THE ASTROPHYSICAL JOURNAL, 367:208–212, 1991 January 20

NGC 6302: IONIZED BY A VERY HOT STAR OR BY A WIND?

N. J. LAME AND G. J. FERLAND
Astronomy Department, The Ohio State University
Received 1989 December 22; accepted 1990 July 23

ABSTRACT

Lines of very highly ionized silicon were recently discovered in the type I planetary nebula NGC 6302 by Ashley and Hyland. They inferred a central star temperature of 450,000 K assuming that the high ionization lines were the result of photoionization. This is the highest central star temperature ever reported for a planetary nebula, and the effects of a luminous soft X-ray source on a surrounding nebula have never been examined.

We present new photoionization model calculations assuming a very hot ($T_* = 450{,}000$ K) central star. Model calculations show that such a high central star temperature can in fact reproduce the observed global spectrum of NGC 6302. There are several consequences of such a hot star: the predicted Balmer decrement of the model is much steeper than case B due to excitation of Hα, and models show that collisional excitation of helium lines cause the helium abundance to be overestimated. However, the models do not work well in detail; an unreasonably small filling factor is needed, and the [O I] λ6300 line, which arises in X-ray–heated neutral gas, is overpredicted unless the nebula is fully ionized, contrary to observations.

It seems more likely that the very high ionization lines are the result of shock ionization produced by strong winds from the central star. Both the level of ionization and the energetics are consistent with such an origin. Thus the ionization of this nebula may be the result of both collisional (the high-ionization lines) and photoionization (the traditional nebular lines).

Subjed headings: nebulae: individual (NGC 6302) — nebulae: planetary — stars: winds

I. INTRODUCTION

NGC 6302 is a bipolar planetary nebula with a filamentary nature and evidence for strong stellar winds ($v \sim 500$ km s^{-1}; Meaburn and Walsh 1980*a*). It has been classified a Peimbert type I nebulae (Peimbert 1978) with high helium and nitrogen abundances. Radio and IR observations show a disk or toroidal structure at the core of the nebula (Danziger, Frogel, and Persson 1973; Rodríguez *et al.* 1985; Lester and Dinerstein 1984). Clearly this is a complex object.

Infrared line spectroscopy reveals the presence of Si^{+5} and Si^{+6} (Ashley and Hyland 1988), indicating that ionizations of ~200 eV are present. Ashley and Hyland estimated that the central star had a temperature of $\sim 5 \times 10^5$ K, assuming that the lines were the result of photoionization, and noted that NGC 6302 has probably the hottest central star of any planetary nebula observed to date. Such a high central star temperature is usual, and there have been no attempts at modeling a planetary nebula with such a luminous soft X-ray source at its center. We present new photoionization model calculations here and investigate both the effects of the high central star temperature and the correspondence of the model with observations.

II. MODEL CALCULATIONS

We model the nebula using version 72 of the "Cloudy" photoionization program described by Ferland (1988). The radiation field of a star with a blackbody temperature of 4.5×10^5 K (the value deduced by Ashley and Hyland 1988) peaks at ~100 eV and has significant flux at energies as high as 1 keV. Accordingly, X-ray ionization and heating processes are likely to be important if NGC 6302 is indeed photoionized by such a star. The code used here includes such processes as inner shell ionization, the Auger effect, Compton scattering, secondary ionization by suprathermal electrons, and collisional ionization of all elements. Hydrogen is modeled as a 10-level atom, and helium as a composite 25-level atom, and all collisional and radiative processes are included (see, for example, Ferland and Rees 1988). In our models, spherical symmetry and constant density were assumed.

