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PECULIAR STARS

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"Tut, tut, child," said the Duchess. "Everything's got a moral if only you can find it."

—Lewis Carroll, *Alice in Wonderland*, Ch. 9.

Introduction

It is one of the fundamental cornerstones of astronomy that the majority of the stars can be classified into a few basic sequences of types. The most important of these is the main sequence, stretching in the Hertzsprung–Russell Diagram from O stars of absolute visual magnitude -4 through B, A, F, G and K to M stars fainter than absolute magnitude $+10$. Stars of the main sequence are generally known also as dwarfs. A second sequence is the giant sequence, comprising stars of absolute magnitudes between about -1 and $+1$, and stretching from spectral type G8 through type K into type M. In addition to the giants and dwarfs there are a number of supergiants which may for the present purpose be regarded as normal stars. There is a small proportion of the stars which cannot be classified into dwarfs, giants or supergiants, and such stars we regard as peculiar stars. Stars are at the present time not regarded as peculiar merely because they happen to be of an unusual size or have an unusual surface temperature; they must have an unusual chemical composition, show unexpected emission lines, have some kind of variability or be associated with other stars or with nebulae in a peculiar way. The existence of peculiar stars was first realized by the Harvard astronomers, especially by Miss Maury. It was found that not all the stars fitted into one sequence (the main sequence). At a later date the existence of giant and supergiant stars was discovered, and as our knowledge of astrophysics developed it was shown that many of the peculiar stars which had been discovered were giants and supergiants. Their spectroscopic peculiarities could be explained in terms of their sizes, correspondingly lower atmospheric pressures, and lower surface temperatures compared with approximately similar dwarf stars. These are not now regarded as peculiar. All this is considered independently of any evolutionary processes which may turn main sequence stars into giants and supergiants, provided that these processes have not affected the stellar spectrum otherwise than through variations in the temperature and pressure of the atmosphere of the star.

Types of Peculiar Stars

When full allowance has been made for the effects of atmospheric temperatures and pressures there remain an appreciable number of stars which must be regarded as peculiar. Table I contains a classification of most types of peculiar stars. There is one important problem in the classification which deserves some discussion at the outset. A number of stars of high velocity—giants, subdwarfs, and others—have long been known to exhibit peculiarities. In recent years these stars have been shown to be members of Baade's Population II, and from the point of view of Stellar Populations they should be regarded not as peculiar stars but as normal stars of Population II. It now appears probable that there exists

TABLE I

Classification of peculiar stars

Group	Type	Example
I	Wolf–Rayet stars	
	(a) Carbon sequence	HD 192103
	(b) Nitrogen sequence	HD 151932
II	Emission-line stars	
	(a) Of stars	9 Sagittae
	(b) P Cygni stars	P Cygni
	(c) Be stars	χ Ophiuchi
III	Shell stars	ζ Tauri
IV	Peculiar A stars	
	(a) Peculiar A stars	HD 125248
	(b) Metallic line stars	63 Tauri
V	White dwarfs	Sirius B
VI	Carbon stars	Y Canum Venaticorum
VII	S stars	π^1 Gruis
VIII	Symbiotic stars	CI Cygni
IX	Hydrogen-poor stars	HD 124448
X	Pulsating stars	
	(a) Classical cepheids	δ Cephei
	(b) Long-period variables	o Ceti
	(c) β Canis Majoris stars	12 Lacertae
	(d) Semi-regulars and others	RV Tauri
XI	Exploding stars	
XII	Miscellaneous	
	(a) Carbon-poor stars	HR 885
	(b) Lithium stars	WZ Cassiopeiae
	(c) Intermediate-carbon stars	GP Orionis
	(d) Ba II stars	ζ Capricorni
XIII	Stars not intrinsically peculiar	
	(a) Binary systems	RW Tauri
	(b) T Tauri stars	T Tauri
	(c) Interacting with nebulosity	SU Aurigae
XIV	Population II stars	
	(a) G-K giants	δ Leporis
	(b) Carbon stars (CH stars)	HD 201626
	(c) Subdwarfs	HD 140283
	(d) Faint blue stars	$+28^\circ$ 4211
	(e) Cluster cepheids	RR Lyrae
	(f) Long-period cepheids	W Virginis

a continuous range of stars and stellar spectra from extreme Population I to extreme Population II. We should therefore regard normal stars as including variations of Population as well as of atmospheric temperature and pressure. Our knowledge of Population II stars is in its infancy (this may apply to Population I as well!); it is still convenient to regard Population II stars as peculiar relative to the conventional normal stars of Population I and they are separately listed as such in Table I.

I. Wolf–Rayet Stars

These strange stars were discovered by Wolf and Rayet in 1867; about 100 are now known, the apparently brightest being γ Velorum. They are present in some spectroscopic binaries and eclipsing variables. Some are probably members of young clusters, associations and aggregates of stars. The nuclei of planetary nebulae, though probably not Wolf–Rayet stars, show many similar spectral features. They are distinguished spectroscopically by the emission bands of very great width which are present in their spectra; these widths

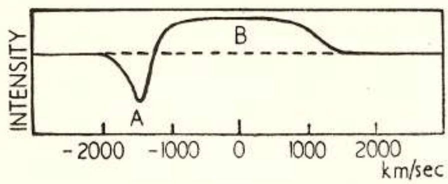

FIG. 1.—*Profile of the line* λ 3889 *of He* I *in the Wolf–Rayet nitrogen sequence star HD* 192163. *Note the absorption A on the violet (negative velocity) edge of the broad emission feature B.* (*Adapted from C. S. Beals*, Pub. Dom. Ap. Obs., **6**, 95, 1934.)

may be as much as 100 A. A typical line profile is shown in Fig. 1. Many of these bands have absorption on their violet edges. Most Wolf–Rayet stars fall into one of two classes:

(*a*) carbon sequence, in which bands of several times ionized carbon and oxygen are present in the spectrum but bands of ionized nitrogen are weak or absent;

(*b*) nitrogen sequence, in which bands of several times ionized nitrogen are present and those of carbon and oxygen are weak or absent.

A few are known which combine the features of the two groups. Hydrogen and helium are present in both sequences, hydrogen being relatively weak and He II very strong. The bands of oxygen are due to O III, O IV, O V and O VI, those of nitrogen to N III, N IV and N V and those of carbon to C II, C III and C IV. The widths of the emission bands vary from star to star, and for a given star from atom to atom. The bands requiring higher excitation generally have smaller widths. This suggests that the atmospheres of the Wolf–Rayet stars are stratified. Further, if the widths of the bands are interpreted as due to Doppler effects, an outward acceleration is implied. This led to C. S. Beals' interpretation of Wolf–Rayet stars as stars which are ejecting atoms from their surfaces at high speeds. The absorption at the violet edge of many of the emission bands is explained as absorption by material thrown off by the star and moving in the line of sight (Fig. 2). The temperatures of the Wolf–Rayet stars are very uncertain; values ranging between 7 000 °K and 100 000 °K have been obtained by various methods. The lack of agreement between the results is probably due chiefly to departures from thermodynamic equilibrium in the Wolf–Rayet atmospheres; the excitation temperatures generally average about 50 000 °K. The visual absolute magnitudes range from -1 to -5 and average -4, somewhat fainter than the majority of O stars.

