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ELECTRON TEMPERATURES IN THE HIGH-EXCITATION ZONES OF PLANETARY NEBULAE

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ABSTRACT

We present airborne infrared and ground-based ultraviolet observations of the [Ne V] 24.3 μm and [Ne V] 3426 Å fine-structure lines of 17 planetary nebulae. From these data we determine the electron temperature within the He III zone. These Ne V electron temperatures are compared with O IV electron temperatures, determined from previous airborne infrared and *IUE* observations. Since both these ions are present in the infrequently studied high-excitation zones of planetary nebulae, comparison of their electron temperatures provides insight into the abundances of the dominant coolants in these zones and provides valuable information needed to determine the overall abundances and to model planetary nebulae. Assuming typical solar abundances for the dominant coolants, the Ne V electron temperature should be higher than the O IV temperature. Of the five nebulae for which temperature comparisons can be made, Hu 1-2 and NGC 2440 show significantly higher Ne V than O IV temperatures while IC 2165, NGC 6818, and NGC 7662 have similar Ne V and O IV temperatures. The most likely explanation of these similar Ne V and O IV temperatures is the presence of large abundances of the dominant coolants (oxygen or neon, or both) in the Ne V zone. We also present Ne V electron temperatures for NGC 6741, NGC 6886, NGC 7027, and an upper limit for NGC 7354, as well as lower limits for J900, M1-1, NGC 2392, NGC 6572, and NGC 7008.

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

I. INTRODUCTION

Planetary nebulae represent the stage during which a significant fraction of a star's mass, enriched in heavy elements, is returned to the interstellar medium. In the process the star exposes its hotter inner regions and becomes one of the hottest stellar objects. These white dwarf progenitors remain shrouded by their recently freed nebulae for 10^4–10^5 yr and much can be learned about these objects by examining the nebulae which they excite. The nebulae themselves are also very interesting in terms of their elemental abundances, since it is through these nebulae that ~25% of all interstellar matter is replenished. Within the inner regions of high-excitation planetary nebulae (ones with very hot central stars) most of the ionic species that produce the emission lines used for temperature and density diagnostics, such as O III and O II, exist in higher stages of ionization, such as O IV. Thus it is necessary to find new temperature and density diagnostic line ratios for this high-excitation region (He III zone) of a planetary nebula.

The emission lines of highly ionized species such as Ne V and O IV can be used to probe the physical conditions in the He III zone. Since the ionization energy of Ne IV (95 eV) is much higher than that of O III (54 eV), then Ne V is found deeper in the He III zone. The cooling mechanism in the O IV zone (the C IV emission doublet of λλ1548, 1550) is not likely to be operating in the Ne V zone, where most of the carbon is in the form of C V. In fact the likely coolants in the Ne V zone: O V, O VI, and Ne V (Hummer and Seaton 1964) are less efficient coolants, at the level of solar abundances, than is C IV. Then for these reasons, a more intense radiation field and less efficient cooling, the Ne V electron temperature [T_e(Ne V)], is expected to be greater than the O IV electron temperature [T_e(O IV)]. In the relative absence of ionic coolants, electron free-bound, and free-free emission becomes more important in cooling the nebula.

As shown by Shure *et al.* (1983*a*, *b*) the [Ne V] 24.28 μm and 3426 Å line flux ratio and the [O IV] 25.87 μm and O IV 1400 Å multiplet line flux ratio can both be used estimate electron temperatures. These spectral lines all arise from levels which are excited by electron collisions. The critical density, n_{crit}, the electron density (n_e) at which collisional deexcitations for a level equal radiative deexcitations, is much higher for the ultraviolet lines because of their much larger A-values. At an electron temperature of 10,000 K: $n_{crit}(24.3\ \mu m) = 1.1 \times 10^4\ cm^{-3}$, and $n_{crit}(25.9\ \mu m) = 1.0 \times 10^4\ cm^{-3}$ for the infrared lines, but $n_{crit}(3426\ Å) = 1.6 \times 10^7\ cm^{-3}$ and $n_{crit}(1297\ Å) = 2.6 \times 10^9\ cm^{-3}$ for the ultraviolet lines. When n_e is well below n_{crit} for both the infrared and UV lines, the line emissivities have the same density dependence so the line ratio is dependent only on temperature. Unfortunately, some planetary nebulae fall in the regime where the electron density is above n_{crit} for the infrared line but below that of the UV lines, so the line ratio is also dependent on the electron density. The $I(25.9\ \mu m)/I(1400\ Å)$ ratio of O IV is a better temperature probe than the $I(24.3\ \mu m)/I(3426\ Å)$ ratio of Ne V because the O IV ultraviolet line has a shorter wavelength and hence greater temperature dependence. When n_e is well above n_{crit} for both infrared lines, both ratios are quite dependent on density, and, in fact, above $n_e = 10^5\ cm^{-3}$ the Ne V line ratio becomes strongly density dependent and almost independent of electron temperature.

We have observed the [Ne V] 24.3 μm and 3426 Å lines in a set of high-excitation planetary nebulae. These observations are used to estimate the electron temperatures in § III. Where possible these Ne V electron temperatures are compared with previously derived O IV electron temperatures.