The assumed parameters are listed in Table 1. A blackbody continuum was used for the central star's radiation field, since little better can be done, and the temperature is the value deduced by Ashley and Hyland (1988). Although a star at this temperature will show large variations from a blackbody spectrum, the effect of using a non–LTE stellar atmosphere model would only increase the high-energy tail of the spectrum, exacerbating the problems we discuss (Mihalas and Auer 1970). Both the presence of mass loss, and the general position of hot planetary nebulae on the Harmon-Seaton sequence, suggest that the central star has a luminosity near the Eddington limit, which we assume. In the interest of simplicity, these parameters were not varied in attempting to model the emission-line spectrum of the nebula. An inner radius to the hollow sphere of 10^{16} cm was chosen to be much smaller than the outer radius of $\sim 10^{18 \pm 1}$ cm, deduced from a typical diameter of ~1′ (see Lester and Dinerstein 1984 for a discussion of the complex geometry) and the range of distances quoted by Meaburn and Walsh (1980*b*) (i.e., 150 pc–1.7 kpc). Tests show that our results do not depend on the precise value of the inner radius.

This object is a luminous infrared source (Danziger, Frogel, and Persson 1973; Lester and Dinerstein 1984); clearly, dust must be present. Dust opacity is included in the calculation as a constant gas/dust ratio; we assume a "standard" extinction curve in the ultraviolet (Draine and Lee 1984), that the total dust abundance is 20% of the standard value (Cota and Ferland 1988), and make standard assumptions concerning grain heating and cooling (Martin 1978).

The observed emission line spectrum, which we try to repro-

TABLE 1

ASSUMED PARAMETERS

Parameter	Value
Blackbody temperature	450,000 K
Blackbody luminosity	10^{38} ergs s^{-1}
Inner radius	10^{16} cm
Filling factor	0.05
log (H density)	4.9 cm^{-3}

TABLE 2

MODEL COMPOSITION

Element	Abundance
He/H	0.14
C/H	3.12×10^{-4}
N/H	2.16×10^{-4}
O/H	3.74×10^{-4}
Ne/H	3.85×10^{-5}
Mg/H	1.6×10^{-7}
Al/H	2.7×10^{-7}
Si/H	2.1×10^{-5}
S/H	3.0×10^{-5}
Ar/H	2.7×10^{-6}
Ca/H	2.3×10^{-7}
Fe/H	5.0×10^{-7}

duce, was compiled from several sources, primarily Aller *et al.* (1981). They observed lines in the region λλ3100–4880. The intensities are corrected for interstellar extinction using a value of $C = 1.22$. Intensities of the [O I] λ6300, Hα, and He λ5876 lines are from Kaler (1976) and the silicon lines are from Ashley and Hyland (1988). There is no correction to these observations for different instruments and apertures since, after all, the point of this paper is the failure of our model to reproduce the spectrum, and only an approximate observational spectrum is needed.

Although many models were computed, only one is presented here, with a He abundance of 14% of hydrogen by number. The other parameters of the model (H density, filling factor, chemical composition) were varied to bring the model predictions as close as possible to the published observations. In particular, the hydrogen density and filling factor were adjusted to fit the [O II] λ3727 and [O III] λ5007 line intensities. Higher hydrogen densities caused a high rate of collisional deexcitation of [O III] λ5007, making the line too weak relative to Hβ. Increasing the filling factor has the same effect, since the nebula is more centrally condensed, and hence the gas tends to be more highly ionized. Next, the abundances of C, N, Ne, S, Ar, and Si were adjusted to find the best matches to the emission lines [C II] λ4262, [N II] λ6584, [Ne III] λ3868, [S II] λλ6717, 6730, [Ar III] λ7135, [Si VI] λ1.96 μm and [Si VII] λ2.48 μm. Figure 1 shows typical H and He ionization structures, and Table 2 gives the deduced composition. Since our model does not fit the observations in any case, the composition is not a prediction but merely what worked best in the Cloudy program to reproduce the spectral lines and is somewhat subjective.

A major consequence of the high central star temperature was that neutral lines predicted by the model are very sensitive to its outer radius. An example is [O I] λ6300, as illustrated in Figure 2. Because of rapid charge exchange, atomic oxygen and hydrogen are usually well coupled (see Osterbrock 1988) and O^0 is predominantly present in regions beyond the hydrogen ionization front. For stellar temperatures $\leq 2 \times 10^5$ K, these regions are heated only by Balmer continuum radiation, equilibriate at very low temperatures ($\sim 10^2$ K), and the resulting [O I] line is fairly weak. For stellar temperatures $T_* \geq 2 \times 10^5$ K, the neutral gas is efficiently heated by penetrating X-rays, and strong [O I] emission results. When this happens the intensity ratio [O I] λ6300/Hβ becomes *very sensitive* to the choice of the outer radius, as is shown in Figure 2. Due to the restriction imposed by the intensity of the [O I] λ6300 line, the model nebula had a radius of 1.40×10^{17} cm, and no hydrogen ionization front is present.

