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DETECTION OF HIGHLY IONIZED SILICON IN THE PLANETARY NEBULAE NGC 6302 AND NGC 6537

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ABSTRACT

We report the discovery of [Si VI] and [Si VII] near-infrared line emission from NGC 6302 and [Si VI] emission from NGC 6537. Both objects are high-excitation helium-rich planetary nebulae (PNs). This is the first time that these lines have been detected in a PN. We have looked for the [Si VI] line unsuccessfully in seven other high excitation PNs. The fluxes we have observed from NGC 6302 in a 27″ square aperture are 3.8×10^{-11} ergs cm^{-2} s^{-1} for the [Si VI] line at 1.96 μm, and 4.3×10^{-11} ergs cm^{-2} s^{-1} for the [Si VII] line at 2.48 μm. For comparison, the H I Brγ flux is 0.64×10^{-11} ergs cm^{-2} s^{-1}. In NGC 6537 the corresponding fluxes are 0.3×10^{-11} ergs cm^{-2} s^{-1} for the [Si VI] line, $<0.05 \times 10^{-11}$ ergs cm^{-2} s^{-1} for the [Si VII] line, and 0.18×10^{-11} ergs cm^{-2} s^{-1} for H I Brγ. In NGC 6302 the [Si VI] line emission is concentrated in an oval region 8″ × 5″ and is coincident with the H I Brγ emitting region. We derive abundances for Si^{5+} and Si^{6+} and use the abundance ratio to estimate the central star temperatures. NGC 6302 has probably the hottest central star of any planetary observed to date.

Subject headings: infrared: spectra — line identifications — nebulae: abundances — nebulae: individual (NGC 6302, NGC 6537) — nebulae: planetary

I. INTRODUCTION

NGC 6302 and NGC 6537 are planetary nebulae (PNs) of Peimbert Type I. Peimbert (1978) defined the Type I PNs to be those which showed large overabundances of helium and nitrogen when compared with solar values. Although the class was defined purely on the grounds of chemical abundances, its members also show strong morphological similarities: many of them, including NGC 6302 and NGC 6537, are bipolar and filamentary (for a recent review of the properties of Type I PN, see Peimbert and Torres-Peimbert 1983). It seems likely that the Type I PNs have evolved from intermediate mass (5–8 $M_\odot$) asymptotic giant branch (AGB) stars. The young Type I PNs can be expected to have extremely hot ($T_* > 1 \times 10^5$ K), and luminous ($L_* > 5 \times 10^3 L_\odot$) nuclei with masses ranging up to the Chandrasekhar mass limit of 1.44 $M_\odot$ (see, for example, Wood and Faulkner 1986). These stars fall in a region of the Hertzsprung-Russell diagram which has been well studied theoretically (see, for example, Paczyński 1971), but has been poorly confirmed observationally. One reason for the difficulty in observing these stars is that the contrast between the star and the bright nebula core is poor at visual wavelengths.

Stellar temperatures in excess of 1×10^5 K enable the formation of highly ionized species, and indeed the optical spectrum of NGC 6302 shows lines attributed to Ne^{4+} and Fe^{6+} (see, for example, Aller and Czyzak 1978). Pottasch *et al.* (1986) report the detection of the 7.65 μm [Ne VI] line in both NGC 6302 and NGC 6537. The only other planetary in their sample of 58 to show the line was NGC 2440, also a Peimbert Type I nebula. To form Ne^{4+}, Fe^{6+}, and Ne^{5+} from their next lower ionization states requires energies of 97 eV, 99 eV, and 126 eV, respectively. This should be compared with energies of 167 eV and 205 eV required to produce Si^{5+} and Si^{6+}, the two ions discussed in this paper. These ions are the most highly ionized species seen to date in PN, and their detection can be used to place limits on the central star temperatures.

II. OBSERVATIONS

In 1985 June we obtained a *K* band (1.9–2.5 μm) spectrum of the core of NGC 6302 at a spectral resolving power of 110 using the IRPS CVF spectrometer on the Anglo-Australian Telescope (AAT). The spectrum had a tendency to rise at both ends. Extending the scan to longer and shorter wavelengths conclusively showed the presence of two previously unidentified lines at either end of the *K* band. The reason that the lines had not been seen before is that they lie in wavelength regions which are strongly affected by the Earth's atmospheric transmission and so are not included in normal *K* band spectra.

Figure 1 shows a spectrum of the core of NGC 6302 taken with the FIGS spectrometer on the AAT. FIGS is a cooled grating near-infrared spectrometer which uses a 16 element indium antimonide array as the detector. It is described by Bailey *et al.* (1988). The largest aperture available with FIGS is 5″.9 square, which is not large enough to measure the total flux from NGC 6302. To do this we used the 27″ square aperture of CIGS, also a cooled grating spectrometer (Jones *et al.* 1982), on the 74 inch telescope at Mount Stromlo. The fluxes we observed from NGC 6302 were 3.8×10^{-11} ergs cm^{-2} s^{-1} for the 1.96 μm [Si VI] line, and 4.3×10^{-11} ergs cm^{-2} s^{-1} for the 2.48 μm [Si VII] line. For comparison, the H I Brγ flux was found to be 0.64×10^{-11} ergs cm^{-2} s^{-1} using the same instrument. The total Hβ flux was measured by Perek (1971) to be 3.0×10^{-11} ergs cm^{-2} s^{-1} in an 88″ aperture.

