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THE HIGHLY IONIZED REGIONS OF NGC 6302 AND NGC 6537

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ABSTRACT

We present [Ne v] 24.32 μm and 3426 Å emission-line fluxes for NGC 6302 and NGC 6537. These fluxes along with those of [Ne v] 14.3 μm allow us to determine the physical conditions within the highly ionized regions of these nebulae. The electron densities found via the [Ne v] line ratios are similar to those found in studies of the low-ionization regions. However, the electron temperatures determined from the [Ne v] line ratios are much greater than those in the low-ionization regions.

We use photoionization models to show that these high derived electron temperatures are inconsistent with the assumption that the nebular ionization is produced solely by radiation from the central star. Much of the intense [Ne v] 3426 Å emission from these objects must arise from highly ionized shocked material; a conclusion which is in accord with other evidence. The fact that the [Ne v] infrared lines are less affected by the shock means that we can estimate the relative volumes of the shocked and radiatively excited portions of these nebulae. In the most likely scenario, the volume of the highly ionized shocked region is less than 10% that of the highly ionized region formed by photoionization. We note that under such conditions, infrared emission lines are more useful than optical or UV emission lines for abundance studies because they are less affected by shocks. With appropriate corrections to the optical and UV emission-line fluxes, these nebulae can still be described by photoionization models.

Subject headings: infrared: ISM: lines and bands — ISM: abundances —
planetary nebulae: individual (NGC 6302, NGC 6537)

1. INTRODUCTION

NGC 6302 and NGC 6537 are two of the highest excitation planetary nebulae known. They both display emission lines of [Si VI] that are not seen in other planetary nebulae (Ashley & Hyland 1988). Such objects must be the evolutionary products of the most massive stars that do not produce supernovae. The nebular show enhanced abundances of helium and nitrogen and depleted carbon, all of which are thought to result from an episode of nuclear burning that is absent in most planetary nebulae progenitors (Kaler 1985). Such nebulae have been classified as Type I in the scheme of Peimbert & Torres-Peimbert (1983) where more typical planetary nebulae are classified as Type II. NGC 6302 and NGC 6537 have abundances which are even more extreme than typical Type I nebulae (Aller et al. 1981; Feibelman et al. 1985). The central stars of these objects are likely to be the hottest, most massive, and most luminous of the planetary nebulae nuclei (PNNs) from which white dwarfs eventually form.

Direct observations of such PNNs are unfortunately difficult because their spectral energy distributions peak in the far-UV and they are immersed in a bright nebulosity. Fortunately, much can be inferred about PNNs from studies of the nebulae they excite. The nebular excitation level reflects on the current evolutionary status of the nuclei, while the nebular abundances provide clues to the earlier evolution of these objects.

In NGC 6302 and NGC 6537 nebular studies are complicated by the presence of high levels of ionization. The usual emission lines that are diagnostic of the nebular conditions are not present in large portions of these nebulae, a factor which especially complicates the determination of nebular abundances. In addition, NGC 6302 shows broad [Ne v] 3426 Å emission-line profiles that are indicative of a fast wind with a velocity of ~ 300 km s^{-1} (Meaburn & Walsh 1980a). The presence of [Si VI] and [Si VII] emission from NGC 6302 and the presence of [Si VI] emission from NGC 6537 is clearly unusual and was initially thought to be caused by central stars hotter than any previously detected (Ashley & Hyland 1988). However, Lame & Ferland (1991) demonstrated that photoionization by such a hot source can not account for the observed nebular spectra of NGC 6302.

High-excitation nebulae do show strong emission lines of [Ne v] which are useful diagnostics of the He^{+2} region. We have obtained [Ne v] 24.32 μm emission-line fluxes for NGC 6302 and NGC 6537 from observations on the Kuiper Airborne Observatory (KAO). These fluxes, along with [Ne v] 14.3 μm line fluxes from *Infrared Astronomical Satellite* (*IRAS*) Low Resolution Spectrometer (LRS) data and 3426 Å line fluxes from ground-based measurements, allow us to obtain n_e and T_e in the He^{+2} regions of these nebulae. The [Ne v] line ratio $R_2 \equiv I(14.3\ \mu\text{m})/I(24.32\ \mu\text{m})$, following the notation of Keenan, Burke, & Aggarwal (1991), is an excellent n_e diagnostic. Such an infrared line ratio is especially useful since these lines are not appreciably affected by interstellar extinction. The [Ne v] line ratios $R_1 \equiv I(14.3\ \mu\text{m})/I(3426\ \text{Å})$ and $R_3 \equiv I(24.32\ \mu\text{m})/I(3426\ \text{Å})$ are very sensitive to the nebular electron temperature but they often have a significant n_e dependence from the infrared line emissivity. In this case R_2 (or some other reliable estimate of n_e) is needed to uniquely obtain the physical conditions (Keenan et al. 1991). We note that in this regard