The eclipsing variable V 444 Cygni (HD 193576) has proved to be one of the most interesting stars in the sky and one of crucial importance for the study of Wolf–Rayet stars. Discovered in 1939, it has a period of 4·2 days and consists of a normal B1 star and a Wolf–Rayet nitrogen sequence star classified as WN 5. Detailed studies of the light and velocity curves have been made, and great difficulties have arisen in their interpretation. For example, the primary minimum in the light curve is twice as wide as the secondary minimum. It is hard to see how this could arise from purely geometrical eclipses. There are also difficulties in understanding the velocity curves. The most reasonable explanation seems to be that the Wolf–Rayet star is surrounded by a large non-luminous atmosphere which absorbs the light of the B1 star when the latter star is behind the atmosphere, but which shows no eclipse effect when the B1 star is in front of the extended atmosphere. This explains the differences in the widths of the light curve minima. Electron densities in the atmosphere ranging from 10^{12} to 10^{9} electrons/cm^{3} are required. This explanation is apparently confirmed by the broadening and weakening by electron scattering of the B1 star lines during primary minimum. From the study of HD 193576 the mass of the WN 5 star is 11 $M_{\odot}$, the radius of the core of the WN 5 star 2·1 $R_{\odot}$, and the radius of the WN 5 star envelope 16 $R_{\odot}$. The whole binary system may possibly be surrounded by a diffuse atmosphere.

We see that to explain Wolf–Rayet stars we must have an outwardly moving shell of gas in which the emission lines are formed, and outside this a large non-luminous scattering atmosphere. These gaseous masses will undoubtedly be turbulent, and this can contribute to the problem of atmospheric support. The details of the physical processes involved in the Wolf–Rayet atmospheres are still not understood.

II. Emission-Line Stars

The Wolf–Rayet stars are among the hottest stars known. Coming to those with somewhat lower surface temperatures we find a group of hot peculiar stars which show emission lines in their spectra and which may be subdivided into Of stars, P Cygni stars and Be stars.

(*a*) *Of stars.*—These are a small group of objects which generally resemble ordinary O stars; the O and Of stars form groups which merge into each other. The Of stars have emission lines of He II λ4686 and N III λ4634/40; the symbol f was introduced by the Victoria observers to denote these characteristics. About 13 per cent of all O stars are Of stars. It is not certain whether there is any significant difference in luminosity between normal O stars and the Of stars; there is some evidence that the Of stars are a little brighter, but other types of stars are known in which the presence of emission lines is not a criterion for high luminosity. In addition to the He II and N III lines mentioned, some Of stars show additional emission lines, which may include Hα and C III λ5696. Special physical mechanisms are required to explain the emission lines of He II, C III and N III, for these three lines are the only lines of these elements observed in emission. The He I absorption lines appear normal, suggesting that the outer atmosphere which gives rise to the emission lines cannot extend far from the stellar surface. No forbidden lines have been observed. The emission lines of He II, N III and C III have been found in the spectra of O-type supergiants. Recent work has shown that the emission lines in O and Of stars have extended wings and these may indicate that processes similar to those in Wolf–Rayet stars contribute to the formation of the emission lines.

(*b*) *P Cygni stars.*—The essential feature of P Cygni stars is the presence of one or more emission lines bordered on the violet edge with absorption lines (Figs. 2 and 3). There are in addition all the usual absorption lines occurring in normal O and B stars. P Cygni profiles are usually seen in a few of the hydrogen lines, some helium lines, and sometimes in lines of other elements. The P Cygni line profile may be superposed on an underlying broadened absorption profile (Fig. 3). The P Cygni stars in many ways resemble

Wolf–Rayet stars, and continuous ejection of material has been suggested as the source of the material in which the emission lines are formed. Many of the P Cygni stars are very bright, with visual absolute magnitudes of -7, and even -9. Those of lower luminosity have underlying broadened lines which show that the stars are rapidly rotating, and rotational instability may contribute to the ejection of material.

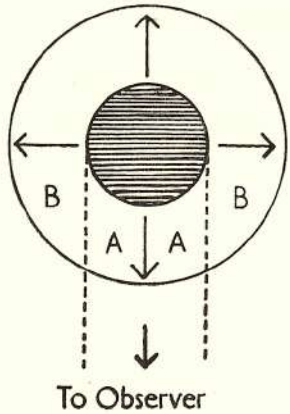

FIG. 2.—*The formation of an absorption edge in stars with expanding atmospheres. The observed emission above the continuum (B in Fig. 1) arises in the regions BB of the atmosphere. The absorption (A in Fig. 1) arises in the region AA when the underlying stellar continuum passes through the expanding atmosphere, the expansion leading to a Doppler shift to the violet relative to the centre of the line.*

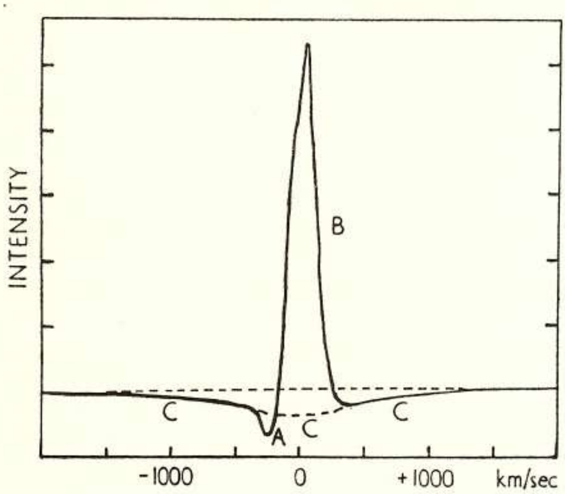

FIG. 3.—*Profile of the Hα line in the P Cygni type star HD* 190073. *A strong emission line B and a violet-shifted absorption A are superimposed on an underlying greatly broadened stellar absorption line CCC.*

(*Adapted from C. S. Beals*, Pub. Dom. Ap. Obs. **9**, 1, 1951.)

(*c*) *Be stars.*—These stars resemble normal B stars except for the occurrence of emission lines of hydrogen, and occasionally of Fe II and other atoms. There are no forbidden emission lines observed in Be stars. Over 1000 Be stars are now known; their frequency of occurrence is of course much lower than that of normal B stars. There does not appear to be any significant difference in luminosity between Be and normal B stars. The one important difference, apart from the emission lines, is that the Be stars show much larger rotational velocities even than those shown by normal B stars; in general their spectrum lines are greatly broadened. Rotational surface velocities of up to 500 km/sec have been observed in Be stars. The widths of the emission lines are proportional to their wave-length, and this suggests a Doppler effect broadening. Some Be stars have narrow lines, and these are presumably seen pole-on. Probably the Be stars are rotationally unstable, and have formed or are forming gaseous rings around their equators. The bright lines are probably formed in these rings. These rings may not be stable; changes are observed in the intensities of the emission lines. The hypothesis of gaseous rings is well confirmed by the peculiarities found in certain spectroscopic binaries.

