THE ASTROPHYSICAL JOURNAL, 215: 609–619, 1977 July 15

SPECTROSCOPIC STUDIES OF VERY OLD HOT STARS. II. SPECTRAL CLASSIFICATION, ABSOLUTE MAGNITUDES, AND DISTANCES OF O-TYPE PLANETARY NUCLEI

SARA R. HEAP
Laboratory for Optical Astronomy, Goddard Space Flight Center/NASA, Greenbelt, Maryland
Received 1976 December 2

ABSTRACT

This paper describes a study of high-dispersion spectrograms of central stars previously classified from low-dispersion plates as O-type stars. The main results of this study are, first, that the spectra of this group of stars show a wide range in excitation (roughly from O7 to O3), but no central star appeared to have a higher excitation than that of the young star HD 93129. Second, the spectra of this group of stars show a wider range in gravity-dependent spectral features than do young O stars. Third, some central stars have spectra identical to those of young O stars, and in these cases, the method of spectroscopic parallax (along with an assumed stellar mass) yields distances in accord with Cudworth's recent distance scale to planetary nebulae. Fourth, the stellar rotational velocities appear to be in a narrow range, with a typical full width at half-maximum (FWHM) corresponding to about 100 km s^{-1}. Fifth, a few central stars show evidence of mass loss.

Subject headings: nebulae: planetary — stars: early-type — stars: luminosities — stars: spectral classification

I. INTRODUCTION

There exists a need to determine reliable values of the atmospheric properties of central stars of planetary nebulae in order to deduce their evolutionary history and to understand their effect on the surrounding nebulae. Most theoretical work in these two areas of research has assumed that planetary nuclei evolve along the Harmon-Seaton sequence (Harmon and Seaton 1966) to become white dwarfs within the lifetime of the visible nebula. The effective temperature (T_e) and luminosity (L) of those central stars which are used to define the Harmon-Seaton sequence were determined with the use of the Zanstra method. This method uses the nebula as a set of photon-counters of stellar continuous radiation beyond the H I, He I, and He II Lyman limits. There is no way to check whether the Zanstra temperatures represent the effective temperatures of most central stars, for they are too faint to be observed spectroscopically at dispersions high enough for analysis. Those few central stars which have been observed spectroscopically show a bewildering array of spectral types (Aller 1968). Although some of these stars have conventional spectral types (O and W-R types), others have spectral types which are unknown among young hot stars. They include the O VI sequence (Smith and Aller 1969), a group of stars which are apparently much hotter than the hottest young star, and the sdO sequence, a group of stars which have higher gravities than hot zero-age main-sequence (ZAMS) stars.

We have attempted to check the Zanstra method by determining the atmosphere properties of a selected group of central stars by means of analysis of the line spectra. Since the O-type stars are most amenable to a quantitative analysis, we have confined our study to central stars previously classified by others as O-type stars. So far, about 25 O-type central stars are known. Most of these stars were classified from spectrograms obtained and described by Swings and Swenson (1952), Aller (1948, 1951, 1956, 1958, 1968), and Aller and Wilson (1954). No quantitative analyses of these spectra have been made because until recently no suitable methods of analysis had been developed for O stars. The theoretical deficiencies have now been alleviated by the non–LTE studies of Auer and Mihalas (1972), which include specific predictions of the strengths and profiles of the hydrogen and helium lines in very hot stars. Conti (1973*b*, *c*) and others have used these predictions to calibrate the spectra of young, massive O stars. It seemed appropriate to apply these predictions and calibrations to central stars as well, and in this way to determine the atmospheric parameters of O-type central stars, and to provide a check on the Zanstra temperatures of these stars.

We have therefore made a study of seven O-type central stars in order (1) to provide the observational data (both equivalent widths and profiles) needed for a critical comparison with theory; (2) to make fine comparisons with the spectra of *young* O stars; and (3) to derive the atmospheric properties of these central stars. In this paper, we report the results of the first two aspects of the study. (In Paper III we shall report the results of quantitative spectral analysis.) In § III, these data are used to classify the spectra in as detailed and rigorous manner as possible. In § IV, the spectra are compared to those of young massive O stars; and in § V, the spectral types of the central stars and young O stars are used to derive absolute magnitudes of and distances to planetary nuclei by the method of spectroscopic parallax.

II. OBSERVATIONAL DATA

The central stars chosen for study are the nuclei of NGC 1535, NGC 2392, NGC 6210, NGC 6826, NGC 6891, IC 2149, and He 2-131. Although these stars were chosen for their spectral type and apparent brightness, they should represent planetary nuclei in general, in that they encompass a wide range of ages, as defined by the size or surface brightness of the nebula, and a significant range in stellar atmospheric properties, as defined by the Zanstra temperatures and luminosities. Figure 1 shows the positions of the seven stars studied here, as derived by Seaton (1966). All seven stars were used by Seaton to derive a mean evolutionary sequence for central stars. This sequence is also shown in Figure 1. Although the scatter about the mean evolutionary sequence is large, it is evident that the young bright nebulae, such as NGC 6210, IC 2149, and He 2-131, have central stars whose Zanstra temperatures are 50,000 kelvins or less, while the older, fainter nebulae have central stars whose Zanstra temperatures are higher than 50,000 kelvins. If these temperatures are a correct measure of effective temperature, these stars must be hotter than any young O star, since young O stars are generally believed to have effective temperatures less than 50,000 kelvins. In studying the spectra of these stars, we have, therefore, asked two questions: (1) do the hotter central stars have spectral features which indicate a higher excitation than do the spectral features of young O stars; and (2) do the cooler central stars have spectral features which indicate about the same excitation as the spectral features of young O stars?

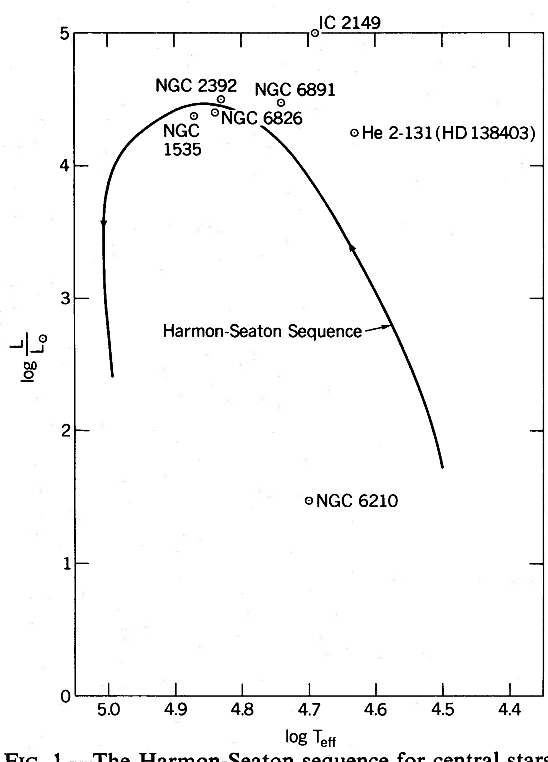

FIG. 1.—The Harmon-Seaton sequence for central stars of planetary nebulae. The mean evolutionary path of central stars in log L–log T_{eff} plane and positions of the seven central stars under study are those given by Seaton 1966.