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R_1 is superior to R_3 because the 24.32 μm emission line is more sensitive to density. R_2 in combination with R_1 (or R_3) will completely determine T_e and n_e in the He^{+2} regions of planetary nebulae.

With the physical conditions thus characterized we then show that the [Ne V] emission from these nebulae is not well fitted by photoionization models. Instead, the presence of [Si VI] emission, large [Ne V] 3426 Å line fluxes, and a fast wind in NGC 6302 appear to indicate the presence of shocks in these nebulae. We use our photoionization model results and the observed [Ne V] line ratios to determine the relative proportion of the nebulae that are affected by these shocks.

2. THE INFRARED EMISSION LINES

2.1. *Airborne Observations*

Table 1 lists [Ne V] 24.32 μm and [S III] 18.71 μm line fluxes for NGC 6302 and NGC 6537 obtained on the Kuiper Airborne Observatory with the HIRES grating spectrometer on 1985 August 21. The instrument has been described by Houck & Gull (1982), and the observations were made in the manner described by Shute et al. (1983) and Rowlands et al. (1989). The absolute calibration was with respect to IRC +10420 (Forrest, McCarthy, & Houck 1979).

Due to strong CO absorption in the Earth's atmosphere which cannot be avoided at even aircraft altitudes, the [Ne V] 14.3 μm emission line in nebulae must be observed from space. Table 1 also presents [Ne V] 14.3 μm and [S III] line fluxes from spectra acquired by the *IRAS* LRS. The [S III] line fluxes are presented so that a direct comparison between the KAO and LRS data may be made.

Good agreement between the KAO and LRS [S III] line fluxes is obtained for NGC 6537, where most of the ionized material is concentrated within 20″ of the center (Felli & Perinotto 1979). However in NGC 6302, the LRS [S III] flux is more than twice that obtained on the KAO. The beam size of the mid-infrared spectrometer was approximately 28″, while that of the LRS spectrometer was 7′.5 × 15′. NGC 6302 is inhomogeneous and elongated, and has filaments of ionized material that extend out to 1′ (Meaburn & Walsh 1980b). The [S III] emission is very likely more extended than the KAO beam size. The ionization energies of S^+ and Ne^{+4} differ by a factor of 5 implying that the [S III] emission will be found well outside that of the centrally concentrated [Ne V] emission. The KAO spectrometer entrance aperture was positioned on the optical centers of the nebulae. The [Ne V] 3246 Å line flux in NGC 6302 is concentrated to within 20″ of the center of the nebula (Meaburn & Walsh 1980a), and the KAO beam would have contained all of the [Ne V] emission.

2.2. *IRAS LRS Data*

Because *IRAS* operated in a survey mode the LRS was a slitless spectrometer and spectra were obtained only when a relatively bright object transited the instrument entrance aperture (Wildeman, Beintema, & Wesselius 1983; Raimond, Beintema, & Olnon 1983). While perhaps 50,000 objects observed by *IRAS* have LRS spectra associated with them, most are of low quality. Spectra with the best signal-to-noise ratios and repeatability have been released as the Atlas of Low Resolution Spectra which contains 5425 objects. LRS spectra of the other objects may be extracted from the LRS database as Volk & Cohen (1990) have done for 170 planetary nebulae. Great care must be exercised in the interpretation of these spectra when attempting to extract emission-line fluxes. In their analysis of LRS database spectra of H II regions Simpson & Rubin (1990) note that obtaining emission-line fluxes is a somewhat subjective process primarily due to the difficulty in locating the continuum level.

We obtained LRS Atlas and LRS database spectra of planetary nebulae for which we have [Ne V] 23.32 μm emission-line fluxes. The LRS database spectra were generally found to be of very low quality and are not useful for our purpose. The LRS atlas are useful, but unfortunately, of the planetary nebulae in the atlas, only NGC 6302 and NGC 6537 have obvious [Ne V] 14.3 μm emission lines. Our estimates of the [Ne V] 14.3 μm and [S III] 18.71 μm line fluxes from fits to these spectra are shown in Table 1. These line fluxes show good agreement with those of Pottasch et al. (1986) who also made fits to LRS atlas spectra.

