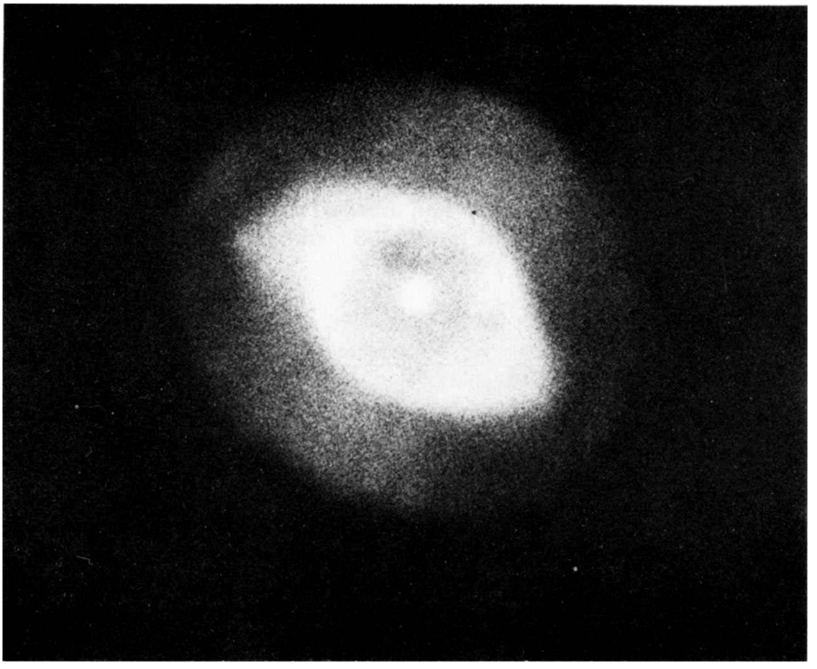

NGC 3242

SESSION IV

THE CENTRAL STARS OF PLANETARY NEBULAE

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ATMOSPHERES OF CENTRAL STARS

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INTRODUCTION

This review begins with a brief summary of atmospheric models that are of possible relevance to the central stars of planetary nebulae, and then discusses the extent to which these models accord with the observations of both nebulae and central stars. Particular attention is given to the significance of the very high Zanstra temperature implied by the nebular He II λ4686 Å line, and to the discrepancy between the Zanstra He II temperature and the considerably lower temperatures suggested by the appearance of the visual stellar spectrum for some of these objects.

For a wider discussion of the central stars, the reader is referred to the very comprehensive review of Aller (1976).

MODELS

The first generation of model atmospheres of central stars include the LTE, plane-parallel, hydrostatic and radiative equilibrium models of Gebbie and Seaton (1963), Gebbie (1967), Böhm and Deinzer (1965, 1966), Böhm (1969) and Hummer and Mihalas (1970a,b). The latter models use better opacities and achieve better flux constancy than Böhm's, but have omitted O VI, so that for very hot stars Böhm's models may be preferable for the far ultraviolet continuum.

The next advance was made when Böhm (1969) pointed out that the geometrical extent of the atmospheres was on the order of the stellar radius because the radiation nearly balanced the gravitational force. Thus the assumption of a plane-parallel atmosphere was no longer valid, and extended, spherically symmetrical models are required. Böhm's student Cassinelli (1971a,b) computed a number of spherical, LTE, static models for hot luminous stars with masses on the order of a solar mass. The outer radii were from about 1.3 to 2.8 times the photospheric radius

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($\tau_R \sim 2/3$). His results indicate that the color temperature tends to decrease towards the infrared and for models having the same photospheric temperature, i.e., at Rosseland optical depth $\tau_R = 2/3$, the color temperature at a fixed wavelength decreases with extension, i.e., the spectrum becomes flatter. In the visual the color temperature has values from 30 to 60% of the "photospheric" temperature. Cassinelli's models also show distinct emission in the Balmer and Lyman continua. Subsequently Castor (1974) discussed more fully the effects of atmospheric extension, on the basis of pure hydrogen spherical models, in order to explain the behavior of the brightness temperature in Of and Wolf-Rayet stars observed by intensity interferometry. He also pointed out that the luminosity necessary to obtain sufficient extension to explain the visual continuum is excluded by stellar evolution theory and discussed the necessity of stellar winds in this connection.