High-dispersion spectrograms of the seven central stars were obtained by L. H. Aller in a continuing study of planetary nebulae. In most cases, the spectroscopic plates were obtained at the coudé focus of the 120 inch (3.05 m) telescope at the Lick Observatory and have a dispersion of 16 Å mm^{-1}. The spectrum of the nucleus of He 2-131 was obtained at CTIO with a plate dispersion of about 40 Å mm^{-1}. All the spectra were recorded on baked Kodak IIa-O emulsion.

The general appearance of the spectra of the seven central stars differs greatly from that of young stars because nebular emission lines are superposed against the stellar spectrum. Sometimes the nebular lines blot out the cores of stellar absorption lines, such as the Balmer lines of hydrogen, and sometimes they reinforce the stellar emission lines. Fortunately, nebular contamination was minimized on the plates under study. First, the high plate dispersion made possible a study of the *profiles* of lines or the wings of lines outside the nebular core. Second, except for He 2-131, the star was not trailed the full length of the slit. Consequently, the nebular lines stick out from the stellar spectrum in the direction perpendicular to the direction of dispersion, and thus they are usually easily identified as nebular emission lines rather than stellar emission lines.

Additional information concerning these objects is given in Table 1. The first two columns of the table give the NGC number and the Perek-Kohoutek (1967) number of the nebula. The next three columns list the approximate magnitude of the central star and the number of spectrograms obtained, and an eye-estimate of their quality. The last three columns give the nebular excitation, χ (cf. Aller and Liller 1968, Fig. 1), expansion velocity (Wilson 1950), and surface brightness at Hβ (Perek and Kohoutek 1967). These nebular data are useful indicators of the nebular contamination of the spectra in that they tell which nebular lines are expected to be present, and how broad and strong they should be. For example, NGC 2392 is a high-excitation nebula ($\chi = 8$) and is therefore expected to show nebular He II λ4686, which would obscure a portion of the stellar He II λ4686 line. NGC 2392 is expanding rapidly for a planetary nebula, so at Hγ, for example, the nebular line is expected to obscure up to 3 Å of the core of the stellar Balmer line. In general, however, nebular contamination is not a serious problem because NGC 2392 has a low surface brightness. In fact, nebular Balmer lines higher than H8 are not visible.

Table 2 gives a list of the equivalent widths and identifications of all visible stellar lines in the spectrum of each central star. The horizontal lines in this table indicate the longward and shortward wavelength limits to the usefulness of the spectrograms. Where there was more than one spectrogram per star, an average equivalent width is given, since the line strengths did not appear to vary by more than could

TABLE 1

CHARACTERISTICS OF THE PROGRAM OBJECTS

NUCLEUS						NEBULAR CHARACTERISTICS	
Identification	PK	m_B	No. PLATES	QUALITY	χ	v_{exp} (km s^{-1})	log $S(H\beta)$
NGC 1535......	206−40°1	11.7	2	Fair	7	40	−1.64
NGC 2392......	197+17°1	10.2	3	Very good	8p	107	−2.47
NGC 6210......	43+37°1	≥9.2	1	Good	5	42	−0.62
NGC 6826......	83+12°1	10.3	3	Very good	5	Not measured	−1.52
NGC 6891......	54−12°1	11.1:(pg)	2	Good	5	Not measured	...
IC 2149........	166+10°1	11.1	1	Very good	4	0	−1.42
He 2-131.......	315−13°1	10.5:(pg)	2	Very good	3?	Not measured	+0.29

TABLE 2

EQUIVALENT WIDTHS

Identification	NGC 1535	NGC 2392	NGC 6210	NGC 6826	NGC 6891	IC 2149	He 2-131
He II 4686..........	A	3:E	0.7:	2.8:E	1.45E	...	...
C IV 4658...........	...	...	...	0.58E	0.46E	...	1.17E neb?
C III 4650–4651......	...	...	...	0.55E	E?	...	2.51E neb?
C III 4647...........	...	...	...	0.29E	E?	1.30E	1.28E neb?
N III 4640..........	...	0.94E	...	0.40E	0.29E	0.47E	5.48E
N III 4634..........	...	0.62E	...	0.18E	0.17E	0.66E	2.23E
N V 4619...........	...	...	0.20	A?	A?	...	...
N V 4603...........	...	...	0.31	0.24:	A?	...	...
He II 4542..........	A	0.84	1.15:	0.70	0.76:	0.57	0.69
? 4504.............	...	...	...	...	...	...	0.63E
? 4486.............	...	...	...	...	...	...	0.71E
He I 4471...........	...	0.45	...	...	...	...	{−E 0.55
Hγ 4340............	1.05	1.96:	1.84	1.95	1.57	1.92	P.Cyg
He II 4200..........	0.6:	0.72	A	0.47	0.50	0.68	0.44
Si IV 4116..........	...	0.20E	...	0.22E(P Cyg?)	...	0.24E	E
N III 4103..........	...	{1.5:					P Cyg
Hδ 4101............	2.5		1.39	1.85	1.70	1.31	P Cyg
N III 4097..........	...	0.5:	...	...	...	...	P Cyg
Si IV 4088..........	...	0.09E	...	0.23E(P Cyg?)	0.20E	0.26E	P Cyg
N IV 4058..........	...	E?	...	0.53E	0.60E	...	E?
He I 4026...........	...						
He II 4025..........	...	{0.82	...	0.52	0.70	...	
H7 3970............	2.4	1.25	1.96	2.35	2.10	0.83	
He II 3923..........	...	0.58	...	0.40	...	0.33	
H8 3889............	1.4	1.10	1.60	1.80	1.60	1.45	
He II 3858..........	...	0.38	...	...	...	0.31	
H9 3835............	1.2	1.07	0.99	1.60	1.30	1.35	
He I 3819...........	...	0.30	...	...	...	...	
He II 3813..........	...	0.28	...	...	...	...	
H10 3797...........	0.9	0.97	0.80	1.50	1.10	1.05	
O III 3791...........	...	...	...	...	...	0.21	
H11 3770...........	0.8	0.60	0.51	...	0.95	1.12	
O III 3759..........	...	...		...	...	0.36	
O III 3757..........	...	...		...	...	0.16	
O III 3754..........	...	...		...	...	0.25	
H12 3750...........	0.5:	0.70		...	0.90	0.90	
H13 3734...........		0.45		0.65:	0.85	...	
N IV 3484..........		0.13		A?	...	...	
N IV 3482..........		0.27		A?	...	...	
N IV 3478..........		0.30		A?	...	...	
O IV 3396..........		0.14		0.17	0.1:	...	
O IV 3390..........		...		0.12	0.08:	...	
O IV 3386..........		...		0.20	0.2	...	
O IV 3381..........		A?		0.20	0.23	...	
O IV 3349..........		A?		0.12	0.22	...	
O IV 3348..........				0.12			