The observed and calculated intensities are listed in Table 3. This list is a nearly complete list of all major lines both observed in the nebula and calculated by the code. The model reproduces the high-ionization emission lines in the infrared, because the central star temperature was chosen with this in mind. One result of the high central star temperature is that the gas is very hot: the electron temperature is 4.4×10^4 K at the inner edge and 1.2×10^4 K at the outer edge of the nebula, and the electron density ranges from 1.0×10^5 to 6.1×10^4 cm^{-3}. For completeness, the total Hβ luminosity in the model is 2.9×10^{35} ergs s^{-1}. This is consistent with the observed flux of 3×10^{-11} ergs s^{-1} cm^{-2}, a reddening of $C = 1.09$, and a dis-

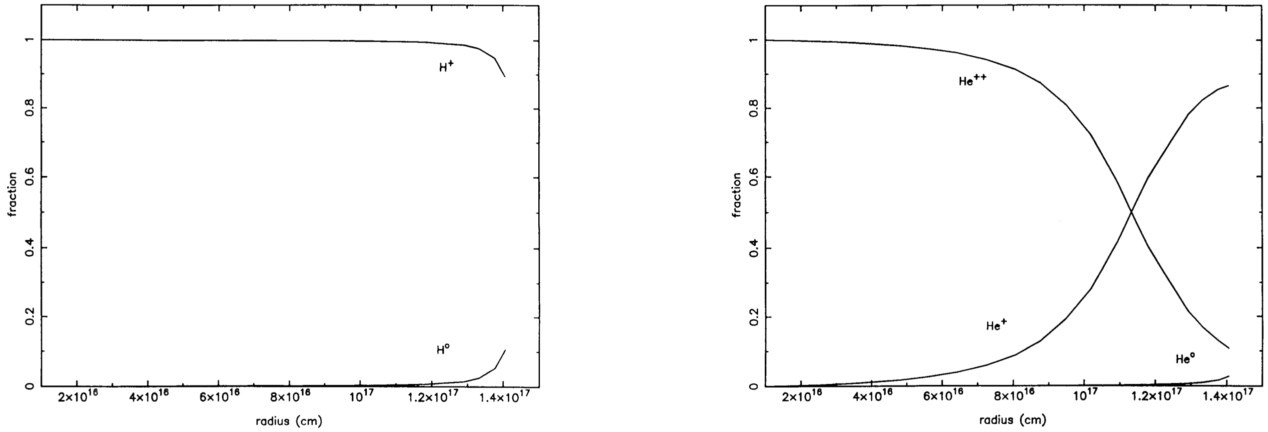

FIG. 1*a*

FIG. 1*b*

FIG. 1.—Ionization structure of (*a*) H and (*b*) He in model. Note the model forces an unnatural looking cutoff

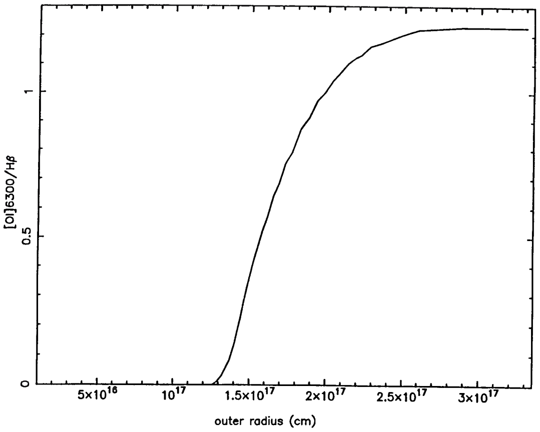

FIG. 2.—Intensity of [O I] λ6300 line as a function of outer radius. This graph goes beyond the outer radius of our model, showing the sensitivity of the emission to outer radius.

tance of 700 pc, assuming a converging factor (solid angle fraction) of $\Omega/4\pi = 0.5$.