In the meanwhile, Auer and Mihalas developed a practical procedure for computing non-LTE plane-parallel models. This work reached its culmination (Auer and Mihalas 1972) with a series of non-LTE plane-parallel model atmospheres containing hydrogen and helium, with $T_{eff} \leq 50{,}000°K$. Subsequently, Mihalas (1972) produced a very extensive grid of models with $T_{eff} \leq 55{,}000°K$ which contained a "mean" metal in addition to hydrogen and helium, in order to represent the effects of carbon, nitrogen and oxygen. I regard these as the best available non-LTE models for nebular work.

Spherical, non-LTE models were first obtained by Mihalas and Hummer (1974a,b) who used an arbitrary radiation pressure multiplier to simulate the effect of the many lines that could not be handled in the model. Although this device made it possible to examine the effects on the spectrum of atmospheric extension, the resulting models are of questionable validity for comparison with observations. This work was concerned primarily with O stars; however Kunasz, Hummer and Mihalas (1975) subsequently produced eight models for central stars with masses of 0.6 and 1.2 $M_{\odot}$, and temperatures of roughly 60,000 and 100,000°K. Again a definite flattening of the spectrum is obtained. Both the Balmer and Lyman edges are in absorption, in contradiction to Cassinelli's (1971a,b) models; the Lyman lines are in emission and the Balmer lines appear in absorption. Strömgren colors were also computed, which show effects of extension on the order of 0.1 magnitude. Although a "mean" metal opacity was used in constructing the models, statistical equilibrium calculations for the metals would have to be carried out in order to obtain sufficiently accurate fluxes for use in nebular models. In view of the arbitrary nature of the radiation force multiplier, such calculations are probably not worth the effort.

The most recent development is due to Cassinelli and Hartman (1975), who have discarded the assumption of hydrostatic equilibrium and allowed the atmospheric gases to flow in response to radiation pressure. Because they have assumed LTE and used a radiation force multiplier similar to that of Mihalas and Hummer (1974a,b) the significance of their emergent flux distribution is primarily illustrative.

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All of the models constructed to date are deficient in several respects. The relevance of models with solar or nebular abundances to a star that is thought to have ejected most, if not all of its hydrogen, is questionable. It would be interesting to construct some models with little or no hydrogen, some helium and very high metal abundances. Since the opacity is more evenly distributed over the spectrum, the spectrum should show more flux shortwards of λ228 Å.

Another defect of these models is the absence of line blanketing, which should be particularly important in the ultraviolet. Although the ATLAS program of Kurucz (1970) can produce LTE models with very extensive line blanketing, the assumption of LTE at such high temperatures is known to be quite poor. A related problem arises in the spectral region longwards of the He II continuum at λ228 Å. Here the opacities of both hydrogen and neutral helium become very small, so the flux is determined largely by the bound-free metal opacities. Recently Balick and Sneden (1976) have discussed the necessity of properly accounting for metal opacities in order to determine the correct ionization structure of H II regions, particularly for ions like N^{+2}, O^{+2}, $S^{+3}$and Ne^{+2}. At present one can either assume LTE and include arbitrarily many sources of continuous opacity, or opt for non-LTE models with a very restricted set of opacities. Balick and Sneden chose the first alternative and used Kurucz's (1970) ATLAS program, without metallic line blanketing, to generate models similar to those of Hummer and Mihalas (1970a,b). The relative importance of metallic absorption and non-LTE effects in this spectral region can be seen from Figure 1, which compares the fluxes from the LTE and non-LTE mean-metal models of Mihalas (1972) with the metal-free non-LTE models of Auer and Mihalas (1972), for T_{eff}=40,000°K and log g = 4.0. Comparison of the mean-metal LTE model with the LTE model of Hummer and Mihalas (1970a,b) demonstrates the essential validity of the mean-metal assumption. The figure shows that the inclusion

