OBSERVATIONS OF CENTRAL STARS

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1. INTRODUCTION

Central stars of planetary nebulae have long presented a difficult problem for observers because most of them are fainter than tenth magnitude and because emission lines from the nebulosity interfere with spectroscopy of stellar features. With the advent of numerous large telescopes and space telescopes it is possible to obtain detailed observations of many central stars. More observing time devoted to central stars has resulted in accurate observations of emission and absorption features in their optical spectra and in the discovery of binary systems among them. Satellites have made possible observations in the ultraviolet. As usual, recent studies have raised as many questions as they have answered. This review will concentrate on a few topics of current interest. The reader should consult Aller (1976) for a comprehensive review on central stars and for an excellent summary of magnitudes and spectral classifications of individual central stars.

2. CLASSIFICATIONS AND POPULATION TYPES

The central stars of planetary nebulae exhibit a surprising variety of spectra. The spectra can be categorized roughly as follows:

(1) Continuous. No spectra features are present except the continuum of a very hot star.

(2) Wolf Rayet. These stars have broad emission lines of H, He, C, N, and O. There are six WC central stars and one possible WN.

(3) Ofp. Emission lines of H I, He II, N III, and C III are present in the spectra. O-type absorption features are also present.

(4) Of. There is only one Of central star known. The spectrum is the same as an Ofp star except that C III is not present.

(5) O-type. The absorption lines of an O star are the only features present.

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(6) O VI. These stars have prominent emission lines of O VI, λ3811,34; otherwise their spectra look like those of Ofp or Wolf-Rayet central stars.
(7) Of+WR; O+WR. These spectra have combinations of WR, O-type, and Of-type emission and absorption features.
(8) O-subdwarf. These spectra have broad absorption lines which are indicative of a hot, high-gravity star.
(9) Peculiar. The absorption features indicate a spectral type somewhere between A and K.
(10) Emission unclassified. These spectra are believed to show emission lines from the central star but they do not fit into any of the above categories.

The number of central stars which have been observed in each of these categories is summarized in Table I. The numbers given in the table are based on material in Aller's (1976) review paper and on recent studies by Lutz (1977a,c). Unfortunately the numbers in Table I are not representative of the true distribution of central stars among the various classifications. There are strong selection effects in that numerous faint central stars have not been observed spectroscopically, and in some planetary nebulae the central star is so faint that it is lost in the bright nebulosity.

TABLE I
Classifications of central stars

Classification	No. of stars
Continuous	21
Wolf-Rayet	7
Ofp or Of	10
O-type	9
O VI	10
WR+O or WR+Of	6
O-subdwarf	6
Peculiar	8
Emission unclassified	7

Central stars of types Of, Ofp, O, O VI and Wolf-Rayet all have analogues among Population I stars. Sometimes central stars and their Population I analogues exhibit systematic differences in their spectra. For example, the Wolf-Rayet central star of BD + 30° 3639 and the Population I Wolf-Rayet star HD 164270 both exhibit the same stellar emission lines, but the line widths and strengths are systematically larger in HD 164270 (Smith and Aller 1970). However, there are cases where it is difficult to tell a Population I star from a similar planetary nebula central star on the basis of stellar spectra alone. Lutz (1977a) finds no systematic difference between the equivalent widths of He II absorption lines in the spectra of Ofp and O-type central stars and those in Population I stars of similar types.

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In fact, there is sometimes difficulty in deciding whether a particular central star belongs to Population I or to the disk population of planetary nebulae. For example, the WN central star of M 1-67 may be a Population I Wolf-Rayet "ring" star, according to Cohen and Barlow (1975)(for a description of WN "ring" stars see Smith 1973). Also, the population type of the Ofp star HD 148937, which is the central star of NGC 6164-5 has been questioned by Catchpole and Feast (1970) and by Danks and Manfroid (1977). Even the population type of NGC 7027 has been questioned by some investigators (see Allen 1975).