III. Shell Stars

This type of star has been extensively discussed; among brighter examples may be mentioned ζ Tauri, Pleione and 48 Librae. Shell stars occur among types B and A, the shell star of latest type known being 14 Comae, the star being A5 and the shell lines corresponding to about F2. Shell stars show broadened lines of all the usual elements observed in B or A stars. In addition, the hydrogen lines have very sharp absorption cores, superposed on broad underlying hydrogen lines, and emission wings may also be observed. A good example of this is illustrated in Fig. 4. The absorption lines of ionized metals tend to be sharp.

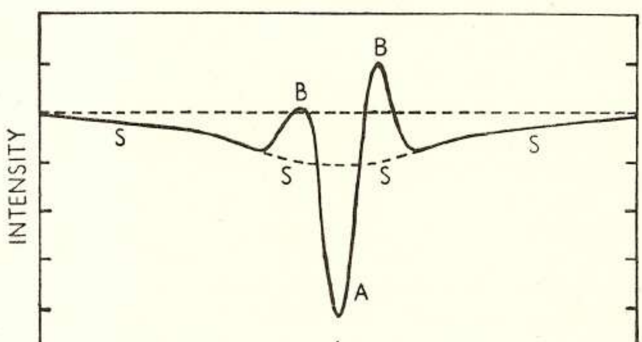

Fig. 4.—*Profile of the Hβ line in the shell star* 48 *Librae in* 1953. *The underlying star has an apparent velocity of rotation of about* 400 *km/sec. For explanation of notation see Fig.* 5. (*Adapted from A. B. Underhill,* Pub. Dom. Ap. Obs. **9**, 363, 1953.)

He I lines are mostly weak and diffuse, but some lines of He I (λ 3888 and λ 3965) may be strong and narrow. The broadened lines of hydrogen and other elements are produced in the atmosphere of a rapidly rotating star (Fig. 5). The emission, if present, arises in a shell of gas; the narrow absorption cores of the hydrogen lines and the sharp lines of He I and the ionized metals arise by the absorption of photospheric light by that part of the shell which lies in the line of sight.

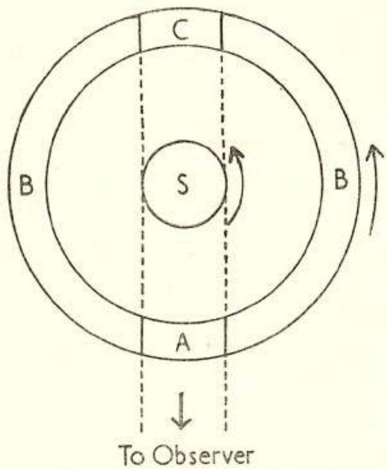

FIG. 5.—*Origin of complex line profiles in shell stars. The star S rotates rapidly, producing very broad absorption lines (SSSS in Fig. 4). The shell rotates relatively slowly. Light from the star passing through the shell at A gives rise to a central absorption feature (A in Fig. 4). The shell itself emits light, and that from the regions B appears as emission wings (B in Fig. 4) bordering the central absorption.*

Because of the distance of the shell from the star the shell must be rotating more slowly than the stellar surface, and in any case only a small part of the shell intercepts starlight in the line of sight, so that lines produced in the shell are not appreciably broadened by rotation. The degree of ionization in the shell is lower than that in the star. Some shell stars show changes, particularly in the intensities of any emission lines, and there are sometimes small irregular fluctuations in light. The densities in the shells have been estimated from the number of Balmer lines visible; values of 10^9 to 10^{13} electrons/cm^3 have been obtained, compared with 10^{15} in a typical stellar atmosphere.

IV. Peculiar A Stars

Most A stars have spectra showing strong lines of hydrogen and very weak metallic lines. During the early Harvard work on spectral classification it was found that a few stars which would be classed as type A on the basis of the hydrogen and Ca II(K) lines had metallic lines of unusual strength. Sometimes these lines belonged to a few particular elements, manganese, silicon, europium, chromium or strontium. These stars became generally known as peculiar A stars. Later other peculiarities of these stars were observed, and they were subdivided into spectrum variables, magnetic stars, and so on. In some stars the strengthening of the spectrum lines was not confined to one or two particular elements, but nearly all lines of all the metallic elements were strengthened. These stars are known as metallic-line stars.

(*a*) *Peculiar A stars.*—As mentioned above, these are distinguished by the abnormal strengths of the lines of some (ionized) elements, other lines having normal intensities. For example, α Andromedae shows strong Mn II lines, and has been called a "manganese star", θ Aurigae shows enhanced Si II, γ Equulei shows enhanced Sr II and 78 Virginis shows enhanced Cr II and Eu II. Peculiar

A stars first appear at about type B8 or B9, and extend throughout type A and into type F as far as F2; at least 10 per cent of all A stars are peculiar. The enhancements of the spectral lines are certainly not due to high luminosity. The absolute magnitudes of the stars are fairly well known; they are slightly above the main sequence. They can occur in galactic clusters and as components of binary systems. Some peculiar A stars are spectrum variables; many others appear not to vary. For example, in HD 125248 lines of Eu II and Cr II vary out of phase with a period of 9·3 days; Cr I and Cr II vary together, so do Eu II and Eu III. The rest of the spectrum is invariable. Many spectrum variables show light variations, with amplitudes of two-tenths of a magnitude or less; phase relationships between light and spectra are different for different stars. It has often been thought that the peculiar line intensities are due to abundance anomalies. This has recently been demonstrated by E. M. Burbidge and G. R. Burbidge, who analysed the spectrum of α^2 Canum Venaticorum and HD 133029. They conclude that calcium is underabundant by a factor of 30, that manganese, chromium, strontium and other metals are overabundant by factors of 5 to 25, and that the rare earths (La, Ce, Pr, Nd, etc.) are overabundant by a factor of 600 on the average. Although there are difficulties in these abundance determinations the differences from normal solar abundances are so large that their reality can hardly be in doubt.

The most important discovery relating to peculiar A stars was made by H. W. Babcock in 1947. He showed that some peculiar A stars have intense magnetic fields in their atmospheres, and he devised an analyser which can measure these fields by means of the Zeeman effect. In his 1958 catalogue Babcock records attempted observations of the Zeeman effect for a selected list of 338 stars. 89 of these have sharp spectral lines and show magnetic fields, 61 have sharp lines and show no evidence of magnetic fields as great as 500 gauss. 66 stars have broader lines and show some evidence of Zeeman effect, 122 have lines too broad to permit Zeeman measurements. All the sharp-line peculiar A stars examined showed magnetic fields; all the magnetic fields are variable to a greater or lesser extent, some showing reversal of polarity. The magnetic variations are synchronous with the spectrum variations in periodic spectrum variables. There is no adequate theory of magnetic fields in stars. The consensus of opinion is that the fields arise in localized regions of the stellar surfaces rather than as general fields. It is not clear to what extent the observed variations of the magnetic fields are related to the rotation and other properties of the stars. It has been suggested that the anomalous abundances are the products of nuclear reactions proceeding in the surface layers of the stars. Such reactions are not possible in normal stars, but in the presence of strong magnetic fields particles may be accelerated to high energies and nuclear reactions become possible.