We note that Pottasch et al. (1986) presents line fluxes obtained from LRS database spectra as well. In the case of [Ne V] these line fluxes should be used with caution. For example, NGC 2440 has a [Ne V] 14.3 μm/24.32 μm line ratio of 0.66 ± 0.05, when the Pottasch et al. (1986) 14.3 μm and the Rowlands et al. (1989) 24.32 μm line fluxes are used. Such a line ratio is unphysical if the Ne^{+4} ions are in equilibrium with the nebular electron gas. Since all the other ionic emission lines for this nebula can be described reasonably well by conditions of collisional equilibrium (Shields et al. 1981) it is very likely that the problem lies with a poorly determined LRS 14.3 μm line flux. Inspection of the LRS database spectrum of NGC 2440 shows that the continuum level is negative at the short wavelength end of the band and that the spectrum is very noisy, making the absolute line fluxes difficult to determine. If log $n_e = 3.7$ is assumed for this object (Stanghellini & Kaler 1989), then a more reasonable [Ne V] 14.3 μm line flux would be 1.5 times the 24.32 μm flux. Even this value is still consistent with the LRS database spectrum of this object considering the large uncertainties present. We note that Keenan et al. (1991) obtained a [Ne V] 14.3 μm/24.32 μm line ratio of $R_2 = 1.5$ for this object using R_1 from Pottasch et al. (1986) and R_3 from Rowlands et al. (1989). However, this R_2 value is misleading. The Pottasch et al. (1986) 3426 Å line flux is from Aller, Czyzak, & Kaler (1968) who used slit spectrometer data scaled by selected whole nebula line fluxes. This scaled 3426 Å flux is 2.3 times smaller than the Rowlands et al. (1989) value. The latter is a true whole nebula flux and is the proper one to use when comparisons to the large-aperture LRS and KAO data are made.

TABLE 1

OBSERVED EMISSION-LINE FLUXES

Line	Source	NGC 6302[a]	NGC 6537[a]
[S III] 18.71 μm	LRS	15 ± 1.3	4.0 ± 1.3
[S III] 18.71 μm	KAO	6.9 ± 0.7	4.4 ± 1.0
[Ne V] 14.3 μm	LRS	45.7 ± 3.1	16.3 ± 1.8
[Ne V] 24.32 μm	KAO	32.3 ± 1.2	9.5 ± 0.9
[Ne V] 3426 Å	Mt. Lemmon	1.92 ± 0.19	0.15 ± 0.02

[a] Units: 10^{-11} ergs cm^{-2} s^{-1}.

3. ULTRAVIOLET DATA AND EXTINCTION

Table 1 also lists whole nebulae [Ne V] 3426 Å line fluxes that we obtained with a narrow-band photometer at the Steward Observatory's Mt. Lemmon 1.5 m telescope on 1986 June 5. Details of these observations and their analysis have been published elsewhere (Rowlands et al. 1989, 1993). To sum-

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marize, a UV sensitive photomultiplier tube was placed behind a narrow bandpass (15.7 Å) filter centered on 3459 Å which was tilted to scan the 3426 Å emission line. The photometer aperture was 48″ and was sufficient to encompass the [Ne v] emission from NGC 6302 and NGC 6537. NGC 6302 was observed at a relatively high air-mass (~2.5) which is reflected in the larger uncertainties in the line flux. The atmospheric extinction for these observations was well characterized by observations of eight standard stars throughout the night, so that accurate fluxes were obtained.

