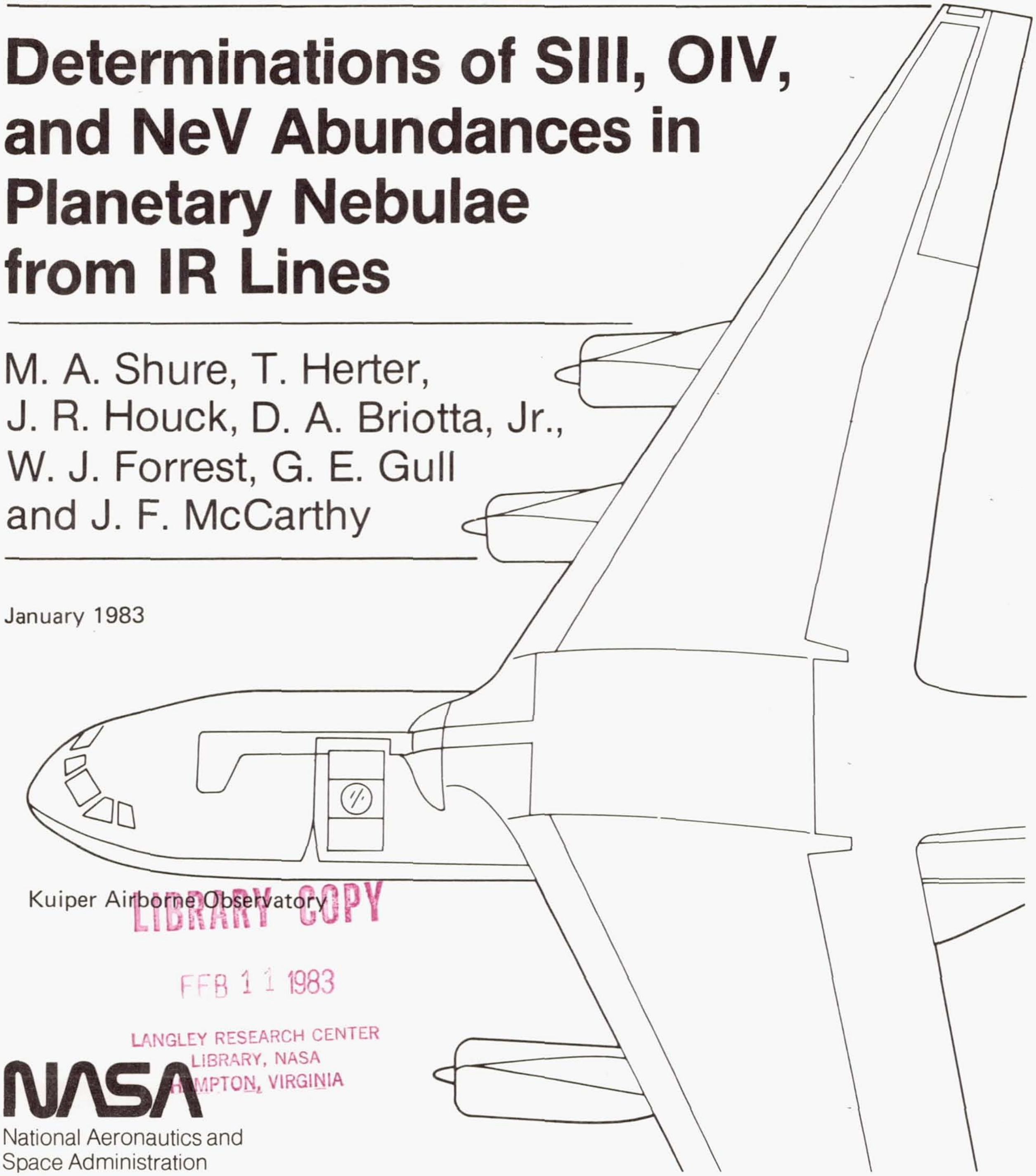

Kuiper Airborne Observatory

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DETERMINATIONS OF SIII, OIV, AND NeV ABUNDANCES IN PLANETARY NEBULAE FROM IR LINES

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ABSTRACT

Airborne observations of the infrared forbidden lines [SIII] 18.71 μm, [NeV] 24.28 μm and [OIV] 25.87 μm have been made for twelve planetary nebulae. One or more of the lines was 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 NeV infrared line flux from NGC 7662 was combined with the 3426Å flux to obtain a NeV electron temperature of $11,200^{+2000}_{-1100}$ K, which overlaps OIII temperature measurements. Since the ionization potential of NeIV is much greater than that of OII, T_e(NeV) would be expected to be much greater than T_e (OIII). In fact, numerical models predict $T_e(\text{NeV}) \approx (16\text{-}20) \times 10^3$K. This discrepancy may indicate inaccuracies in currently available atomic parameters for NeV.

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 and Peimbert 1981). It is therefore of interest to make elemental abundance measurements of planetary nebulae to obtain information about pre-nebular 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 planetaries. Recently, there have been abundance studies of planetary nebulae which include measurements of infrared forbidden lines which are accessible from ground-based observatories: [ArIII] 8.99 μm, [SIV] 10.51 μm and [NeII] 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 twelve planetary nebulae obtained with the NASA Kuiper Airborne Observatory (KAO) for three infrared lines: [SIII] 18.71 μm, [NeV] 24.28 μm and [OIV] 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 et al. 1977). The [OIV] and [NeV] 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 was detected. The electron densities necessary in calculating ionic abundances were obtained from optical 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 NeV IR line flux from NGC 7662 with the [NeV] 3426Å 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, the derived NeV abundances will be in error as well.

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

II. OBSERVATIONS

Observations of twelve planetary nebulae were made between May 1978 and July 1980 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 $\Delta\lambda \approx 0.16\,\mu m$ (FWHM). Used in conjunction with the KAO, the spectrometer has a beam diameter on the sky of 30 arcsec. 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 1σ while upper limits are 3σ. 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 $\pm 0.02\,\mu m$. 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 ($0.04\,\mu m$) of the expected line center position (except as noted below). Gaussian plus linear baseline fits to lines thus observed were performed by fixing the instrumental response function at the expected line center. Observations of [OIV] in

NGC 6543 and [NeV] 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 3σ upper limits at 25.87 μm. It should be kept in mind that these fluxes are integrated over a 30-arcsec 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 of the beam. The complete 16-30 μm spectrum has been previously published for three of the nebulae: NGC 7027 (Forrest et al. 1980) and IC 418 and NGC 6572 (Forrest et al. 1981).