(*b*) *Metallic-line stars.*—These stars show a well-developed metallic-line spectrum which is a good match for a late A or an early F star, hydrogen lines which are slightly stronger than expected on the basis of the metallic lines, and a Ca II (K) line very much too weak for the spectral type indicated by the other metallic lines. The Ca II (K) line corresponds in strength to a normal early A type star. The metallic lines probably give the best indication of temperature; the equivalent spectral type from the metallic lines corresponds to the observed colour indices. About 100 of these stars are known outside clusters, and in addition about 30 are members of galactic clusters. Among the brighter metallic line stars may be mentioned Castor B, δ Capricorni and ζ Ursae Majoris B. The stars have absolute visual magnitudes of about $+1$ or $+2$, they lie slightly above the main sequence in the Hertzsprung–Russell diagram. Detailed studies of high dispersion spectra of metallic-line stars have been made by J. L. Greenstein and others, and there are apparent abundance anomalies of scandium, sodium, calcium, strontium and zinc. No satisfactory explanation of these abnormalities has yet been found. Seven metallic-line stars are known to possess magnetic fields which seem to be irregularly variable. In others no field is seen. It is not yet clear to what extent the peculiarities of the metallic-line stars are due to physical conditions (including magnetic fields) and whether we must postulate surface nuclear reactions as the cause of abundance anomalies.

V. White Dwarfs

It is not certain whether one should regard the white dwarfs as peculiar stars, for they may be a perfectly normal stage in stellar evolution. But their spectra do not fit into the normal sequences of dwarf, giant and supergiant, and for that reason they are included in this article under the heading of peculiar stars.

White dwarfs are both apparently and intrinsically faint, and so are hard to observe. The first white dwarf to be discovered spectroscopically was 40 Eridani B, found by W. S. Adams in 1914; Adams demonstrated the white dwarf nature of Sirius B in 1915 and van Maanen found a third in 1917. Others were subsequently found by searching among stars of large parallax or large proper motion; some have recently been discovered using three-colour photoelectric photometry. By 1939 some 18 were known, and the total known in 1958 was about 200, of which about 80 are well-observed. A number of white dwarfs occur in binary systems (the best known being Sirius B) and there is one binary, LDS 275, in which both components are white dwarfs. In spite of their name the white dwarfs in fact cover a range of colour, in the photoelectric system of Johnson and Morgan from $B-V=-0{\cdot}2$ to $+0{\cdot}6$; redder white dwarfs are very difficult to find. Their $U-B$ colour indices are mostly much more negative than ordinary main sequence stars of the same $B-V$ colour, that is, they show an apparent excess of ultraviolet radiation. Absolute magnitudes have been obtained for some white dwarfs directly from their trigonometric parallaxes, for others statistically from their proper motions. The absolute visual magnitudes vary from $+10$ (for colour index $B-V=-0{\cdot}2$) to $+14$ (for $B-V=0{\cdot}6$).

Many white dwarf spectra show only very broad hydrogen lines, broader and stronger than ordinary dwarf A stars. Some of the bluer stars show He I lines, and the hydrogen lines in these are usually relatively weak. The redder white dwarfs often show lines of Ca II, Mg I and Fe I, and little else. Some white dwarfs of various colour indices show continuous spectra, apparently devoid of all lines; the conclusion is inescapable that these are hydrogen-poor stars. There are many other spectral peculiarities in white dwarfs; the observations of Greenstein have shown how many strange features remain to be explained. There must be parameters other than temperature and pressure affecting the spectra; probably the abundance ratios of hydrogen, helium and metals are involved.

Estimates of the surface temperatures of the white dwarfs have been made from their colours, and the derived values range from 5 000 °K to 20 000 °K. Combining these with the absolute magnitudes of the stars leads to estimates of the radii; they range from 0·006 to 0·024 solar radii, or about 0·6 to 2·5 Earth radii. The masses of three white dwarfs are known from binary star orbits: Sirius B 0·98☉, Procyon B 0·4☉ and 40 Eridani B 0·43☉. The average value of the observed radii is 0·013 solar radii; combining this with the theoretical mass–radius relation yields an expected average mass of 0·56 solar masses, an average mean density of $3{\cdot}5 \times 10^5$ gm/cm³ and a central density (based on theoretical models) of $2{\cdot}6 \times 10^6$ gm/cm³, or say 40 tons per cubic inch. The discovery of the existence of these enormous densities was a major surprise in astrophysics.

The theoretical explanation of the structure of the white dwarfs represents a triumph of statistical mechanics. The introduction of the correct quantum theoretical statistics (Fermi–Dirac Statistics) into statistical mechanics in 1926 led R. H. Fowler to a theory of the white dwarfs. He showed that under the conditions prevailing in white dwarfs quantum theory leads to a behaviour of matter very different from that of ordinary gases under laboratory conditions. The matter becomes *degenerate*, and obeys an equation of state different from the ordinary gas laws. The theory has been developed in great detail, especially by Chandrasekhar. There are two main results of the theory. Firstly, there is (in the limiting case of complete degeneracy), a unique relation between the mass of a white dwarf and its radius. Secondly, there is an upper limit to the mass of a completely degenerate star. The observed masses and radii mentioned above are in good agreement with the mass–radius relation provided that it is assumed that their interiors are devoid of hydrogen. Accepting this, the maximum mass of a white dwarf predicted by the theory is 1·4 solar masses. The known white dwarf masses are well below this limit. This limit has an important bearing on theories of stellar evolution. Many of the heavier stars formed early in the life of the Galaxy have burnt themselves out. It is not certain what has been their fate, but if they have become white dwarfs, they must have undergone a substantial loss of mass at some evolutionary stage. Little is known of the processes by which this could happen. When once the stars have become white dwarfs, they can have no remaining nuclear energy sources, and they probably radiate by cooling. Their low luminosity indicates that cooling is a slow process; the redder white dwarfs are clearly very long lived, and may indeed be almost as old as the Galaxy. The problem of Sirius may also be mentioned. Sirius A is a young star; Sirius B is a white dwarf. If Sirius B has evolved from a main-sequence star of the same age as Sirius A it must have been more massive than Sirius A; Sirius B is now less massive than Sirius A, and must therefore have lost mass. This is further evidence for the loss of mass from stars during their evolution.

White dwarfs are of interest in the testing of the theory of relativity. Einstein predicted that light from a star would be red-shifted by a calculable amount compared with the laboratory wave-length. The classical case is Sirius B, for which agreement between theory and observation has been claimed, but for which the observations are difficult. Recent observations of 40 Eridani B yield a red-shift, in velocity units, of $+21(\pm 4)$ km/sec. Einstein's theory, with the best available values of the stellar mass and radius, predicts $+16$ km/sec The agreement is as good as we can reasonably expect.