In order to compare the infrared and ultraviolet data we must correct the 3426 Å line fluxes for interstellar extinction. For NGC 6537 the various methods for determining this extinction yield consistent values, considering the uncertainties associated with such measurements. From a comparison of the radio flux at 5 GHz ($S_{5\,\mathrm{GHz}}$) and the Hβ flux Cahn (1976) finds that the logarithmic extinction of Hβ is 1.85 ± 0.13, while Kaler (1983) finds $c(\mathrm{H}\beta) = 2.02 \pm 0.14$ from the Hα/Hβ ratio. From the H I Brγ to $S_{5\,\mathrm{GHz}}$ ratio, Ashley & Hyland (1988) find that $c(\mathrm{H}\beta) = 2.0$. The various extinction corrections obtained for NGC 6302 are less consistent. The Hβ to $S_{5\,\mathrm{GHz}}$ ratio gives a value of $c(\mathrm{H}\beta) = 1.33 \pm 0.11$ (Cahn 1976), while the Balmer decrement gives 1.22 (Aller et al. 1981). Barral et al. (1982) obtain $c(\mathrm{H}\beta) = 1.59$ from the ratios of He II recombination lines observed by the *International Ultraviolet Explorer* (*IUE*) satellite, while Ashley & Hyland (1988) find $c(\mathrm{H}\beta) = 2.1$ from the H I Brγ to $S_{5\,\mathrm{GHz}}$ ratio. Ashley & Hyland attribute these discrepancies to some internal extinction which weights an optical H or He recombination line to regions of lower extinction thus biasing the extinction determination. The general appearance of NGC 6302 in radio and Hα images is significantly different indicating a substantial amount of internal extinction in this nebula. For our purposes we require the extinction between the observer and the high-excitation (He^{+2}) regions of these objects; thus we adopt the Barral et al. (1982) value of $c(\mathrm{H}\beta) = 1.59$ for NGC 6302. Unfortunately, the He II recombination line fluxes in the *IUE* spectrum of NGC 6537 are very uncertain (Feibelman et al. 1985), probably due to the large interstellar extinction. We adopt $c(\mathrm{H}\beta) = 1.94$ for NGC 6537, the average of the values presented above. The extinction function of Seaton (1979) is used to correct our 3426 Å line fluxes.

Shocks are almost certainly present in these nebulae, thus it must be kept in mind that the estimates of extinction from recombination lines may be uncertain since the true recombination line ratios may not conform to their values under case B conditions, the usual assumption. The ramifications of different $c(\mathrm{H}\beta)$ values will be discussed in the following section.

4. THE PHYSICAL CONDITIONS

To obtain the nebular physical conditions from our observed [Ne v] line fluxes we have used the Ne^{+4} collision strengths of Lennon & Burke (1991) and the transition probabilities of Nussbaumer & Rusca (1979). There have been some problems in the past with the collision strength calculations for Ne^{+4}; however, there are now two independent calculations providing similar values (Aggarwal 1983 and Lennon & Burke 1991). The [Ne v] emission lines should thus provide accurate diagnostics of highly ionized regions.

Figure 1 shows the intersections of the [Ne v] line ratios R_1 and R_2 in the n_e-T_e plane for both nebulae. For NGC 6537 an electron temperature of 4.5×10^4 K and an electron density of $\log n_e = 4.20$ are found. In NGC 6302 the corresponding values are 6.5×10^4 K and $\log n_e = 4.14$. The uncertainties in n_e are approximately 0.1 dex and are due to the line flux uncertainties. The [Ne v] density values compare quite well with those found in the lower ionization regions. For example, using emission lines of [Ar IV] Stanghellini & Kaler (1989) find that $\log n_e = 3.99$ and $\log n_e = 4.19$ in NGC 6302 and NGC 6537 respectively. Infrared density diagnostics will tend to be weighted to regions of lower density because fine-structure energy levels are collisionally de-excited in regions of high density. However, this effect is not seen in our data. In fact the n_e in NGC 6302 found from the [Ne v] emission lines is larger than that found from the [Ar IV] emission lines.

The uncertainties in T_e are much larger and are dependent on the uncertainties in the interstellar extinction values. If $c(\mathrm{H}\beta)$ is uncertain by ± 0.1 then the corresponding uncertainties in T_e would be $+2.3 \times 10^4$ K or -1.6×10^4 K in NGC 6302 and $+1.4 \times 10^4$ K or -1.0×10^4 K in NGC 6537. In any case, the electron temperatures derived for these nebulae are still very large, much larger than those usually