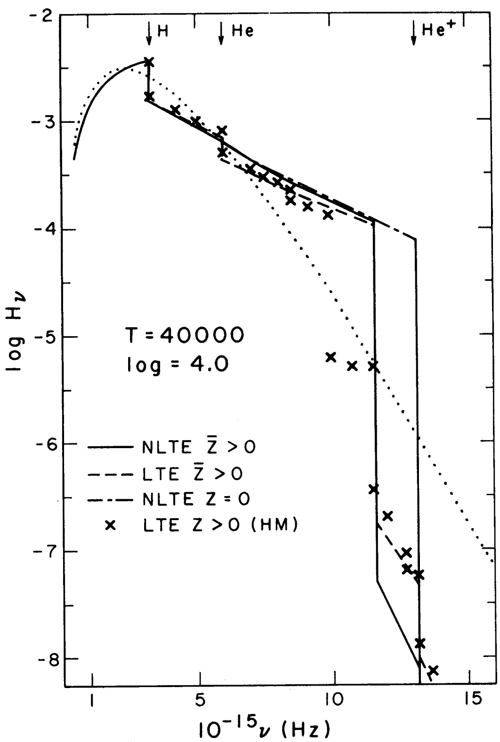

Fig. 1. Model atmosphere fluxes for a star with T_{eff} = 40,000°K, log g = 4.0. The mean-metal models of Mihalas (1972) are denoted by $\bar{Z}$ and the model with Z = 0 was constructed by Auer and Mihalas (1972). The crosses denote Model 217 of Hummer and Mihalas (1970a,b). The dotted curve represents the blackbody flux.

of metals leads to the largest effect, but that non-LTE effects are still very substantial.

COMPARISON WITH OBSERVATIONS

Direct comparison of model fluxes with ultraviolet observations is now possible. Boksenberg *et al.* (1975) have obtained the spectrum of NGC 6543 from 1350 to 2550 Å from observations with the TD1 satellites. They showed that the flux, corrected for extinction with the average extinction curve of Bless and Savage (1972), could be fit well by a blackbody curve at 35,000°K. They also found that Cassinelli's (1971b) spherical models with photospheric temperatures in the range 40,000-50,000°K also fit, and that his model at 95,000°K could not be ruled out. The Zanstra method involving the intensity of He I 4471 Å and the stellar flux at Hβ using blackbody fluxes yields an effective temperature of 45,000°K, and using Cassinelli's model fluxes, gave a photospheric temperature of 36,000°K. All of these determinations yield an angular radius of $2\text{-}3 \times 10^{-11}$ rad, which is about 5×10^{-7} of the angular size of the nebulae, a quite reasonable figure. Bounds on the distance can be obtained of 0.5 and 1.5 kpc, which yield luminosities and stellar radii in accord with the Harmon-Seaton sequence.

Gurzadian (1975) has obtained the spectrum of IC2149 down to 2400 Å. By assuming a λ^{-1} interstellar absorption law, he obtains a corrected flux that fits approximately to a LTE models at 50,000°K, from λ3800 Å to λ2700 Å; at shorter wavelengths there is an excess of radiation.

Pottasch *et al.* (1977) have obtained highly accurate narrow-band photometric measurements in five spectral regions between λ1500 Å and λ3300 Å, and discuss the central stars of 19 of these objects. For O-type stars, in the spectral region λ1500 Å - λ3300 Å, and in many cases to λ5400 Å, blackbody curves fit the fluxes fairly well. At the lower temperatures, the Hummer-Mihalas LTE fluxes were too steep in the region λ1800 Å - λ1500 Å. The blackbody temperatures agreed with the temperatures inferred from the visual lines, and were in accord with the effective temperatures of main sequence O-stars with the same spectral characteristics. For the stars with purely continuous spectra, no blackbody fits were possible; in the region λ5400 Å - λ3000 Å, the flux is too steep for either the Hummer-Mihalas models or blackbodies, and from λ2500 Å - λ1500 Å, the spectra are too flat for the models. The Wolf-Rayet stars showed spectra that are flatter than either other central stars or Cassinelli's (1971a,b) models. Among the O VI stars, NGC 246 fit a blackbody at 100,000°K, but the others showed fluxes that are steeper than an infinite-temperature blackbody. The gradient of the spectra is similar to, but larger than, that seen in spectra of stars with continuous spectra.

Many nebular models have been constructed in the past decade that should give some information on stellar fluxes; this subject is discussed in the review of Miller (1974). Although many features of the nebular spectrum as predicted by nebular models are sensitive to the central star flux distribution, these models depend on a number of unavoidable assumptions, so that our information about the central star is more or less distorted. As it is nearly impossible, after the fact, to decide which aspects of the stellar flux are reliably obtained from nebular models, attention to this question by model makers would be most useful.