In order to identify the lines we used CIGS at a spectral resolving power of 400 to determine accurate line wavelengths. Our best observational wavelengths are 1.9613 ± 0.0020 μm and 2.4852 ± 0.0025 μm. These wavelengths are given in air and correspond to vacuum wavenumbers of 5097 cm^{-1} and 4022 cm^{-1}, respectively. The instrument was wavelength calibrated by using the two other strong lines in the *K* band spectrum of NGC 6302: the He I line at 2.0581 μm and the H I Brγ line at 2.1655 μm.

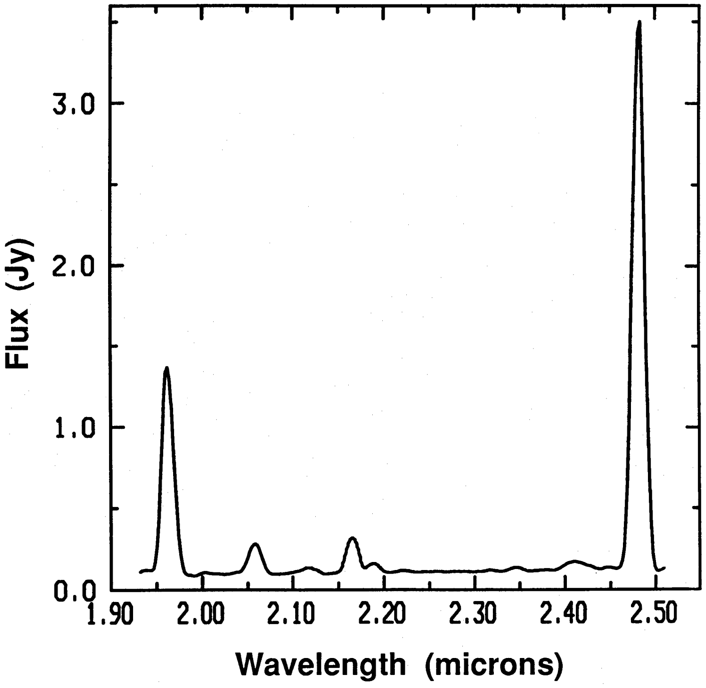

FIG. 1.—An extended K band spectrum of NGC 6302 taken with the FIGS spectrometer on the AAT using a 5″.9 square aperture with a 60″ north-south chop. The strong lines at 1.96 μm and 2.48 μm are due to [Si VI] and [Si VII], respectively. Also visible are lines due to He I at 2.058 μm, a blend of He I and H_2 $S(1)$ at 2.12 μm, H I Brγ at 2.166 μm, He II at 2.189 μm, and the H_2 Q-branch at 2.41 μm.

Subsequent to our discovery of the lines in NGC 6302 we searched for evidence of the 1.96 μm [Si VI] line in eight other high excitation PNs using CIGS. The PNs we selected were all Peimbert Type I objects suspected of having hot central stars. The survey resulted in the detection of the line in NGC 6537; see Figure 2. The observed flux in a 27″ square aperture was 0.3×10^{-11} ergs cm^{-2} s^{-1}, comparable with the H I Brγ flux of 0.18×10^{-11} ergs cm^{-2} s^{-1}. The Hβ flux was measured by Perek (1971) to be 0.22×10^{-11} ergs cm^{-2} s^{-1} in a 31″ aperture. We found no evidence for the 2.48 μm [Si VII] line at a 2 σ flux limit of 0.05×10^{-11} ergs cm^{-2} s^{-1}.

TABLE 1

FLUX UPPER LIMITS

Object	1.96 μm [Si VI] 2 σ Flux Limit[a] (10^{-12} ergs cm^{-2} s^{-1})	Heliocentric Velocity Correction[b] (km s^{-1})
NGC 2440	0.7	−12.8
NGC 3132	1.6	−15.8
NGC 5315	2.9	+3.9
NGC 6445	1.4	+20.1
NGC 6741	1.0	+27.8
He 2-15	1.6	−16.6
IC 4406	1.6	+1.7

[a] All observations were made using CIGS on the Mount Stromlo 74 inch telescope using a 27″ square aperture centered on the brightest optical part of the nebula.

[b] The heliocentric velocity correction should be added to the geocentric radial velocity of the nebula to obtain its heliocentric radial velocity at the time of observation.

Table 1 gives approximate upper limits on the [Si VI] line flux for the other nebulae in our survey. Table 1 also gives the heliocentric velocity correction for the time of observation since, as discussed in the next section, it is possible for the line to be Doppler shifted into an opaque wavelength region of the Earth's atmosphere.