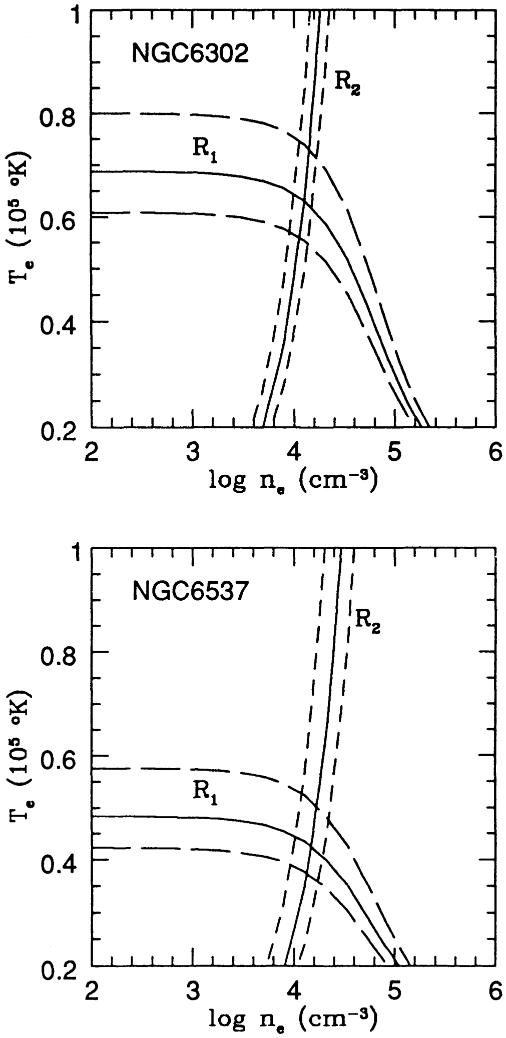

FIG. 1.—Nebular Diagnostic Plots. The observed [Ne v] line ratios R_1 and R_2 for NGC 6302 and NGC 6537 vs. n_e and T_e. The uncertainties (*dashed lines*) shown for these ratios are due to the uncertainties in the line fluxes. See the text for an estimate of the additional uncertainties in the derived T_e values arising from possible uncertainties in the interstellar extinction correction.

found in planetary nebulae. For example, Kaler (1986) finds that T_e is 1.65×10^4 and 1.57×10^4 K for NGC 6302 and NGC 6537 respectively using line ratios of [O III] and [N III]. In the following section we will consider whether such high electron temperatures are consistent with conditions in the He^{+2} region of these nebulae by constructing nebular models with plausible input parameters to explain our observed [Ne V] line ratios.

5. COMPARISON WITH PHOTOIONIZATION

We could compare the electron temperatures found via the observed line ratios with those produced in nebular models, but a better technique is to compare the observed and model line ratios directly. The [Ne V] 3426 Å emission line is weighted to regions of high temperature making the T_e found from R_1 or R_3 difficult to compare with a photoionization model which computes T_e throughout the nebula.

We use the photoionization code CLOUDY version 80.06g (Ferland 1991). As the exciting source we use the pure helium stellar model atmospheres of Wesemael (1981). These model atmospheres were chosen because they cover a large range in stellar effective temperature, and they include opacity effects for photons with energies of 54.4 eV and higher. The latter has been shown to be important for planetary nebulae nuclei, since blackbody model atmospheres apparently have a deficiency of short-wavelength photons (Méndez et al. 1988 and Henry & Shipman 1989). We also constructed nebular models with the model atmospheres of Clegg & Middlemass (1987) with helium fractions of 0.1 and with blackbodies. For model stars with similar effective temperatures ($T_{\rm eff}$) the resulting nebular [Ne V] line strengths were found to be similar whether the Clegg & Middlemass model stellar atmospheres or the Wesemael models were used. However, the [Ne V] UV line strengths were found to be substantially smaller in the nebular models excited by blackbodies. Since these line strengths are strongly dependent on T_e which is a measure of the hardness of the ionizing radiation, the smaller [Ne V] UV line strengths in nebular models excited by blackbodies simply reflect the smaller number of short wavelength photons from blackbody stellar models. As we discover below, the difficulty in our photoionization models is in trying to reproduce the strong observed [Ne V] UV line strengths. We adopted stellar models having excesses of photons with energies greater than 54.4 eV rather than blackbody stellar sources because the latter would only exacerbate this difficulty. Since we will conclude in this section that photoionization by nonblackbody exciting sources cannot account for the observed line ratios, we can also conclude that the same will hold true for the less strongly ionizing blackbody exciting sources.

Our goal is to then reproduce the observed [Ne V] line ratios R_1 and R_2 in nebular photoionization models having plausible input parameters. The nebular models used, aside from the model stellar atmosphere inputs, were fairly straightforward. The hydrogen densities in the nebular models were chosen so that R_2 was reproduced. All of the models presented here had an inner nebular radius of 10^{17} cm and did not contain dust. Including dust typical of planetary nebulae or reducing the inner radius by a factor of 10 does not substantially affect the [Ne V] line ratios and will not affect our conclusions. We note that increasing the inner nebular radius will substantially reduce the ionization level and be inconsistent with the nebulae we are trying to model. In all cases we consider the nebula to be optically thick to the ionizing radiation of Ne^{+3} ($h\nu > 97$ eV) so that all the stellar photons that can produce Ne^{+4} do so.