II. OBSERVATIONS

a) Airborne Infrared Observations

A data set of [Ne V] 24.3 μm line emission from planetary nebulae has been accumulated by our group using the Kuiper Airborne Observatory over a period of 8 yr. The observations were made with either a six channel (Δλ = 0.03 μm) or a 10 channel (Δλ = 0.17 μm) grating spectrometer. See Houck and

TABLE 1

LINE FLUXES AND RATIOS

Nebula	F_{obs}(24.3 μm) ($\times 10^{-18}$ W cm^{-2})	F_{obs}(3426 Å) ($\times 10^{-18}$ W cm^{-2})	c(Hβ)	Extinction References	F_{corr}(3426 Å) ($\times 10^{-18}$ W cm^{-2})	F_{obs}(24.3 μm)[a] / F_{corr}(3426 Å)
NGC 2392	<2.1	0.13 ± 0.03	0.24 ± 0.06	1	0.26 ± 0.08	<10.0
NGC 2440	13.6 ± 0.8	2.5 ± 0.1	0.69 ± 0.06	2	21.1 ± 2.8	0.64 ± 0.14 (0.07)
NGC 6210	<2.5	<0.05	0.11 ± 0.02	3	<0.07	...
NGC 6572	<1.4	0.05 ± 0.02	0.32 ± 0.04	4	0.13 ± 0.05	<17.5
NGC 6741	3.3 ± 0.5	0.07 ± 0.01	1.05 ± 0.09	5	1.8 ± 0.6	1.8 ± 0.7 (0.4)
NGC 6790	<2.6	<0.02	0.56 ± 0.15	1	<0.18	...
NGC 6818	5.92 ± 0.36	0.8 ± 0.1	0.29 ± 0.06	6	2.0 ± 0.3	3.0 ± 0.5 (0.4)
NGC 6886	1.47 ± 0.4	0.14 ± 0.01	1.13 ± 0.16	1	4.6 ± 2.6	0.32 ± 0.20 (0.09)
NGC 7008	<1.5	0.04 ± 0.01	0.76 ± 0.06	7	0.42 ± 0.12	<5.0
NGC 7027	33.1 ± 5.0	2.35 ± 0.09	1.35 ± 0.02	8	153 ± 19	0.22 ± 0.04
NGC 7354	3.56 ± 0.91	<0.014	1.77 ± 0.02	5	<3.56	>0.74
NGC 7662	3.58 ± 0.72	0.59 ± 0.15	0.23 ± 0.05	9	1.20 ± 0.31	3.0 ± 1.0
Hu 1-2	1.45 ± 0.39	0.63 ± 0.03	0.65 ± 0.03	8	4.7 ± 0.5	0.31 ± 0.09
IC 2165	1.9 ± 0.6	0.29 ± 0.02	0.58 ± 0.07	2	1.75 ± 0.25	1.1 ± 0.4
J900	<1.9	0.04 ± 0.01	0.83 ± 0.06	2	0.52 ± 0.15	<5.0
M1-1	<1.8	0.22 ± 0.01	0.33 ± 0.03	3	0.6 ± 0.03	<3.2
VV 503	<3.4	<0.06	0.44 ± 0.04	4	<0.27	...

[a] The numbers in parentheses represent line ratio errors without the interstellar extinction error in the UV flux included. If no value is indicated here, then the interstellar extinction error does not contribute significantly to the total uncertainty in the line ratio.

REFERENCES.—(1) Cahn 1976; (2) Shure 1984, from He II line ratio; (3) Barker 1978; (4) Noskova 1979; (5) Kaler and Lutz 1985; (6) Feibelman 1982; (7) Pottasch 1984; (8) Kaler *et al.* 1976; (9) Harrington *et al.* 1982.

Gull (1982) and McCarthy (1980) for descriptions of the instruments and the data reduction methods. In all cases the beam size was ~30″, which entirely contained the nebulae (except for NGC 7008). The emitting region in which we are interested (the He III zone) is expected to be small compared to the visible extent of the nebula. A secondary mirror chopper throw of a few arc minutes was nominally used. Of the 17 planetary nebulae observed we detected the [Ne V] line at the 3 σ or greater level in nine nebulae (see Table 1). The errors are due primarily to the large-sky background photon noise at 24 μm and possible systematic errors are excluded from the error estimate. Observations of a bright calibrator source such as: α Ori, IRC +10420, Mars, Callisto, or the Moon were used to set the absolute calibration. After calibration, a Gaussian instrument profile plus a linear baseline were fitted to the data. A sample spectrum and fit for NGC 6818 is shown in Figure 1. Most spectra were sampled at three points per resolution element.

b) Ground-based Ultraviolet Observations

The 3426 Å line of [Ne V] was detected in 22 of the 45 planetary nebulae observed during the periods 1986 May 31–June 7 and 1987 January 18–January 22 at the 1.5 m Mount Lemmon telescope operated jointly by NASA and the University of Arizona. The instrument used was a tilting interference filter spectrometer. This arrangement provided a beam size of 48″, which allowed a measure of the total integrated emission from the nebulae for comparison with the airborne infrared measurements described above. Many other workers have presented measurements of the [Ne V] 3426 Å in planetary nebulae with slit spectrometers, which do not include emission from the whole nebulae, and slitless spectrographs, which do not provide sufficient accuracy for the relatively dim lines of Ne V.