To determine the spatial distribution of the line emission in NGC 6302 we used the IRPS CVF spectrometer on the AAT at a spectral resolving power of 110. We imaged the core of the nebula in DC mode (i.e., without chopping) with a 2″ circular

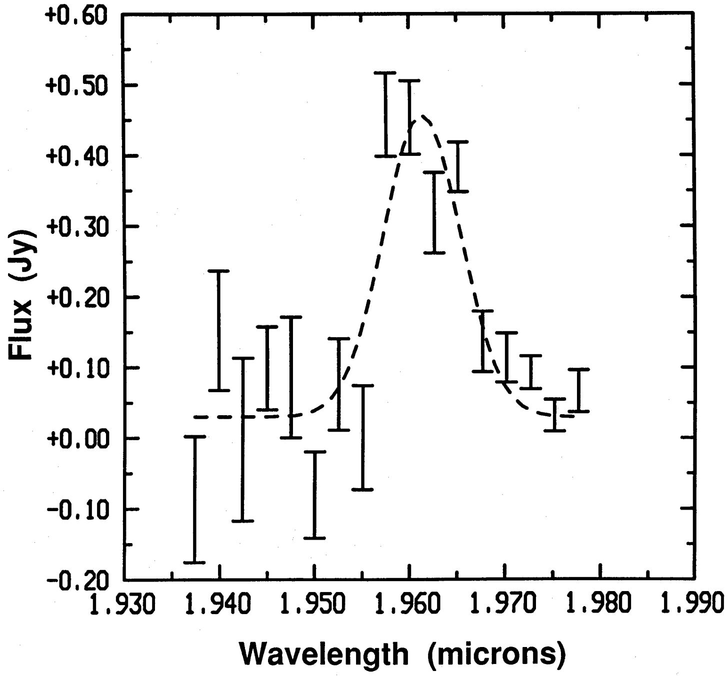

FIG. 2.—The 1.96 μm [Si VI] line in NGC 6537. This spectrum was taken with the CIGS spectrometer on the 74 inch telescope at Mount Stromlo using a 27″ square aperture and a 96″ east-west chop. Dashed curve is a least-squares fitted Gaussian.

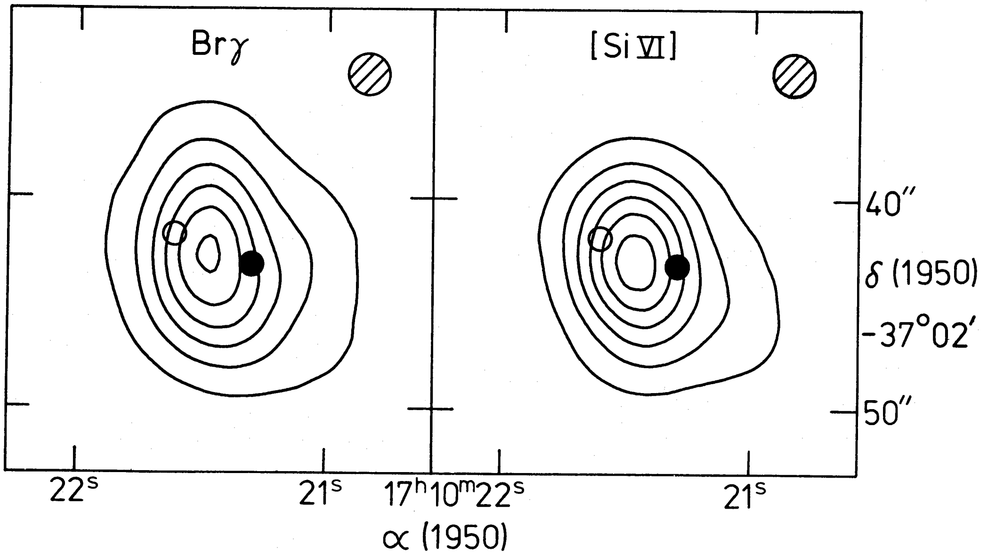

FIG. 3.—Maps of the spatial distribution of H I Brγ and the 1.96 μm [Si VI] line in NGC 6302. The contour intervals are at 0.15, 0.30, 0.45, 0.60, 0.75, and 0.90, of the peak intensity. The signal to noise in the peak is ~50 for both maps. Shaded region represents the aperture size on the sky. Open circle is the location of the peak of the Hα emission. Filled circle is the location of the peak of the 4.9 GHz continuum emission.

aperture and a stepsize of 1″. Figure 3 shows contour plots of the H I Brγ and [Si VI] images. The seeing was ~1″.5 on average during the 57 minutes needed to make the images. In both images the emission is concentrated in an oval shaped region with dimensions 8″ × 5″ full width at half-maximum. The H I Brγ emission appears to be slightly more extended than the [Si VI] emission at the lower contour levels, although greater signal to noise would be needed to be sure. The centers of the ovals were coincident within the 1″ repeatability of the scan lines. Figure 3 also shows the locations of the peaks of Hα line emission and 4.9 GHz continuum emission from the nebula. The location of the Hα peak was determined from a narrow-band interference filter image we obtained using the Photon Counting Array on the 40 inch telescope at Siding Spring. The location of the 4.9 GHz peak was measured from the Very Large Array image of Rodríguez *et al.* (1985). The positions of the peaks have an absolute accuracy of better than 1″. The fact that the peaks are not coincident is presumably a result of the intranebula extinction—a point which is discussed further in the section on extinction below.

III. ANALYSIS

a) Flux Determinations

The wavelengths of the new lines places them in a region where the Earth's atmospheric transmission is poor, making it difficult to obtain accurate fluxes. The transmission variations with wavelength at the edges of the *K* band are shown in Figures 4 and 5. These figures were adapted from observations of the solar spectrum from Mount Wilson (Mohler *et al.* 1950). The absorption lines are mainly due to H_2O molecules, with some contribution from CO_2 and N_2O. Since the transmission varies on a wavelength scale much shorter than the resolution of our instruments it is not possible to correct for it by simply dividing by an observed standard star spectrum. The Doppler shift caused by the heliocentric motion of the Earth is sufficient to move the lines from wavelength regions where the atmosphere is transparent to regions where it is opaque. We have observed this effect in the case of the [Si VI] line in NGC 6302: observations made when the heliocentric velocity correction was $+28$ km s^{-1} fail to show the line, whereas the line was visible if the velocity correction was between -1 km s^{-1} and -29 km s^{-1}. From this we conclude that the full width at zero intensity of the line is less than ~30 km s^{-1}.