We use three different sets of nebular abundances in the models as listed in Table 2. The first is representative of typical planetary nebulae and is the average of the 102 nebulae considered by Perinotto (1991) to be of Type II. The other two abundance sets were found from detailed studies of the optical and UV spectra of NGC 6302 and NGC 6537 (Aller et al. 1981 and Feibelman et al. 1985, respectively). For all three sets we consider the abundances of elements heavier than neon to be that of Perinotto (1991) for Type II nebula. The abundances of these elements has little effect on the calculated models.

From the PNN evolutionary tracks of Paczyński (1971) we chose representative luminosities and effective temperatures for 0.6, 0.8, and 1.2 $M_\odot$ central stars. In all three cases we chose Wesemael models which are close to points on the constant luminosity portions of these PNN evolutionary tracks. These central star parameters are listed in Table 3 along with the [Ne V] line ratios produced by the models. The [Ne V] line strengths are strongly dependent on the PNN effective temperature and luminosity; they are not very dependent on the surface gravity (log g) of the models. Raising the PNN effective temperature and luminosity (models A to C) increases T_e within the nebulae and decreases R_1. This is due to the increasing ionization level within the nebula which diminishes the relative abundance of the dominant coolant in the He^{+2} region, C^{+4}. Models A and B contain central stars with the highest $T_{\rm eff}$ and luminosities attainable by 0.6 and 0.8 $M_\odot$ nuclei, respectively. The PNN in model C is representative of a 1.2 $M_\odot$ object approaching its highest $T_{\rm eff}$. Unfortunately there are no suitable model stellar atmosphere calculations for $T_{\rm eff} > 3 \times 10^5$ K. To determine if a central star temperature greater than this limit can explain the observed R_1 we constructed similar nebular models with blackbody exciting sources up to the theoretical maximum for a 1.2 $M_\odot$ PNN, 7×10^5 K. We found that there is a limit to the trend of decreasing R_1 with $T_{\rm eff}$ and above $T_{\rm eff} \gtrsim 3 \times 10^5$ K, an increase in stellar temperatures does not result in a substantially smaller R_1. We also note that a 1.2 $M_\odot$ PNN will evolve through the stage where $T_{\rm eff} > 3 \times 10^5$ K in ~200 yr (Paczyński 1970), though it may be possible that a helium flash could extend the time spent at this stage. For NGC 6302, a very high $T_{\rm eff}$ of 4.5×10^5 K has been suggested by Ashley &

TABLE 2

NEBULAR ABUNDANCES

Nebula	He/H	C/H	N/H ($\times 10^{-4}$)	O/H	Ne/H	Reference
Type II	0.10	6.6	1.2	4.6	1.0	Perinotto 1991
NGC 6537	0.19	0.4	8.9	1.7	1.0	Feibelman et al. 1985
NGC 6302	0.18	1.0	8.3	5.0	1.0	Aller et al. 1981

TABLE 3

LINE RATIO COMPARISON

	STELLAR PARAMETERS			NEBULAR PARAMETERS		LINE RATIOS	
MODEL	T_*	$\log L_*/L_\odot$	$\log g$	Abundances	$\log n_H$	R_1	R_2
A	1.5×10^5	3.5	6.0	Type II	3.66	3.22	1.54
B	2.0×10^5	4.0	7.0	Type II	3.66	2.19	1.52
C	3.0×10^5	4.5	8.0	Type II	3.66	1.69	1.49
D	3.0×10^5	4.5	8.0	NGC 6537	3.80	0.91	1.70
E	3.0×10^5	4.5	8.0	NGC 6302	3.60	1.13	1.43
Observed NGC 6537						0.22	1.72
Observed NGC 6302						0.15	1.42

Hyland (1988) based on the detection of infrared lines of [Si VI] and [Si VII]. We conclude that such a large T_{eff} cannot explain the observed R_1 in either object. This is in agreement with the conclusions of Lame & Ferland (1991) who compared a model of NGC 6302 excited by such a high-temperature blackbody to the observed ionic emission lines.