VI. Carbon Stars

Carbon stars were discovered early in the development of stellar spectroscopy. Secchi in 1866 outlined the first system of spectral classification; his classes III and IV were red stars, the former with flutings shaded to the red and the latter with flutings shaded to the violet. The former are now classed as M or S stars and the latter as carbon stars. The carbon stars were classed as types R and N in the Henry Draper system and these types are still in general use, although more recently use has been made of a C classification due to P. C. Keenan and W. W. Morgan. Carbon stars show strong bands of C_2, CH and CN, and TiO and ZrO are generally invisible. Bands of NH are also present. A famous group of band-heads at $\lambda 4050$, also present in comets, has been shown to be due to triatomic C_3, a linear molecule. This identification was made by examining the bands produced by a mixture of the carbon isotopes C^{12} and C^{13}; there are six possible types of linear triatomic molecule C_3 which can be formed from mixed carbon isotopes, and the $\lambda 4050$ bands have precisely six heads, as required if their origin is C_3. There is another set of bands in the blue–green spectral regions; these long resisted identification, but recently B. Kleman has suggested that they are due to SiC_2. One of Kleman's spectrograms is reproduced on Plate 23 (A).

All the carbon stars so far discovered are either giants, or in a few cases supergiants; no dwarf carbon stars are known. The mean visual absolute magnitudes have been determined from radial velocities and proper motions, values of $-0{\cdot}5$ and $-1{\cdot}8$ being obtained for classes R and N respectively. Many carbon stars are long-period or irregular variables.

An important feature of the spectra of some carbon stars is the occurrence of the isotope C^{13} of carbon. This isotope was first identified in 1929 by R. F. Sanford, who showed that a band head at $\lambda 4744$ was due to the diatomic molecule $C^{12}C^{13}$, the molecule $C^{12}C^{12}$ producing a band head at $\lambda 4737$. D. H. Menzel found a weaker band at $\lambda 4752$ and identified it as due to the molecule $C^{13}C^{13}$. It was at once apparent that the bands involving C^{13} were stronger in many stars than they were in the laboratory, and presumably C^{13} must be more abundant relative to C^{12} in these carbon stars than in terrestrial carbon samples. Many isotopic analyses of terrestrial carbon samples have been made, and an average ratio $C^{12}/C^{13} = 90 \pm 2$ has been found, with occasional variations of a few per cent; none has been found with a much smaller value of this ratio. Searches for C^{13} in the solar atmosphere have proved unsuccessful; the conclusion is that $C^{12}/C^{13} \geqslant 36$. A. McKellar studied many carbon stars, and for twelve for which the analysis could be made found a mean ratio $C^{12}/C^{13} = 3{\cdot}4$. Still more surprising, however, was his result that not all carbon stars showed the C^{13} isotope, and for three stars $C^{12}/C^{13} \geqslant 30$, 60 and 70. Among these, HD 182040 shows other peculiarities (see Section IX) and the others are CH stars (see Section XIV (*b*)).

The immediate cause of the spectral peculiarities of the carbon stars is undoubtedly the presence of an unusually high carbon/oxygen ratio. In M stars carbon is less abundant than oxygen. Most of the carbon is used up in forming the stable and astrophysically unobservable CO molecule, and surplus oxygen is available for the production of TiO. In the carbon stars carbon is probably more abundant than oxygen; all the oxygen is used up in forming CO and surplus carbon is available for the production of C_2, CH and CN. One cannot conclude that all the carbon stars have the same carbon/oxygen ratio; this ratio probably has a range of values in different stars. The origin of the excess carbon is not understood; C^{12} may be produced by helium burning in a hydrogen-deficient core, but this is a possible explanation only if a mechanism can be found for transporting the carbon to the outer parts of the star. The abundant presence of the C^{13} isotope further requires that the material must have undergone a carbon–nitrogen cycle subsequent to the production of the excess C^{12}.

VII. S Stars

The classification S was introduced by P. W. Merrill and standardized by the International Astronomical Union in 1922 as an addition to the then existing Henry Draper classification. A number of stars were known which broadly resembled M stars, but in which zirconium oxide bands were more prominent than those of titanium oxide. Stars are known with various relative strengths of TiO and ZrO, and there may even be a continuous sequence of stars ranging from S to M. In the best examples of S stars the ZrO bands are stronger than the TiO bands. A typical S star is π^1 Gruis. Many S type stars are long-period variables, including R Andromedae and R Geminorum. More than a hundred S type stars are known, but only a few have been studied in detail. In addition to ZrO and TiO, bands of YO, LaO and SiH are present in S type spectra. Some absorption lines are enhanced relative to K or M stars, for example Ba II, Sr I, Sr II, Zr I, Y II, and many of the lines of the rare earths also show enhancement. No trigonometrical parallaxes are available, and the spectral peculiarities render application of the normal spectroscopic luminosity criteria hazardous. No interstellar lines are visible because of blending with star lines. M. W. Feast showed that π^1 Gruis had a normal companion star which, if the pair was a real physical double, led to an absolute magnitude of the S star between -1 and 0. P. C. Keenan studied the proper motions of 17 S stars and obtained a mean absolute magnitude of -1. It thus seems that S stars are normal giants; no supergiant or dwarf S stars have yet been discovered. S stars seem to be less frequent than carbon stars, but this may be partly because they are harder to recognize; they form a low velocity group and have a galactic distribution similar to carbon stars.

Perhaps the most remarkable discovery concerning S stars was made by P. W. Merrill in 1951. Element number 43 in the Periodic Table was first identified in 1937 as an artificial product of neutron bombardment of molybdenum and it was named technetium. No completely stable isotope is known; the most nearly stable has a half-life of 200 000 years. It had not been found in nature up to 1951. Merrill found the three strongest lines of neutral technetium in the spectra of R Andromedae, R Geminorum and other S stars. The lines can be seen in the spectrum of R Andromedae on Plate 23 (B). This identification must be considered well-established, and we must seek an explanation.

The range of relative strengths of ZrO and TiO in S and M stars prompts the question whether a range of physical conditions alone are a sufficient explanation. Dissociation theory has been applied to this problem, and although some part of the variations in line and band intensities may be due to differing physical conditions it seems as if we must look to real variations in the chemical abundances of zirconium, technetium and the rare earths to provide an adequate explanation. Processes have been suggested which enable these heavier elements to be built up from elements not heavier than iron by means of successive neutron-captures and beta-decays.

VIII. Symbiotic Stars

Symbiotic stars were named and have been discussed extensively by P. W. Merrill. The study of these stars really began with the work of H. H. Plaskett on Z Andromedae. Spectrograms of this star taken at Victoria showed the presence of high-excitation emission lines of the kind found in gaseous nebulae superposed on a continuum at the relatively low temperature of 5200 °K. Subsequently Hogg and Merrill identified bands of TiO in the spectrum. This feature—the superposition of a high-excitation emission line spectrum on a low temperature absorption spectrum—is the essential characteristic of symbiotic stars, and explains the term *combination spectra* applied to their spectra.