III. IONIC ABUNDANCES

The ground state fine-structure energy levels for SIII, OIV and NeV are shown in Figures 1, 2 and 3. Ionic abundances are calculated by using the line emissivity per ion density per electron density,

$j/n_x^i n_e$, of the i^{th} 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),

$$\frac{n_x^i}{n_H} = 2.95\times10^{-6} \left(\frac{F_\ell}{10^{-18}\mathrm{W\ cm^{-2}}}\right) \left(\frac{S_\nu}{1\ \mathrm{Jys}}\right)^{-1} \left(\frac{T_e}{10^4\mathrm{K}}\right)^{-0.35}$$

$$\left(\frac{\nu}{10\ \mathrm{GHz}}\right)^{-0.1} \left(\frac{j/n_x^i n_e}{10^{-22}\mathrm{erg\ cm^3\ s^{-1}\ sr^{-1}}}\right)^{-1} \quad (1)$$

where we have assumed an effective positive ion density of $1.16n_H$. 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 $j/n_x^i n_e$ is evaluated as a function of density and temperature by solving the two-level atom for OIV and the five-level atom for NeV and SIII using the transition probabilities and collision strengths compiled by Mendoza (1982a) and given in Table 3. The emissivities are shown in Figures 1, 2 and 3 for SIII, OIV and NeV, 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 OIV, SIII, and NeV 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, $j/n_x^i n_e$ becomes independent of electron density and therefore the resulting abundance determinations are independent of the assumed density. However, at densities above the critical density $j/n_x^i n_e$ decreases linearly with increasing electron density, and so the derived abundances increase linearly with assumed density (see equation 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 OIV and NeV. The choice of electron temperature is not critical since the line emissivities are nearly independent of temperature over the range of interest here (see Figures 1, 2 and 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 x 125 arcec 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-arcsec diaphragm in addition to his own measurements (obtained with a 8 x 200-arcsec slit). For

NGC 7662, he used only the results of Peimbert and Torres-Peimbert (1971) from 21-and 30-arcsec 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.

(a) NGC 2392. This nebula shows a very inhomogenous distribution of optical forbidden line emission (see Aller 1956 and Aller and Walker 1970). Using line fluxes integrated over the entire nebula, Zipoy (1976) obtained electron densities of 1800 cm^{-3} from the [SII] line ratio and 1000 and 4000 cm^{-3} from [OII] 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 [OIII] lines.

(b) 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 and Kaler et al. 1976). From the results of Kaler et al. these densities range from $3.5x10^4$ cm^{-3} for OII to $2.4x10^5$ cm^{-3} for ArIV and $3.4x10^5$ cm^{-3} for KV, assuming their value of T_e = 11,500 K.

Although the atomic parameters for ArIV and KV are suspect (Kaler et al. 1976, Czyzak et al. 1980 and Mendoza 1982a), the hydrogen and helium decrements obtained by Kaler et al. indicate even higher densities than do these lines (as high at 10^7 cm^{-3}). Therefore, high densities are confirmed, and we have adopted $n_e = 3.5x10^5$ cm^{-3} for the density in the OIV-and NeV-emitting regions. This is slightly higher than the value $2.5x10^5$ 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 from [OIII] and [NII] line ratios.

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

(d) NGC 7662. Recent measurements of the NeIV UV line ratio yield $1300 \leq n_e \leq 4000$ cm^{-3} (Flower, Penn and Seaton 1982). (Earlier, less accurate measurements of these lines had implied a density of 11,000 cm^{-3} (Lutz and Seaton 1979).) 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 [OII], [OIII] and [SII] line ratios.

(e) IC 2003. The electron density and temperature were both determined by Barker (1978) using [OII], [OIII], [NII] and [SII] line ratios.

(f) NGC 6543. The electron density is taken from the [CℓIII] 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 [OIII] and [NII] lines, respectively.

(g) BD+30°3639. The electron density and temperature are those of Barker (1978), who used the [OII] and [NII] 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 SIII and NeV, those derived abundances are less sensitive to density uncertainties than those of OIV.

Ignoring faint ansae (43" apart) in the case of NGC 6210 and a 5-arcmin 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" 18x22 arcsec in size surrounded by "a ring or disk of much fainter matter, rather more circular in form and 32 arcsec across." Since our beam diameter was 30 arcsec and this outer disk was so faint, we did not make any corrections to the observed line fluxes. In addition, only the OIV and NeV 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 [NeV] and most of the λ5007 [OIII] emission is restricted to the inner shell of 18-arcsec diameter (Wright 1918, Wilson 1950 and Aller 1956). This implies that the NeV and OIV infrared line emission is also confined mainly to the inner region of the nebula, well within our 30-arcsec beam. Thus, our measurements yield estimates of the ionic abundance for the entire nebula for all of the nebulae we observed.

Because of uncertainties in the collision strengths for NeV (see discussion in Section IV), the NeV abundances are possibly overestimates. For example, Figure 6 implies that the NeV abundance in NGC 7027 is greater than the Ne cosmic abundance. Because the density in 7027 is uncertain, this result may also be due in part to an overestimated density. More accurate results for this ion must await more accurate calculations of the atomic parameters.

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 4363/(4959+5007) line ratio of OIII. To ionize OII, 35eV photons are required. In contrast, NeIV requires 97 eV photons to be ionized and so NeV probes regions much closer to the central star.

Nussbaumer (1972) suggested using the [NeV] 14.3μm to 3426Å [NeV] line ratio to determine electron temperatures. The 14.3μm line is situated in a strong atmospheric CO_2 feature and so is unobservable, even from airborne altitudes. However, the 24.28μm line also originates in the ^3P multiplet (see Figure 3), and the 24.28μm to 3426Å ratio is also sensitive to temperature and nearly independent of density for $n_e < n_{crit}$ $(^3P_1) \approx 57{,}000\ cm^{-3}$. 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 3426Å 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 1974) and the high-density ($n_e \approx 3.5\text{x}10^5$ cm^{-3} >> n_{crit} ($^3P_1$)), we will not attempt to use the NeV line ratio to derive a temperature for this nebula. The integrated 3426Å 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±0.08 from Cahn (1976) and the Whitford reddening curve as tabulated in Kaler (1976). The resulting [NeV] 3426Å flux is $(2.3\pm0.9)\text{x}10^{-18}$W cm^{-2}. (A possible blend with the OIII 3429Å line was suggested by the slit spectra of Aller and Czyzak (1979), who found I(3429)/I(3426) ≈ 0.4. However, examination of O. C. Wilson's slitless spectrum (Aller 1956) shows that the 3429Å image is just barely visible, and so blending in Aller's integrated 3426Å flux is ignored. Since the 3426Å image is not uniformly bright, Aller and Czyzak's entrance slit might have been placed on a dim portion of the [NeV] image.)

The flux ratio $R = \frac{F(24.28\mu)}{F(3426\text{Å})}$ 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 1σ 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 uncertainties of the value 13,500±800 K obtained by Barker (1978) from [OII], [OIII] and [SII] line ratios. Barker's value is probably a slight overestimate due to weighting toward high-temperature regions. An [OIII] 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 [OIV] 1402Å and HeII 1640Å lines, Harrington et al. (1979, 1982) obtained a lower limit to the OIV temperature of 14,100 K. Since OIII ions require 55 eV to be ionized and NeIV requires 97 eV, this provides us with a lower limit to the NeV temperature.

