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NEBULAR OBSERVATIONS AND STELLAR CORONAE

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ABSTRACT

We examine the ways in which nebular observations of He II λ4686 can be used to infer the existence of coronae or hot winds of early-type stars. The O VI λλ3811, 3834 doublet is seen in the spectra of some central stars of planetary nebulae, and several authors have considered this to be evidence of a coronal wind. Observations of NGC 6751 reinforce this view by showing that radiative equilibrium model atmospheres cannot sufficiently photoexcite the O VI transitions without producing too much nebular emission at λ4686. The hot gas in the coronal model produces a significant amount of radiation at energies above 54 eV; therefore, the He II Zanstra temperatures can be affected. Discrepancies between the He II Zanstra temperatures and effective temperatures derived from other methods may indicate coronal emission from planetary nebula central stars.

Observations of diffuse nebulae about Population I early-type stars may also prove useful in detecting hot winds. The Lamers and Morton model of the wind of the O4f star ζ Pup predicts a small amount of He$^+$ ionizing radiation. If NGC 7635 is associated with the Of star BD +60°2522, then the observation of nebular emission at λ4686 may indicate coronal emission.

Subject headings: nebulae: planetary — stars: atmospheres — stars: coronae — stars: mass loss — stars: Of-type

I. INTRODUCTION

Recent *Copernicus* ultraviolet observations of O VI in early-type stars (Snow and Morton 1976) have generated interest in the possible existence of hot stellar winds ($T \gtrsim 2 \times 10^5$ K). The optical doublet of O VI at λλ3811, 3834 is also seen in emission in WC stars, both in Population I and planetary nebula central stars (Smith and Aller 1969; Smith 1973). The hot gas inferred to be present in these winds (Lamers and Morton 1976; Aller 1968*a*) will emit in the far-ultraviolet. In this paper we explore the possibility of detecting coronal radiation by observing its effects on the gaseous nebulae surrounding these early-type stars.

II. CORONAE OF PLANETARY NEBULA STARS

We take NGC 6751 and NGC 6905 as examples of the class of O VI stars with a broad $3p$–$3s$ λ3800 optical doublet in emission (Aller 1951; Smith and Aller 1969). Photoexcitation from the $2s$ ground state to $3p$ requires 82 eV photons. Since the nebular observations of He II λ4686 can be used to infer the number of photons emitted by the star with energies above 54 eV, such observations can be used to assess the importance of photoexcitation.

The He II λ4686 Zanstra temperature is based on determination of the number of photons above 54 eV relative to the optical continuum of the star. Because the O VI emission lines may be related to the continuum via Aller's (1968*b*) spectra, it follows that the number of photons in the O VI emission can be directly compared with the number of He$^+$ ionizing photons, independent of distance and virtually independent of reddening corrections. The only assumption necessary is that, for these hot stars, the continuum flux ratio at λ3800 and λ4686 be given by a Rayleigh-Jeans distribution, which in any event cannot introduce a serious error.

We examine the results for NGC 6751 and NGC 6905 using the data listed by Harman and Seaton (1966), plus the photoelectric magnitudes for NGC 6751 of C.-Y. Shao and W. Liller ($B = 13.56$ [private communication]) and the *B*-magnitude flux calibration given by Johnson (1965). Denoting the He$^+$ continuum photon flux in photons cm^{-2} s^{-1} as N(He II) and the stellar continuum flux near Hβ in ergs cm^{-2} s^{-1} Hz^{-1} as F(Hβ), we find log [N(He II)/F(Hβ)] ≈ 25.6 and 26.5 for NGC 6751 and NGC 6905, respectively.

Aller's (1968*b*) spectra show that the O VI λ3800 lines in NGC 6751 are about 1500 km s^{-1} wide and are roughly twice as bright as the continuum. Then the number of photons in the two O VI lines is $\sim 10^{-1}$ of the total number of photons above 54 eV. In NGC 6905 the O VI lines are about 10 times as strong as the continuum, and so once again the number of O VI photons is $\sim 10^{-1}$ of the entire He$^+$ continuum.

a) *Excitation of* O VI *by Photospheric Radiation*

We now show that photoexcitation due to radiation from radiative equilibrium models such as those of Hummer and Mihalas (1970) fails to provide sufficient excitation of the λ3800 lines in NGC 6751. First, assume that excitation to the $3p$ state (82 eV above ground) is predominantly from the $2s$ ground state;

the consequences of neglecting other processes will be examined later.