The tilting filter spectrometer consisted of a narrow (15 Å) passband interference filter at 3459 Å in front of a near-UV

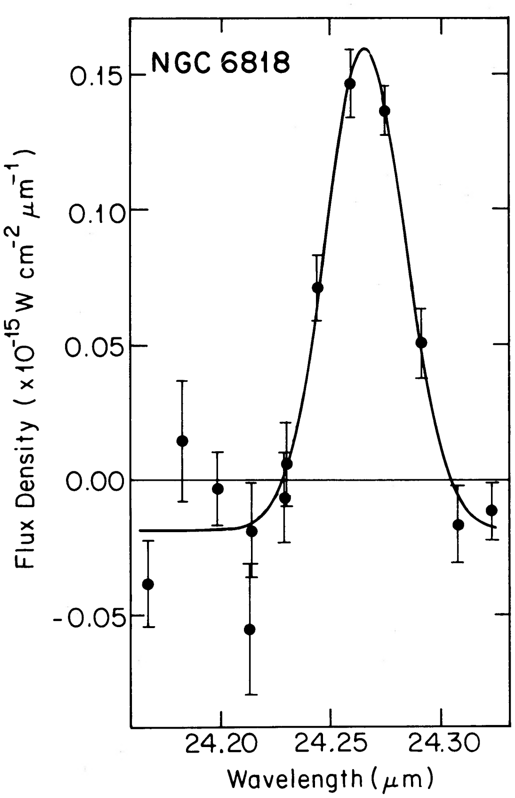

FIG. 1.—Grating spectrometer spectrum of NGC 6818 taken aboard the Kuiper Airborne Observatory on 1984 May 22. A Gaussian instrumental function is fitted to the [Ne V] 24.3 μm line. The wavelength resolution (FWHM) was determined from other data and is 0.04 μm.

sensitive photomultiplier tube. The output of the tube was fed to a standard pulse-counting data system. As the interference filter was tilted with respect to the incoming beam, its passband shifted to shorter wavelengths ($\lambda_{\text{peak}} \approx \sin^2 \theta$, where λ_{peak} is the peak of the passband and θ is the angle of tilt of the filter from normal incidence) in this way a spectral region of over 100 Å can be scanned. Unfortunately, as the filter tilts, its passband becomes wider and its peak transmission decreases. Both of these effects must be accounted for in the analysis of the spectra (see Shure 1984). A nebular spectrum consisted of photon counts at 12 positions of the filter equally spaced in terms of the shift of the passband. A total integration time of 40 s was spent at each position. Half the integration time was obtained on either side of normal incidence. For each object an identical spectrum, with half the integration time, on nearby blank sky provided a measure of the sky background which was subsequently subtracted from the nebula spectrum. Typical sky counts were 20–30 s^{-1}, while the nebulae counts at the line peaks ranged from this level to more than 1000 counts s^{-1}. The dark current from the ambient temperature photomultiplier tube was 7–8 counts s^{-1} in the summer and 2–3 counts s^{-1} in the winter. The temperature of the filter was kept constant (± 1.0 K) for all observations to stabilize the passband. The filter profile was determined by fitting an analytic function to scans of neon and helium lines from discharge lamps. These laboratory measurements provided the wavelength calibration and indicated that the filter profile was well fitted by Gaussian core with exponential wings.

The absolute flux calibration was performed by observing six standard stars (51 Vir, 39 Aql, 21 Crt, 7 Hya, 29 Psc, and 73 Cet). The stellar specific fluxes, relative to Vega, were taken from Hayes (1970), and the absolute calibration of Vega was from Hayes and Latham (1975). Due to the large and variable amount of scattering/absorption of light at 3400 Å by the atmosphere it was necessary to follow the calibration stars each night in order to determine the airmass correction. At 3459 Å the average extinction was 0.63 ± 0.03 mag per airmass in the summer and 0.47 ± 0.03 mag per airmass in the winter.

i) *Data Reduction*

Within the short range of wavelengths we scanned, the three brightest lines are [Ne V] at 3426 Å and O III at 3429 Å and 3444 Å. The 3429 Å line falls within the passband of the filter when it is tilted to pass 3426 Å since the FWHM at this angle is 23 Å. Since the two lines of O III originate from the same upper level they should have a constant ratio. Saraph and Seaton (1980) calculate $I(3429 \text{ Å})/I(3444 \text{ Å}) = 0.331$, and this constant was used in our fitting routine to determine our final values of $F(3426 \text{ Å})$. However, Likkel and Aller (1986) found, for their observed sample of nebulae, an average O III $I(3429 \text{ Å})/I(3444 \text{ Å})$ line ratio of 0.2 the reason for this lower ratio is not clear. A smaller ratio would affect our results by raising the [Ne V] 3426 Å line flux by an amount no larger than the flux previously attributed to the O III 3429 Å line. Since the [Ne V] 3426 Å line is usually much brighter than the O III 3429 Å line in most of our nebula this effect is unimportant for all but NGC 2392, J900, and NGC 7662. If the Likkel and Aller ratio is used instead of the Saraph and Seaton ratio, the Ne V electron temperatures we derive in the next section for these three nebulae would increase by ~ 1000 K.