The early work of Williams (1968), Harrington (1969) and Kirkpatrick (1970) suggested that blackbody fluxes were preferable to the models of Böhm and Deinzer (1966). Flower (1969) claimed that the models of Hummer and Mihalas (1970a,b) were in some ways superior to the blackbody fluxes for both high-excitation and low-excitation objects. Kirkpatrick (1972), in his work on NGC 7662, started with Cassinelli's model at 95,000°K, and then made arbitrary changes in the flux distributions in order to improve the fit of the model to the observed nebular spectrum. He suggests that his alterations may simulate the flux blocking by resonance lines of He II, C III, N III and O III. Bohlin, Harrington and Stecher (1977) have also found it necessary to adopt a modified blackbody curve in order to model NGC 7662.

The strongest indications of the failings of existing central star model atmospheres, and perhaps of our general understanding of these objects, comes from the Zanstra temperatures. Kaler (1976) has inferred stellar temperatures by a modification of Stoy's method, which uses the intensities of the forbidden lines relative to the nebular Hβ line. He finds that the Hummer-Mihalas LTE models give significantly lower temperatures than do the blackbody fluxes. Thus He II λ4686 Å appears in the nebula first at about 46,000°K on the Hummer-Mihalas scale and at about 60,000°K on the blackbody scale. However, the observed λ4686 Å/Hβ ratio is inconsistent with the Hummer-Mihalas fluxes in the H and He^+ continua at 46,000°K, whereas it agrees with the blackbody fluxes at 60,000°K.

The most complete and systematic comparison between blackbody and model fluxes has been made by Heap (1977a,b), in two extremely important papers. This work makes two distinct points: 1) He II Zanstra temperatures obtained using blackbody fluxes are much higher than those inferred from the appearance of the visual spectra; 2) He II Zanstra temperatures obtained from model fluxes are considerably higher than those based on the blackbody law, thus exacerbating the problem. The first of these points has been stressed earlier by Aller (1976). In Figure 2 the ratio of the number of photons ionizing He^+ to the astrophysical flux at Hβ is plotted versus the effective temperature, for a variety of models; this ratio is proportional to the ratio of the nebular He II λ4686 Å line to the stellar flux at Hβ and is used to determine the He II Zanstra temperatures. The values of $N_{He^+}/F_{H\beta}$ determined by Heap (1977b) for five nebulae with O-type stars are shown in the figure. The temperatures corresponding to these observed ratios can be read off directly for each of the models represented; they are *all* higher than the blackbody value. In addition to the blackbody curve,

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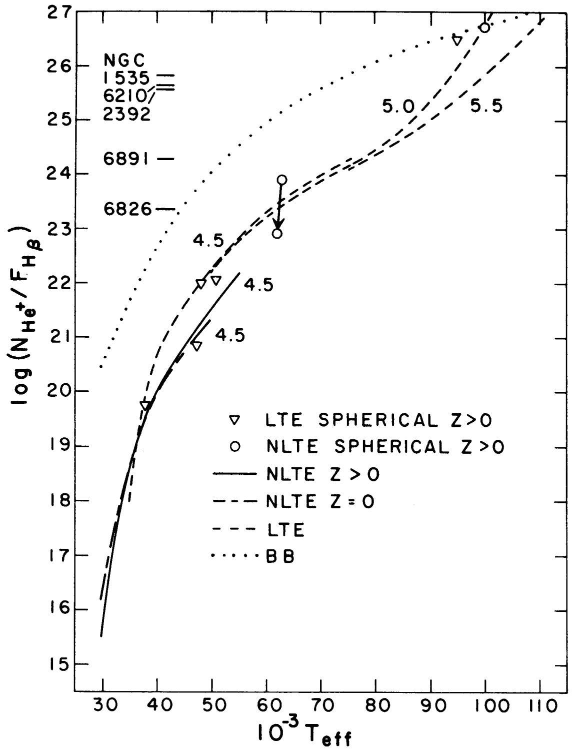

Fig. 2. The ratio of the number of photons in the He II continuum to the astrophysical stellar flux at Hβ. The LTE spherical models are those of Cassinelli (1971a,b) and Cassinelli and Hartman (1975), the non-LTE spherical models are from Kunasz, Hummer and Mihalas (1975), the non-LTE $Z > 0$ models are from Mihalas (1972), the non-LTE $Z = 0$ models are from Auer and Mihalas (1972), and the LTE models are those of Hummer and Mihalas (1970a,b); 300-series models are used for log $g = 4.5$ and 200-series models for high gravities.