be ascribed to observational error. In most cases, the identification of a line as a stellar line is certain, but where there was felt to be some doubt, the comment "neb?" is written after the value of the equivalent width of the line. This uncertainty arose only in the spectral region, λλ4630–4690, which contains the so-called Of emission lines, possibly including C III λλ4647, 4650–4651, and C IV λ4658. In low- or moderate-excitation nebulae, the nebular emission lines Ne II λ4647, O II λ4649, O III λ4651, Ar II λ4657, and O II λ4661 are present and can be confused with the stellar emission lines. The confusion was severe in the case of He 2-131, because the nebula is a bright, low-excitation nebula, and because the star was trailed the full length of the slit. The wavelengths of the lines, although not precisely known, suggest that the emission lines are nebular in origin. Finally, in the cases where a line was visible but measurements were not possible or were uncertain, the strength of a line is listed as "A" or "E" if the line is in absorption or emission, respectively.

Table 3 gives the measured width at half-intensity of selected stellar lines, expressed in km s^{-1}. Figure 2 shows the profiles of Hγ λ4340, He II λ4542, and He I λ4471 (if present). The profiles of Hγ are aligned in this figure so that the centers of symmetry of the nebular line coincide. Except for NGC 1535, the stellar Hγ lines appear slightly blueshifted with respect to the nebular component. This apparent shift may be due to expansion of the stellar atmosphere, although high-quality, high-dispersion spectra of several Balmer lines are needed to confirm this possibility. It is worth pointing out that, for young O stars, expansion velocities are always given relative to the visual absorption lines, on the assumption that the material in which the visual absorption lines are formed is at rest. This may not be the case, and planetary nuclei offer the opportunity of measuring photospheric velocities with respect to the center of the nebular expansion, which is presumably the center of the star.

The remainder of § II describes the main features in the spectrum of each star.

a) *NGC 1535*

The spectrum of the nucleus of NGC 1535 was previously classified from low-dispersion plates as continuous by Aller (1951) and as continuous with emission lines by Swings and Swenson (1952). The present plates, although of only fair quality, show that the star has a purely absorption-line spectrum. The two stellar emission lines reported by Swings and Swenson, C II λ4267 and O II λ4416, are visible on the present plates, but these lines clearly originate in the nebula. The main absorption lines are the Balmer series of hydrogen. Two He II lines at λ4542 and λ4200 are undoubtedly present, but they are broad and shallow—broader than in the spectra of young O stars—and they are not easily separated from the plate noise, which is considerable. N V λ4603 is probably present also.

b) *NGC 2392*

The spectrum of the central star of NGC 2392 has been one of the most closely studied of all the absorption-line central stars (Aller 1948; Wilson 1948; Aller and Wilson 1954). In 1969 Smith and Aller classified its spectrum Of pec because it shows no trace of C III emission at λ4647, λλ4650–4651, whereas the other Of-type central stars do show C III emission. (We shall argue in § III*b* that the lack of C III emission is normal for the star's spectral type.) This star and the nucleus of He 2-131 are the only central stars studied here which show prominent He I lines at λ4471 and λ4026. The N III spectrum is very strong: λ4097 is a strong absorption line, while λ4634 and λ4640 are the strongest N III emission lines in any Of star known to the author.

c) *NGC 6210*

NGC 6210 is a small nebula of moderately high surface brightness, still opaque in the Lyman continuum of H I. Balmer continuum emission from the nebula obscures the stellar spectrum below the Balmer jump, so the usefulness of the stellar spectrum extends down to about 3700 Å.

The stellar spectrum has been previously described by Aller (1948), who classified the spectral type as O. The N V lines at λ4603 and λ4619 are strong, so the excitation of the stellar spectrum is very high. Of the two usually prominent He II lines, λ4542 and λ4200, λ4542 is unusually shallow and broad, and λ4200 is

TABLE 3

WIDTHS (FWHM) OF SELECTED LINES (km s^{-1})

NUCLEUS	ABSORPTION LINES				EMISSION LINES (or components of lines)					
	O III	O IV	N III	N IV	He II	N III	N IV	C III	Si IV	Unidentified
NGC 1535.....	...	...	...	...	...	...	...	...	...	...
NGC 2392.....	...	...	130	90	140:	110	...	...	100	...
NGC 6210.....	...	Not available	...	Not available	...	...	...	...	...	...
NGC 6826.....	...	120	...	...	520:	60:	110	160	130	...
NGC 6891.....	...	...	...	90	600:	65:	120	80:	110	...
IC 2149.......	100	...	...	...	...	80	...	120	...	...
He 2-131......	Not available	Not available	...	Not available	...	125	...	...	85	90
Lines used.....	λ3754	λ3381	λ4097	λ3478	λ4686	λ4634	λ4058	λ4647	λ4088	λ4486
	λ3757	λ3440	...	λ3482	...	λ4640	...	λ4650	λ4116	λ4501
	λ3759	...	...	λ3484	...	...	...	...	...	...