There are three main difficulties in correcting for the atmospheric transmission: the lack of accurate knowledge of the transmission at the time of observation, the lack of sufficiently accurate wavelengths for the silicon lines and the lack of an accurate radial velocity for the emitting material. The effect of the atmosphere can be minimized by observing from a high-altitude observatory such as the United Kingdom Infrared Telescope (UKIRT), although even at altitudes of 4 km the atmosphere has completely opaque regions near the wavelengths of interest.

Given that the line wavelengths may be in error by as much as 4 cm^{-1}, which is much larger than the characteristic scale length of the atmospheric variations (typically 0.08 cm^{-1}), it was not possible to correct an individual observation for the atmosphere. However, by letting the Earth's heliocentric velocity scan the lines through the atmospheric absorption features over a period of months, a reasonable estimate of the true fluxes can be made. The fluxes quoted for NGC 6302 in § II were obtained by averaging ~10 measurements of each line taken over a period of 6 months. The individual measurements were fluxed prior to averaging by dividing by standard star observations. The final fluxes we have quoted have an uncertainty of ~25%. They agree within 15% with those measured from a spectrum obtained by T. R. Geballe and M. J. Barlow (private communication) with the 19″.6 circular aperture of the UKT9 spectrometer on UKIRT. Our [Si VI] flux for NGC 6537 was the average of only two measurements, and hence should be treated with caution.

b) Line Identifications

The new lines are almost certainly due to the ground-state fine-structure transitions [Si VI] $^2P^0_{1/2}$–$^2P^0_{3/2}$ at 1.9625 μm (5094.1 cm^{-1}), and [Si VII] $^3P_1$–$^3P_2$ at 2.4808 μm (4029.8 cm^{-1}). The lines have been previously seen in Nova Cygni 1975 and Nova Vulpeculae 1984 No. 2 (Grasdalen and Joyce 1976; Grasdalen *et al.* 1986). The wavelength of the [Si VI]

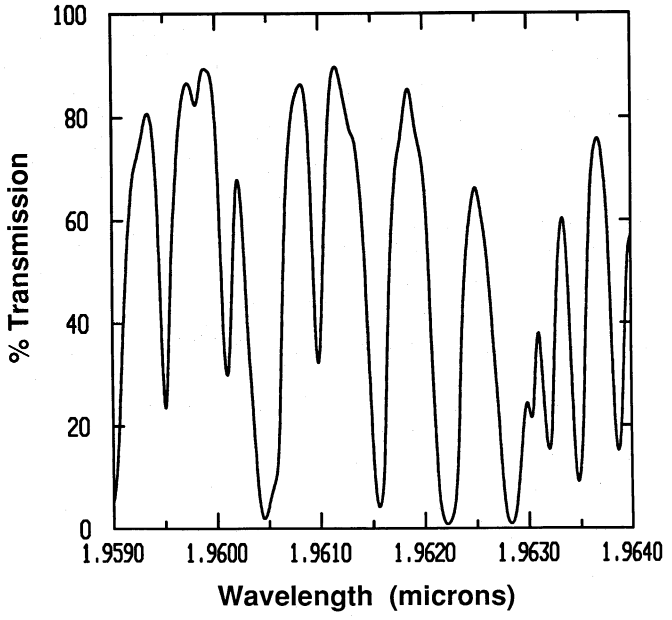

FIG. 4

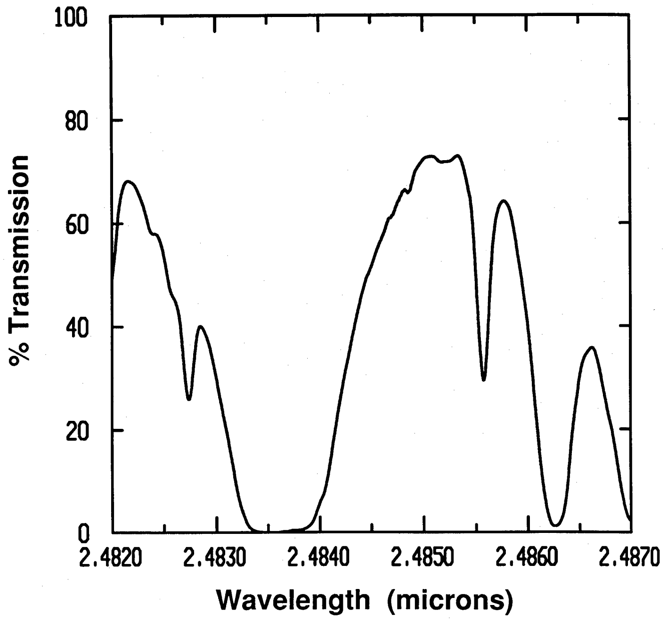

FIG. 5

FIG. 4.—The approximate transmission of the Earth's atmosphere near the observed rest wavelength of the [Si VI] line. The nominal line center is at 1.9613 μm. Depending on the position of the Earth in its orbit, the line emitted by NGC 6302 could be shifted from the nominal center by amounts varying from −0.0006 μm to −0.0001 μm. The line wavelength itself could be in error by up to ±0.0020 μm.