Figure 2 contains the non-LTE metal-free models of Auer and Mihalas (1972) and the mean-metal models of Mihalas (1972), all with log g = 4.5, as well as the LTE models of Hummer and Mihalas (1970a,b) at the indicated values of log g. The spherical models of Cassinelli (1971a,b) and of Kunasz, Hummer and Mihalas (1975) are also represented; where appropriate, the arrows indicate increasing extension. The fact that the less extended spherical non-LTE model lies above the plane-parallel curve suggests that the photospheric temperature assigned to these model is too low, and that the loci of these models should be moved to the right. There are a number of points to be made. 1) If we assign a temperature of 40,000-50,000°K on the basis of visual and near ultraviolet spectra, the flux given by the models in the He II continuum is *too small by some four or five orders of magnitude*. 2) The models agree among themselves to within an order of magnitude, if we exclude the blackbody curve. 3) The more refined the model, the more acute is the discrepancy (the effects of gravity and assuming LTE will be discussed shortly). In particular, increasing the metal abundance lowers the curve.

The effect of atmospheric extension can be seen in Figure 3, where $N_{He^+}/F_{H\beta}$ is plotted as a function of ratio of the radius at $\tau_R = 0$ to the radius at $\tau_R = 2/3$, which is a measure of extension. Clearly, increasing the extension lowers the ratio, with the effect being stronger for the low mass models.

Figure 4 shows $N_{He^+}/F_{H\beta}$ as a function of log g, computed from Mihalas' (1972) mean-metal models; clearly the non-LTE models give lower values for this ratio. For temperatures lower than 40,000°K,

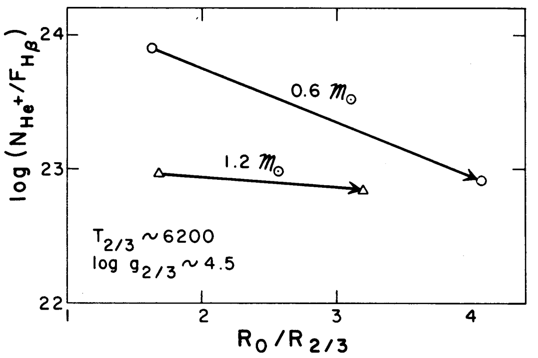

Fig. 3. The effect of extension on $N_{He^+}/F_{H\beta}$. R_0 and $R_{2/3}$ are the radii at $\tau_R = 0$ and $\tau_R = 2/3$, respectively. Models from Kunasz, Hummer and Mihalas (1975).

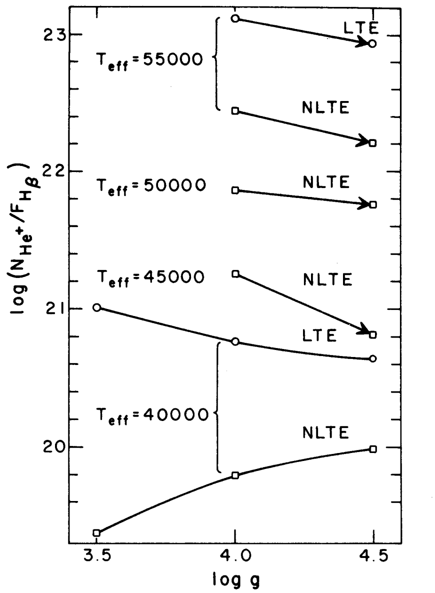

Fig. 4. Effect of gravity and LTE on $N_{He^+}/F_{H\beta}$. Mean-metal models from Mihalas (1972).

the NLTE value of the ratio increases with gravity, and for temperatures of 45,000°K and above, it decreases as the gravity increases.

Pottasch *et al.* (1977) have determined Zanstra temperatures for the H I, He I and He II continua, referred to the stellar flux at Hβ. They have used only blackbody fluxes in their work. The results are summarized in Table 1, where the resulting Zanstra temperatures are compared with the blackbody temperature obtained from the continuum. We include for comparison Heap's (1977b) values of the Zanstra temperatures found using blackbody and Hummer-Mihalas fluxes. For the O stars showing no He II lines, the hydrogen and neutral helium Zanstra temperatures, T_z(H I) and T_z(He I) agree reasonably well with the continuum blackbody temperatures T_{cont} inferred from the fluxes between λ1550 and λ5400. The O stars with He II lines yield values of T_z(H I), T_z(He I) and T_{cont} that are all in reasonable accord, but are well below the He II Zanstra temperatures. For the O VI and Abell objects, in one case, NGC 3587, T_z(H I) and T_z(He II) agree, but are somewhat larger than the He I and (here poorly determined) continuum temperatures. For NGC 246, T(He II) $\sim T_{cont} \gg$ T(H I), while for NGC 1360, T_z(H I) < T_z(He II) < T_{cont}. The Wolf-Rayet stars yield T_z(H I) ~ T_z(He I) << T_z(He II), although in view of the non-blackbody nature of the observed flux, the meaning of these temperatures is quite uncertain. Finally, for pure continuum stars, T_z(H I) ~ T_{cont} << T_z(He II). Pottasch *et al.*