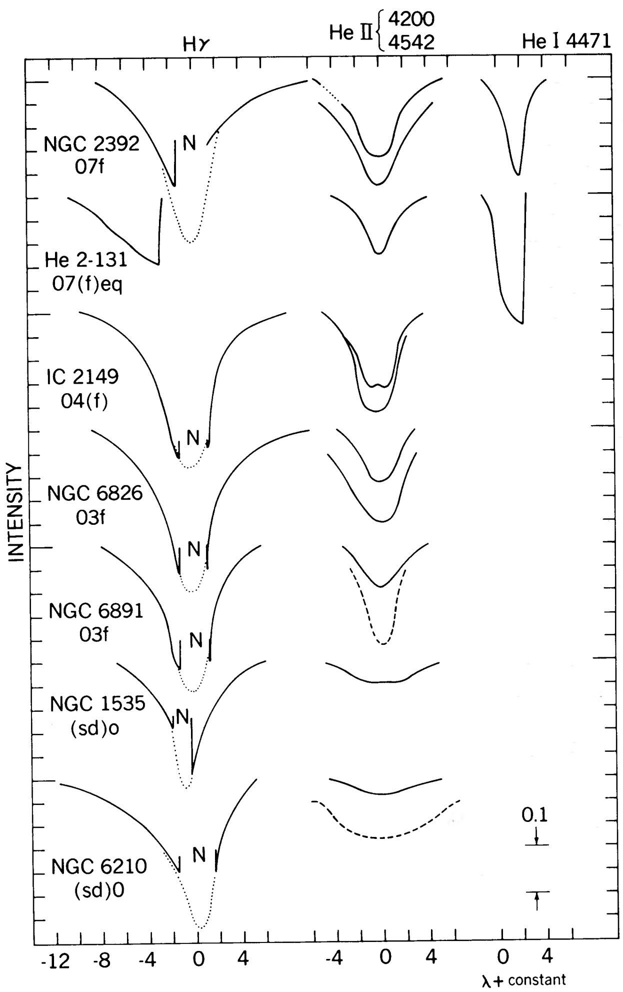

FIG. 2.—Normalized intensity profiles of selected hydrogen and helium lines in the spectra of seven central stars. The stars are identified by the names of their surrounding nebulae. If a spectral line is not shown, it was not present in the tracings. *Solid lines*, mean, smoothed observed profile. *Dotted lines*, estimated underlying stellar profile obscured by nebular emission. The nebular emission profile is not shown but is denoted by the letter N. Dashed lines indicate a very large uncertainty in the observed profile. All profiles are shown up to the point where their wings have a normalized intensity of 1.0. The intensity scale is indicated at the lower right. The abscissa gives the wavelength with respect to an arbitrary zero point.

almost indistinguishable from the plate grain. The He II line at λ4686 is a very weak absorption line. The most outstanding characteristic of the stellar spectrum is the pronounced asymmetry of the Balmer lines. Whether this is due to blending with He II, to atmospheric mass motions, or to the presence of a companion is not clear. This is the only O (as opposed to Ofeq) star known whose Balmer lines show strong asymmetry.

d) *NGC 6826*

The spectrum of the central star of NGC 6826 was classified earlier as W-R-type by Beals (1930, 1940) and Swings and Swenson (1952) and as O-type by Payne (1930) and Aller (1948). The present plates show that the spectrum has an Of-type of very high excitation. C IV and N IV emission lines are present as well as the usual "Of emission lines" of N III, C III, Si IV, and He II. The absorption spectrum is a normal early O-type spectrum. In the ultraviolet, there are strong O IV absorption lines (multiplets 3 and 4 but *not* 5), but oddly enough, the N IV triplet at λ3478–3484 does not appear.

e) *NGC 6891*

The spectrum of the nucleus of NGC 6891 was first studied by Aller (1948). The present plates show that its spectrum is almost identical to that of the central star of NGC 6826.

f) *IC 2149*

The spectrum of the nucleus of IC 2149 was first studied by Aller and Wilson (1954). The present plates indicate an early Of-type spectrum. There is no evidence of stellar He I absorption lines, although nebular He I emission would obscure a weak stellar He I absorption line, if it were present. Absorption lines of O III at λ~3750 are prominent, while O IV lines are absent. The nuclei of IC 2149 and IC 418 are the only O- or Of-type central stars known to the author to show these O III lines.

g) *He 2-131*

As Koelbloed (1962) noted, most of the stellar lines have P Cygni profiles. Lines of N III λ4634, λ4640, and C III λ4647, λλ4650–4651 are purely in emission, and He II λ4686 is neutral. The closest approximation to this spectrum among young Ofeq stars is HD 152408. The C III and N III emission lines are stronger than in any other Of star known to the author. In addition, the unidentified lines which sometimes occur in the spectra of Of stars, λ4486 and λ4503, are present and stronger than in any other Of spectrum known to the author.

III. SPECTRAL CLASSIFICATION

It is well known that, among stars of normal composition and negligible velocity fields, the appearance of the spectrum is determined by the effective temperature and gravity. In addition, the luminosity-to-mass (L/M) ratio is also determined by T_e and g, since, from Stefan's law,

$$L/L_\odot = (R^2/R_\odot^2)(T^4/T_\odot^4) = \frac{M/M_\odot}{g/g_\odot} T^4/T_\odot^4 . \quad (1)$$

The converse to these statements is also generally believed to hold: if two stars have the same spectral appearance, then they have the same temperature and gravity (and hence the same effective gravity and bolometric correction) and thus the same visual luminosity-to-mass ratio, (L_v/M). In particular, if the spectral appearance of a central star of a planetary nebula matches that of a young O star, then it is valid to assign to the planetary nucleus values of effective temperature, gravity, and L_v/M which are characteristic of that young O star.

A detailed comparison of the spectra of young O-type stars and O-type central stars therefore appeared to be worthwhile. Since the only spectral region available for examination and comparison is the wavelength interval, 3300 to 4800 Å, the spectrograms needed to be classified in a more detailed manner than that normally used to determine spectral type. Consequently, the strengths and profiles of both absorption and emission lines were taken into account in the procedure of classification. The rest of this section describes the methods and results of this effort. The basic question asked was, to what extent are the spectra of young O stars and O-type central stars similar? The answer to this question is given in the summary of § IV.

a) *Spectral Type*

Conti and Alschuler's (1971) system of classification of young O stars by spectral type was adopted for use with the spectra of the planetary nuclei. Here, the spectral type is defined explicitly by the equivalent-width ratio, W_λ(He I 4471)/W_λ(He II 4542). This system was used because of the large number of O stars already classified by Conti in this way from spectroscopic material identical to that used here (coudé spectra at 16 Å mm^{-1} taken at the Lick Observatory).

This classification system is precisely defined only through spectral type O5 in that all spectra whose W(4471)/W(4542) ratio is less than 0.2 are grouped together into the O4 spectral type. Since the majority of the spectra of central stars studied here turned out to be O4, it was necessary to develop new criteria to differentiate among O4 stars. The classification system was therefore extended to earlier spectral types. The extension is based on the equivalent-width ratio W_λ (N V λλ4603 + 4619)/W_λ(He II λ4542). Table 4 defines the system. When this extended classification scheme was applied to the central stars, the spectrum of the nucleus of IC 2149 remained O4, while those of the central stars of NGC 1535, NGC 6210, NGC 6826, and NGC 6891 were reclassified O3.