Most atoms will radiatively de-excite into the ground state, with a branching ratio given by the ratio of transition probabilities $A(3p\text{–}2s)/A(3p\text{–}3s) = 508$. (Collision rates are small compared with the A-values $\sim 10^8\text{–}10^{10}\ \mathrm{s}^{-1}$.) However, if the resonance transition is very optically thick, photons will be scattered many times until they escape via $3p\text{–}3s$ and further cascade. Thus, at maximum efficiency, every stellar 82 eV photon results in a $\lambda 3800$ photon. Denote the frequencies of the $3p\text{–}3s$ and $3p\text{–}2s$ lines by ν and ν', respectively. Then the number of 82 eV photons scattered in the line is

$$N_{82} = \frac{L_{\nu'}\Delta\nu'}{h\nu'}\,, \tag{1}$$

where $L_{\nu'}$ is the stellar luminosity and $\Delta\nu'$ is the line Doppler (P Cygni) width. The number of photons emitted in the $3p\text{–}3s$ transition is the same, so

$$\frac{L_{\nu'}\Delta\nu'}{h\nu'} = \frac{L_\nu \Delta\nu}{h\nu}\,,$$

where L_ν is the luminosity per frequency in the optical line. Using the Doppler formula, we have $L_{\nu'} = L_\nu$.

Therefore, simple inspection of model atmosphere fluxes shows whether a particular radiative equilibrium model can possibly photoexcite the O VI emission. Since the model atmospheres also yield the photon flux above 54 eV, this can be directly compared with the He II Zanstra temperature.

If we adopt the Hummer and Mihalas (1970) models, we find effective temperatures of 1×10^5 K for both stars ($\log g = 6.0$ for NGC 6751; $\log g = 5.0$ for NGC 6905) from the He II Zanstra temperature (Harman and Seaton 1966). The model for NGC 6751 has an 82 eV flux that is about 10^{-2} of the required flux to produce the O VI emission. Looked at in the opposite way, the $T = 1 \times 10^5$ K, $\log g = 5.0$ model has the right order-of-magnitude 82 eV flux but produces 10 times too much He II continuum flux for NGC 6751. The reason for the difference is that the slope of the stellar spectrum between 54 and 82 eV is dependent on gravity. In either case the discrepancy between the flux required to produce the O VI emission and the flux inferred from the He II Zanstra temperature of NGC 6751 is striking. Because the O VI emission of the central star of NGC 6905 is ~ 10 times that of the continuum, the necessary 82 eV flux also requires about 10 times the observed photon flux above 54 eV.

This analysis neglects photoexcitations to higher levels which might cascade through $3p\text{–}3s$, depending on the optical thickness of the various resonance lines. We can place an upper limit to the cascades by assuming all photoexcitations and photoionizations to result in $3p\text{–}3s$ photons. We further make the extreme assumption that all photons with energies greater than or equal to 100 eV (level 4 and above) are absorbed by O VI and cascade downward through $3p\text{–}3s$. Since the O VI continuum is at 130 eV and since the spectrum of the Hummer and Mihalas model for NGC 6751 falls off steeply with energy, this provides a generous upper limit to the possible photoexcitation. The result is that the number of photons above 100 eV in the model for NGC 6751 is $\sim 10^{-1}$ that of the O VI emission. Thus the nebular observations show that photoexcitation from the radiative equilibrium Hummer and Mihalas model cannot produce the O VI emission of NGC 6751.

For NGC 6905, the total flux above 100 eV is of the correct order of magnitude. However, since this is an upper limit, detailed line transfer calculations may rule out photoexcitation.