A recent catalogue by Bidelman lists 23 of these stars. They include Z Andromedae, R Aquarii, CI Cygni, BF Cygni, AX Persei and AG Pegasi. The emission lines generally include hydrogen, He I, He II, Fe II, Si II, and other permitted lines, such forbidden lines as [O III], [Ne III], [Fe II] and [Fe III], and sometimes some highly excited lines, for example [Fe X]. The absorption spectrum includes in addition to TiO all the usual low-excitation metal lines such as Fe I. Many of the symbiotic stars show variations in light (they are named according to the usual variable star system) of an irregular nature; there is evidence in some cases of underlying periods of a few hundred days. Recent three-colour photometry has shown that the $B-V$ (blue-visual) colour indices of these stars corresponds to types G or K, while the $U-B$ (ultraviolet-blue) colour indices correspond to type B. The radial velocities of the stars are also variable. Two symbiotic stars have been shown by H. W. Babcock to have variable magnetic fields.

The simultaneous occurrence of high and low excitation features in these objects suggests that there is considerable stratification of some kind. The most obvious explanation is that the systems consist of an M type giant, probably an irregular variable, together with a hot early type variable companion, both stars being immersed in a large nebulous envelope whose density is intermediate between planetary nebulae and the shells of shell stars. It is, however, by no means certain that the symbiotic stars are binaries. Neither mutual eclipses nor orbital velocities have been extracted from the complexity of light fluctuations and velocity variations; but orbital velocities would be difficult to separate from the velocities of erupting gases, so that failure to detect orbital motion is not conclusive proof of its absence. Another suggested explanation is that symbiotic objects are a single star surrounded by a large distant cool shell of relatively high density (compared to most extended envelopes of stars). In some cases the forbidden line $\lambda 4959$ of [O III] has been weakened relative to its companion $\lambda 5007$, and this is thought to be due to absorption by a TiO band-head at $\lambda 4957$. This implies that the TiO absorption takes place outside the region where the forbidden lines are formed. For the present the symbiotic stars remain very much of a mystery.

IX. Hydrogen-Poor Stars

These are very rare objects, recognized by the very great weakness of hydrogen in their spectra. So few are known that the stars of this group must be considered as individuals.

HD 124448.—This star was discovered by D. M. Popper. No absorption or emission lines of hydrogen are visible, and no Balmer discontinuity is present, The helium lines are stronger than in any other star, and helium discontinuities are seen in the ultraviolet; the great strength of these helium features suggests great excess of helium in the stellar reversing layer. Other elements (oxygen, carbon, nitrogen, neon, etc.) are present and, apart from the absence of hydrogen and enhancement of helium, the star resembles a B2 dwarf. Even a small amount of hydrogen would render the helium discontinuities invisible, so that a real deficiency of hydrogen seems to be the only possible explanation of the observed spectrum. HD 168476, another star of this type, was found by A. D. Thackeray and A. J. Wesselink. HD 160641, found by W. W. Morgan and discussed by W. P. Bidelman, is also similar to Popper's star; it appears to be still hotter, most nearly resembling an O star. Interstellar lines in its spectrum suggest an absolute magnitude of about -3.

υ Sagittarii.—This star was studied by J. L. Greenstein, and by others. It is roughly similar to an A star, but the hydrogen lines are exceptionally weak, and metallic lines are stronger than normal. Standard astrophysical procedures indicate a real hydrogen deficiency in the atmosphere of υ Sagittarrii. HD 30353, discovered by W. P. Bidelman, is a cooler star, approximately F-type, also showing very weak hydrogen lines and strong metallic lines.

HD 182040.—This is a carbon star, showing strong bands of C_2 and CN but no bands at all of CH. Hydrogen lines are very weak and C I lines are strong. No C^{13} isotope is present. Several other stars of this type are now known. Plate 23 (C) shows the spectrum of HD 182040 compared with that of the normal carbon star HD 156074.

R Coronae Borealis.—This famous variable star and others of the same type have spectra at maximum light resembling F or G supergiants, but they show unusually strong features of C I and C_2 and very weak hydrogen lines. The carbon isotope C^{13} is not present. At minimum light emission lines appear in the spectrum and the absorption lines become very indistinct. This strange apparent veiling of the absorption spectrum has no adequate explanation; in any case no reason for the variability of these stars is known. They appear to be hydrogen-poor carbon stars of high luminosity, but the evidence for real hydrogen deficiency is not so strong as for the other hydrogen-poor stars.

It is very difficult to see how the peculiarities of these stars can be explained otherwise than as a real deficiency of hydrogen in their atmospheres. Yet these stars still seem to be radiating energy at something approaching their normal rate. This implies either that there is still plenty of hydrogen in their interiors or that nuclear reactions are consuming elements other than hydrogen. The latter process seems more probable, and helium burning may be the source of excess carbon and oxygen.

X. Pulsating Stars

It is not possible to discuss variable stars in detail in this article, and we shall confine attention to a few salient points of interest. A large number of variable stars are believed to be pulsating, the disturbance affecting the whole star. It is possible that all stars in the course of their evolution pass through an unstable stage, and that pulsating stars are to be regarded as normal rather than peculiar. The pulsation gives rise to a number of effects not present in other normal stars.

(*a*) *Classical cepheids.*—At maximum light these resemble normal F5 to F8 supergiants; at minimum, they resemble F8–K1 supergiants, the type advancing with increasing period and giving rise to the period–spectrum relation. Emission lines of Ca II are usually visible on the ascending part of the light curve. These probably arise when superheated gases become visible deep in the atmospheres of the cepheids and are caused in some way by the pulsations.

(*b*) *Long-period variables.*—These occur among stars of types M and S and among the carbon stars. Their spectra are broadly similar to the normal stars of these types, but at various phases they show emission lines of hydrogen and other elements. A well-known set of emission lines in χ Cygni (and other stars) near minimum has recently been shown by Herbig to be due to unusual processes in the molecule AlH. Many of the emission lines have superposed absorption components, showing that the emission lines are formed deep in the atmospheres. The most probable suggestion advanced so far to explain the emission lines is that we are seeing the upper part of a hydrogen convection zone beneath the normal photosphere. This explanation fulfils the requirement that the underlying cause of the line emission is more fundamental than the division between the spectral types, M, S, R and N.

(*c*) *β Canis Majoris stars.*—These stars are of spectral types B1 or B2 and are above the main sequence. They show light variations of up to one- or two-tenths of a magnitude and variations in apparent radial velocity. Some stars have variations with one period, in others two periodic variations are superposed; the periods are between 3 and 6 hours. The velocity curves of some β Canis Majoris stars are apparently discontinuous. This might be due to successive mild ejections of layers of the atmospheres, but there are many objections to this idea and no more satisfactory mechanism has yet been proposed.