It should be noted that the classification of some of the central stars is uncertain. Because central stars are faint objects, their spectra were not always widened fully, so the tracings of the spectra were moderately noisy, and weak absorption lines ($W_\lambda \leq 0.15$) could not be detected with certainty, especially in the spectral region near the N V lines where a IIa-O plate is not particularly sensitive. In addition, He I nebular emission at λ4471 sometimes obscured a significant portion of the underlying stellar absorption line.

b) *Emission Lines*

A classification scheme was devised in order to characterize those O-type spectra showing emission lines on IIa-O plates. The criteria of this scheme included the presence (or absence) of certain emission lines, the apparent excitation of the emission-line spectra, and the breadths of the lines.

Originally, Pearce (1930) defined an Of star as an O star whose spectrum showed He II λ4686 in emission. Oke (1954) later showed that early (O5–O6) young O stars show N III λ4634, λ4640 emission, even though He II λ4686 may still be in absorption; and Conti and Alschuler (1971) then classified every O star which showed N III emission as an Of star. In this study, we have kept to Pearce's original definition, given the understanding that early O stars generally show N III emission. However, we have kept open the possibility that an early O star might not show N III emission (or any other emission lines) by introducing the spectral type (sd)O, in which case the spectral type is early O and yet no emission lines are present. The spectral type sdO is then reserved for those O stars whose H and He lines are much stronger and broader than in O stars. The terminology used here is shown in Table 5A in order to avoid confusion.

The apparent excitation of the N emission lines and C emission lines (if present) was classified according to criteria used in Table 5B. Classification of the N emission spectrum closely follows Smith's (1968) system developed for WN stars. Classification of the C emission spectrum differs markedly from the standard classification system of WC stars, in that it takes advantage of the fact that in Of-type spectra, C III λλ4647, 4650–4551 and C IV λ4658 are sharp enough to be separated easily, so that the ratio of their strengths can be used as an indicator of excitation.

The breadths of the emission lines were classified according to criteria listed in Table 5C. The breadths merely quantify a classification scheme first used by Smith and Aller (1969).

c) *Application to Young Stars and Planetary Nuclei*

Table 6 gives the results of these classification schemes as applied to the central stars under study. In addition, it lists three other central stars, the nuclei of IC 418, IC 4593, and NGC 6543, since the published spectral data by Aller and Wilson (1954) made classi-

TABLE 4
REVISED SPECTRAL CRITERIA

Spectral Type	Defining Features on IIa-O Plates
O3................	W_λ(N V 4603 + 4619) ≥ 0.2; He I λ4471 absent
O4................	W_λ(N V 4602 + 4619) < 0.2; W_λ(He I 4471)/W_λ(He II 4542) < 0.2
O5–O9.............	W_λ(He I 4471)/W_λ(He II 4542) (Conti 1973*b*, Table 3)

TABLE 5

Classification of Emission Lines on IIa-O Plates

A. By Presence of Selected Lines

Criterion	Designation	Reference
He II λ4686 is in emission	Of	Pearce 1930
He II λ4686 is neutral	O(f)	Walborn 1971
H I lines have P Cygni profiles	Ofeq	Beals 1950
No emission lines despite early O spectral type	(sd)O	...

B. By Apparent Excitation of Lines

Type	Defining Features	Type	Defining Features
N8...	N III present	C8....	C III present
N7...	N IV present but weak; N III ≫ N IV	C7....	C IV present but weak; C III ≫ C IV
N6...	N IV ≳ N III; N V weak or absent	C6....	C IV ≈ C III
N5...	N V ≈ N IV	C5....	C IV > C III
Notation:		Notation:	
	N III = W_λ (λ4634, λ4640)		C III = W_λ (λ4647, λ4650–1)
	N IV = W_λ (λ4058)		C IV = W_λ (λ4658)
	N V = W_λ (λ4603, λ4619)		

C. By Breadths of Lines

Type	Defining Features	
	FWHM (He II λ4686)	FWHM (N III λ4634, λ4640)
Sharp	≤150 km s^{-1}	≤150 km s^{-1}
Mixed	≥300 km s^{-1}	≤150 km s^{-1}
Broad	≥300 km s^{-1}	≥300 km s^{-1}

fication possible. For comparison purposes, Table 7 gives the results of the classification scheme extended to some well-known young stars for which there were sufficient published data or for which we have spectroscopic plates.

IV. COMPARISON WITH YOUNG O STARS

The data in Table 6 and 7 indicate a considerable range in the appearance of the absorption and emission spectra of O stars. It is therefore appropriate to ask (1) if the characteristics of the emission-line spectra are correlated with those of the absorption-line spectra, and (2) if such apparent correlations hold for both the central stars of planetary nebulae and young massive O stars. Below we consider the possible relationships of spectral type to the presence, excitation, and breadths of the emission lines in Of stars.

Among young O stars, the presence of selected C and N emission lines (on IIa-O plates) is correlated with spectral type: C III λ4647, λ4650 emission appears in some Of stars earlier than O6, and is absent in all stars later than O6, except the Ofeq stars (Underhill 1966; Heap 1970; Conti 1973*a*); and N III λ4634, λ4640 emission occurs in all young stars earlier than O6 (Oke 1954; Conti and Alschuler 1971). These generalizations concerning the C emission spectrum hold for the central stars studied here as well. C III emission at λ4647, λλ4650–4651 is present in the Of stars earlier than O6, and possibly in the O7feq star, but it is absent in the nucleus of NGC 2392, an O6f star. Hence the emission spectrum of the nucleus of NGC 2392 is compatible with its spectral type. We therefore do not list it as a peculiar star, as did Smith and Aller (1969). On the other hand, the generalizations concerning the presence of N emission do not always apply to central stars of planetary nebulae. The central stars of NGC 6210 and NGC 1535 have very early spectral types, but there is no evidence that either shows an emission spectrum of N III or any other ion. We suggest that the presence of emission lines is indicative of an extended atmosphere, and that the absence of emission lines in the nuclei of NGC 6210 and NGC 1535 is due to the suppression of an extended atmosphere by means of a higher than ZAMS gravity ($\log g \approx 4.5$), typical of young O stars. For this reason we assign a quasi-subdwarf, (sd)O, classification to these two stars.