FIG. 5.—Approximate transmission of the Earth's atmosphere near the observed rest wavelength of the [Si VII] line. The nominal line center is at 2.4852 μm.

transition is from a theoretical result given by Mendoza (1983), and that for [Si VII] from a calculation by Edlén (1972). The uncertainties in the theoretical wavelengths are of the order of ±0.002 μm (4 cm^{-1}).

No other common ionic species have transitions capable of being collisionally excited which would produce the observed wavelengths. The fact that the lines appear to come from neighboring ionization stages of the same element further strengthens our argument. The identification of the 2.48 μm line could be confirmed by the observation of the [Si VII] $^3P_0$–$^3P_1$ transition at 6.4993 μm, which would be possible from the Kuiper Airborne Observatory. We predict a flux of 2.5×10^{-12} ergs cm^{-2} s^{-1} for this line in the case of NGC 6302.

Energy level diagrams for Si^{5+} and Si^{6+} are shown in Figure 6. Collisional excitation by electrons will cause the low lying levels to be populated. In the case of Si^{5+} this will result is the emission of a 1.96 μm photon. In the case of Si^{6+} the pos-

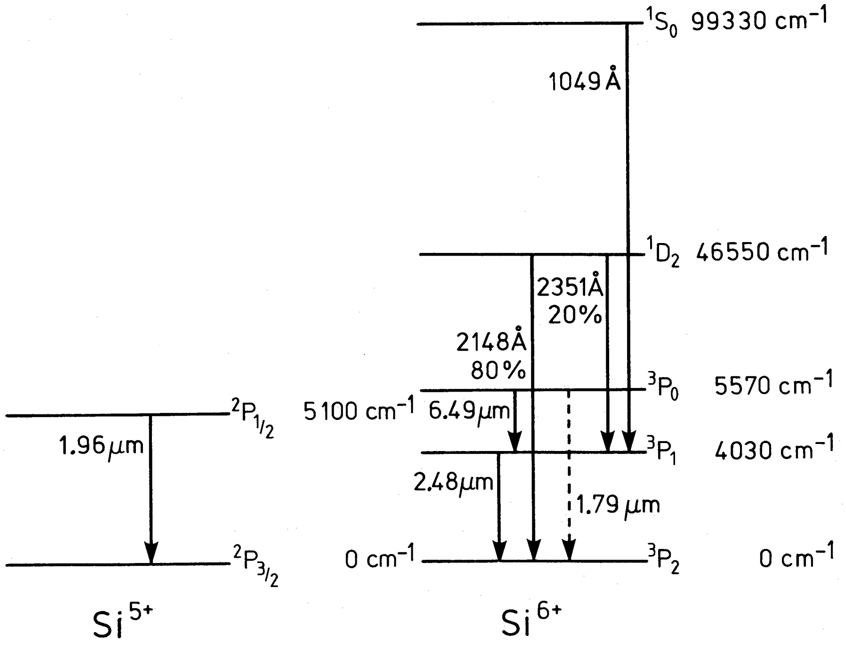

FIG. 6.—Energy level diagrams and important transitions for Si^{5+} (a p^5 ion of the fluorine isoelectronic sequence) and Si^{6+} (a p^4 ion of the oxygen isoelectronic sequence). The energy levels are not drawn to scale. The 1.79 μm transition is dashed since it is ~3×10^{-4} times lower in probability than the 6.49 μm transition.

sibilities are emission of a 2.48 μm photon or the emission of a 6.49 μm photon followed by one at 2.48 μm—the probability of emission of a single 1.79 μm photon is lower by a factor of 3×10^{-4}. The high-energy tail of the electron distribution will also cause some populating of the $^1D_2$ and $^1S_0$ levels in Si^{6+}, with the subsequent emission of ultraviolet photons at 2351 Å, 2148 Å, and 1049 Å.

In order to calculate the level populations in Si^{5+} and Si^{6+} we used the transition probabilities and collision strengths given by Kafatos and Lynch (1980) and solved the detailed balance equations for a five-level ground-state term. The results of these calculations are summarized in Table 2, which shows for both NGC 6302 and NGC 6537 the intensities of the most important lines with respect to the case B H I Brγ intensity. Table 2 also shows the values we have adopted throughout this paper for the electron temperature T_e, and the electron density N_e. The critical electron densities for collisional deexcitation of the [Si VI] and [Si VII] lines we have observed are $\sim 2 \times 10^7\ \mathrm{cm}^{-1}$ and $2 \times 10^6\ \mathrm{cm}^{-1}$, respectively.