(*d*) *Semi-regulars and others.*—There are a large number of semi-regular and irregular variables, whose spectra may be types F, G, K or M and whose light variations are not regular. The spectra look somewhat like supergiants, but there are many minor peculiarities.

XI. Exploding Stars

Many stars are known which show sudden outbursts. These range from flare stars and U Geminorum type variables through recurrent and non-recurrent novae to supernovae. A detailed discussion of these objects is outside the scope of this article. It may however be noted that all show emission lines and other spectroscopic peculiarities, and that the spectral features of the brighter supernovae still resist identification.

XII. Miscellaneous

(*a*) *Carbon-poor stars.* HR 885 (= HD 18474) was found by W. P. Bidelman to have an unusual spectrum. No CH or CN bands are visible; other spectral features indicate a spectral type of G5 III, and normal stars of this type do show CN and CH absorption. HR 6791 (= HD 166208) was shown by J. L. Greenstein and P. C. Keenan to share the same peculiarities. These peculiarities are almost certainly to be interpreted as an actual deficiency of carbon in the stellar atmospheres.

(*b*) *Lithium stars.*—In 1941 A. McKellar discovered that the lithium resonance doublet at λ6708 was very strong in the N star WZ Cassiopeiae. This was the first detection of lithium in stars other than the Sun. R. F. Sanford showed that WX Cygni had strong λ6708 and M. W. Feast found that T Arae was a third star of this type. These are the only N type stars showing strong λ6708 among about a hundred which have been examined. All the lithium stars show the C^{13} isotope. It is not yet certain whether abnormally low surface temperatures can account for the strength of the lithium lines, but the indications are that this is not possible and we must regard the lithium stars as a group of peculiar carbon stars with abnormally high abundance of lithium. It would appear that there can have been little mixing between the atmospheres and interiors of these stars, because the internal temperatures of the stars are almost certainly high enough to destroy lithium by nuclear reactions.

(*c*) *Intermediate-carbon stars*. The star GP Orionis is an unusual object in which both TiO and ZrO are weak, but which otherwise resembles an S star. It seems probable that this star is intermediate between carbon stars and S stars. If the abundances of carbon and oxygen are comparable the formation of CO molecules (a highly probable process) will remove most of the carbon and oxygen atoms and neither oxides nor other carbon molecules will form. This will lead to low atmospheric opacity and the strengthening of many spectral lines. CY Cygni is another star which may have approximately equal abundances of oxygen and carbon; it is a red star but has no strong absorption bands.

(*d*) *Ba* II *stars*.—In normal stars, lines of Ba II increase in strength with increasing luminosity after about type F5, and one may therefore be tempted to suppose that cool stars with strong Ba II lines are supergiants. We have seen that the Ba II lines are strong in S stars, and the latter are not supergiants, so that Ba II must be used cautiously as an indicator of high luminosity. Another small group of stars is now known with enhanced Ba II not due to high luminosity. This group, called the Ba II stars, most nearly resembles G and K stars. In addition to the enhancement of Ba II lines, lines of Sr II, Y II and of the rare earths are enhanced, C_2 bands may be seen faintly when they are invisible in similar normal stars, and the CH band is enhanced. No technetium is seen, and no ZrO, although atomic zirconium lines are strong. The best example of a Ba II star is ζ Capricorni, and others include HR 774 and HR 5058. HR 5058 has a relatively large proper motion, and calculations show that on any reasonable assumption of the space velocity of the star, it is unlikely to be a supergiant. The star is probably a giant. The enhancements in the spectra are probably due primarily to abundance peculiarities. E. M. and G. R. Burbidge showed that the heavier elements from strontium onwards have abundances at least ten times those in normal stars. It is possible that these abnormal abundances are the product of neutron-capture element-building processes.

XIII. Stars Not Intrinsically Peculiar

There is a possibility that a star which is not itself abnormal may develop abnormalities when it suffers interaction with other stars or with nebulosity. Such stars are discussed briefly in this section.

(*a*) *Binary systems*.—There are many binary systems which consist of pairs of normal stars. Among the closer binaries there are to be found a number whose integrated spectra show peculiarities; these systems are nearly all spectroscopic binaries, too close to be separated visually. The observed peculiarity is the occurrence of emission lines in the integrated spectra. These are undoubtedly due to the presence near the stars of streams of gas ejected from the stars. Considerable progress has been made in this field in recent years; a general review has appeared in *Occasional Notes* and we shall not discuss the matter further in this article.

(*b*) *T Tauri stars.*—These have a distinctive emission-line spectrum of hydrogen, Ca II and selected lines of Fe I, and sometimes forbidden lines of ionized sulphur. Their underlying absorption spectra lie in the range F to M and they are on or a little above the main sequence. They are invariably on or near the edges of obscured regions, and they often illuminate small bright patches of nebulosity. They are all irregular light variables. The T Tauri stars are the largest group of stars associated with nebulosity. There are a number of spectral peculiarities which indicate that the emission lines are produced in an extended region of gas at relatively low pressure. The T Tauri stars are believed to be objects of relatively recent origin; they are present in some of the younger galactic star clusters, when they are usually above the main sequence, and are possibly in a state of rapid evolution towards the main sequence.

(*c*) *Interacting with nebulosity.*—In addition to the T Tauri stars there are other objects which are associated with nebulosity. They are broadly of types A, F, G or K, with luminosities well above the main sequence. Ca II and $H\alpha$ are often seen in emission; the stars are situated in dark clouds and illuminate small reflection nebulae.

XIV. Population II Stars

Spectroscopic differences between the high-velocity stars and the low-velocity stars were found in 1922 by B. Lindblad. The subsequent development of the concept of the two stellar populations has led to correlations between the properties of the stars. Most high-velocity stars are members of Population II. The earlier types (roughly equivalent to normal Population I A, F and early G types) of Population II stars show a general weakening of metallic lines in their spectra. The later G and K giants show weakening of the CN bands. Among the stars of Population II are a number of distinct groups which will be discussed separately.

(*a*) *G–K giants.*—The spectra of Population II giant stars of types G6 to K4 show a weakening of the CN bands; those of somewhat earlier types show a general weakening of atomic lines and a strengthening of CH bands. It is possible that differences in chemical composition are responsible for these peculiarities. M. Schwarzschild, L. Spitzer and R. Wildt suggested that a low abundance of metals relative to hydrogen in Population II stars could explain the peculiarities in G–K giants. A reduction in the metal/hydrogen ratio by a factor of three is required, together with a reduction by a factor two in the (carbon + oxygen + nitrogen)/hydrogen ratio. Most of the brighter stars in globular clusters show similar peculiarities to an even greater degree than nearby high-velocity giant stars; the metallic lines in globular cluster stars are much too weak by comparison with hydrogen lines and colour indices, and a metallic abundance deficiency by a factor ten is required to explain the metallic-line weakness.