Criteria for distinguishing between the central stars of planetary nebulae and their Population I counterparts on the basis of stellar spectra alone are not well-established at least in part because investigators have relied on the presence of a nebular shell as an indicator that the star therein is a disk population central star. There are two factors which preclude the use of the nebular shell criterion alone: (1) Some Population I stars have nebular shells. (2) There is at best only sketchy evidence that the planetary nebula central star evolves from protoplanetary star to the white dwarf stage during the lifetime of one nebular shell (approximately 30,000 years). Thus the absence of a nebular shell is not proof that a given hot star is Population I. Some hot disk population stars could be in a stage between shell ejections (see Kaler 1974 for a study of multiple shells around planetary nebulae) or be finished with ejection but not yet evolved to the white dwarf stage. Thus, while central stars as a whole are representative of the disk population, some detailed consideration is necessary before deciding the population type of a particular central star.

3. TEMPERATURES

Temperature determination for central stars is a topic of much current interest. Zanstra temperatures can be obtained by using emission lines of H I, He I, or He II, depending on which of these lines are present in the nebular spectrum. When emission lines of all three species are present, the Zanstra temperatures derived from H I and He I lines generally agree, but for some planetary nebulae the He II Zanstra temperatures are found to be much higher. Harman and Seaton (1966) argued that the He II Zanstra temperature was most representative of the radiation field from the central star because there is incomplete absorption of H ionizing photons. Pottasch, et al. (1977) and Heap (1977) have recalculated Zanstra temperatures for central stars using the increased amount of observational data that have become available since Harman and Seaton's study. Pottasch et al. also derive colour temperatures for central stars by combining ANS ultraviolet satellite data in the 1550Å to 3300Å region with optical photometry. They find that usually there is not agreement between the ultraviolet colour temperatures and the various Zanstra temperatures. Sometimes the ultraviolet colour temperature is consistent with the He II Zanstra temperature and sometimes it agrees with the lower H I or He I temperatures. When there are no He II lines from the nebula, the ultraviolet colour temperature invariably agrees with the H I and He I Zanstra temperatures. Other observations available of the ultraviolet (Gurzadyan 1975, Lutz and Carnochan 1977)

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tend to confirm that there is disagreement between different methods of temperature determination. So far no satisfactory explanation has been offered for these discrepancies.

Kaler (1976) has employed a modified Stoy method to derive temperatures for the central stars of 35 low-excitation planetary nebulae. These Stoy temperatures and the ultraviolet colour temperatures are generally in good agreement.

Temperatures can also be derived by evaluating the radiation field required to produce a spectral feature observed in the central star. From the O VI lines in the central star of NGC 246, Heap (1975) deduced a central star temperature of 200,000^{o}K, which is considerably higher than the values derived from the ANS ultraviolet observations and from the Zanstra temperatures (100,000^{o}K or less). Heap (1977) also finds difficulty in resolving Zanstra temperatures with temperatures derived by comparing spectral features of O- and Of-type central stars with model atmospheres (also see Aller 1977).

Several possible ways to determine the temperatures of central stars have been discussed. For most central stars in which there is no He II emission from the nebular spectrum, temperatures determined by different methods are usually in agreement. For other central stars there appear to be substantial differences between temperatures derived by various methods. This disagreement is providing information about both the central star's atmosphere and about the optical thickness of the nebula to various wavelengths of radiation. At the present time the means for interpreting this information are just being developed, i.e. much effort is going into theoretical models of central star atmospheres and nebulae.

4. BINARIES

Until recently a section written on binary central stars would have been a very short section indeed. However, recent work has revealed quite a number of binaries among the central stars, and the characteristics of these binaries are summarized in Table II.

The only confirmed visual binary system is the central star of NGC 246, where the O VI-type exciting star has a K-type companion. Cudworth (1973) has proposed some other candidates for central stars in visual binary systems, and these may be confirmed after extended periods of proper motion observations.