In 1963, Wolff pointed out faint emission lines at λ4486 and λ4504 appearing in the spectra of some young Of stars. Further study by Conti (1973*b*) showed that these lines are usually present if (and only if) the spectral type of the star is between O7 and O9.5 and He II λ4686 is neutral or in emission. The spectra of all the central stars were searched for evidence of emission at λ4486, λ4503, and, as expected from Conti's work, definite identification could be found in only one star, the nucleus of He 2-131, an O7feq star. Comparison of the strengths of these lines in the spectrum of this central star (Fig. 3) with those

1977ApJ...215..609H

TABLE 6

SPECTRAL CLASSIFICATION OF CENTRAL STARS

Nucleus	Absorption Lines: Spectral Type	Absorption Lines: Revised Spectral Type	Emission Lines: Excitation N	Emission Lines: Class C	Emission Lines: Breadth Class
NGC 1535...........	O4:	(sd)O3:	...	...	...
NGC 2392...........	O6f	O6f	N8	...	Sharp
NGC 6210...........	O4	(sd)O3	...	...	...
NGC 6826...........	O4f	O3f	N6	C6	Mixed
NGC 6891...........	O4:f	O3:f	N6	C6	Mixed
IC 2149.............	O4(f)	O4(f)	N8	C8	Sharp
He 2-131............	O7(f)eq	O7(f)eq	N7	?	Sharp
NGC 6543...........	Of	O3feq	N5	C5	Mixed
IC 418..............	O7f	...	N8	C8	Sharp
IC 4593.............	O7f	...	N8	C8	Sharp

TABLE 7

SPECTRAL CLASSIFICATION OF SOME YOUNG Of STARS

Identification	Absorption lines: Spectral Type	Absorption lines: Reference	Absorption lines: Revised Spectral Type	Emission Lines: Excitation N	Emission Lines: Class C	Emission Lines: Breadth Class
HD 108................	O7 If	1	O7feq	N8	C8	Sharp
HD 15570..............	O4f	1	O4f	N7	C8	Mixed
HD 66811..............	O4f	2	O3f	N7	C8	Broad
HD 93129..............	O3f	3	O3f	N6	...	Sharp
HD 152408.............	O8 If	1	O8feq	N8	C8	...
HD 188001.............	O8 If	1	O8f	N8	...	Sharp
HD 190429A...........	O4f	1	O3f	N7	...	Mixed
HD 210839.............	O6f	1	O6f	N8	C8	Broad
Nucleus of NGC 6164−5........	O6f	4	O6f	N8	C8	Sharp

REFERENCES.—1, Conti and Alschuler 1971; 2, Heap 1972; 3, Walborn 1973; 4, Aller and Wares, unpublished.

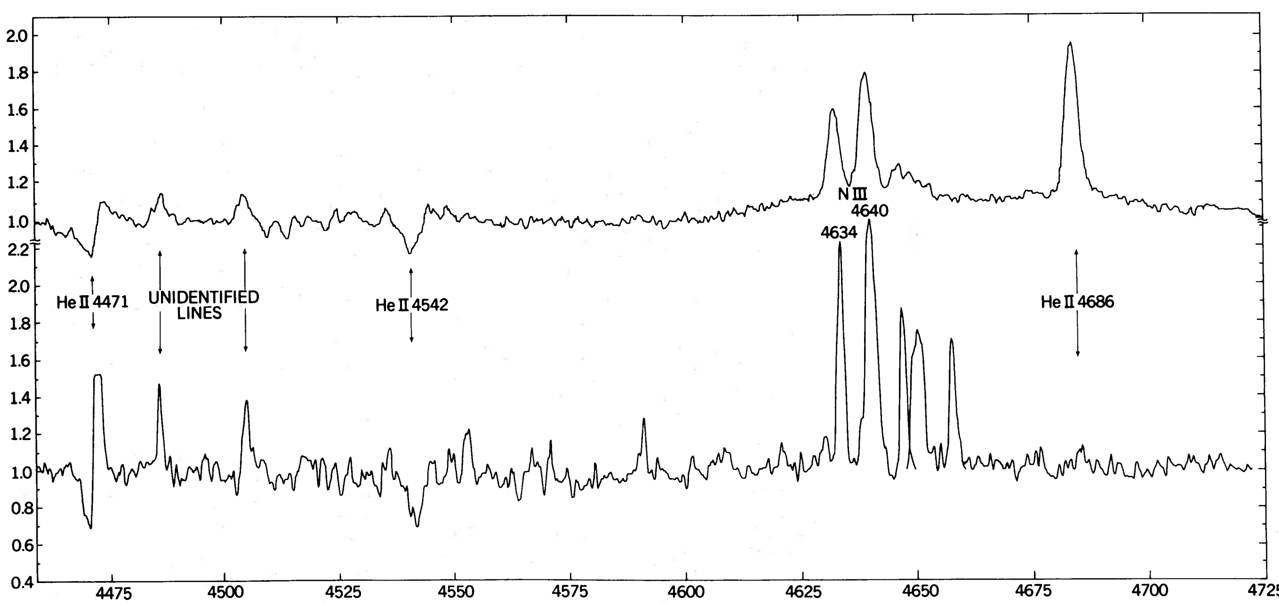

FIG. 3.—Normalized tracings of the young star, HD 152408 (*upper*), and the nucleus of He 2-131 (*lower*). Both stars have spectral types, Ofeq.

measured by Wolff (1963) and Conti (1973*b*) in the young Of stars shows that this central star has the strongest λ4486, λ4503 known.

The apparent range in excitation of the emission lines is much wider in the planetary nuclei than in the young O stars. Among central stars, the excitation class ranges from N8 to N5 and from C8 to C5, while among young stars, the excitation class ranges from N8 to N7 and is never earlier than C8. It is significant that those planetary nuclei belonging to the highest excitation class are all O3 stars. Hence there is evidence that the excitation of the emission lines is correlated with that of the absorption lines.

Young O stars have members belonging to all three breadth classes, while the central stars studied all belong either to the sharp or to the mixed class. The He II λ4686 profile in the spectrum of the nucleus of NGC 6826 merits special attention (see Fig. 4). The emission line is broad with wings extending to ± 1000 km s^{-1}, and it shows a blueshifted self-reversal, suggestive of an expanding atmosphere. This emission line is also broad in the spectrum of the exciting star of NGC 6891, but the spectrogram is too faint in this wavelength region to characterize the line further.

The FWHM of the emission lines and representative, non–Stark-broadened absorption lines in the central stars were measured with the results as shown in Table 3. Except for He II λ4686, the widths of the emission and absorption lines are about the same. This finding parallels that of Oke (1954), that in young O stars the N III emission lines have the same width as the absorption lines. If the values of FWHM are treated as rough indicators of projected velocity, $v \sin i$, then all the O- and Of-type central stars studied here have about the same velocity, $v \sin i \approx 100$ km s^{-1}.