(*b*) *Carbon stars (CH stars).*—There exist a number of high-velocity carbon stars. Their spectra show very strong CH bands, in line with the behaviour of other high-velocity giant stars. Atomic lines are very weak; even the line Ca I λ4227 is inconspicuous in the CH stars. The bands of C_2 and CN are quite strong, although the CN bands may be somewhat weaker than normal carbon stars. Atomic lines of a few ionized elements (Sr II, Ba II) are strengthened relative to normal carbon stars; this would suggest high luminosity, but other evidence seems to show that the CH stars are normal giants. Their effective temperatures probably range from 3 600 °K to 4 600 °K. There is good reason to think that the appearance of CN, CH and C_2 in the spectra of the CH stars is what would be expected if in any high-velocity star the ratio carbon/oxygen were increased to the amount characteristic of carbon stars. It is interesting to note that among the CH stars there are examples showing the isotope C^{13} and others in which this isotope is not seen.

(*c*) *Subdwarfs.*—These stars were first discovered by Adams from the weakness of certain features in their spectra. The normal stars most nearly resembling the subdwarfs range through spectral types B to K. Subdwarfs of all types show a general weakening of their absorption spectra compared to corresponding normal stars. Subdwarfs of approximate type A have abnormally narrow lines of hydrogen and very weak lines of metals, especially Mg II and Fe II. Those of types F and G have a very weak CH band, and those of later types have a strengthened CN band. Chamberlain and Aller found the atmospheres of HD 19445 and HD 140283 deficient in calcium and iron relative to hydrogen.

Trigonometrical parallaxes are available for some subdwarfs; the visual absolute magnitudes of the subdwarfs are found to fall two or three magnitudes below the main sequence. They appear to be well separated from the white dwarfs if the usually quoted spectral types are accepted. Many of the subdwarfs have high proper-motions and high radial velocities. Most have highly eccentric orbits about the centre of the Galaxy, and during their motions pass quite close to the galactic nucleus. The motion of the Sun relative to the subdwarfs is very high, similar to that relative to the RR Lyrae stars. They form a nearly spherical distribution about the galactic centre.

Many subdwarfs show abnormally negative $U-B$ (ultraviolet minus blue) colours for a given $B-V$ (blue minus visual) colour, that is, they are abnormally bright in the ultraviolet. Miss Roman has suggested that this is due to the general weakness of the metallic lines in the spectrum; she has shown that the ultraviolet excess is especially frequent among subdwarfs with high velocities relative to the Sun. When account is taken of the ultraviolet excess O. J. Eggen and A. R. Sandage have found that the total radiation emitted by a subdwarf (i.e. its bolometric magnitude) is the same as that by a normal star of the same effective temperature. In the $M_{bol}-\log T_e$-diagram there is effectively just one main sequence which includes normal stars and high-velocity subdwarfs.

(*d*) *Faint blue stars.*—A number of hydrogen-poor helium-rich objects have been found among faint blue stars. They show weak hydrogen, strong and broad He I and He II, very strong and sharp N II, N III, Si IV, no C II and weak C III. This strength of nitrogen and weakness of carbon is in contrast to hydrogen-poor stars such as HD 124448 (mentioned above in Section IX) which have strong carbon lines. An example is HZ 44, an eleventh magnitude blue star, probably of luminosity similar to that of the Sun. Another interesting example is B.D. $+28°4211$. Weak interstellar calcium lines indicate an absolute magnitude of $+4$. It has a large proper motion and is almost certainly a high velocity star. These stars are about 8 magnitudes below the main sequence.

(*e*) *Cluster cepheids.*—In general appearance these have spectra similar to other high-velocity F stars, with metallic lines very weak at maximum light and quite weak at minimum light.

(*f*) *Long-period cepheids*.—These are rather similar to classical cepheid variables, they show a characteristic hump in their light curves and their spectra show bright hydrogen lines during increasing brightness.

Conclusion

In the present article we have given a brief outline of the main types of peculiar stars and we have indicated a few of the most outstanding peculiarities. There are many other peculiarities which have been discovered and studied, and although some have been understood and possible mechanisms for others suggested, many phenomena remain for which no explanation is available. And it is unfortunately true that even in cases where the observable peculiarity has an obvious physical interpretation we are still completely ignorant of the underlying cause of the phenomena. Some progress has been made; more than ever remains to be done before the intriguing peculiarities of the stars are fully unravelled.

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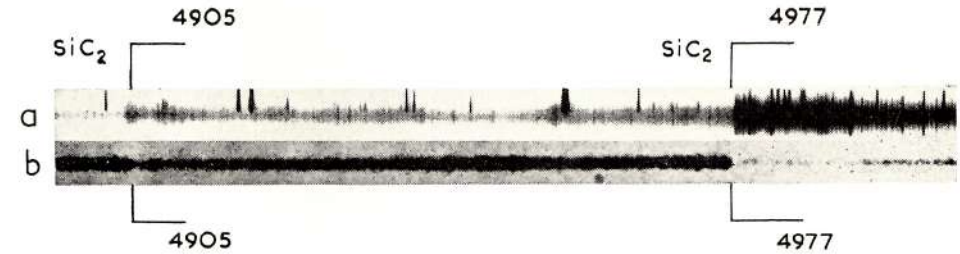
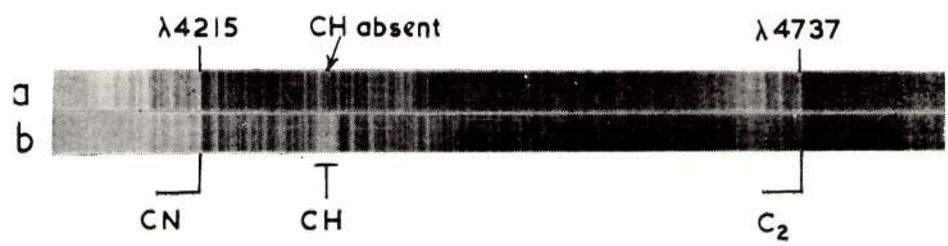


A.—*Identification of SiC_2 bands in carbon stars.* Part of the laboratory emission spectrum ascribed to SiC_2 is shown in (a). The corresponding part of the spectrum of the N7 type star VX Andromedae is shown in (b), with two previously unidentified bands at λ 4977 and λ 4905 marked.
(B. Kleman, *Ap. J.*, **123**, 162, 1956.)

B.—*Identification of technetium lines in S stars.* Part of the spectrum of the S type long-period variable star R Andromedae, taken 1944 August 1, 10 days after maximum. The three lines identified in 1952 by P. W. Merrill as due to neutral technetium are marked, together with a few other representative lines. Note the emission lines Fe II λ 4233 and Fe I λ 4308.
(The spectrum is reproduced from P. W. Merrill, *Ap. J.*, **105**, 360, 1947.)



C.—*Hydrogen-poor carbon star.* The hydrogen-poor carbon star HD 182040 (a) compared with the normal carbon star HD 156074 (b). The absence of CH bands in HD 182040 and the presence of strong CN and C_2 bands suggest a real hydrogen deficiency in the atmosphere of this star.
(W. P. Bidelman, *Ap. J.*, **117**, 25, 1953.)