Four A-type central stars have been investigated for evidence that they are binary. The central star of NGC 1514 has been the subject of many investigations (Kohoutek 1968, Greenstein 1972). Recent ultraviolet observations (Pottasch, et al. 1977) and radial velocity observations (Acker 1976) have added still more evidence that this AO III star has a hot companion. Kohoutek and Senkbeil (1973) argue that there is an excess of blue radiation from the A-type central star of NGC 2346. Another viewpoint on NGC 2346 is that it is not a planetary nebula, but a cometary nebula excited by an AO star (Cohen and Barlow 1975). Mendez (1975) did a detailed spectroscopic investigation of the AO V central

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star of NGC 3132 but could find only indirect evidence for a spectroscopic binary system. The ANS ultraviolet observations do not provide any positive evidence for hot companions to either of these A-type central stars (Pottasch, et al. 1977). It may be that the companions are very faint. A fourth A-type central star, that of VV 1-7, has been studied by Kohoutek and Wehmeyer (1975) who concluded that VV 1-7 is a reflection nebula rather than a planetary nebula.

Interest in the only eclipsing binary central star discovered so far was stimulated by a paper (Bond 1976) on coincidences between objects in the Catalogue of Galactic Planetary Nebulae (Perek and Kohoutek 1967) and objects in the General Catalogue of Variable Stars (Kukarkin and Parenago 1958). This eclipsing binary, UU Sge happens to be the central star of A63. Miller (1976) finds that the duration of eclipse is about 70 minutes and the depth of eclipse is about 4 magnitudes.

Several central stars have been reported to be single-line spectroscopic binaries. Acker (1976) has reported radial velocity variations in the spectra of the central stars of NGC 6543, NGC 6572, and He 1-5 (FG Sge). From a study of the radial velocity variations, Mendez and Niemala (1977) conclude that the spectroscopic binary central star of NGC 1360 has a sum of masses less than one solar mass.

There are undoubtedly more binary central stars awaiting discovery. In those discovered so far there is a striking range of periods and spectral types involved. It is a bit too early to start asking whether all stars in planetary nebulae are binary. However, models of planetary nebula formation must be able to account for shell ejection by stars involved in a wide variety of binary systems.

TABLE II
Reported binary central stars

Nebula	Type	Sp.type	Period	Var.*	Ref.
NGC 246	Visual	O VI+K-type			1
NGC 1514	Spectroscopic	AO III+sd(O)	0.41 days:		2
NGC 1360	"	sd(O)	8 days		3
He 1-5(FG Sge)	"	G-peculiar	18.7days	100:	2
NGC 6543	"	O7+WR	1.45 hours	60	2
A 63 (UU Sge)	eclipsing	O-type	11 hours		4

References: 1 Aller (1976), 2 Acker (1976), 3 Mendez and Niemala (1977)
4 Miller (1976) *in km s^{-1}

5. PECULIAR CENTRAL STARS

Some planetary nebulae have central stars which appear to be too cool to account for the ionization of the nebular shell. The characteristics of some of these peculiar central stars and their nebulae are summarized in Table III. The data for Table III were taken from a spectroscopic survey of sixteen peculiar central stars by Lutz(1977c). In general, the peculiar central stars have spectral types between A and K. The nebulae

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associated with them show a range in excitation from low to very high. Some peculiar central stars (e.g. NGC 1514) have been shown to be binary but in other cases there is no evidence that the central star is binary despite extensive investigations. For example, M 1-2 (VV 8) has no directly detectable binary nature according to several studies (Adams 1975, Zipoy 1975, Lutz 1977b,c) since O'Dell's (1966) investigation of radial velocities in this luminous G-type central star.