The [OIII] line originates in lower excitation regions than the NeV 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 NeV zone. Earlier numerical models predict temperatures of ~20,000 K in the NeV zone (Flower 1969a,b and Kirkpatrick 1972). Since the density we are assuming for this nebula is much less than $n_{crit}(^3P_1)$, 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 cm^{-3}, the upper bound on the temperature has only reached 13,300 K. It should be noted that at 2650 cm^{-3}, the flux ratio R is only 1.6σ away from a value which implies 16,000 K in Figure 8.

Before any clear conclusions may be drawn from the NeV 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 NeV have been calculated fairly recently. The ^3P_J-$^3P_{J'}$ collision strengths, however, have not been updated and may be somewhat questionable (Mendoza 1982a). They are the most likely candidates for revision. Changing only the ^3P_J-$^3P_{J'}$ collision strengths to bring the NeV line ratio into agreement with a temperature of 16,000 K at 2650 cm^{-3} requires an increase in the sum $[\Omega(^3P_0-^3P_1) + \Omega(^3P_0-^3P_2)]$ of $\approx$3.1, where Ω is the collision strength between the indicated levels. Such a change would also decrease the derived ionic abundances of NeV by the same factor. 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 (SIII) and two high excitation ions (OIV and NeV) 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 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, where available choosing 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 NeV in NGC 7354 and 7662.

By combining our [NeV] 24.28 µm observations in NGC 7662 with an integrated [NeV] 3426 Å line flux, we were able to estimate the electron temperature for the NeV-emitting regions of NGC 7662. We found the NeV temperature to be equal within uncertainties to the temperature from the lower excitation ions. We would expect NeV to be found in high-excitation regions with higher temperatures, in agreement with numerical models of NGC 7662. Our NeV electron temperature can be made to temperatures, in agreement with numerical models of NGC 7662. Our NeV electron temperatures 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 our derived NeV abundances, so that our results are questionable for this ion. We suggest new calculations be carried out for the NeV ^3P_J - $^3P_{J'}$ collision strengths. Also, a new measurement of the integrated [NeV] 3426Å flux for NGC 7662, to compare to the photographic result used here, would be useful.

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FIGURE CAPTIONS

Figure 1 - SIII level diagram (to scale) and emissivity per electron density per ion density versus electron density. The higher $^1D_2$ and $^1S_0$ levels are omitted.

Figure 2 - OIV level diagram and emissivity per electron density per ion density versus electron density.

Figure 3 - NeV level diagram (to scale except for $^1D_0$ level) and emissivity per electron density per ion density versus electron density. The higher $^1S_0$ level is omitted.

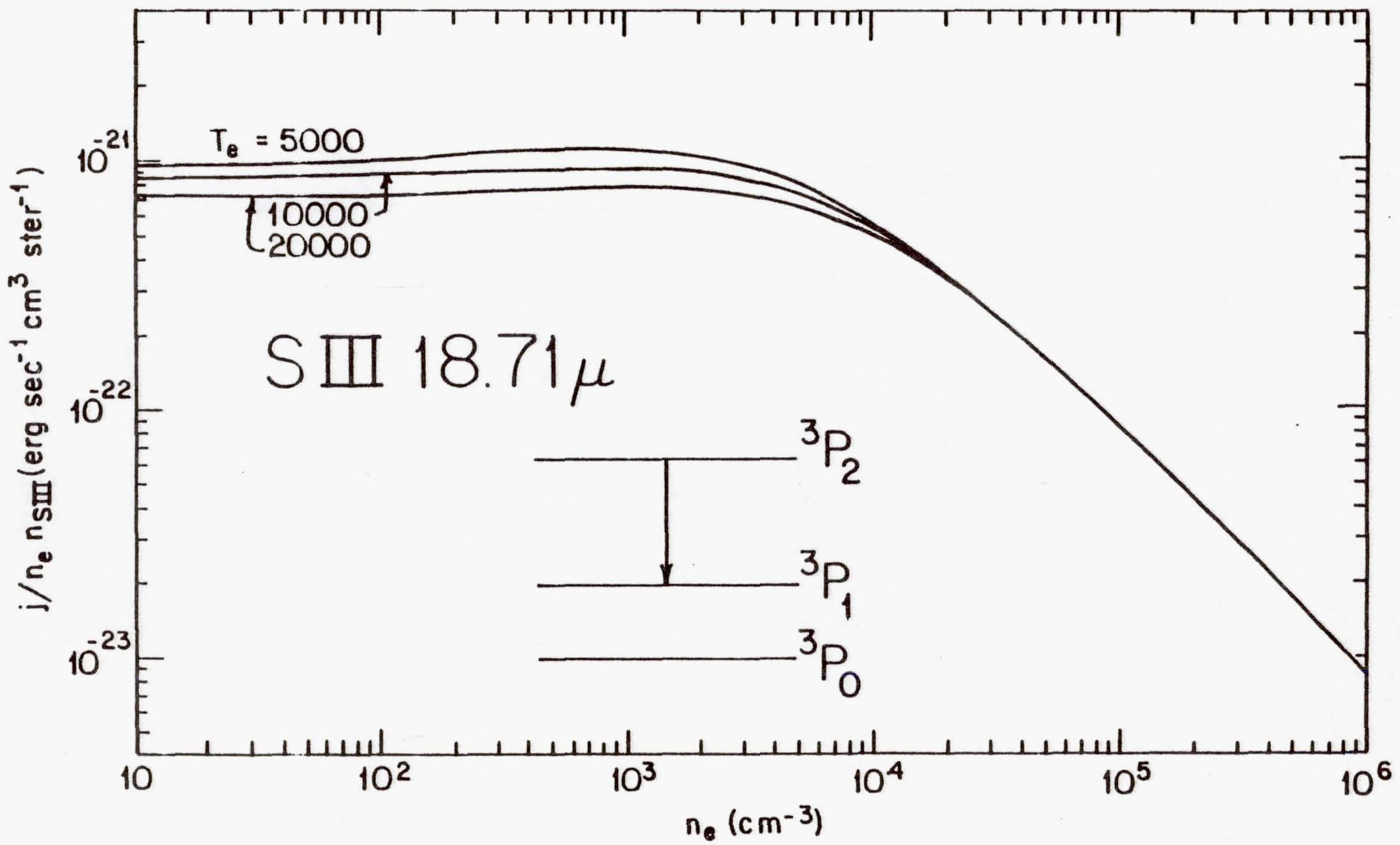
Figure 4 - SIII ionic abundance versus assumed electron density. The plotted points indicate abundances for the best estimates of electron density given in Table 4. The error bars on the points denote the range resulting from uncertainties in line and radio fluxes (given in Table 2) being used in equation (1). The brackets indicate the range in assumed electron densities, where available.

Figure 5 - Same as Figure 4 for OIV.

Figure 6 - Same as Figure 4 for NeV. As discussed in Section IV, these abundances are possibly overestimates.

Figure 7 - Contours of the ratio R of [NeV] 24.28 μm to 3426 Å flux for a range of nebular temperatures and densities.

Figure 8 - Ranges of temperature and density consistent with [NeV] 24.28 μm to 3426 Å flux ratio in NGC 7662 (dotted curves denote 1 σ uncertainty limits).