For the most part, the model agrees with the observations. The H, He, and O lines are in reasonable agreement, and at least one ion of each of the other elements agrees well. It was frequently the case that the individual elemental abundances could be adjusted to bring the emission from a specified ion to the observed value. The total predicted infrared luminosity (mainly produced by Lyα heating of dust within the H^+ region) is $10^{37.0}$ ergs s^{-1}, consistent with the inferred infrared luminosity of $10^{36.4\pm1}$ ergs s^{-1}, computed assuming the observed infrared continuum (Lester and Dinerstein 1984) and the quoted range of distances.

Although we argue below that the central star is not actually as hot as Ashley and Hyland (1988) postulate, the model does have several interesting properties which we discuss here. An important prediction of this model is that the intrinsic Balmer decrement is Hα/Hβ ~ 3.7, i.e., much larger than case B (~2.8). This is because regions of the nebula with significant hydrogen neutral fractions are strongly heated by high-energy radiation, and collisional excitation of hydrogen lines results. The correction for intranebular dust should be small, ~0.02–0.03% for Balmer lines, and we suspect the dust in the nebula is associated with neutral gas. This high Balmer decrement would cause the reddening to be overestimated if case B is assumed, and the reddening deduced from the hydrogen lines. We can estimate the difference the altered Balmer decrement would cause in the calculation of the extinction parameter C from the formula

$$\frac{I_{H\alpha}}{I_{H\beta}} = \frac{I_{H\alpha 0}}{I_{H\beta 0}} e^{-C[f(H\alpha) - f(H\beta)]}$$

Osterbrock (1988). If a normal case B 10^4 K nebula with $I_{H\alpha 0}/I_{H\beta 0} = 2.87$ is assumed, but the actual emissivity is described by our model, the reddening will be overestimated by $\delta C \approx 0.75$. Aller *et al.* (1981) find that values of C for NGC 6302 are ≈1.41–1.49. Thus the reddening would be only half the deduced value if our model is correct. Such an error in reddening could affect some distance determinations also, which might explain the wide range (150–1700 pc) of values reported in the literature (Meaburn and Walsh 1980*b*). Further, dust in the neutral region outside the nebula may also affect distance calculations.

Another consequence of the high temperature of the central star is that helium lines are collisionally enhanced, leading to an overestimate of the helium abundance. The many models computed showed that the true He abundance need not be as high as the observationally deduced value of 0.18H. In fact, He abundances as low as 0.14H produced better agreement with the observed H and He line intensities. This error in the abundance would be compounded by errors in the reddening correction due to collisional excitation of the hydrogen lines. Calculations of the abundance of He based on the λ4686 relative to Hβ would be too low, and those using λ5871 would have values too high, if the reddening is overestimated.

III. A SHOCK-HEATED COMPONENT?

Although the global spectrum of the model nebula does agree with the observations, this model argues against a photo-

TABLE 3

LINE INTENSITIES

Line	Observed	Model
Hβ 4861	1.00	1.00
Hα 6563	12.00	3.654
Hγ 4340	0.456	0.488
2-γ	...	5.629
He I 4471	0.057	0.032
He I 5876[a]	0.40	0.114
He II 4686	0.73	0.762
C II 4267	0.0015	0.002
[C III] 1906	5.25	6.166
C IV 1549	6.77	16.523
[N II] 6584	4.13	3.084
[N III] 1747	5.14	2.804
[N IV] 1487	7.76	2.058
N V 1240	11.92	2.058
[O I] 6300[a]	0.14	0.407
[O II] 3727	0.62	0.637

Line	Observed	Model
[O III] 4363	0.46	0.48
[O III] 5007	16	17.699
[O III] 1663	1.18	1.407
[Ne III] 3868	1.16	1.123
Ne IV 4725	0.035	0.027
[Ne IV] 2422	3.37	0.391
[Ne V] 3426	2.92	0.602
[S II] 6717+6730	0.194	0.112
S III 6312	0.045	0.252
[Ar III] 7135	0.259	0.275
[Ar IV] 4740	0.257	0.187
[Ar V] 7005	0.149	0.079
[Si VI] 1.96 μm[b]	0.138	0.178
[Si VII] 2.48 μm[b]	0.157	0.148

NOTE.—All lines from Aller *et al.* 1981 except as noted.