The [Ne V] 3426 Å line fluxes for all the nebulae were found by synthesizing a spectrum, consisting of [Ne V] and O III lines plus a linear continuum, convolved with the measured filter profile. This synthetic spectrum was then compared to the observed spectrum, after the sky background had been subtracted and the result corrected for atmospheric extinction. The parameters of the synthetic spectrum were adjusted to reduce the mean squared differences between the two spectra. This fit returned absolute line fluxes by reference to the known fluxes of the standard stars. As a consistency check, fits to the same standard stars' spectra from different nights were compared and found to agree within 3%. In addition M1-1 was observed in both June and January and our fitted line fluxes for these observations agree within 6%. A sample planetary nebula spectrum and fit is shown in Figure 2. The abscissa corresponds to the wavelength of the peak of the filter's passband which is related to the filter tilt. The ordinate is the observed counts per second after subtracting the background and correcting for atmospheric extinction. The line asymmetry is due to the changing bandwidth and transmission of the filter with tilt angle. These nonlinear effects prevent a simple flux density labeling of the ordinate in Figure 2. The error bars shown in the plot are due mostly to counting statistics, and this is the error considered when the fitting was done. The errors associated with the final line fluxes are due to the error in the fit and the uncertainties in the atmospheric extinction. The final 3426 Å line fluxes of the nebulae that were also observed with the KAO are given in Table 1.

ii) *Interstellar Extinction*

For the UV line fluxes a further correction must be made for interstellar extinction. This correction can be determined by a variety of methods: a comparison of radio and Hβ fluxes, a comparison among the Balmer lines (Balmer decrement), the depth of the 2200 Å absorption feature and the observed He II $F(1640 \text{ Å})/F(4686 \text{ Å})$ recombination line ratio. In many cases all four methods yield similar results. The error in the value of the extinction is usually given as the deviation amongst the various methods. However, sometimes the errors are large and one is forced to choose one method over the others. In this case the He II line ratio was used because this line radiation comes from the He III region of the nebula and will therefore include any effects of internal extinction relevant to the Ne V and O IV line fluxes. Uncertainty in the extinction is then calculated from the uncertainties in the line fluxes. All the extinction corrections require the use of an assumed extinction curve. In this work the extinction curve of Seaton (1979*a*) was used to convert from E_{B-V} to $c(\text{H}\beta)$, the logarithmic extinction at 4861 Å, and from $c(\text{H}\beta)$ to $c(\lambda)$ at any other wavelength. The values of $c(\text{H}\beta)$ used, and their sources are listed in Table 1.

III. ELECTRON TEMPERATURES

a) *Calculations*

For conditions found in planetary nebulae, only the lowest five levels (the multiplets of the ground level) of Ne V need to be considered. To a very good approximation, the only processes controlling the level populations are spontaneous radiative decay and electron collisions that cause either excitation or deexcitation. The background flux due to stellar continuum, infrared emission from dust, diffuse nebular radiation, and recombinations do not contribute significantly to the excitation of the levels. Also, to a good approximation the electron velocity distribution in a planetary nebula is Maxwellian and thus is completely specified by the electron temperature, T_e (see Osterbrock 1974). The relative populations of the five levels of Ne V, and hence the line ratios, can be calculated as functions