The central stars analyzed here are Wolf-Rayet stars, which have spherical atmospheres (Hartmann and Cassinelli 1977); so questions as to the relevance of the plane-parallel Hummer and Mihalas models are raised. We have computed some radiative equilibrium spherical atmospheres for central stars, which will be reported elsewhere (Hartmann 1978, paper in preparation). The results for the spherical models do not change the above conclusions. The basic reason is that He II bound-free opacity determines the stellar continuum at 54 eV and at 82 eV, so that the flux at 82 eV cannot be large unless there is also a large 54 eV flux.

We note that the broad-band magnitudes of WC stars include a sizable contribution from emission lines, so they do not exactly represent the true stellar continuum. From Aller's (1968*b*) spectra we estimate that the lines, in particular, the C III $\lambda 4650$–He II $\lambda 4686$ complex, may cause an overestimate of the continuum flux by about a factor of 2. This will not seriously affect the order-of-magnitude arguments made above. The problem is much less severe for NGC 6905, with relatively weaker emission lines.

To sum up: We have shown that models for the production of O VI emission by photoexcitation due to the photospheric radiation of the central star of NGC 6751 require a much larger He II continuum flux than that inferred from nebular observations. Detailed models may show a discrepancy for NGC 6905 as well. This argument is independent of distance and of any assumed properties of the stellar wind. Therefore, coronal models for the production of the $\lambda 3800$ doublet must be seriously considered.

b) Hot Wind Model for the Production of O VI

We next examine a model where hot gas produces the O VI, as suggested by Aller (1968*a*). First, we obtain rough estimates of the properties of these winds. For these central stars, $T_{\mathrm{eff}} \approx 1 \times 10^5$ K and $L \approx 10^4\, L_\odot$ (Harman and Seaton 1966). This implies radii $\sim 0.3\, R_\odot$; using the Hummer and Mihalas (1970) model results in a luminosity per frequency $\sim 3 \times 10^{20}$ ergs s^{-1} Hz^{-1} at 3800 Å. If the O VI lines are as bright as the continuum and are broadened $\sim 10^3$ km s^{-1}, the required luminosity L of O VI emission is $L \approx 10^{33}$ ergs s^{-1}, or $\sim 10^{44}$ photons s^{-1}. With the assumption of optical thinness,

$$L = N(3p)VA(3p\text{–}3s)h\nu\,, \tag{2}$$

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where $N(3p)$ is the number density in the $3p$ level; V is the volume; A, the transition probability, is equal to $0.51 \times 10^8\ \mathrm{s}^{-1}$ (Wiese, Smith, and Glennon 1966); and $h\nu$ is the energy of the $\lambda3800$ photons. With the above radius estimate, $V \approx 4 \times 10^{31}\ \mathrm{cm}^3$ and $N(3p) \approx 10^5\ \mathrm{cm}^{-3}$. If we use this density as an estimate of the $3s$ population and a column length of $\sim 1\ R^*$, then the computed line-center optical depth is ~ 4 for $10^3\ \mathrm{km\ s}^{-1}$ broadening; so the assumption of optical thinness leading to equation (2) may not be strictly correct, but we shall continue to use it as an order-of-magnitude estimate.

The electron density N_e in these winds may be estimated from the photospheric density, at optical depth $\tau = 1 = \sigma N_0 r_0(n-1)$ for a power-law density $N \propto r^{-n}$, where r is the radial distance and σ is the electron-scattering cross section. Hartmann and Cassinelli (1977) have shown that $n \approx 2$ in Wolf-Rayet atmospheres; so, with the previous radius estimate, $N_e \lesssim 10^{14}\ \mathrm{cm}^{-3}$. Assuming that the corona or hot gas is outside the photosphere, we adopt $N_e \approx 10^{13}\ \mathrm{cm}^{-3}$ in the wind, which leads to a rough emission measure estimate $\sim 4 \times 10^{57}\ \mathrm{cm}^{-3}$. This corresponds to beginning the hot wind at an electron-scattering optical depth $\tau \approx 0.14$. To have a much larger emission measure in the wind, it is necessary to start the hot wind in the photosphere, a solution which we reject because it changes the effective temperature of the star. Another way of looking at this is to note that, according to the calculations of Raymond and Smith (1977), the above emission measure at 2×10^5 K cools radiatively at a rate $\sim 5\%$ of the luminosity. Thus, increasing the emission measure by an order of magnitude requires a mechanical energy flux comparable to the photon luminosity of the star.