[a] From Kaler 1976.

[b] From Ashley and Hyland 1988.

ionization by a very hot blackbody for two reasons. First, the models all require a very low filling factor of 0.05, in order to fit [O III] λ5007 as explained before. This filling factor is physically unreasonable since clumps on this scale would disperse within a decade, unless they are confined. Second, the models require a matter-bounded nebula which is very sensitive to the outer radius, because of the constraint imposed by the intensity of the [O I] λ6300 line. It is clear from the ionization structure diagrams that little neutral gas can be present, if the line is to be as weak as is observed, and the star as hot as we have assumed. The hard X-rays from the central star would penetrate the nebula and dust to ionize the neutral gas and drastically raise the [O I] λ6300 emission (Martin and Ferland 1980). This is in contrast with observations, which show that substantial quantities of neutral gas must exist. Neutral hydrogen has been detected in NGC 6302 by Rodríguez and Moran (1982), and molecular hydrogen has been detected by Phillips, Reay, and White (1983) near the core of the nebula. Moreover, Rodríguez *et al.* (1985) argue for an extended low-density neutral halo around NGC 6302. The fact that the observed neutral gas shows no evidence of X-ray heating suggests that the central star is not hot enough to be a soft X-ray source (i.e., $T_* \leq 2 \times 10^5$).

It is more likely that shocks due to winds play a role in producing the high ionization in the nebula. The stellar wind observed by Meaburn and Walsh (1980*a*) could easily account for the high ionization of silicon. The shock temperature of the wind is given by

$$T_{\text{shock}} = \frac{\mu m_{\text{H}} v^2}{16R} = 10^{7.05}\left(\frac{v}{10^3 \text{ km s}^{-1}}\right)^2 \text{ K}$$

The observed wind velocity of 500 km s^{-1} gives $T_{\text{shock}} = 10^{6.5}$ K. A shock with this temperature produces predominantly Si^{+12} (Jordan 1969) which can then cool and recombine in post-shock regions to produce Si^{+5} and Si^{+6}, with ratios according to their recombination coefficients. The luminosity due to the stellar wind, which can be deposited in shocks, is given by

$$L_{\text{wind}} = \frac{1}{2}\dot{m}v^2 = 10^{36}\,\frac{\dot{m}}{10^{-5}\,M_{\odot}\text{ yr}^{-1}}\left(\frac{v}{500 \text{ km s}^{-1}}\right)^2 \text{ ergs s}^{-1}\,.$$

The luminosity in the high excitation silicon lines ranges from 10^{31} to 10^{34} ergs s^{-1} depending on the distance assumed and is much less than the total luminosity present in the wind. Compared with the assumed luminosity due to photons, $L_{\text{photon}} \approx L_{\text{Edd}} \approx 10^{38}$ ergs s^{-1}, the luminosity carried by the wind is a significant fraction of the total energy budget and so could play a noticeable role in producing the ionization of the nebula. Other highly excited ions could be checked to test this.

Although it seems likely that the traditional nebular emission lines in NGC 6302 are produced by photoionization by a fairly hot central star, the arguments presented above, especially the absence of soft X-ray–enhanced [O I] emission, suggest that the central star is not hot enough to produce Si^{+6}; the weak high ionization lines are more likely the result of shock ionization. This is not to say that shocks are always responsible for high ionization lines, but only that they seem to be the most likely candidate in this nebula. Along these same lines, Meaburn and Walsh (1980*a*) note that the [Ne V] λ3426 line may have been produced by shocks. They also note that even if there is a very hot central star in NGC 6302, strong winds would still be needed to explain the observations. Composite shock/photoionized nebulae are not unique; an energetics argument was used by Harrington and Feibelman (1984) to attribute certain anomalously strong lines in A30 as evidence for shocks due to winds. NGC 6302 could well have similar shock excited lines.