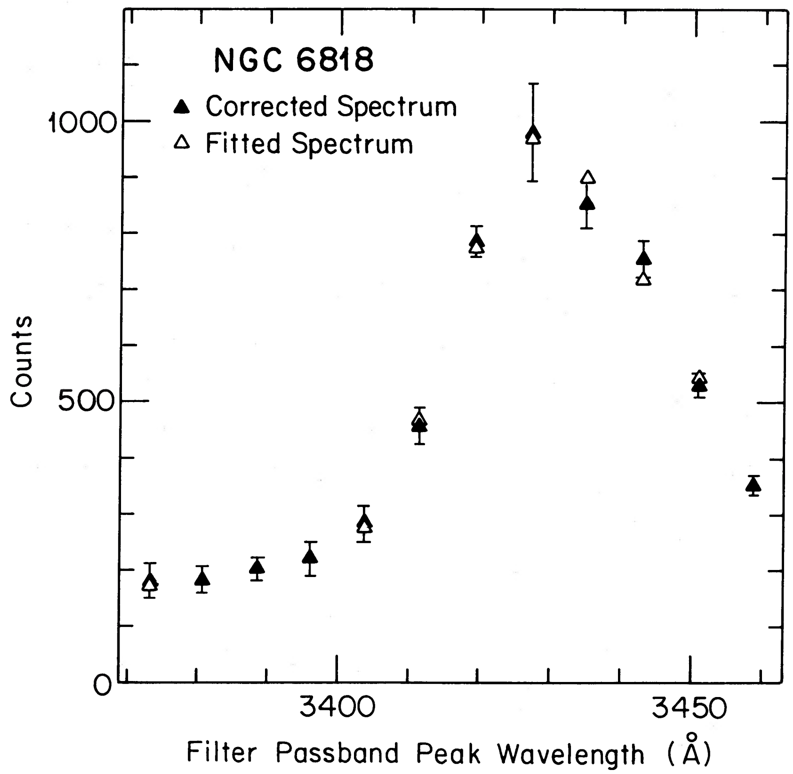

FIG. 2.—Tilting filter spectrum of NGC 6818 taken at the Mount Lemmon Observatory (1.5 m) on 1986 June 4. The ordinate, corrected counts, refers to the averaged nebula spectrum minus the average sky background, and the result corrected for atmospheric extinction. The 12 points correspond to 12 filter positions with the indicated passband peak wavelength for each point. The fitted points represent a synthesized spectrum, consisting of emission lines of [Ne v] 3426 Å, O III 3444 Å and 3429 Å and a linear continuum. The absolute line flux was obtained by taking similar spectra of standard stars.

of electron temperature and electron density assuming collisional equilibrium conditions for each level (see Osterbrock 1974). To perform these calculations the ionic parameters of Ne v must be known. Nussbaumer and Rusca (1979) have determined the radiative transition probabilities. The electronic collision strengths have been tabulated, as functions of temperature, by Baluja, Burke, and Kingston (1980) for the $^1S_0$ and $^1D_2$ levels of Ne v, and by Aggarwal (1983), for the ^3P levels of Ne v.

However, the Ne v collision strengths calculated by Aggrawal have recently been called into question by Clegg *et al.* (1987), who suggest that these constants have been overestimated. The thermally averaged collision strengths are very sensitive to resonances especially for the ^3P levels of Ne v since there are very large resonances near their excitation threshold. Therefore, small errors in the energies of the resonances can result in large errors in the collision strengths. Such errors in the collision strengths would of course affect the electron temperatures derived from the observations. Lennon (1988) has recalculated the collision strengths for the ^3P levels of Ne v and his preliminary results are almost a factor of 2 smaller than Aggarwal's results. Reducing the collision strengths has the effect of reducing the electron temperature derived from the observed line ratios. This effect is nonlinear in temperature. For example, in the low electron density limit, a nebula with a [Ne v] $I(24.3\ \mu\text{m})/I(3426\ \text{Å})$ line ratio of 1.0 would have a T_e(Ne v) of 26,000 K derived with Aggarwal's collision strengths but would have a T_e(Ne v) of 20,000 K using Lennon's results. A nebula with a [Ne v] line ratio of 3.0, however, would have a T_e(Ne v) of 18,000 K using Aggarwal's results, but a T_e(Ne v) of 15,000 K using Lennon's results. While the Ne v temperatures we present obviously depend on the collision strength values used, the qualitative discussion which follows would only be effected by a drastic change in the collision strengths and is in fact equally valid whether Aggarwal's or Lennon's collision strengths are used.

In the following analysis we have used Lennon's collision strengths to calculate our Ne v electron temperatures from the line ratios. With this ionic data the relative level populations and hence the line ratios can be calculated for a given T_e and n_e. A contour plot, in the $T_e - n_e$ plane, of various values of the $I(24.3\ \mu\text{m})/I(3426\ \text{Å})$ line ratio is shown in Figure 3. For each nebula the line ratio and associated error bars for each nebula were plotted on the $T_e - n_e$ plane (as an example the line ratio for NGC 6818 is shown in Figure 4). Then for an assumed number density, the electron temperature can be found.

b) Results

Table 2 presents our values of T_e(Ne v) found from the line ratios of Table 1. The values of n_e used to find T_e(Ne v) are given in Table 2 and, unless otherwise indicated, are derived from Aller and Czyzak (1979) and Torres-Peimbert and Peimbert (1977). These electron densities are the average of density values derived from emission line ratios of ions such as O II, O III, S II, S III, Ne III, Ar III, and Ar IV. The values of T_e used in finding the densities were those relevant to these lower excitation ions, but fortunately n_e is not very dependent on the choice of this T_e.