Model C shows the highest He^{+2} region electron temperatures attainable in a typical planetary nebula: approximately 1.6×10^4 K. Higher temperatures can be obtained in a nebula which has unusual abundances. Both NGC 6302 and NGC 6537 fall into this category as their helium and nitrogen abundances are considerably enhanced while carbon is substantially depleted. Nebular models D and E show the effects of these abundances changes on R_1, which is indicative of T_e. We chose the model central star with the highest T_{eff} for models D and E so that we would obtain lower limits to the model R_1. The spectral studies of these nebulae indicate $T_{eff} \gtrsim 2 \times 10^5$ K (Aller et al. 1981 and Feibelman et al. 1985). Even with these unusual abundances and hot central stars the photoionization models D and E show He III region electron temperatures that are no larger than $\sim 2.0 \times 10^4$ K.

Since the abundances used in nebular models D and E were obtained primarily from observations of lower ionization ions, we examined the possibility that even more extreme abundances could be present in the He^{+2} regions of NGC 6302 and NGC 6537. Since both a helium enhancement and a carbon depletion will contribute to larger He^{+2} region electron temperatures, such abundance variations could be responsible for the small observed R_1 in these nebulae. A larger helium concentration will result in a higher optical depth to photons with energies greater than 54.4 eV producing a proportionally greater energy input per unit volume to the high highly ionized regions. We found that increasing the model helium abundances up to $n_{He}/n_H \sim 1$ will increase the He^{+2} region T_e but not enough to explain our observed line ratios. In all these cases n_e was constrained by R_2 so that when n_{He}/n_H was increased the hydrogen density (n_H) was made correspondingly smaller. Depletion of carbon, which apparently occurs in the more massive progenitors of planetary nebulae through CNO processing (Kaler 1985), increases T_e throughout the He^{+2} region because of the depletion of C^{+4}, the major coolant. However, we found that T_e does not increase when the carbon abundance in the models is further reduced. This is partly due to the fact that the process which depletes the carbon produces a larger nitrogen abundance which then takes over the cooling function. Even without the cooling due to nitrogen, oxygen and neon will be significant coolants of the He^{+2} region, and their abundance is not significantly affected by the nucleosynthesis processes occurring in planetary nebular progenitors (Henry 1989). Even if the helium abundance were significantly enhanced *and* carbon and nitrogen were eliminated as coolants, we still would not be able to reproduce the line ratios observed from NGC 6302 and NGC 6537 with photoionization models.

6. SHOCK EXCITATION OF [Ne V]

We showed in the last section that $T_e \gg 2.0 \times 10^4$ K cannot be produced by the photoionization processes prevalent in planetary nebulae. If we take the physical parameters determined from the [Ne V] line ratios at face value, they indicate that at least some of the [Ne V] emission must arise from a shocked region. Electron temperatures in excess of 10^5 K can be produced in the postshock gas by a ~ 150 km s^{-1} wind incident on a region with densities of $\sim 10^3$ cm^{-3} (Shull & McKee 1979). The collisional ionization caused by such a shock would also produce highly ionized species such as Si^{+5} and Si^{+6} which would not be expected under normal photoionization conditions. In addition to the emission lines of [Si VI] seen in these nebulae, further evidence for shocks is present in NGC 6302 which shows emission-line profiles indicative of internal velocities of ~ 300 km s^{-1} (Meaburn & Walsh 1980a, b).

Except for the emission lines of some highly ionized species (notably [Ne V] 3426 Å) standard photoionization models have been fairly successful in reproducing the spectra of NGC 6302 and NGC 6537 (Aller et al. 1981 and Feibelman et al. 1985). Thus it seems reasonable to suppose that, for the most part, the spectra of these nebulae are due to photoionization with a small contribution from a shocked region. With some simple assumptions we can obtain a rough estimate of the relative contributions of the collisionally and photoionized gas to the overall [Ne V] emission from the nebulae and hence the proportions of the nebulae affected by shocks. We will assume that the photoionized portion of the nebular Ne^{+4} region has an electron temperature of $\sim 2 \times 10^4$ K and that R_1 produced in this portion is ~ 1, as indicated by our nebular models. After the passage of a shock front the highly ionized, high-temperature gas will first cool and then recombine, thus there are two cases to consider.