The relationships between peculiar central stars and late-type emission line objects such as symbiotic stars, slow novae, SRd variables and RV Tauri stars unknown and should be studied by spectroscopic and photoelectric programs in the visible and in the infrared. Some of the peculiar central stars, be they single or binary may be related to the protoplanetary phase of evolution. Objects such as V 1016 Cygni and HBV 475 may also fall into the protoplanetary nebula category. Various objects that are possible protoplanetaries are being reported. Stover and Sivertsen (1977) obtained a spectrum of an object which brightened from 16 mag to 12 mag between April and September 1976 (Dokuchaeva 1976). The spectrum shows emission lines which are characteristic of a planetary nebula and a late-type continuum. Certainly much interesting work remains to be done on the subject of peculiar central stars and related objects.

TABLE III
Characteristics of some peculiar central stars

M 1-2	133-8°1	stellar	G2 Ib	H I, (O III), (Ne III)
IC 2120	169-0°1	25"	G met.defic.	H I, (O II)
NGC 2346	215+3°1	30"	A2 V	H I, (O III), (Ne III)
NGC 3132	272+12°1	30"	AO V	H I, (O II), (O III)
Cn 1-1	330+4°1	stellar	GO II	H I, (O III), (Ne III)
Bl 3-11	1-0°1	stellar	FO II	H I, He I, Fe II
T 53		stellar	KO III	H I, He II, (Ne III), (O III)
He 2-467	63-12°1	stellar	G5 II	H I, He I, He II

6. SUMMARY

There are many unanswered questions. For example, the reason why central stars exhibit such a variety of spectra is not clear. Also unknown is whether a given central star exhibits all the different types of spectra during its evolution to the white dwarf stage or whether the spectral appearance is determined primarily by some other factor such as the star's mass. Any relationships between parameters of the central stars (e.g. spectral features, temperature) and parameters of the nebulae (e.g. size, chemical composition) have yet to be well-established. Some of the difficulty in resolving these problems may be a result of not all planetary nebulae being of the same population type. Another problem with central stars is the difficulty of understanding why different methods of temperature determination yield different values for temperature. The occurrence of binary and peculiar central stars are factors which must be considered in working out the evolutionary

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scenario for planetary nebulae. New ideas on these problems will come forth during this symposium.

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DISCUSSION

Finzi: I would like to ask whether the peculiar central stars fit in the main sequence. To what extent could the observed periods of binaries represent a selection effect?

Lutz: Most of their absorption spectra appear to be characteristic of luminous stars. This may be a shell-star phenomenon in some cases. The central star of NGC 2346 appears to be a main sequence A star. So far the observations have strongly favored the discovery of short period binaries.

Cudworth: Improved proper motions for central star and companion in NGC 6853 indicate the motion is common. The companion is near 17th magnitude, is yellow or red, and is 6 arc seconds from the central star. I strongly encourage observers who can do so to get spectra and photometry of this companion to obtain another solid distance as in NGC 246.

Tylenda: It seems that many central stars are binary systems and some of them are even close binary systems. It is well-known that there is a good chance for mass transfer in close binaries. If so, then an accretion disc can be formed around the compact companion. The temperature of inner parts of the disc can easily exceed 10^4°K, but the radiation spectrum produced by the disc is flatter than that emitted by a single star. Moreover, the boundary layer between the disc and the accreting star can be hotter than 10^5°K. Thus, if the accretion is important, the ionizing radiation should be significantly different from that calculated for single stars. This may have some important effects on the ionization structure of nebulae.

Pottasch: There is some evidence that the luminosity at the top of the Harman-Seaton sequence has been overestimated, and that the initial increase of luminosity with increasing temperature does not exist. First of all, it is clear from the ANS measurements that in the previous work the bolometric correction has been overestimated, sometimes by as much as an order of magnitude. This affects especially the O, Of, and continuous spectra stars whose temperatures have been taken to be the HeII Zanstra Temperature and which were mostly used to define the maximum luminosity region. A second contributor is the use of the magnitude

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measurements of the central stars by Vorontsov-Velyaminov in the work of O'Dell and Seaton. The magnitudes are sometimes considerably too high, which means the luminosities should be lowered by the same amount since these magnitudes were used to define the entire scale.

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