For comparison, the O IV electron temperatures listed in Table 2 are from Shure (1984), but were updated using the

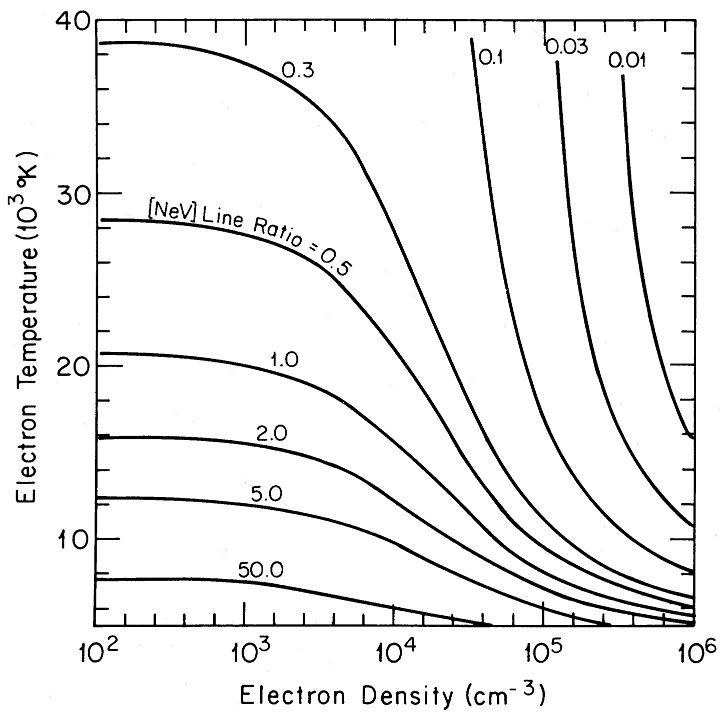

FIG. 3.—[Ne V] $I(24.3\ \mu m)/I(3426\ Å)$ contours as a function of electron temperature vs. the logarithm of electron density. The range of temperatures and densities encompasses the range of the physical conditions expected in planetary nebulae. Note that this line ratio goes from a probe of temperature (*horizontal lines*) to a probe of density (*vertical lines*) as the line ratio becomes smaller. The transition occurs at a density of $\sim 1.1 \times 10^4\ cm^{-3}$, the critical density.

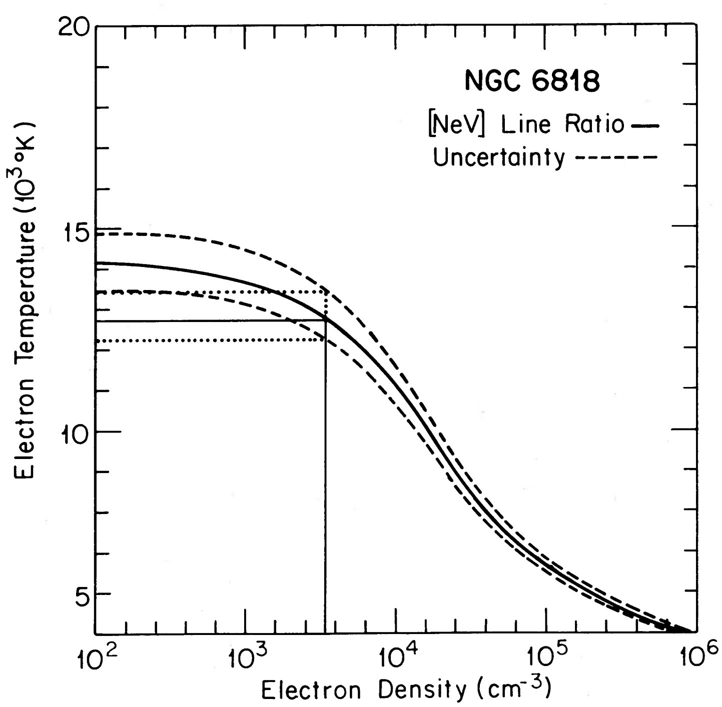

FIG. 4.—A plot of the [Ne V] $I(24.3\ \mu m)/I(3426\ Å)$ ratio for NGC 6818 (*Solid line*). The uncertainty ($1\ \sigma$) in the ratio is indicated by the broken lines. This ratio constrains the range of T_e and n_e values in the Ne V zone. Taking a density of 3500 cm^{-3} (*as indicated on the plot*) that has been derived from optical forbidden lines (*see text*) a Ne V electron temperature of 12.700^{+800}_{-500} K is found.

TABLE 2

ELECTRON TEMPERATURES

Nebula	n_e (cm^{-3})	References	T_e(O IV)[a] (K)	T_e(Ne V) (K)
NGC 2392	3300	1	17300^{+2000}_{-900}	>9300
NGC 2440	4000	2	17100^{-1400}_{-800}	22100^{+2600}_{-1900}[b]
NGC 6572	8900	1	...	>7600
NGC 6741	10800	1	...	12700^{+2200}_{-1200}
NGC 6818	3500	1	13800^{+800}_{-500}	12700^{+800}_{-500}
NGC 6886	12000	3	...	25300^{+6500}_{-3400}[c]
NGC 7008	300	3	...	>12100
NGC 7027	300000	4	...	8800^{+600}_{-200}[d]
NGC 7354	5600	5	...	<19600
NGC 7662	2650	6	14400^{+800}_{-500}	13200^{+1600}_{-1000}
Hu 1-2	10500	1	13900^{+600}_{-300}	27200^{+7100}_{-3500}
IC 2165	5000	2	16500^{+1800}_{-500}	16900^{+3500}_{-1900}
J900	4600	1	16300^{+1500}_{-900}	>10900
M1-1	2500	1	...	>12800

[a] All T_e(O IV) values are derived from Shure 1984.
[b] See § IV for an estimate based on a different n_e.
[c] Value does not include interstellar extinction uncertainty.
[d] See § III*b*.