T_e = 5000
10000
20000
S III 18.71μ
$^3P_2$
$^3P_1$
$^3P_0$
10^{-21}
10^{-22}
10^{-23}
j/n_e n_{SIII}(erg sec^{-1} cm^3 ster^{-1})
10
10^2
10^3
10^4
10^5
10^6
n_e (cm^{-3})

Figure 1

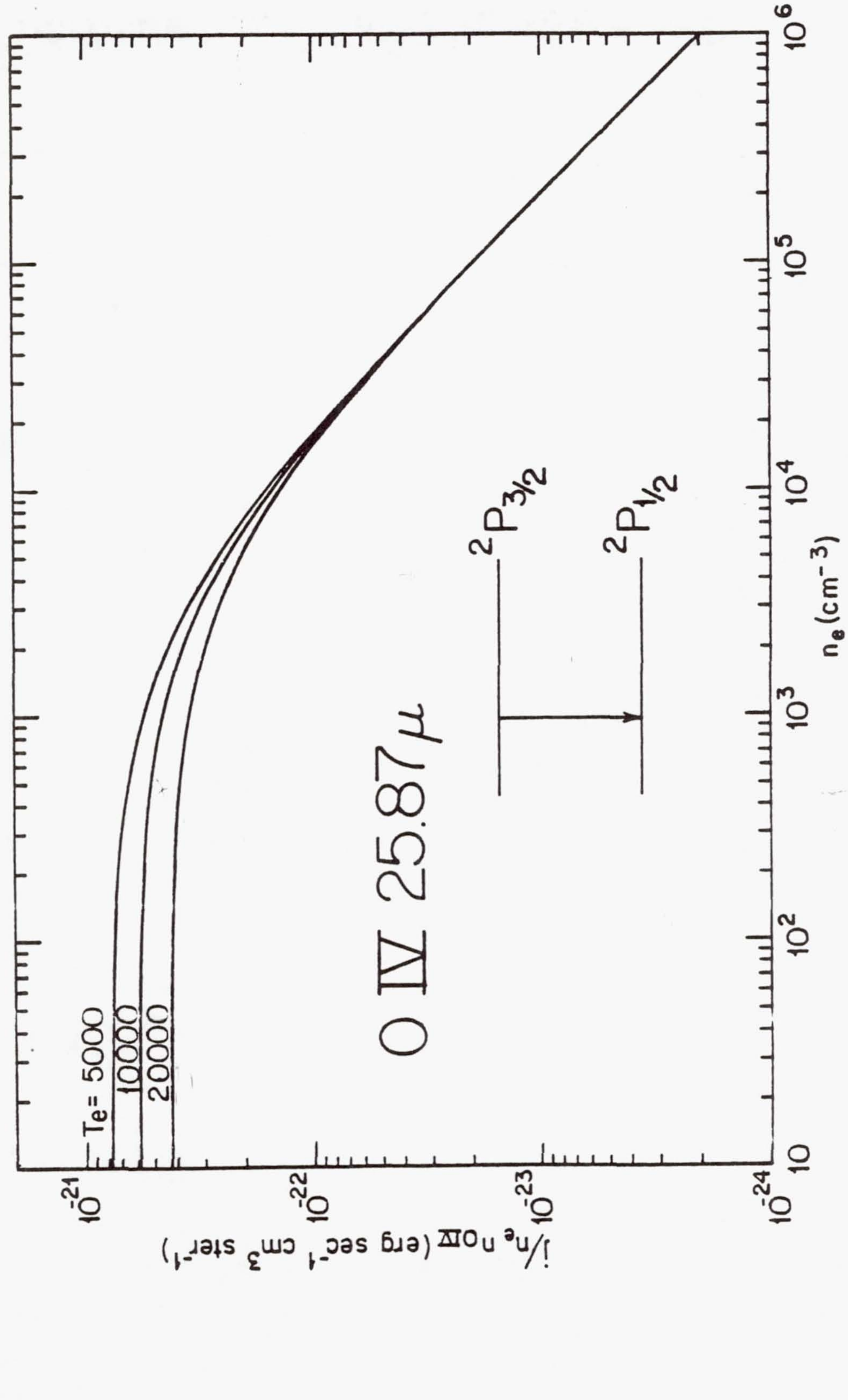

Te= 5000
10000
20000
O IV 25.87μ
$^2P_{3/2}$
$^2P_{1/2}$
n_e (cm^{-3})
$j/n_e\, n_{OIV}$ (erg sec^{-1} cm^3 ster^{-1})
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10
10^2
10^3
10^4
10^5
10^6