We now turn to a discussion of the production of O VI emission in the hot gas. Collisional excitation will be more important than collisional ionization followed by recombination. Consider a situation where the primary population of the $3p$ state at 82 eV occurs via collisions from the $2s$ ground state. Then in the optically thin case the luminosity in the O VI lines is

$$\begin{aligned} L &= N(2s)N_e q V h\nu[A(3p\text{–}3s)/A(3p\text{–}2s)] \\ &= X(\mathrm{O\ VI})E q h\nu[A(3p\text{–}3s)/A(3p\text{–}2s)]\,, \qquad (3) \end{aligned}$$

where q is the collisional excitation rate, E is the emission measure $N_e{}^2V$, and $X(\mathrm{O\ VI})$ is the fractional abundance of O VI relative to N_e. Using collisional rates from Bely (1966) and Mewe (1972), and using $A(3p\text{–}2s) = 2.59 \times 10^{10}\ \mathrm{s}^{-1}$ (Wiese, Smith, and Glennon 1966), $X(\mathrm{O\ VI})E \approx 5 \times 10^{56}\ \mathrm{cm}^{-3}$ at 2×10^5 K and $X(\mathrm{O\ VI})E \approx 2 \times 10^{55}\ \mathrm{cm}^{-3}$ at 1×10^6 K; these values, close to the *total* emission measure estimated earlier, imply $X(\mathrm{O\ VI}) \approx 10^{-1}\text{–}10^{-2}$.

However, the $3p$–$2s$ line will be very optically thick. To show this, the line-center optical depth of the $3p$–$2s$ line, which is proportional to the column density $\eta = X(\mathrm{O\ VI})N_e r$, can be written in terms of the O VI emission measure $X(\mathrm{O\ VI})E \approx X(\mathrm{O\ VI})N_e{}^2r^3$. The result is $\eta \approx [X(\mathrm{O\ VI})E]^{1/2}[X(\mathrm{O\ VI})]^{1/2}r^{-1/2}$. Putting in numbers for $10^3\ \mathrm{km\ s}^{-1}$ broadening yields

$$\tau_0 \approx [X(\mathrm{O\ VI})]^{1/2}r^{-1/2}[X(\mathrm{O\ VI})E]^{1/2}10^{-16}\,. \qquad (4)$$

Therefore, $\tau_0[X(\mathrm{O\ VI})]^{-1/2} = 1.5 \times 10^7$ and 3×10^6 at 2×10^5 K and 1×10^6 K, respectively; so for $X(\mathrm{O\ VI}) \gtrsim 10^{-10}$ the line will be very optically thick. The photons will scatter until they escape via the $3s$–$3p$ line and via further cascades, so that the branching ratio now approaches unity. The new values of $X(\mathrm{O\ VI})E$ are $\sim 10^{54}\ \mathrm{cm}^{-3}$ and $4 \times 10^{52}\ \mathrm{cm}^{-3}$ at 2×10^5 K and 1×10^6 K, respectively, to produce the $\lambda3800$ emission. If we assume collisional populations, we can convert this into the required oxygen abundance. Summers (1974) gives fractional O VI abundances of 5×10^{-2} and 10^{-2} at 2×10^5 K and 1×10^6 K, at $N_e = 10^{12}\ \mathrm{cm}^{-3}$ (the result does not appear to depend sensitively on density). Then we find $X(\mathrm{O}) \approx 5 \times 10^{-3}$ and 1×10^{-3} at 2×10^5 K and 1×10^6 K, respectively. This is an acceptable range, especially in view of the possibility that oxygen is overabundant in these stars (Paczyński 1973).