REFERENCES FOR THE ELECTRON DENSITIES USED.—(1) Derived from Aller and Czyzak 1979; (2) Torres-Peimbert and Peimbert 1977, (3) Pottasch 1984; (4) Kaler *et al.* 1976; (5) Kaler 1978; (6) Flower *et al.* 1982.

electron densities adopted here. The assumption of uniform electron density is discussed in more detail in the next section. Because of the Ne V line ratio's greater density dependence the choice of n_e is more critical in terms of the resulting T_e for Ne V than for O IV. While the T_e values for both Ne V and O IV are sensitive to the value of interstellar extinction used, the dependence is similar and the relative results are only mildly dependent on the interstellar extinction, although the 3426 Å flux is less dependent on $c(\mathrm{H}\beta)$ than is the 1400 Å flux.

Comparison of the nebulae for which there are complete Ne V and O IV temperatures seems to indicate two categories; those with high (>20,000 K) Ne V temperatures that are much higher than the O IV electron temperatures, and those with smaller T_e(Ne V) values (<20,000 K) which are similar to the T_e(O IV) values.

The nebulae IC 2165, NGC 6818, and NGC 7662 have T_e(Ne V) values that range from 12,700 K to 16,900 K, and each shows roughly equal T_e(Ne V) and T_e(O IV). Although two of these nebulae have T_e(O IV) values greater than their T_e(Ne V) values, we cannot conclude that there are any temperature gradients in these nebulae, due to the large errors involved. Our results are consistent with T_e(Ne V) $\sim$ T_e(O IV) and hence a uniform temperature in the He III region of these nebulae.

Hu 1-2 and NGC 2440 show high Ne V temperatures, significantly higher than the corresponding O IV values. This could mean that there exists large temperature gradients in the nebulae, with the Ne V emission originating from the hotter regions. The temperature differences would then be $13{,}300^{+7100}_{-3500}$ K for Hu 1-2 and 5000^{+1700}_{-1500} K for NGC 2440. The latter value was calculated without the interstellar extinction error since both T_e(Ne V) and T_e(O IV) are affected by this uncertainty in a similar manner. Unfortunately the uncertainty in T_e(Ne V) for Hu 1-2 is due to the large error in the observed infrared flux and excluding the interstellar extinction uncertainty has little effect.

The two nebula for which only T_e(Ne V) is available are NGC 6741 and NGC 6886. NGC 6741 appears to be of the same type as the low T_e(Ne V) group (IC 2165, NGC 6818, NGC 7662), while NGC 6886 falls in the high-temperature group (Hu 1-2 and NGC 2440). The nebula for which lower limits to T_e(Ne V) are given (NGC 2392, NGC 6572, NGC 7008, J900, and M1-1) cannot be classified as either high- or low-temperature nebulae, whereas the upper limit to T_e(Ne V) given for NGC 7354 may exclude it from the high-temperature group. Unfortunately, *IUE* O IV 1400 Å line fluxes are not available for any of the other nebula in Table 2 except J900.

The results for NGC 7027 are not very useful, as there is strong differential extinction across the face of the nebula (Seaton 1979*b*), and the high density derived from the emission-line ratio of a high-excitation ion (K V) places the [Ne V] line ratio in a regime where it is a better monitor of the density than the temperature. The derived T_e would be much higher if the assumed electron density was smaller.

IV. DISCUSSION

Hummer and Seaton (1964) predict that for a typical planetary nebula, the electron temperature should be less than 19,000 K in the region where C IV is the dominant coolant. This is borne out by Shure's (1984) results presented in Table 2. The only nebula model that actually presents an electron temperature distribution is that by Harrington *et al.* (1981) of NGC 7662. Their model II would indicate an observed T_e(O IV) of 18,000 K, which is higher than our observed value of 14,000 K. The electron temperature in the Ne V zone in their model II (assumed here to run from 1″ to 3″ from the nebula center) ranges from 19,000 K to 25,000 K. This would imply an observed T_e(Ne V) in the neighborhood of 22,000 K, which is higher than our observed T_e(Ne V) of 13,200 K. Since the line ratios used to obtain the observed electron temperatures are fairly insensitive to the assumed electron density, one cannot reconcile observation with theory by decreasing the assumed n_e.

A possible explanation for the unexpected observed similarity of electron temperatures in the inner [T_e(Ne V)] and outer [T_e(O IV)] He III regions for three of our nebulae, would be the existence of abundance anomalies in these regions. If the dominant coolant(s) in the Ne V region is (are) significantly more abundant than expected, then the cooling of the Ne V zone might efficient enough to counteract the more intense radiation field present there and similar T_e(Ne V) and T_e(O IV) might be seen. This would mean a large abundance of oxygen (in the form of O V or O VI), or neon (in the form of Ne V) in this highly ionized region. Planetary nebulae show evidence for nucleosynthesis, and consequently abundance gradients should exist within the nebula, depending on how mixing took place in its formation. Therefore it is not unreasonable to expect elemental abundances to be different in the Ne V region which is deep within the nebula.