Using our observed 2.48 μm line flux for NGC 6302 we can predict the flux in the 2148 Å line, the strongest ultraviolet line in the Si^{6+} spectrum. Without correcting for differential reddening the expected flux is 1.9×10^{-11} ergs cm^{-2} s^{-1}. The *International Ultraviolet Explorer* (*IUE*) spectrum of Aller *et al.* (1981) shows no line at this wavelength to a limiting flux of 1.0×10^{-13} ergs cm^{-2} s^{-1}. This implies that the absorption in visual magnitudes to the Si^{6+} emitting region is greater than $A_v = 4$, which is consistent with our estimates in the next section.

c) *Extinction Corrections*

To obtain the intrinsic line fluxes we need to correct for interstellar absorption. Additionally, we might expect considerable amounts of intranebula absorption due to dust. The optical polarization study of King, Scarrott, and Shirt (1985) shows evidence for dust throughout NGC 6302, and the 10 μm image by Lester and Dinerstein (1984) shows a strongly peaked infrared disk centered on the 4.9 GHz radio center of Rodríguez *et al.* (1985). In contrast, the brightest point in our Hα image of NGC 6302 lies $\sim 4''$ to the west of the 4.9 GHz peak (see Fig. 3), and there is a dark lane obscuring the brightest parts of the radio continuum source. It is clear that the Hα intensity is not a true indicator of the ionized gas distribution. The simplest explanation for this is that there are large amounts of absorbing material within the nebula near the radio core. This interpretation is also consistent with the peak of the H I Brγ emission lying between the Hα and 4.9 GHz peaks.

Previous estimates of the extinction to NGC 6302 have been based on the ratio of the total 5 GHz radio flux density to the total Hβ line flux, or on the H I Balmer line or He II Pickering line decrements. Milne and Aller (1975) use the first of these techniques to derive a value of the logarithm of the ratio of the true to the observed Hβ flux of $c = 1.41$. This result is difficult to interpret in the case of NGC 6302 since the bulk of the radio emission comes from an area which contains just a small fraction of the Hβ emission. Aller *et al.* (1981) obtain $c = 1.22$ using the Balmer line decrement, and Barral *et al.* (1982) obtain $c = 1.59$ using the Pickering line decrement. The problem with these determinations is that when the extinction varies spatially within the emitting region, most of the optical and UV flux comes from the regions of lowest extinction, and so the derived values for c will be lower than that appropriate for the central core. This effect can be reduced by using the infrared H I Brackett lines, which have a lower optical depth than the Balmer lines, and hence sample regions of higher extinction.

To derive a value for the extinction appropriate to the K band, we compared our observed total H I Brγ flux with the 5 GHz flux density. Assuming Menzel and Baker case B recombination for the hydrogen lines and that the nebula is optically thin at 5 GHz, Milne and Aller (1975) show that,

$$\frac{S(5\ \mathrm{GHz})}{F(\mathrm{H}\beta)} = 3.05 \times 10^{-18}\left(\frac{T_e}{10^4}\right)^{0.4} \ln\left[9900\left(\frac{T_e}{10^4}\right)^{3/2}\right] \times [1 + (1 - x'')y + 3.7x''y]\,, \quad (1)$$

where, $S(5\ \mathrm{GHz})$ is the observed 5 GHz continuum flux density in W m^{-2} Hz^{-1}, $F(\mathrm{H}\beta)$ is the predicted unreddened Hβ flux in ergs cm^{-2} s^{-1}, y is the number abundance ratio of helium to hydrogen, and x'' is the fraction of helium atoms that are doubly ionized. Additionally, the case B value of the ratio of the H I Brγ flux to the Hβ flux is 0.0233 at $T_e = 20{,}000$ K and $N_e = 10^4\ \mathrm{cm}^{-3}$ (Giles 1977). The ratio is relatively insensitive to the electron temperature and density. Aller *et al.* (1981) quote a value for the helium abundance ratio of $y = 0.18$, which we assume to be all doubly ionized. Using equation (1) and the observed ratio of the 5 GHz flux density (3.0 Jy; Rodríguez *et al.* 1985) to the total H I Brγ flux (0.64×10^{-11} ergs cm^{-2} s^{-1}), we find that for NGC 6302 the absorption in magnitudes at the wavelength of the H I Brγ line is $A_{\mathrm{Br}\gamma} = 0.50$. Using the interstellar extinction law given by Rieke and Lebofsky (1985) this corresponds to $A_{[\mathrm{Si\,VI}]} = 0.59$, $A_{[\mathrm{Si\,VII}]} = 0.41$, $A_v = 4.3$, and $c = 2.1$. Comparing this extinction estimate with the optical value suggests that there may be an additional 1.3 mag of visual extinction in the core region of NGC 6302.

Milne and Aller (1985) quote a value of $c = 1.79$ for NGC 6537 from a comparison of the 5 GHz flux density and the Hβ flux. Kaler (1983) obtains $c = 2.02 \pm 0.14$ from the Hα/Hβ flux ratio in a 40″ aperture. Kaler (1985) obtains $c = 2.16$ from the Hα/Hβ flux ratio in a 5″ aperture positioned on an arc of nebulosity 1′ north of the nebula. Note that while NGC 6537 has faint optical extensions up to 1′ from its core, the 5 GHz

TABLE 2

PREDICTED SILICON LINE INTENSITIES RELATIVE TO H I Brγ[a]

Object	T_e (10^4 K)	N_e (10^4 cm^{-3})	1.96 μm	2.48 μm	6.49 μm	2351 Å	2148 Å	1049 Å
NGC 6302....	2.0[b]	2.0[b]	3.38	1.80	0.104	0.186	0.79	0.0069
NGC 6537....	1.6[c]	0.4[c]	2.55	1.38	0.078	0.066	0.29	0.0010

[a] The line intensities are normalized to an abundance of 1.0×10^{-6} for Si^{5+} and Si^{6+}. No corrections for differential reddening have been made.

[b] Meaburn and Walsh 1980.