We have neglected collisional excitation to higher states which could cascade through $3s$–$3p$. Bely (1966) shows that the collision strengths $\Omega(2s\text{–}3d)$ and $\Omega(2s\text{–}4d)$ are larger than $\Omega(2s\text{–}3p)$. The branching ratio $A(3d\text{–}2p)/A(3d\text{–}3p) = 6 \times 10^4$, so cascades through $3d$ will be important only if the $3d$–$2p$ transition is very optically thick. This in turn requires the population of $2p$ to be significant compared with that of $2s$, a result that will require detailed radiative transfer calculations. Assuming all collisions to $3d$ cascade through $3p$ reduces the above estimates of the amount of O VI needed by a factor of 6. The collisional rates to level 4 and above drop off rapidly with increasing n. We conclude that our order-of-magnitude estimates of the amount of O VI necessary to produce the observed emission lines are high by no more than one order of magnitude. We have also neglected collisional excitation from $3s$ to $3p$; that the rate given by Sampson and Parks (1974) is an order of magnitude down from the A-value at $N_e = 10^{13}\ \mathrm{cm}^{-3}$ justifies our approximate treatment.

We now consider whether the hypothetical hot gas emits sufficient He^+ ionizing radiation to influence the He II $\lambda4686$ emission of the nebula. The photon luminosity in the He^+ continuum from the Zanstra method relative to the $\lambda3800$ luminosity is independent of the assumed distance to the planetary, because both are referred to the stellar continuum. The only variables entering the problem are the temperature of the gas and the abundance $X(\mathrm{O\ VI})$. Because the abundance of oxygen in the gas is uncertain, we compute the amount of gas needed for the He II ionizing radiation and then see whether $X(\mathrm{O\ VI})$ is unreasonable.

Calculations of the emissivity of optically thin hot gas by Raymond and Smith (1977) supplemented by calculations at higher electron densities show that gas at 2×10^5 K to 1×10^6 K will emit $\sim 2\text{–}4 \times 10^{-13}$ photons $\mathrm{cm}^3\ \mathrm{s}^{-1}$ which can ionize He^+. These calculations include line emission which is about an order of magnitude larger than that of the continuum. An emission measure $\sim 10^{57}$ cm^{-3} will then account for all of the He$^+$ continuum radiation of NGC 6751. The O VI $\lambda 3800$ radiation requires $X(\text{O VI}) \approx 10^{-3}$ at 2×10^5 K, or $X(\text{O VI}) \approx 10^{-4}$ at 1×10^6 K. This result shows that the possible contribution of coronal emission to the He$^+$ continuum must be considered. It also places an upper limit on the amount of hot gas in the wind, for, if $E \gg 10^{57}$ cm^{-3}, then the $\lambda 4686$ emission would be much larger than is observed.

c) *Photoexcitation of* O VI *by Emission from a Thin Corona*

Cassinelli, Olson, and Stalio (1977) have advanced models of early-type stellar winds to account for the P Cygni O VI lines seen in the ultraviolet. In their model, O VI is formed throughout the wind by photoionization from radiation originating in a hot, narrow region of the wind.

To see whether a similar model might hold for the central star of NGC 6751, we once again assume that all 83 eV photons and photons with energies greater than ~ 100 eV are converted to $\lambda 3800$ photons via cascades. Using the previous radius estimate, we require 10^{44} photons, which in turn requires an emission measure $\sim 10^{57}$ cm^{-3}. Again, the emission measure is that required to produce the He$^+$ continuum, so even in this situation effects of coronal radiation on the He II Zanstra temperature may be significant. The size of the emission measure suggests that the coronal region is not narrow and will approach the situation considered in § II*b*.

d) *Zanstra Temperatures of Planetary Nebula Stars*

The He II Zanstra temperature depends on the He$^+$ continuum flux, which is a relatively small part of the star's output. Thus coronal emission can change the Zanstra temperature without affecting the real effective temperature.

In the cases of NGC 6751 and 6905, we note that the nebular Hβ fluxes, which refer to the Lyman continuum, imply a much lower effective temperature for these stars than the He II Zanstra temperature (Harman and Seaton 1966). Harman and Seaton concluded that this meant the nebulae are optically thin in the Lyman continuum. However, one would obtain the same situation if stellar coronal emission were superposed on a normal radiative equilibrium continuum. A similar explanation of the temperature discrepancy was in fact advanced by Zanstra (1961), although he did not identify the source of the excess He II continuum. Thus the determination of the optical thinness of these nebulae is not straightforward.