It is doubtful that the source of velocity broadening in central stars is rotational. First, the radii of the O(f)- and Of-type central stars are probably greater than the radius of the Sun (see § V). If the central star were originally a solar-type star, then it should have an angular momentum typical of that of the Sun, and its equatorial rotational velocity should be less than 2 km s^{-1}. Hence the 100 km s^{-1} broadening observed in these planetary nuclei must arise from some source other than rotation. Second, the radii of the central stars studied are most likely greater than those of the hot subdwarfs. (It is generally believed that central stars contract to become hot subdwarfs and then cool off at a constant radius as white dwarfs.) Hence if the source of broadening in central star spectra were rotational, one would expect sdO stars to show a marked increase in line broadening. However, the observations show that the non–Stark-broadened lines of the hot subdwarfs are sharper than those in O- and Of-type central stars (Auer and Heap 1971).

A nonrotational source of broadening also appears to exist in young early O and Of stars. Slettebak (1956) has argued that if the observed broadening in the spectra of these stars were due to rotation, we should expect to see some O and Of stars pole-on, and the spectra of such stars should show narrow lines. In fact, the line spectra of *all* early O and Of stars show evidence of broadening corresponding to at least 75 km s^{-1}.

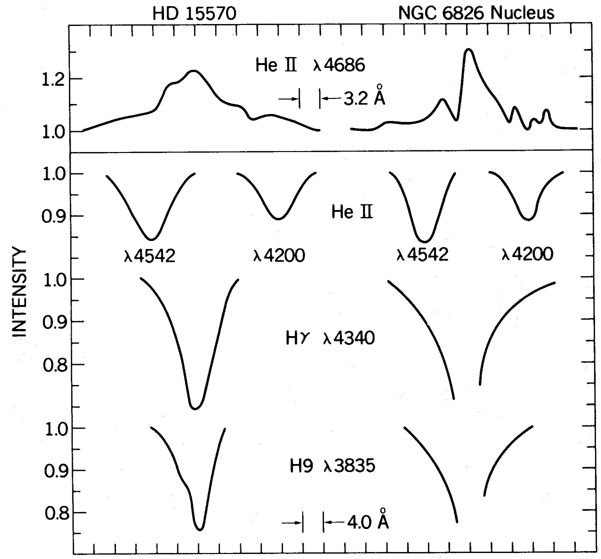

FIG. 4.—Normalized intensity profiles of selected hydrogen and helium lines in the nucleus of NGC 6826 and the young star, HD 15570. The abscissa is wavelength. The cores of the hydrogen lines in the nucleus of NGC 6826 are not shown, since they are obscured by nebular emission.

The profiles of the Stark-broadened lines (hydrogen and helium) were compared with those of young early O stars. The comparison spectra are those described by Heap (1971), obtained from spectrograms at the same dispersion as that of the central stars. An example of this comparison is illustrated in Figure 4, which shows selected hydrogen and helium lines in the spectrum of the young star, HD 15570 (O4f), and the nucleus of NGC 6826 (O3f). Note the very strong similarity in the strengths and profiles of these two stars despite the differences in mass and age. In general, the Of- and Ofeq-type central stars have H and He line profiles almost identical to those of young O stars. Only the two (sd)O stars, the nuclei of NGC 1535 and NGC 6210, which were classified as quasi subdwarf on the basis of their lack of emission lines despite their early spectral type, have peculiar line profiles. In these two stars, the H I lines are strong but the He II lines are very shallow and broad; and in the nucleus of NGC 6210, the H I lines are all asymmetrical in having steeper red wings than violet wings.

a) *Summary*

The following conclusions were reached concerning the similarities of spectra of O-type central stars and young O-type stars.

1. The central stars studied show a significant range in absorption-line excitation. The spectral types ranged from O7 to O3. No central star showed a higher excitation that that of the young Of star, HD 93129, described by Walborn (1971).

2. The excitation of the emission lines generally parallels that of the absorption lines. No central star

showed a N emission spectrum more excited than that of HD 93129. Two central stars showed a highly excited C emission spectrum, which is unknown among young Of stars.

3. The central stars studied show a significant range in gravity-dependent spectral features. Two of the central stars may have gravities higher than is known among young O stars. The Of and Ofeq stars are thought to have low effective gravities.

4. The central stars studied show a very small range in the line-broadening velocities. A typical value of the FWHM is 100 km s^{-1}. Hence these stars are like young early O stars in the sense that no central star studied has lines which are sharper than ~ 70 km s^{-1}. No central star studied showed evidence of rapid rotation ($v \sin i > 200$ km s^{-1}) that is found in some young O and Of stars.

5. The profiles of the H and He lines of a central star are similar to that of a young O or Of star of the same spectral type.

6. A few central stars show evidence of a moving atmosphere as indicated by P Cygni–type lines or by asymmetrical He II λ4686 profile.

The spectra of the seven central stars studied may be summarized by the following statements.

1. The nuclei of IC 2149, NGC 2392, and He 2-131 have spectral features characteristic of young stars. Were it not for nebular contamination of the stellar spectra, it would be impossible to distinguish these spectra from those of young stars.

2. The nuclei of NGC 6826 and NGC 6891 have spectra which are very similar to that of the young Of star HD 93129, except that their spectra show moderately strong C IV emission lines. No young Of star is known to the author to exhibit such highly ionized carbon lines.

3. The nuclei of NGC 1535 and NGC 6210 are different from any young O star known to the author in that their spectra show no emission lines despite their very early spectral types.

4. The nucleus of NGC 6210 is a unique object. It is the only O star known to the author to have markedly asymmetric Balmer lines.

V. ABSOLUTE MAGNITUDES AND DISTANCES

We have estimated the visual absolute magnitudes and distances to the central stars under study, using two different methods: (1) "spectroscopic parallax," a method common to the study of young stars but never before applied to planetary nuclei; and (2) "Shklovsky's method," first developed by Minkowski and Aller (1954) for determining distances to planetary nebulae. There were sufficient observational data for only four of the seven stars under study (the nuclei of NGC 1535, NGC 2392, NGC 6826, and IC 2149), so our results may be biased by such a small sample. Nevertheless, the system of spectroscopic parallax yields 82% higher distances than the Shklovsky method when Seaton's (1968) calibration is used, but only 17% higher distances when Cudworth's (1974) calibration is used.

By the arguments presented earlier in § III, the ratio of the luminosity of a young star (ys) to the luminosity of a central star (cs) having the same spectral type (L_{ys}/L_{cs}) should be equal to the ratio of their masses (M_{ys}/M_{cs}). Since young, early O stars must have masses approaching 60 $M_{\odot}$, and central stars must

TABLE 8

ABSOLUTE STELLAR MAGNITUDES AND DISTANCES

A. METHOD OF SPECTROSCOPIC PARALLAX

Nucleus	M_v of Young Star of Same Spectral Type	Central Star M_v	Central Star V	Central Star $B-V$	Distance
NGC 1535	−6.1	−1.7	11.92	−0.26	3900
NGC 2393	−6.3	−1.9	10.43	−0.24	2300
NGC 6826	−6.5	−2.1	10.48	−0.21	2500
IC 2149	−6.3	−1.9	11.03	−0.04	2000
He 2-131	−6.5	−2.1	...	...	...