Figure 2

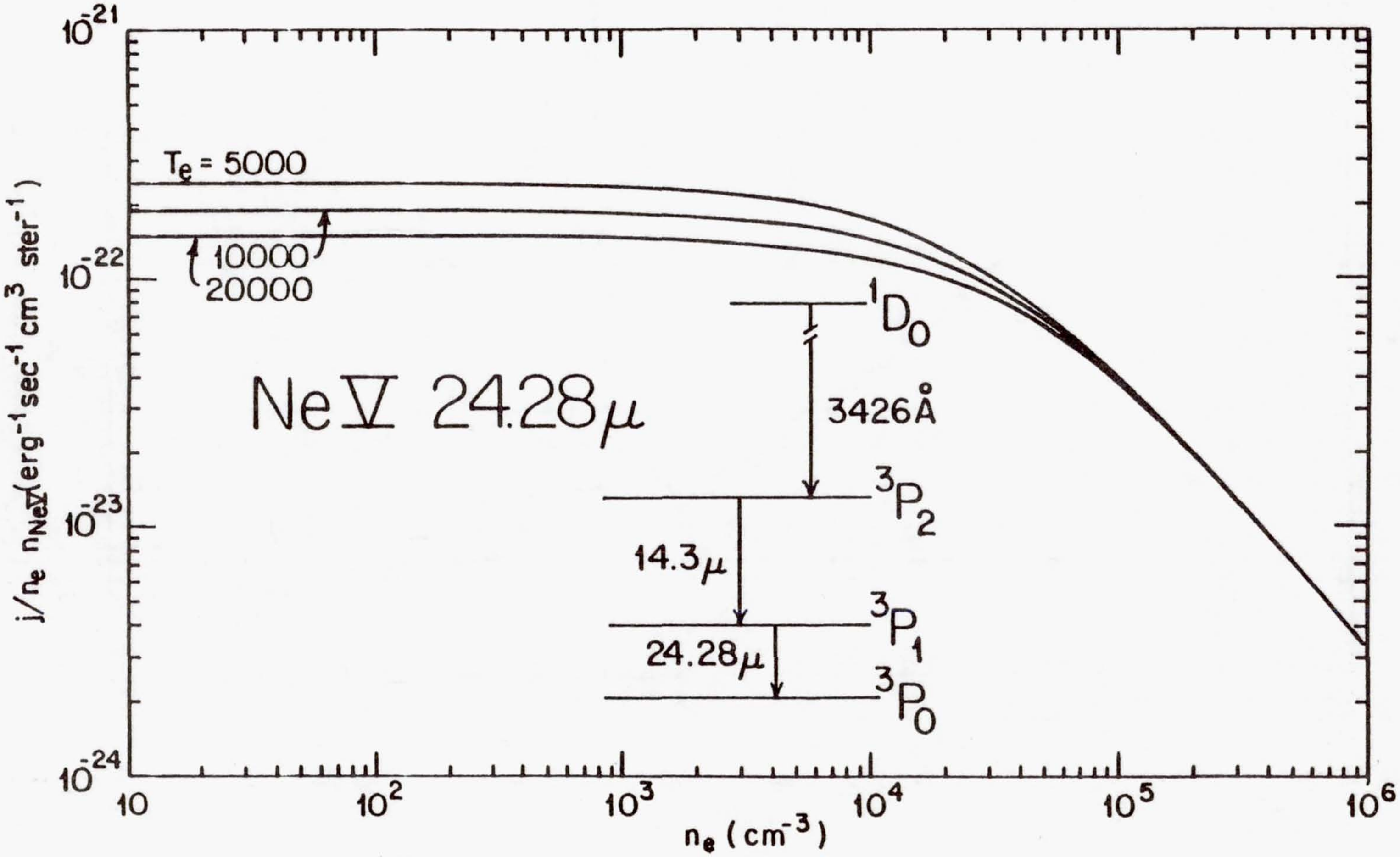
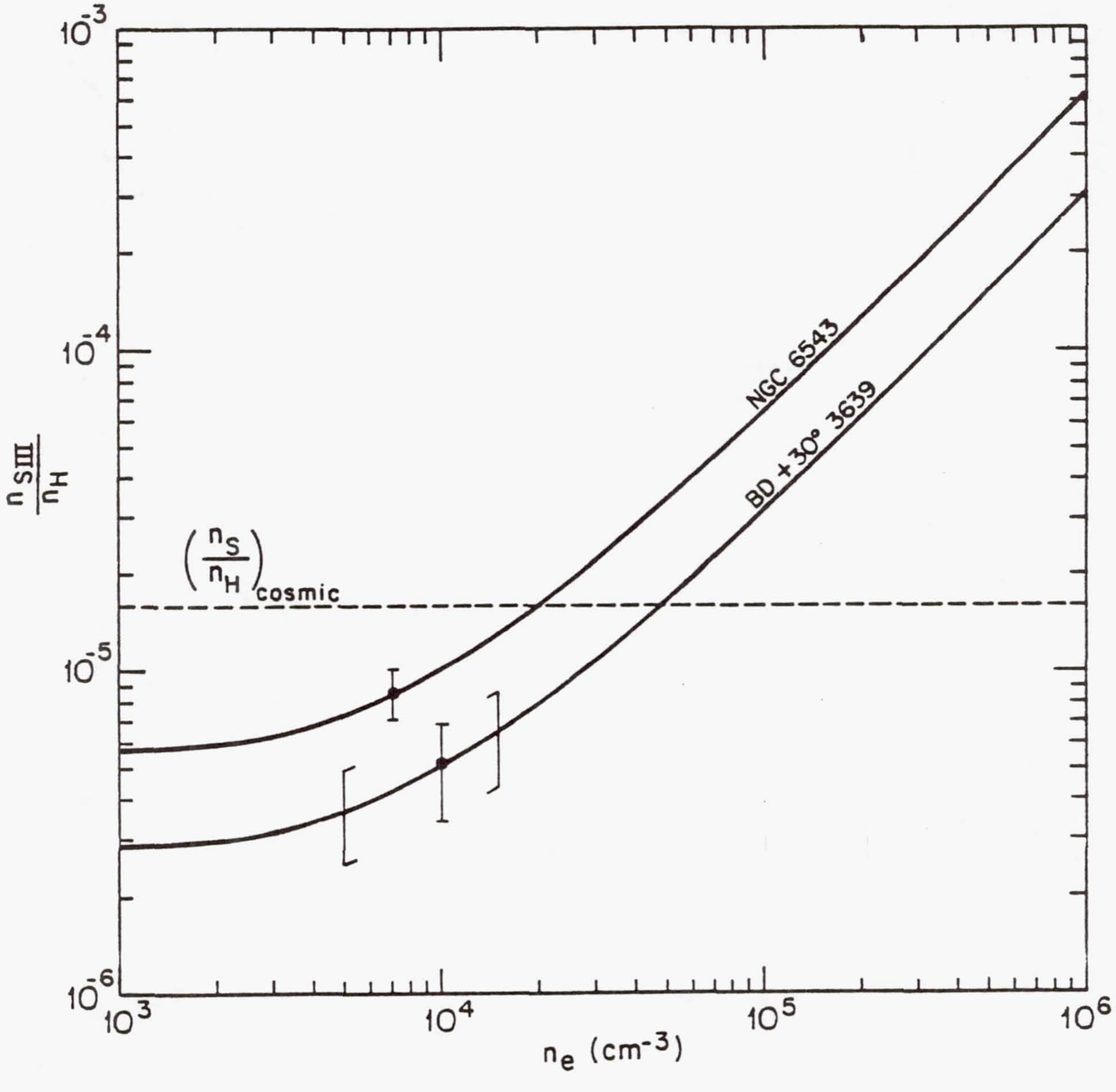

10^{-21}
10^{-22}
10^{-23}
10^{-24}
$j/n_e \, n_{NeV}$ (erg^{-1} sec^{-1} cm^3 ster^{-1})
T_e = 5000
10000
20000
NeV 24.28μ
$^1D_0$
3426Å
$^3P_2$
14.3μ
$^3P_1$
24.28μ
$^3P_0$
10
10^2
10^3
10^4
10^5
10^6
n_e (cm^{-3})

Figure 3



$\frac{n_{S\,III}}{n_H}$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\left(\frac{n_S}{n_H}\right)_{cosmic}$
NGC 6543
BD +30° 3639
10^3
10^4
10^5
10^6
n_e (cm^{-3})