The analysis presented in this section rests on the large fluxes in the O VI lines relative to the He$^+$ continuum fluxes obtained from the $\lambda 4686$ flux. It is possible that the flux of He$^+$ ionizing radiation is underestimated if the nebula is not optically thick to it, although the estimates of Harman and Seaton strongly suggest the opposite. However, if the He$^+$ continuum is optically thin in the nebula, then photoexcitation of O VI requires $T_{\text{eff}} \approx 2 \times 10^5$ K, so the wind would be warm just by radiative equilibrium.

We also note that Aller's (1951) spectra show C III and other lower-excitation ions. From Summers's (1974) ionization calculations we find $T \lesssim 2 \times 10^5$ K to be preferred for a homogeneous wind.

Warm winds may not be restricted to WC central stars. Population I Of stars like ζ Pup show the ultraviolet $\lambda 1030$ lines of O VI (Snow and Morton 1976), so Of stars in planetary nebulae may also have coronal winds. The appearance of the optical O VI lines may be controlled by the emission measure of the wind, or possibly by an overabundance of oxygen in WC stars (Paczyński 1973). Heap (1977) has found Of central stars with effective temperatures from spectral line analysis that are much lower than their He II Zanstra temperatures. We suggest that this might be the result of the increase by warm wind emission of the He II continuum radiation.

III. CORONAE OF POPULATION I EARLY-TYPE STARS

Lamers and Morton (1976) have developed a model for the wind of the O4f star ζ Pup in which the gas is uniformly at a temperature of 2×10^5 K, with an emission measure of $\sim 5 \times 10^{58}$ cm^{-3}. While the effective temperature of the star is too low to emit any He$^+$ ionizing photons (5×10^4 K [Conti 1973]), the wind will emit some radiation above 54 eV.

Unfortunately, ζ Pup is not surrounded by a dense nebula; so any nebular observations must involve another star.

Ideally, one would wish to verify the Lamers and Morton model with a star of the same spectral type. The difficulty is that the He emission will be very weak. To make this more concrete, consider NGC 6523 (M8), which is predominantly excited by the O4f star 9 Sgr. With the assumption of a $\log g = 4.0$, 50,000 K model for 9 Sgr (Morton 1969; Conti 1973), the Lamers and Morton coronal wind produces 10 times the stellar continuum flux of He$^+$ ionizing photons and raises the He II Zanstra temperature to 60,000 K. In the central regions of the nebula, $N_e \approx 10^3$ cm^{-3} (Meaburn 1969) and the He II $\lambda 4686$ emission will be confined to a Strömgren sphere less than 1 pc in radius.

An interesting possibility for the detection of excess He II emission is NGC 7635, which appears to surround BD +60°2522 (O6.5 IIIf [Conti 1973]). Sometimes called the Bubble Nebula, it has been interpreted as the result of interaction of the stellar wind with the interstellar medium (Israel, Habing, and de Jong 1973). Sabbadin and Bianchini (1977) report the detection of $\lambda 4686$ in one knot of the nebula; using their values of electron density (10^4 cm^{-3}) and temperature ($T_e = 15{,}000$ K), we infer a flux of $\sim 1 \times 10^8$ photons cm^{-2} s^{-1} above 54 eV. Suppose the Lamers and Morton model of ζ Pup holds for BD +60°2522. At a distance of 2 kpc (Sabbadin and Bianchini 1977), the diameter of the Bubble is ~ 2 pc and the nearest projected distance from nebula to

BD +60°2522 is 0.4 pc. Assuming the observed knot is therefore ~ 1 pc from the star, we predict an ionizing flux above 54 eV of about 8×10^7 photons $\mathrm{s}^{-1}\ \mathrm{cm}^{-2}$, on the basis of the emissivity calculations of Raymond and Smith (1977), or roughly what is required to match the observations, while the stellar continuum flux above 54 eV is an order of magnitude lower (Hummer and Mihalas 1970, 40,000 K model). On the other hand, if NGC 7635 is a planetary nebula as suggested by Johnson (1971), then the λ4686 line can be produced without invoking a corona but invoking instead an unseen hot planetary nebula star.