[c] Kaler 1983.

map of Felli and Perinotto (1979) shows that almost all the flux is contained within a 20″ aperture.

Using the 5 GHz flux density of Felli and Perinotto (1979) (0.755 ± 0.030 Jy), our H I Brγ flux (0.18×10^{-11} ergs cm^{-2} s^{-1}), and adopting $y = 0.2$ and $x'' = 1.0$, we find $A_{\rm Br\gamma} = 0.47$, $A_{\rm [Si\,VI]} = 0.55$, $A_{\rm [Si\,VII]} = 0.38$, $A_v = 4.0$, and $c = 2.0$, in good agreement with the optical values.

d) Silicon Ion Abundances

Little is known about the abundance of silicon in planetary nebulae. This is primarily due to the lack of interpretable optical emission lines. The only information that has been available is from the collisionally excited ultraviolet lines Si III] $\lambda\lambda$1883, 1892, and Si IV] $\lambda\lambda$1394, 1403. These lines are blended at low resolution with C III] λ1909 and O IV] λ1400, respectively, making accurate observational data scarce.

The new lines we have observed enable an estimate to be made of the abundances of Si^{5+} and Si^{6+} with respect to hydrogen. Using the observed ratio of the lines to H I Brγ, correcting these ratios for the reddening found in § IIIc, and using the relative line intensities given in Table 2, we arrive at $N(Si^{5+})/N(H) = 1.9 \times 10^{-6}$ and $N(Si^{6+})/N(H) = 3.4 \times 10^{-6}$ for NGC 6302, and $N(Si^{5+})/N(H) = 0.7 \times 10^{-6}$ and $N(Si^{6+})/N(H) < 0.2 \times 10^{-6}$ for NGC 6537. Aller *et al.* (1981) used a spectrum of NGC 6302 taken with *IUE* to determine the abundance of Si^{2+}, and obtained $N(Si^{2+})/N(H) = 2.7 \times 10^{-6}$. An estimate of the total silicon abundance in NGC 6302 can be made by assuming that the unobserved ionization states (Si^+, Si^{3+}, and Si^{4+}) have abundances equal to that of Si^{2+}. This assumption results in a silicon abundance of $N(Si)/N(H) = 1.6 \times 10^{-5}$, which can be compared with the solar value of $N(Si)/N(H) = 4.3 \times 10^{-5}$ (Lambert and Luck 1978). It is possible that the silicon is depleted by grain formation during the early stages of formation of the nebula (see Shields 1983 for a discussion).

e) Central Star Temperatures

It is possible to use the abundances of Si^{5+} and Si^{6+} we have derived for NGC 6302 to estimate the temperature of the central star. These ions are ideal for this purpose since they come from neighboring ionization states, their lines are close in wavelength hence minimizing differential reddening, and their ionization potentials are such that their abundance ratio depends sensitively on the stellar temperature. The basic idea is to equate the number of photoionizations of Si^{5+} with the number of recombinations of Si^{6+}. Osterbrock (1974) shows that for a shell of gas at a distance $R_{\rm neb}$ from the central star,

$$N(X^n)\left(\frac{R_*}{R_{\rm neb}}\right)^2 \int_{\nu_T}^{\infty} \frac{4\pi J_\nu}{h\nu}\,\sigma(X^n, \nu)\,d\nu = N(X^{n+1})\,N_e\,\alpha_{\rm rad}(X^{n+1}, T_e)\,, \tag{2}$$

where $N(X^n)$ is the number density of atom X in ionization stage n, R_* is the stellar radius, J_ν is the mean intensity of radiation at the surface of the star at frequency ν, ν_T is the frequency corresponding to the ionization threshold, $\sigma(X^n, \nu)$ is the photoionization cross section, and $\alpha_{\rm rad}(X^{n+1}, T_e)$ is the effective radiative recombination coefficient.

We obtained the photoionization cross section from the parametric form given by Seaton (1958),

$$\sigma = \sigma_T\left[\beta\left(\frac{\nu_T}{\nu}\right)^S + (1 - \beta)\left(\frac{\nu_T}{\nu}\right)^{S+1}\right],$$

where σ_T is the cross section at the ionization threshold frequency ν_T, and β and S are dimensionless constants. Raymond (1976) gives for Si^{5+}, $\sigma_T = 1.52 \times 10^{-18}$ cm^2, $\nu_T = 4.96 \times 10^{16}$ Hz, $\beta = 1.95$, and $S = 2.34$.

The radiative recombination coefficient, $\alpha_{\rm rad}$, is given by Aldrovandi and Péquignot (1973) as,

$$\alpha_{\rm rad} = A\left(\frac{T_e}{10^4}\right)^{-\eta},$$

where for Si^{6+}, $A = 3.0 \times 10^{-11}$ cm^3 s^{-1}, and $\eta = 0.702$. Dielectronic recombinations are negligible ($\alpha_{\rm di}/\alpha_{\rm rad} < 0.2$), provided that $T_e < T_{\rm crit}$ where $T_{\rm crit} \approx 7.4 \times 10^4$ K.