B. COMPARISON WITH SHKLOVSKY'S METHOD

Nucleus	Distance by Spectroscopic Parallax (pc)	Distance by Shklovsky's Method: Cudworth (pc)	Distance by Shklovsky's Method: Cahn and Kaler (pc)
NGC 1535	3900	3126	2230
NGC 2392	2300	1982	1160
NGC 6210	...	1663	2040
NGC 6826	2500	2265	1480
NGC 6891	...	4861	< 2960
IC 2149	2000	...	< 3190
He 2-131	...	...	< 3330

have masses in the range 1–3 $M_{\odot}$ (Paczyński 1971), central stars should have absolute visual magnitudes which are about 3.25 to 4.45 mag fainter than those of young stars of the same spectral type. And since very early young O and Of stars have absolute visual magnitudes in the range -6.1 to -6.5 (Heap 1971; Conti and Alschuler 1971), the O and Of stars under study should have absolute magnitudes in the range -1.6 to -3.3. Table 8A gives the actual value of M_v for each star based on the magnitude difference $\Delta M_v = 4.45$ mag. The distance D to each star was then estimated with the use of the standard formula,

$$M_v = V - 3.1\,E(B - V) + 5 - 5 \log D\,, \quad (2)$$

where the color excess, $E(B - V)$, was determined from the observed value of $(B - V)$ and an assumed intrinsic value for very hot stars, $(B - V)_o = -0.40$. The *UBV* values used here and shown in Table 8A were obtained by Shao and Liller (1970).

The distances to most of the central stars under study were determined both by Cahn and Kaler (1970, Table 1), who used Seaton's (1968) calibration, and by Cudworth (1974), who used his own calibration based on statistical parallaxes from proper motion measurements.

Our distances, obtained by the method of spectroscopic parallax, and those of Cudworth and of Cahn and Kaler, are compared in Table 8B. The data of this table show that, for the few objects in common, our distances are only 17% greater than Cudworth's, while they are 82% greater than Cahn and Kaler's. Our spectroscopic parallaxes therefore support Cudworth's new distance scale to planetaries. We note that, where the Shklovsky method is clearly invalid (optically thick nebulae), as is the case for He 2-131, NGC 6210, and IC 2149, the method of spectroscopic parallax is probably the superior method.

Most of the spectrograms were reduced at UCLA, and the results of that effort were included in a Ph.D. thesis submitted to UCLA in 1970. I thank my thesis advisor, Dr. L. H. Aller, for pointing out the need for spectral analyses of planetary nuclei, for lending me his spectrograms of these stars, and for giving me helpful advice.

REFERENCES

Aller, L. H. 1948, *Ap. J.*, **108**, 462.
———. 1951, *Ap. J.*, **113**, 125.
———. 1956, *Gaseous Nebulae* (London: Chapman & Hall).
———. 1958, *Mém. Soc. Roy. Sci. Liège IV*, **20**, 100.
———. 1968, in *IAU Symposium No. 34, Planetary Nebulae*, ed. D. E. Osterbrock and C. R. O'Dell (Dordrecht: Reidel), p. 339.
Aller, L. H., and Liller, W. 1968, in *Nebulae and Interstellar Matter*, ed. B. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press), p. 483.
Aller, L. H., and Wilson, O. C. 1954, *Ap. J.*, **119**, 243.
Auer, L. H., and Heap, S. R. 1971, unpublished data.
Auer, L. H., and Mihalas, D. M. 1972, *Ap. J. Suppl.*, **24**, 193.
Beals, C. S. 1930, *Pub. Dom. Ap. Obs.*, **4**, 271.
———. 1950, *Pub. Dom. Ap. Obs. Victoria*, **9**, 1.
———. 1940, *J.R.A.S. Canada*, **34**, 169.
Cahn, J., and Kaler, J. 1970, *Ap. J. Suppl.*, **22**, 319.
Conti, P. 1973*a*, in *IAU Symposium No. 49*, ed. M. K. V. Bappu and J. Sahade (Dordrecht: Reidel), p. 97.
———. 1973*b*, *Ap. J.*, **179**, 161.
———. 1973*c*, *Ap. J.*, **179**, 181.
Conti, P., and Alschuler, W. R. 1971, *Ap. J.*, **170**, 325.
Cudworth, K. M. 1974, *A.J.*, **79**, 1384.
Harmon, R. J., and Seaton, M. J. 1966, *M.N.R.A.S.*, **132**, 15.
Heap, S. R. 1970, Ph.D. thesis, University of California, Los Angeles.
Heap, S. R. 1971, *Astr. Ap.*, **15**, 7.
———. 1972, *Ap. Letters*, **10**, 49.
Koelbloed, D. 1962, *Bull. Astr. Inst. Netherlands*, **16**, 163.
Minkowski, R., and Aller, L. H. 1954, *Ap. J.*, **120**, 261.
Oke, J. B. 1954, *Ap. J.*, **120**, 22.
Paczyński, B. E. 1971, *Acta Astr.*, **21**, 417.
Payne, C. H. 1930, *Harvard Bull.*, No. 878, p. 1.
Pearce, J. A. 1930, *Pub. Dom. Ap. Obs.*, **5**, 110.
Perek, L., and Kohoutek, L. 1967, *Catalogue of Galactic Planetary Nebulae* (Prague: Academia Publishing House).
Seaton, M. J. 1966, *M.N.R.A.S.*, **132**, 113.
———. 1968, *Ap. Letters*, **2**, 55.
Shao, K., and Liller, W. 1970, unpublished data.
Slettebak, A. 1956, *Ap. J.*, **124**, 173.
Smith, L. F. 1968, *M.N.R.A.S.*, **138**, 109.
Smith, L. F., and Aller, L. H. 1969, *Ap. J.*, **157**, 1245.
Swings, P., and Swenson, J. W. 1952, *Ann. d'Ap.*, **15**, 290.
Underhill, A. B. 1966, *The Early Type Stars* (New York: Gordon & Breach).
Walborn, N. 1971, *Ap. J. Suppl.*, **23**, 257.
———. 1973, *A.J.*, **78**, 1067.
Wilson, O. C. 1948, *Ap. J.*, **108**, 201.
———. 1950, *Ap. J.*, **111**, 279.
Wolff, R. J. 1963, *Pub. A.S.P.*, **75**, 485.

S. R. HEAP: Code 672, Goddard Space Flight Center, Greenbelt, MD 20771