The arguments against the planetary nebula hypothesis can be summarized as follows. The extinctions of nebula and BD +60°2522 are the same (Sabbadin and Bianchini 1977). The nebula is brightest at the nearest point to the Of star (Johnson 1971). The velocities of NGC 7635 and the adjacent H II region S162 are the same (Deharveng-Baudel 1973). The Zanstra temperature of BD +60°2522 is 35,000 K (Morton 1969), in fair agreement with the mean effective temperature for that spectral type (38,000 K [Conti 1973]). The various nebular line ratios agree empirically with H II regions and not with planetary nebulae (Sabbadin and Bianchini 1977).

The agreement of the hydrogen Zanstra temperature with model atmosphere results suggests that the nebula is optically thick in the Lyman continuum. If we assume that the nebula is thick in the He I continuum as well, and that all photons with energies above 24.4 eV are absorbed by He I (Harman and Seaton 1966), then we obtain, from the ratio of He I λ5876 to Hβ, a ratio of the fluxes above 24.4 eV and 13.6 eV equal to 0.18, using $T_e = 15{,}000$ K and rates from Osterbrock (1974). This agrees with the flux ratio of 0.21 for the 40,000 K, $\log g = 4.0$ model of Hummer and Mihalas (1970).

In principle, the [O I], [O II], and [O III] lines can be used to find the ratio of the flux above 35 eV to the flux above 13.6 eV; however, charge exchange can significantly enhance [O I] in neutral regions relative to other lines (Williams 1970), and there is evidence that the region observed by Sabbadin and Bianchini (1977) contains a neutral knot (Deharveng-Baudel 1973).

While the evidence for the association of NGC 7635 with BD +60°2522 is strong, the [Ar IV] λ4740 line reported by Sabbadin and Bianchini poses a difficulty. Balick and Sneden (1976) have stressed that normal model atmospheres are heavily blanketed above 41 eV for $T_e \leqslant 50{,}000$ K, so this line indicates a very hot star. However, λ4740 is the weakest line listed by Sabbadin and Bianchini. There is no mention of the other member of the doublet, λ4711, which should be equally strong for $N_e \leqslant 10^4\ \mathrm{cm}^{-3}$ and which is suppressed only for densities approaching $10^5\ \mathrm{cm}^{-3}$ (Saraph and Seaton 1970). From Robbins's (1968) calculations of line intensity ratios, we find that the He I λ4713 line should be present with about the same strength and may be confused.

A spectrum taken by Dr. John Huchra at Kitt Peak on the 90 cm telescope is too short an exposure to test reliably for λ4686, but it does appear to show He I λ4713.

Therefore, it is of importance to determine whether NGC 7635 is a planetary nebula and to confirm the presence of He II λ4686. The existence of [Ar IV] λλ4740, 4711 is a critical indicator. If it is much weaker than supposed by Sabbadin and Bianchini (1977), then there is no difficulty in reconciling the inferred stellar spectrum with the spectrum of BD +60°2522. Johnson (1973) did not detect λ4740 but reported λ4713 (Ar IV) + He I, which supports this view. The presence of the He II λ4686 line should also be confirmed, as it may provide a confirmation of the Lamers and Morton (1976) model of Of winds.

Another possibility for producing He II ionization is radiation from the hot gas presumably inside the bubble, on the assumption that the bubble is produced by the interaction of the fast ($10^3\ \mathrm{km\ s}^{-1}$) stellar wind with the interstellar medium (Castor, McCray, and Weaver 1975). However, the emission measure required is $10^{58}\ \mathrm{cm}^{-3}$, and this would produce huge amounts of [Fe X] λ6374 or [Fe VII] λ6087, depending upon the temperature of the gas. N. Carleton and J. Vrtilek (private communication) have not found such emission to a level sufficient to rule out this possibility for $T \leqslant 1 \times 10^6$ K. Thus the coronal model appears to be the most likely explanation for He II λ4686 in NGC 7635.

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