Figure 4

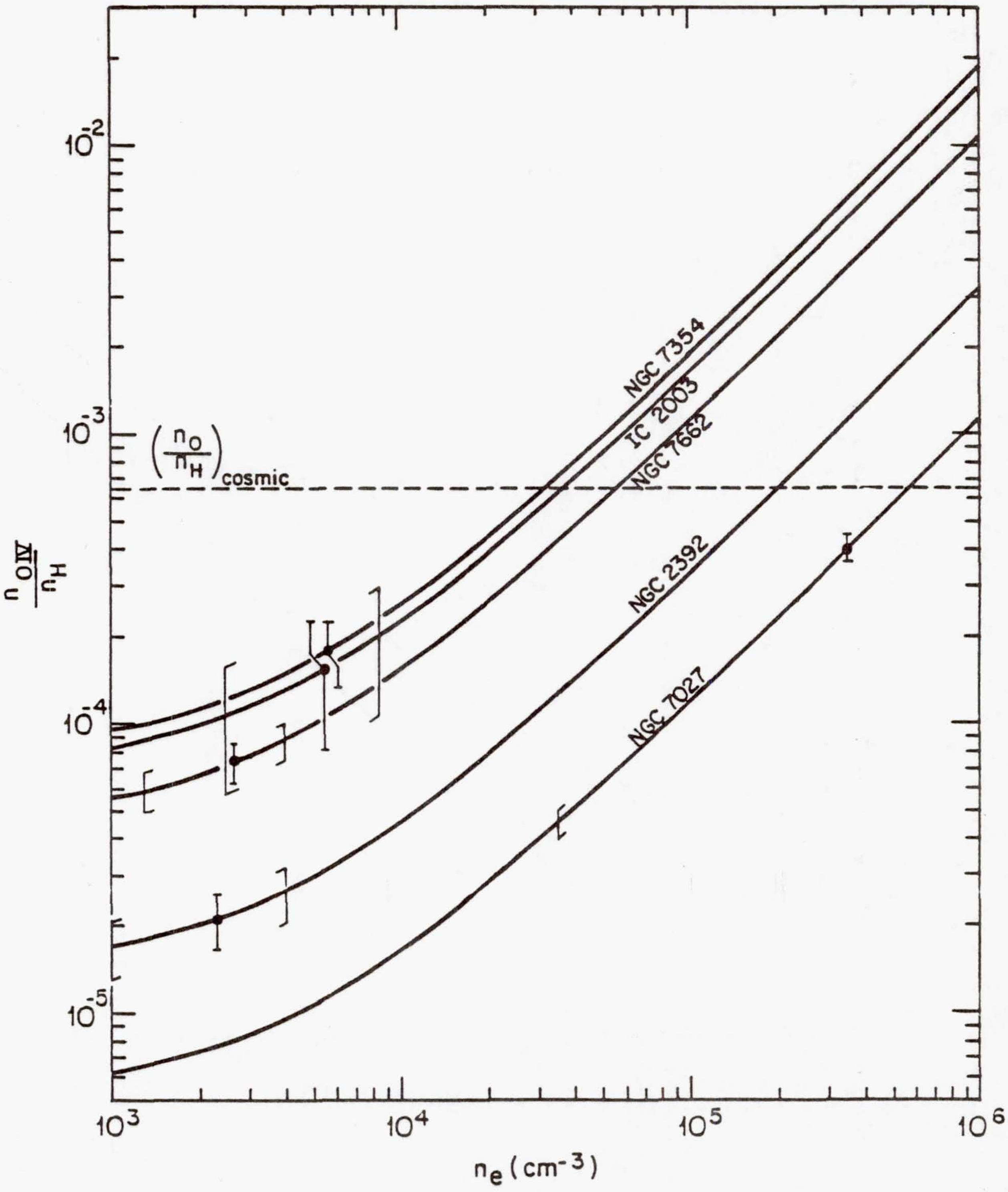

$\frac{n_{O\,IV}}{n_H}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$\left(\frac{n_O}{n_H}\right)_{cosmic}$
NGC 7354
IC 2003
NGC 7662
NGC 2392
NGC 7027
10^3
10^4
10^5
10^6
$n_e\,(cm^{-3})$

Figure 5

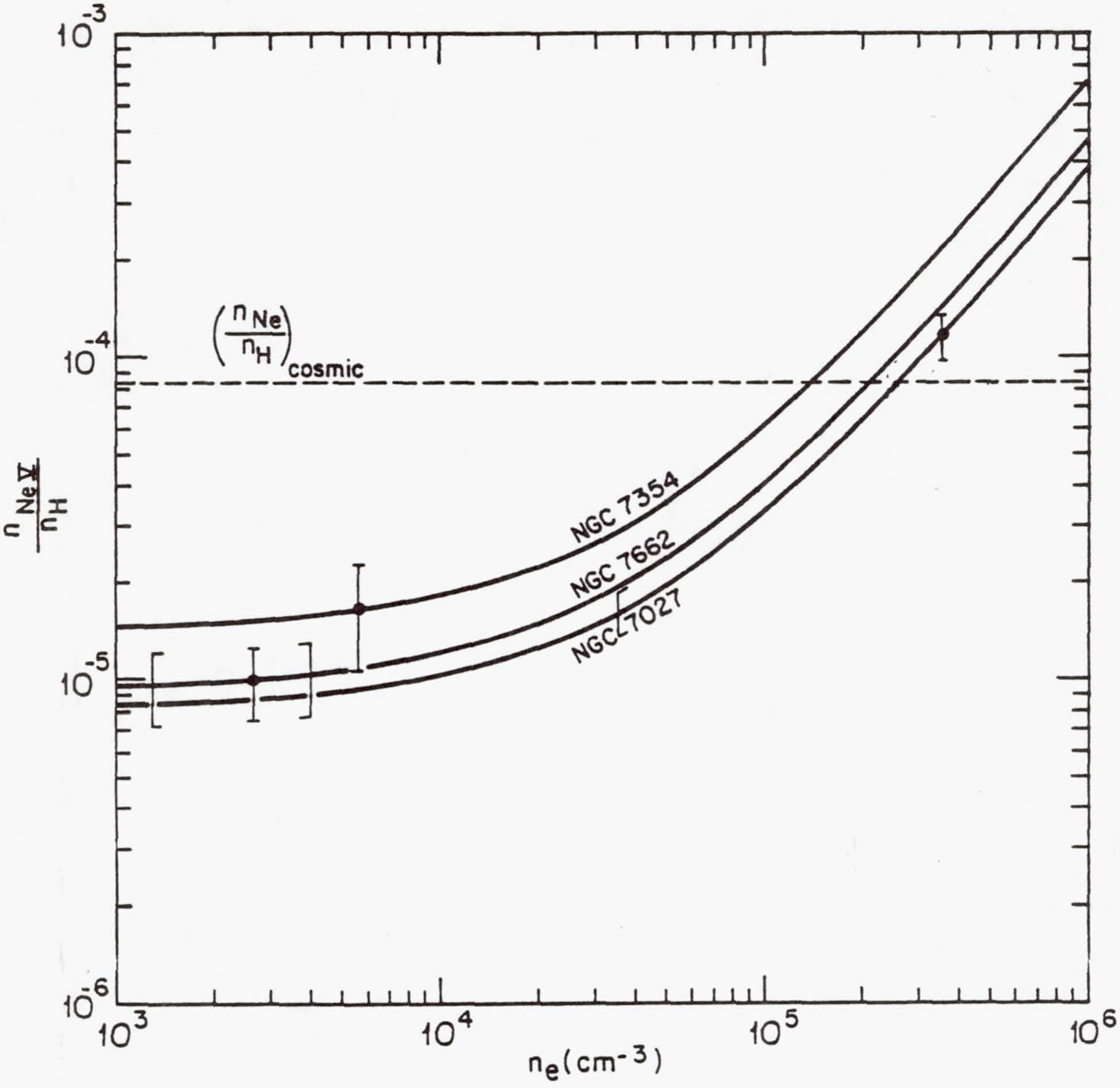

10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\left(\frac{n_{Ne}}{n_H}\right)_{cosmic}$
$\frac{n_{Ne V}}{n_H}$
NGC 7354
NGC 7662
NGC 7027
10^3
10^4
10^5
10^6
$n_e(cm^{-3})$