Shocked gas in its radiative cooling stage will show extremely high temperatures, and such gas will dominate the [Ne V] UV nebular emission. R_1 will then be weighted to the high-temperature shocked region, while R_2 will reflect the average density of the collisionally and photoionized regions. If we can estimate the effective T_e of the shocked region then we can determine the relative extents of the two nebular components. The observed R_1 suggest T_e of up to $\sim 6 \times 10^4$ K, if the cooling postshock gas is at this electron temperature, then the Ne^{+4} component of the nebula must be completely formed by collisional excitation. If the cooling postshock gas has a temperature of $\sim 3 \times 10^5$ K, as would arise in gas shocked by a 300 km s^{-1} wind (Meaburn & Walsh 1980a), then the shocked portion of the Ne^{+4} region would be 20% of the total. We can conclude that if the regions affected by the passage of the shock are still cooling, then the highly ionized proportion of the nebula that has been affected by this shock is quite large.

If the shocked gas is currently recombining, then the energy levels in the ground term of the Ne^{+4} ion will be populated according to their statistical weights, not according to any thermal conditions. This would result in R_1 approaching a very small value, 0.013, while R_2 would approach 5.9. If we were to observe such ratios and ascribe them to photoionization conditions, we would obtain extremely large values for T_e and n_e. However, if the recombining region were only a small proportion of the total [Ne v] emitting portion of the nebula, then we would observe line ratios similar to those for NGC 6302 and NGC 6537. The fact that the value of R_2 under recombination conditions is of the same order as its typical value for photoionized gas allows us to estimate the relative proportion of the shocked Ne^{+4} region. To obtain an R_1 similar to those observed would require that the recombining region producing [Ne v] emission be only 7% and 5% of the total Ne^{+4} emitting region for NGC 6302 and NGC 6537 respectively, the rest of the [Ne v] emission being produced by photoionization. Since the recombining region would produce a relatively large R_2, the density in the photoionized Ne^{+4} region would have to be smaller than we have estimated; $\log n_e = 3.2$ and $\log n_e = 3.6$ for NGC 6302 and NGC 6537 respectively.

The cooling time of the shocked nebular gas is likely to be much shorter than the recombination time (Kafatos 1973). This would make the second case the more likely possibility. In this picture, the nebulae would consist primarily of gas photoionized by hot central stars, but they would also contain a small collisionally ionized region that is now recombining. The recombination of highly ionized species will produce strong emission lines that are either much weaker, as in [Ne v], or completely absent, as in [Si vi], under normal photoionized conditions. The bi-polar, or in the case of NGC 6302, polypolar morphology is a good argument for the occurrence of a fast wind in the planetary nebulae formation process, one which has already shaped these nebulae (Kwok, Purton, & FitzGerald 1978). This would imply that most of the shock interaction has already taken place and that the shocked gas is currently recombining. A plausible model of the present structure of these nebulae would then consist of three components. The first component would be of a relatively low-density, highly-ionized region that has been swept out by a fast wind but is now photoionized by the hot central star. The second component would be the recombining region behind the shock created by this fast wind. This component would have a filling factor of 5%–7% and would be highly ionized, it would be the source of the highly ionized silicon emission and the bright [Ne v] UV emission. The third component would make up the bulk of the photoionized nebulae and would have a higher density but lower ionization than the first component. Due to the inhomogeneous nature of these objects the three regions are not likely to exist as symmetric shells. Instead the first photoionized region could surround denser lower ionization clumps, the third region, while the second recombing region is located in the shock interface between them.

7. CONCLUSION

We have determined accurate physical condition within the highly ionized regions of NGC 6302 and NGC 6537 from [Ne v] line ratios. The electron densities were found to agree quite well with those found by other workers from the emission lines of lower ionization species. In contrast, the electron temperatures in the He^{+2} region were found to be extremely high. We used photoionization models to explore the nebular parameter space affecting T_e and found that the electron temperatures in the He^{+2} region will not appreciably exceed 2.0×10^4 K, even in nebulae with unusual abundances. A realistic explanation for the observed [Ne v] line ratios in these nebulae is that shocks are present. These shocks produce usually strong [Ne v] emission, either by producing very large electron temperatures, or more likely, by producing a region with small filling factor where highly ionized gas is recombining.

We note that the key to our analysis is the availability of the 24.32 μm, 14.3 μm, and 3426 Å emission-line fluxes for these nebulae. The [Ne v] infrared line ratio is a very useful nebular diagnostic, since it is independent of the internal or interstellar extinction and it is not weighted to regions of higher T_e as are the usual optical line ratio diagnostics of n_e.

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