Table 1
Stellar Temperatures (10^3 °K)

Nebula	Type(P)	Type(H)	Pottasch *et al.* $T^{bb}_{cont.}$	Pottasch *et al.* T^{bb}_z(HI)	Pottasch *et al.* T^{bb}_z(HeI)	Pottasch *et al.* T^{bb}_z(HeII)	Heap T^{bb}_z(HI)	Heap T^{bb}_z(HeII)	Heap T^{HM}_z(HeII)
NGC 1535	05	sd 03:	45.	35.	36.5	69.	>37.	74.	94.
IC 3568	05		44.	50.	46.5	65.5			
NGC 6629	0		44.	37.	38.	---			
NGC 6210	06	sd 03	38.	47.5	42.	62.	43.	70.	92.
NGC 2392	07f	06 f	36.	28.2	30.	70.	>27.	69.	92.
IC 4593	07f		34.	29.5	34.5	---			
IC 418	07f		32.	35.	36.	---			
NGC 6826	06f	03f	30.	32.	35.	59.	>40.	44.	63.
NGC 6891	07	03:f	30.	35.5	36.5	---	>28.	52.	76.
He2-131	07.5	07 feq	25.	28.5	---	---	31.	---	---
NGC 1360	?		100.	36.5	---	68.			
NGC 3587	?		75.	116.	68.	118.			
NGC 7293	?		95.	115.	---	---			
A31	sd 06		75.	77.	---	---			
A33	sd Op		75.	35.	---	---			
IC 2419		04(f)	---	---	---	---	29.	---	---
NGC 40	WC8		---	27.5	30.	---			
NGC 6543	Of-WR	03 feq	---	39.	40.	59.			
BD+30°3639	WC9		---	31.	35.	64.			
NGC 3242	Con		---	45.5	42.5	86.			
NGC 7662	Con		---	42.	40.	86.5			
NGC 246	OVI		100.	37.5	---	92.			
NGC 2371	OVI		---	48.	38.	102.			
NGC 4361	OVI		---	42.5	34.	98.			

P = Pottasch *et al.* (1977)
H = Heap (1977b).

(1977) have suggested that the different distributions of λ4686 Å and Hβ in the nebula cause the intensity of the former to be overestimated, but admit that this effect can, at most, account for a small part of the discrepancy.

PROPOSED EXPLANATIONS

A number of explanations have been proposed to account for the discrepancy between the high Zanstra temperature and those inferred from the visual spectra.

Corona

Aller (1977) has proposed that some central stars have a corona that is optically thick and emits strongly shortward of λ228 Å. This suggestion receives some support from a very recent paper by Stothers (1977) who finds pulsational instabilities for radial modes that originate in the CNO ionization zone in his models of central stars. This instability appears to arise from the CNO "bump" in the new unpublished opacities of Carson. It is then possible to envisage the resulting pulsation creating shock waves that cause atmospheric heating. On the other hand, Lasker and Hesser (1971) report no detectable periodic activity with amplitude greater than 0.003 mag from 4 to ~700 sec in the power spectra they computed from photoelectric time-series data for 16 central stars.

It is illustrative to estimate the additional energy that must be put into the ionization of He^+ in order to increase the ratio $N_{He^+}/F_{H\beta}$ to the observed level, say 10^{25}. For Mihalas (1972) models with effective temperatures of 40,000 and 50,000°K, the ratio of the luminosity in the He II continuum to the total luminosity is 6×10^{-8} and 3×10^{-6}, respectively. Increasing N_{He^+} by factors of 5×10^5 and 4×10^3, in these two cases, to give the observed value of $N_{He^+}/F_{H\beta}$, we find that the resultant energy being deposited in the He II continuum by the unknown source is a few percent of the total luminosity! In the Sun the ratio of mechanical to radiative luminosity is less than 10^{-4}.