Figure 6

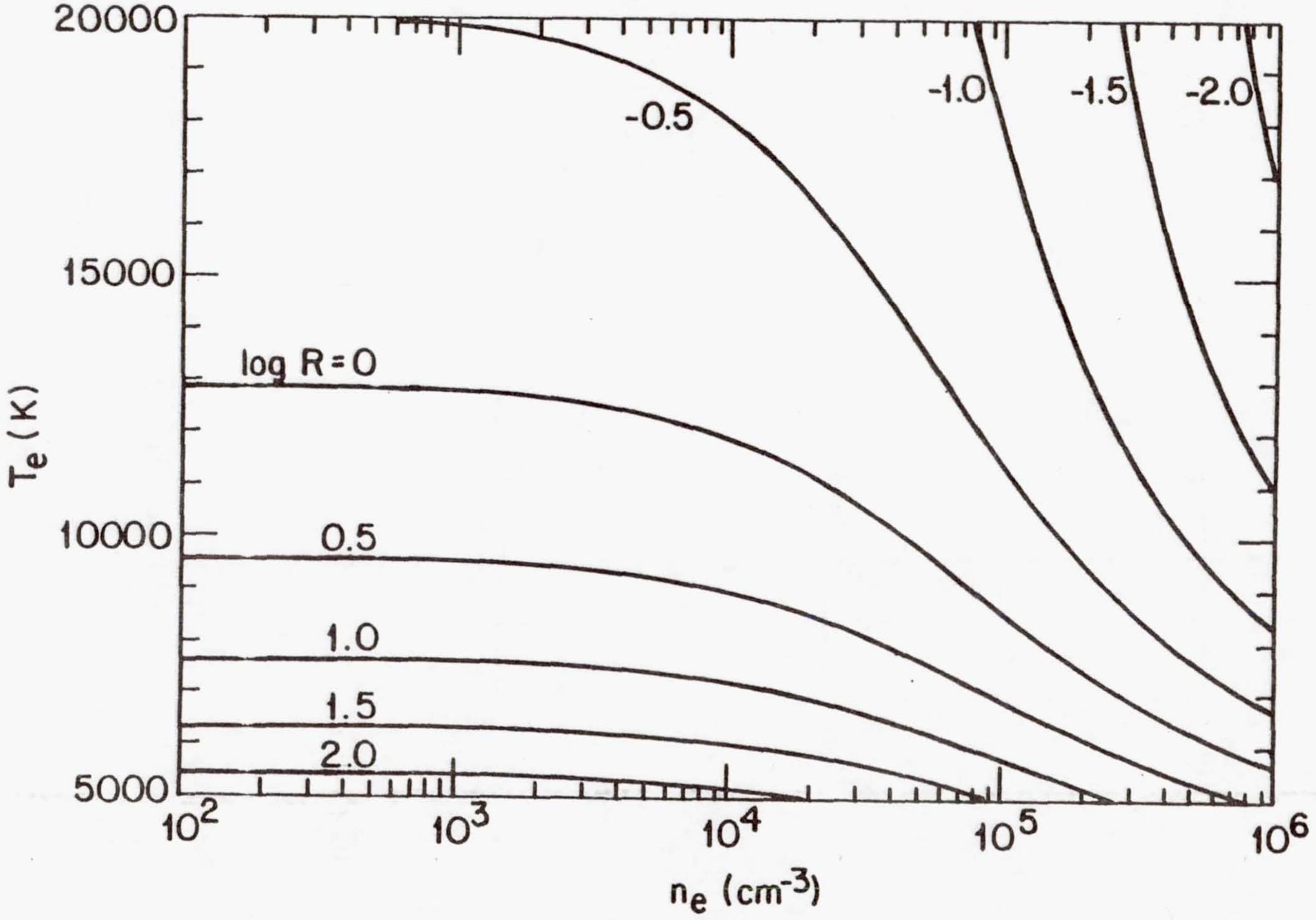

20000
15000
10000
5000
T_e (K)
10^2
10^3
10^4
10^5
10^6
n_e (cm^{-3})
log R = 0
0.5
1.0
1.5
2.0
-0.5
-1.0
-1.5
-2.0