If we assume that the central star has a blackbody flux distribution at a characteristic temperature of T_*, then

$$J_\nu = \frac{2h\nu^3}{c^2}\,\frac{1}{\exp(h\nu/kT_*) - 1},$$

where c, h, and k, are the usual physical constants. Finally, by substituting the expressions for σ, $\alpha_{\rm rad}$, and F_ν into equation (2) and defining $x = \nu/\nu_T$, we obtain

$$\frac{N(X^{n+1})}{N(X^n)} = \frac{8\pi}{c^2} \times \frac{\sigma_T \nu_T^3}{A} \times \frac{1}{N_e} \times \left(\frac{T_e}{10^4}\right)^{\eta}\left(\frac{R_*}{R_{\rm neb}}\right)^2 \times \int_1^{\infty} \frac{\beta x^{2-S} + (1 - \beta)x^{1-S}}{\exp[(h\nu_T/kT_*)x] - 1}\,dx\,, \tag{3}$$

where the integral can be conveniently solved numerically by using a nine-point Laguerre polynomial.

We used equation (3) to calculate the value of T_* required to produce the observed ratio $N(Si^{6+})/N(Si^{5+})$. We assumed that the distance to the nebula was 2 kpc (Rodríguez *et al.* 1985) and used the values for T_e and N_e given in Table 2. The stellar radius was estimated by using the luminosity calculated by Rodríguez *et al.* (1985) ($L_* = 1.1 \times 10^4\ L_\odot$), and assuming a blackbody flux distribution with an effective temperature $T_{\rm eff} = 4 \times 10^5$ K. This resulted in the value $R_* = 0.022\ R_\odot$. An approximate lower limit to the stellar radius is $R_* = 0.010\ R_\odot$, which applies if the star is a fully evolved white dwarf of mass 0.8 $M_\odot$. The value of $R_{\rm neb}$ to use depends on the detailed spatial distribution of the ionized silicon. We used $R_{\rm neb} = 4''$ as a first approximation.

With these parameters, equation (3) gives $T_* = 4.3 \pm 0.5 \times 10^5$ K for NGC 6302, which agrees reasonably with the value $T_* = 3.5 \times 10^5$ K derived by Stoy's energy balance method (Pottasch 1983). To examine the sensitivity of our temperature estimate to errors in the input parameters, we took extreme values of each of the parameters and noted the effect on T_*. Varying the nebula radius from 3″ to 6″ produced a range in T_* from 4.0×10^5 K to 4.9×10^5 K. Halving the distance to the nebula resulted in $T_* = 3.6 \times 10^5$ K. Reducing the stellar radius to $R_* = 0.010\ R_\odot$ produced $T_* = 5.6 \times 10^5$ K. Increasing N_e to 4×10^4 cm^{-3} gave $T_* = 4.8 \times 10^5$ K.

The derived value for T_* is relatively insensitive to the observed silicon line ratio: increasing and decreasing the ratio by a factor of 2 produced a range in T_* from 4.8×10^5 K to 3.9×10^5 K. So our conclusions about the temperature of the central star of NGC 6302 are not greatly affected by the uncertainty in the atmospheric corrections for the line fluxes.

If we plot the position of the central star of NGC 6302 on a

Hertzsprung-Russell diagram and compare it with theoretical evolutionary tracks (see, for example, Wood and Faulkner 1986), we find that it lies in a region which corresponds to a star of mass $M_* \approx 0.89\ M_\odot$ which has left the AGB within the last few hundred years. However, the kinematic age of NGC 6302 obtained from its expansion velocity and radius is estimated to be 4×10^3 yr (Rodríguez and Moran 1982). One explanation for this discrepancy is that the central star has recently suffered a helium shell flash. This may have been the event which caused the initial departure from the AGB, or it could have occurred when the planetary formation was well advanced. In either case the effect of a helium shell flash can be to prolong by up to several thousand years the period during which the star is at high temperature and luminosity (Schönberner 1979, Iben 1984).

In the case of NGC 6537 an upper limit for T_* can be calculated from the upper limit on the [Si VII] flux. The distance to NGC 6537 is constrained by 21 cm absorption line observations to lie between 2 and 3 kpc (Pottasch 1983)—we used a value of 2.5 kpc. The characteristic radius of the emitting region was estimated from an Hα image to be $R_{\rm neb} = 5''$. We obtained $R_* = 0.085\ R_\odot$ from the luminosity and temperature estimates given by Pottasch (1981). These parameters resulted in $T_* < 2.4 \times 10^5$ K, which is consistent with the lower limits on the Zanstra temperatures given by Reay *et al.* (1984) [T_Z(H I) > 110,000 K, T_Z(He II) > 150,000 K].

IV. CONCLUSION

We have detected emission lines due to [Si VI] and [Si VII] in NGC 6302, and [Si VI] in NGC 6537. This is the first time that these lines have been seen in a planetary nebula. They are also the highest excitation lines yet seen in a planetary nebula. Obtaining accurate fluxes for the lines is difficult due to both the poor transmission of the Earth's atmosphere at the wavelengths of interest, and the uncertain amount of interstellar extinction to the emitting region. Our observations of the H I Brγ line in NGC 6302 indicate considerable amounts of intranebula extinction near the central star, presumably due to dust.

We have used the new lines to determine the abundance of Si^{5+} and Si^{6+} in NGC 6302 and NGC 6537. The abundance ratio can be used as a diagnostic of the central star temperature. We obtain $T_* = 4.3 \pm 0.5 \times 10^5$ K for NGC 6302, and $T_* < 2.4 \times 10^5$ K for NGC 6537, in good agreement with previous determinations. The central star of NGC 6302 may have suffered a helium shell flash in the last few thousand years.

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