IV. CONCLUSION

In this paper, we have explored the consequences of photoionization by an extremely hot blackbody. The models show that a photoionized nebula with a very hot central star will have a much steeper Balmer decrement than case B due to a high collisional contribution to Hα. This would affect both the reddening estimates and the inferred helium abundance. Helium lines will also be collisionally excited. A second, more dramatic, effect is that X-rays penetrating into neutral gas produce exceptionally strong [O I] emission, unless the nebula is fully ionized.

These predictions do not seem to fit the particular nebula NGC 6302. The filling factor required to reproduce the spectrum is unusually low; such clumps would disperse unless somehow confined. The intensity of the [O I] λ6300 line demands that the gas be fully ionized, in contradiction with observations.

Both problems can be solved if the central star is hot, but with $T_* \leq 2 \times 10^5$ K rather than the temperature needed to produce Si^{+6} (4.5×10^5 K). We argue that the high-ionization region of this nebula is due to shock heating by winds. The wind velocities and mass-loss rate of NGC 6302 are certainly large enough to account for both the high levels of ionization and the luminosity of the high-ionization emission lines. Although the central star of NGC 6302 gives every indication of being a very hot star, it is unlikely that the temperature is as high as 4.5×10^5 K, and stellar winds are the most likely cause of the observed high-ionization silicon lines.

We thank The Ohio State University for a Graduate Student Fellowship, and the National Science Foundation for support through grant AST 87-19607. The comments of Jay Frogel and Brad Peterson are also gratefully acknowledged.

REFERENCES

Aller, L. H., Ross, J. E., O'Mara, B. J., and Keyes, C. D. 1981, *M.N.R.A.S.*, **197**, 95.
Ashley, M., and Hyland, A. R. 1988, *Ap. J.*, **331**, 532.
Cota, S. A., and Ferland, G. J. 1988, *Ap. J.*, **326**, 889.
Danziger, J. J., Frogel, J. A., and Pearsson, S. E., 1973, *Ap. J. (Letters)*, **184**, L29.
Draine, B. T., and Lee, H. M. 1984, *Ap. J.*, **285**, 89.
Ferland, G. J. 1988, The Ohio State University Astronomy Department Internal Report 88-001.
Ferland, G. J., and Rees, M. J. 1988, *Ap. J.*, **332**, 141.
Harrington, J. P., and Feibelman, W. A. 1984, *Ap. J.*, **277**, 716.
Lester, D. F., and Dinerstein, H. L. 1984, *Ap. J. (Letters)*, **281**, L67.
Jordan, C. 1969, *M.N.R.A.S.*, **142**, 501.
Kaler, J. B. 1976, *Ap. J. Suppl.*, **31**, 517.
Meaburn, J., and Walsh, J. R. 1980*a*, *M.N.R.A.S.*, **191**, 5P.
———. 1980*b*, *M.N.R.A.S.*, **193**, 631.
Martin, P. G. 1978, *Cosmic Dust* (Oxford: Clarendon Press).
Martin, P. G., and Ferland, G. J. 1980, *Ap. J. (Letters)*, **235**, L125.

Mihalas, D., and Auer, L. H. 1970, *Ap. J.*, **161**, 1129.
Osterbrock, D. E. 1988, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (Mill Valley: University Science Books), pp. 42 and 207.
Peimbert, M. 1978, in *IAU Symposium 76, Planetary Nebulae*, ed. Y. Terzian (Dordrecht: Reidel), p. 215.
Phillips, J. P., Reay, N. K., and White, G. J. 1983, *M.N.R.A.S.*, **203**, 977.
Rodrígiez, L. F., *et al.* 1985, *M.N.R.A.S.*, **215**, 353.
Rodríguez, L. F., and Moran, J. M. 1982, *Nature*, **299**, 323.

G. J. FERLAND and N. J. LAME: Astronomy Department, Ohio State University, Columbus, OH 43210