The next group of nebulae, Hu 1-2, NGC 2440, NGC 6886, and NGC 7027 all show small (<0.7) [Ne V] I(24.3 μm)/I(3426 Å) line ratios. As can be seen in Figure 3, these line ratios place the nebulae in a regime where the line ratio is quite dependent on the electron density, and hence the T_e estimates are not as accurate as in the first group of nebulae. Assuming the same density for the Ne V and O IV regions yields T_e(Ne V) > T_e(O IV) for Hu 1-2 and NGC 2440 (Table 2). In the case of NGC 6886 the assumed density, from lower excitation ions, gives a very high temperature of 25,300 K.

One can use the [Ne V] line ratio to derive the electron density if an assumption about T_e(Ne V) is made. If one assumes that the electron temperature is uniform throughout the He III region as implied by the first group of nebulae, then T_e(Ne V) can be set equal to T_e(O IV) for the second group and the [Ne V] line ratio will then provide a value for the electron density. This method gives electron densities of 54,800 cm^{-3} and 13,600 cm^{-3} for Hu 1-2 and NGC 2440, respectively. These results are considerably higher than those from optical forbidden line ratios. Still, the [Ne V] line ratios for Hu 1-2 and NGC 2440, are consistent with the possibility that T_e(Ne V) ~ T_e(O IV), as in the first group of nebulae. It should be noted that because the T_e(Ne V) values for the first group of nebulae are largely density independent, all of our data are then consistent with a picture of the high-excitation regions of planetary nebulae as having T_e(Ne V) ~ T_e(O IV) and as having high densities in the Ne V zone. However, the indications of high densities in the inner He III regions for our nebulae are hardly conclusive, and the observed line ratios could still be indicative of high temperatures or a combination of high temperatures and densities in the He III regions of these planetary nebulae.

To accurately determine the electron temperatures in nebulae with small [Ne V] I(24.3 μm)/I(3426 Å) ratios, a probe of the electron density of the Ne V region is needed. If [Ne V] 14.32 μm line fluxes were available then the I(14.3 μm)/I(24.3 μm) line ratio would provide an excellent density diagnostic that is almost independent of temperature. Unfortunately, this line is inaccessible even from airplane altitudes because of absorption by atmospheric CO_2. The Low Resolution Spectrometer of *IRAS* did observe this line in some planetary nebulae but the data are difficult to interpret. The LRS 14.3 μm fluxes, however, have been used by Pottasch *et al.* (1986) in conjunction with 3426 Å fluxes to determine electron densities, and they found that the n_e values given by this method are larger by a factor of 10 than densities derived from other line ratios of ions like O III and C III. Unfortunately, they assumed a Ne V temperature that is approximately the same as the temperature derived from lines of ions like O III; therefore T_e(Ne V) is underestimated and n_e is overestimated. Thus this evidence for a high density in the Ne V regions is not conclusive. Comparison of the LRS data of some planetary nebulae with other line fluxes from our airborne observations is currently being studied in order that the [Ne V] 14.3 μm line fluxes from the LRS may be rescaled for a density determination of the Ne V region (Rowlands, Houck, and Herter 1989).

V. CONCLUSIONS

We have derived temperatures of the high-excitation Ne V zone of planetary nebulae and compared the results with temperatures of the O IV zone. One group of nebula, consisting of IC 2165, NGC 6818, and NGC 7662 has T_e(Ne V) ~ 13,000–17,000 K ~ T_e(O IV). Such similar temperatures for the outer (O IV) zone and inner (Ne V) zone of the He III region are difficult to explain due to the predicted absence of an efficient coolant in the Ne V zone which should elevate the temperature there. It is suggested, however, that higher than expected abundances of oxygen or neon might cool the Ne V zone to a temperature similar to that of the O IV zone. The other group consisting of Hu 1-2 and NGC 2440 have T_e(Ne V) > 20,000 K > T_e(O IV) if n_e(Ne V) = n_e(O IV). These implied high electron temperatures are the result of small [Ne V] line ratios for these nebulae. Another interpretation of these ratios is that they are due to large densities in the Ne V zone rather than high temperatures, and then it is possible that T_e(Ne V) ~ T_e(O IV) for all the nebulae in our sample. This question of whether or not planetary nebula in general have uniform temperatures and density gradients in their He III regions, can be resolved by obtaining high quality [Ne V] 14.3 μm line fluxes which would allow an unambiguous density determination since the [Ne V] I(14.3 μm)/I(24.3 μm) line ratio is almost temperature independent.

In summary, the technique of using the [Ne V] I(24.3 μm)/I(3426 Å) line ratio to determine electron temperatures, has been shown to be a viable probe of the highly ionized regions of planetary nebulae. These two lines, with the addition of the 14.3 μm line, should also prove useful in determining the electron temperatures and densities of other high-excitation regions, as in supernova remnants and, with the operation of ISO and SIRTF, in active galactic nuclei and quasars.

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