Stellar wind

In analogy with Of and Wolf-Rayet stars, we would expect central stars to produce substantial stellar winds. In a 1000 km/sec wind, a proton has an energy of 5 keV. A mass loss rate of 10^{-7} $M_\odot$/yr corresponds to 3×10^{42} proton sec^{-1}. The energy in the wind is about 10^{-3} of that emitted radiatively by the star, so that the nebular energy balance is unaffected. At first sight this mechanism looks quite promising, since the energy in the wind with the above parameters is five thousand times that in the He II continuum for a 40,000°K star with $R = R_\odot$, and is negligible compared to the energy in the Lyman continuum. Unfortunately, elementary energy-loss calculations show that essentially all of the proton energy goes to the electrons, and that only roughly 5×10^{-6} of it goes to processes producing He^{++} or excited He^{+}. Thus the stellar wind cannot account for the high Zanstra temperatures, even if one uses very favorable values of the wind parameters and proton cross sections.

Small hot companion star

Heap (1977b) has suggested that the discrepancy between the Zanstra temperatures and those estimated from the visual spectra may be attributed to the presence of a small, very hot companion to the observed star. A few cases of binary central stars are fairly well established. Cudworth (1973,1977) lists six visual binaries. Kohoutek (1966) has reported fluctuations of $0.2^m - 0.3^m$ in three stars and could not exclude variability in five more objects. Kohoutek (1967) and Kohoutek and Hekela (1967) have found substantial evidence that NGC 1514 is a binary system consisting of an A0 III star and a small, very hot object, which Greenstein (1972) has identified as a visually subluminous O star. Kohoutek and Senkbeil (1973) suggest that the central star of NGC 2346 is similar to that of NGC 1514. Mendez and Niemala (1977) have shown that the planetary nebula NGC 1360 contains a spectroscopic binary system containing a sub-dwarf O and either a white dwarf or a late-type main sequence star. Several cases are known of nebulae whose apparent central stars are too cool to account for the apparent ionization. In one such case, NGC 3132, Mendez (1975) has suggested that there are real variations in the stellar radial velocity relative to the nebula, indicative of the presence of a companion. Lutz *et al.* (1976) and O'Dell (1966) have discussed objects with a G-type absorption spectrum, in which no evidence is found for a companion; O'Dell has hypothesized a complex model with a single star and a thick circumstellar shell for such cases.

Although the hot companion star hypothesis does seem to explain the excitation of the nebula in several cases, from the point of view of stellar atmospheres the problem is compounded. As both stars contribute to the stellar flux at Hβ, while only the hotter and *smaller* one ionizes He^{+}, it must have a very high temperature indeed.

Leaky shell model

I would like to end this review by sketching an idea that, in some sense, represents a merger of the hot and cool stars of the binary system into one object. This model has two basic elements: 1) a hot star with an effective temperature roughly that of the He II Zanstra temperature, and 2) an optically thick circumstellar "shell" that only *partially* surrounds the star. The shell may be a low velocity wind, or some gas recently ejected, possibly on its way to becoming a secondary nebular shell, or perhaps the normal atmosphere of a cooler, extended star, in which holes have been burned by ionization or been torn by the ejection of gas. The point of the "leaks" is that they allow far-ultraviolet radiation to escape from the hot object, in order to produce the observed ionization of He^+ and of other highly-stripped ions, while the relatively cool shell produces the visual and near-ultraviolet spectrum. In this way we resolve the discrepancy between the Zanstra and visual temperatures and can account for the very large range of ionization observed in both the star and the nebula. This kind of model also could account for the nebulosity surrounding stars with late A- or G-type spectra. If the shell is confined to a belt or disc surrounding the central region of the star, so that it shadows part of the nebula, it may account for the bi-polar intensity distribution seen in many nebulae. Further, the different types of central stars may be related to the mass, distribution and physical state of the gas in the shell, which would be expected to evolve with time.

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DISCUSSION

Panagia: About your suggestion of a "leaky shell" model to explain the peculiarities of the far UV spectrum, it seems to me that such a circumstellar shell, to be effective, must absorb a large fraction of the hard radiation. Therefore, $H\alpha$ and the other emission lines should appear very strong in the spectrum of the star. An observational check should be relatively easy.

Nussbaumer: Concerning the leaky shell, one might recall that the solar wind does not represent a spherically symmetric expansion but an expansion originating from restricted patches on the sun.