Figure 7

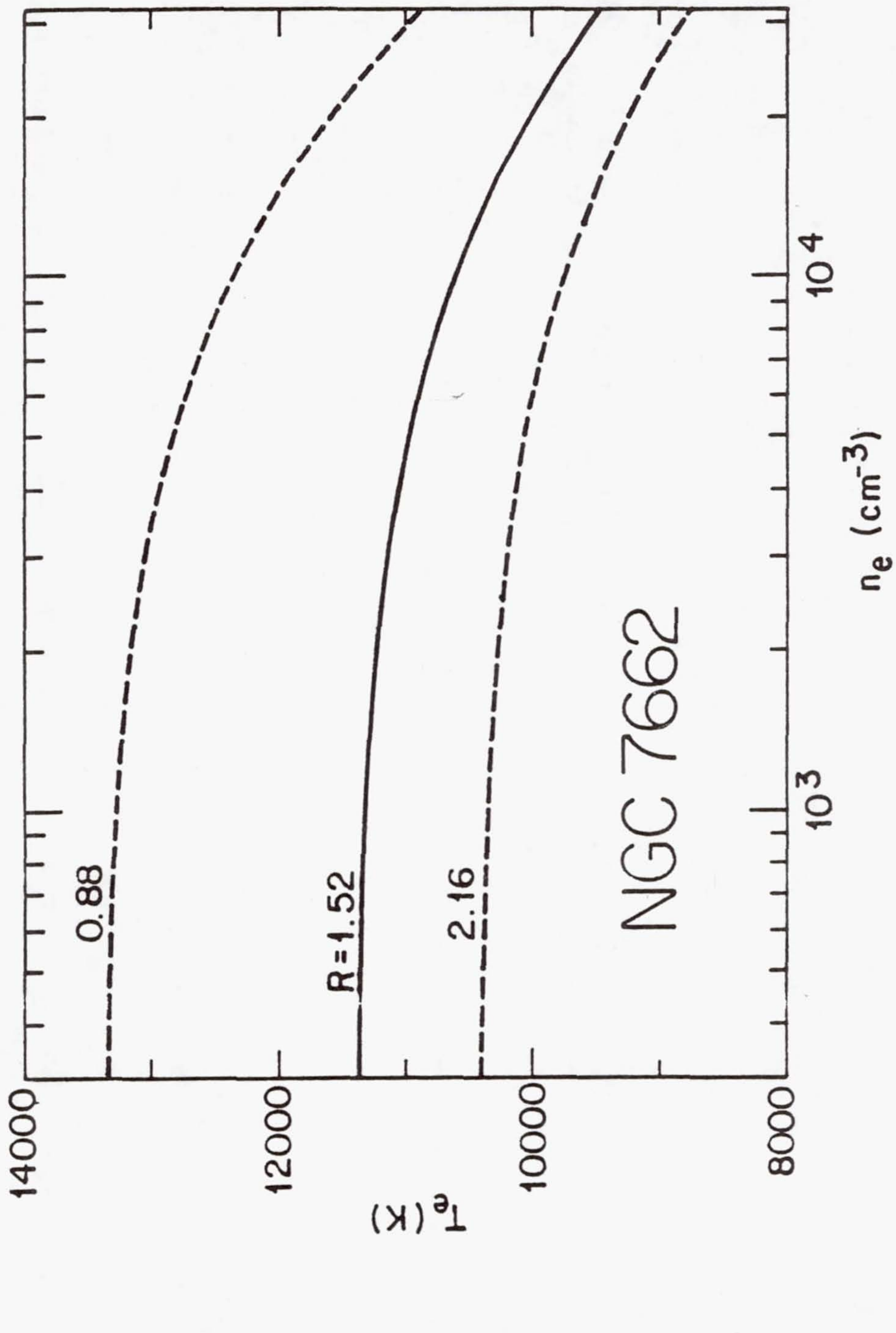

NGC 7662
0.88
R=1.52
2.16
T_e (K)
14000
12000
10000
8000
n_e (cm^{-3})
10^3
10^4

Figure 8

TABLE 1

Observations Summary

Object	Observing Night	Spectral Region Scanned		
NGC 2392	3-4-80	SIII	NeV	OIV
6210	7-16-79	SIII		OIV
6543	5-8-78	SIII		OIV
6572	7-22 & 31-80	16-30 microns		
6790	7-22-80	SIII	NeV	OIV
6884	7-18-79			OIV
7027	7-10-79	16-30 microns		
7354	7-24-80		NeV	OIV
7662	7-24-80		NeV	OIV
IC 418	3-6-80	16-30 microns		
2003	3-6-80			OIV
BD+30°3639	7-12-79	16-30 microns		

TABLE 2

Planetary Nebula Sizes and Fluxes

Object	Size[a]	Radio Flux[b] (Jys)	F_{SIII}[18.71μ] (10^{-18} W cm^{-2})	F_{NeV}[24.28μ] (10^{-18} W cm^{-2})	F_{OIV}[25.87μ] (10^{-18} W cm^{-2})	$F_{\text{continuum at 25.8}}$ (10^{-18} W cm^{-2} μm^{-1}
NGC 2392	∿18" (45" outer region)	0.32±0.06	≤9.2[f]	≤2.1[f]	8.3±1.1	<2.4
6210	8" (13"×20" fainter region)	0.39±0.06	≤4.8[f]	≤2.5[f]	≤3.6[f]	10.3±1.0
6543	16"×22" (300" faint shell)	0.77±0.08	13.6±2.0		≤6.6[f,g]	63.2±2.1
6572	13"×16"	1.15±0.25[d]	≤6.5	≤1.4[f]	≤1.3[f]	88.8±0.9
6790	5"×10"	0.34±0.06	≤7.7[f]	≤2.6[f]	≤2.3[f]	12.9±0.9
6884	7.5"	0.22±0.05	≤4.5[f]	≤2.1[f]	≤5.1[f]	4.9±1.1
7027	10"×15" at 8GHz[c]	6.37±0.48	≤23	33.1±5.0	59.9±6.2	535±3
7354	18"×22" (32" fainter region)	0.39±0.10		3.56±0.91[f]	56.4±1.7	8.7±1.6
7662	25"	0.60±0.09		3.58±0.72[f]	51.4±2.0	6.9±1.0
IC 418	11"×14"	1.56±0.14	≤11[f]	≤4.5[f,g]	≤4.5[f]	92.5±5.5
2003	6"×7"	0.020[e]			5.24±0.48[f]	<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 & Kohoutek (1967) and Curtis (1918).

[b] from Higgs (1971) — all fluxes at 10.63 GHz unless noted otherwise.

[c] from Terzian et al. (1974).

[d] flux at 9.6 GHz.

[e] flux at 6.63 GHz.

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

[g] based on signal measure at >0.25× (resolution element) from expected line center (see text).

TABLE 3

References for Transition Probabilites and Collision Strengths Used in Line Emission Calculations*

Ion	Transition(s)	A	Ω
SIII	All among ^3P_J, $^1D_2$, $^1S_0$	Mendoza and Zeippen, 1982.	Mendoza, 1982b.
OIV	$^3P_{1/2} - {}^3P_{3/2}$	Hayes, 1982.	Hayes, 1982.
NeV	$^3P_J - {}^3P_{J'}$	Nussbaumer and Rusca, 1979.	Saraph, Seaton and Shemming, 1969.
	Others among ^3P, $^1D_2$, $^1S_0$	Nussbaumer and Rusca, 1979.	Baluja, Burke and Kingston, 1980.

---

*All references are from Mendoza (1982) compilation.

TABLE 4

Derived Abundances

Object	$\frac{n_{SIII}}{n_H}$	$\frac{n_{OIV}}{n_H}$	$\frac{n_{NeV}}{n_H}$[h]	$n_e(cm^{-3})$	$T_e(K)$
NGC 2392		$(2.1\pm0.5)\times10^{-5}$		2300[a]	14,000[b]
7027		$(4.1\pm0.5)\times10^{-4}$	$(1.2\pm0.2)\times10^{-4}$	3.5×10^{5}[a]	16,000±1500[d]
7354		$(1.8\pm0.5)\times10^{-4}$	$(1.7\pm0.6)\times10^{-5}$	5600[c]	13,500[c]
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[e]	8250±450[a]
BD+30°3639	$(5.1\pm1.7)\times10^{-6}$			10,000±5000[d]	9500±1000[d]
Cosmic Elemental Abundance[g]	$\frac{n_S}{n_H} = 1.6\times10^{-5}$	$\frac{n_O}{n_H} = 6.6\times10^{-4}$	$\frac{n_{Ne}}{n_H} = 8.3\times10^{-5}$		

---

[a] see text.

[b] Zipoy (1976).

[c] Kaler (1978).

[d] Barker (1978).

[e] Saraph and Seaton (1970).

[f] Flower, Penn & Seaton (1982).

[g] Allen (1981).

[h] NeV abundances subject to question due to uncertainty in atomic parameters (see text).

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16. Abstract

Airborne observations of the infrared forbidden lines (SIII) 18.71 μm, [NeV] 24.28 μm, and [OIV] 25.87 μm have been made for twelve planetary nebulae. One or more of the lines was 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 NeV infrared line flux from NGC 7662 was combined with the 3426Å flux to obtain a NeV electron temperature of $11,200^{+2000}_{-1100}$ K, which overlaps OIII temperature measurements. Since the ionization potential of NeIV is much greater than that of OII, T_e(NeV) would be expected to be much greater than T_e(OIII). In fact, numerical models predict $T_e(\text{NeV}) = (16\text{-}20) \times 10^3$K. This discrepancy may indicate inaccuracies in currently available atomic parameters for NeV.

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