29. COMMISSION DE CLASSIFICATION SPECTRALE DES ÉTOILES

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MEMBRES: Mlle Cannon, MM. Baxandall, Bosler, R. H. Curtiss, Deslandres, Harper, Henroteau, Hertzsprung, Lindblad, Lockyer, Merrill, Milne, Newall, H. H. Plaskett, J. S. Plaskett, Russell, Saha, Shapley, Stratton, Wright.

The past three years have seen a rapid advance in the analysis of line and band spectra. Almost every line which is of concern to the astrophysicist, whether in the sun, the stars or the nebulae, is now physically intelligible as the result of a transition between specifiable energy states in some definite atom or molecule, either neutral or ionized. The recent identification of the principal nebular lines is the most spectacular and in a true sense the crowning success of these new developments in our knowledge.

The first great problem of astronomical spectroscopy, the empirical classification of the spectral lines, is therefore substantially complete, and the way is now open for the second, which is the development of a rational theory of astrophysical spectra, and of stellar spectra in particular. Such a theory, in its fully matured state, should be able to start with a few fundamental data, such as the values of effective temperature and gravity at a star's surface and the general composition of its atmosphere, and predict the intensities and widths of the spectral lines in detail; or, conversely, to derive the former data from the latter.

We are still far from being in a position to do this. Thermodynamic considerations make it possible to calculate the relative numbers of atoms which should be in given states of excitation and ionization for a gas in thermodynamic equilibrium under specified conditions. The relative numbers of atoms in a given state which will be involved in the production of the individual lines of a particular multiplet can be predicted from quantum principles. The relative numbers which will produce different multiplets cannot yet be calculated, although the prospects for a solution of the problem appear hopeful. The relationships connecting the width and "depth" of an observed "absorption" line with the number of atoms (per square centimetre of the star's surface) which produce it are still imperfectly understood. Similarly, neither the "intrinsic" width of a line nor the additional broadening by extraneous influences can be handled satisfactorily by existing theory. Finally, the equilibrium of a stellar atmosphere needs further study, especially in the upper chromospheric regions where radiation pressure becomes important and thermodynamic equilibrium fails, as well as in the more difficult region of transition at the base of the chromosphere.

Although a complete theory is still well in the future, notable progress has been made toward an understanding of the general character of the sequence of spectral classes. That this depends mainly upon changes of ionization with temperature has been shown clearly. The average pressure in stellar atmospheres has been determined, as, for example, by Fowler and Milne, with results which are surprisingly low, but doubtless correct in order of magnitude: and the theory of opacity of an ionized gas explains why the light from regions of higher pressure is unable to escape to us.

The outcome of all these investigations has been to confirm the practical value of the empirical system of classification of the Draper Catalogue, which was developed many years ago, adopted by the International Solar Union in

1910, and again in a slightly amplified form by the International Astronomical Union in 1922. This system appears to be well suited to the needs of the present day, and the only changes recommended by the Committee deal with the spectral types near the extremes of the sequence where the advance in our knowledge enables better correlation of the observable criteria.

STARS OF TYPE O

A system for classifying the absorption spectra of O-type stars on a decimal notation has been suggested by H. H. Plaskett*. It is based on the relative intensities of lines of different excitation potentials, in particular of *H* and ionized *He*.

Later work indicates that the system can be extended to all O stars in which absorption lines are well observable, which may in time include all O stars which can be studied with adequate dispersion. Merrill has suggested that the symbol e be used for stars which show bright hydrogen lines similar to those often found in types B0–B3: while stars showing absorption lines and in which the Wolf-Rayet bands are visible be denoted by the suffix w, and those in which these bands are conspicuous by w!. These suggestions have been referred to the members of the Committee and have met with general approval.

A more detailed system prepared by Miss Payne† has been communicated to the Chairman of the Committee in advance of publication, but too late to make it possible to obtain the opinions of the members at large. The recommendations which have been made, therefore, are based mainly on the work of Plaskett and Merrill, but they have been planned to leave room for modification in the directions suggested by Miss Payne, if such action should later be deemed advisable.

GASEOUS NEBULAE

Bowen's identification of the principal nebular lines opens the way for a rational classification of the spectra of galactic nebulae. A system has been proposed by Miss Payne (*loc. cit.*) on the decimal notation P0 to P10. In the earlier subdivisions the lines N_1 and N_2 [*O* III] are relatively strong; at P8 they disappear, leaving λ3729 [*O* II] and the hydrogen lines; P9 shows a mixture of emission and continuous spectrum, and P10 continuous spectrum (with possible absorption lines) only. The spectral type of a nebula shining by reflected light may be added in parenthesis, as, for example, P10 (B5).

GENERAL STELLAR CLASSIFICATION

The plan recommended at the Cambridge meeting of the International Astronomical Union of selecting the spectra of representative stars photographed on a variety of linear scales, and placing reproductions in the hands of observers in this field has been the subject of considerable discussion. The desirability of securing spectra in the ultra-violet and the yellow and red portions, as well as in the region usually photographed with slit spectrographs, and the difficulty of securing complete agreement on representative stars have caused delay, but very real progress has been made. In the case of the A-type stars, in particular, ultra-violet spectrograms with slit-spectrographs covering the H and K region are

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† *Bulletin Harvard College Observatory*, **855**, 1928.

needed to aid in determining the cause of the tendency to systematic differences in estimations of type from objective-prism and slit spectrograms. Especial attention has been called to this subject by J. S. Plaskett.

Several members of the Committee have shown much interest in the possible development of a new system of classification based on physical principles and expressible in numerical terms of definite parameters. The following general observations are offered as representing the views of certain of the members, and as affording a basis for discussion.

1. From Harvard (Shapley, H. H. Plaskett, Miss Payne).

In many astrophysical problems, including that of stellar classification, *intensity-distribution* rather than wave-lengths of lines is the principal means of investigation. Until recently, however, such intensity determinations have been based on visual estimates from photographic plates, with the result that the intensities, as well as the conclusions drawn from them, have been subject not only to the well known photographic sources of error, but also to the uncertainties of estimates. Unquestionably one of the outstanding developments since the last report of the Commission has been the improvement in the technique of measuring intensities with full spectrophotometric accuracy. Mention need only be made of the work at Edinburgh, Greenwich, Victoria, and Harvard on intensity-distribution in the continuous spectrum, by Shapley and Miss Payne on central line intensities in stellar spectra, and of von Klüber, Minnaert, and Unsöld on line intensities, contours and total absorptions in the solar spectrum. It is the purpose of this supplement to the formal report of the Commission to indicate how these improved methods might be used in setting up a physical system of stellar spectroscopic classifications.

(*a*) *Detailed Analysis of Stellar Spectra.* Clearly the first step in setting up a physically satisfactory method of classification is the detailed analysis of typical spectra with the highest possible dispersion and resolving power.

Important progress has already been made in this direction. Of special interest have been the investigations of colour temperature of emission line stars, and the theoretical studies of Unsöld which, applied to his own measures of line contour in the sun and to Miss Payne's stellar contours, probably give some measure of the number of atoms per square centimetre column on the stellar surface. For the future the high dispersion spectra at Mount Wilson in the hands of Adams and Russell give promise of being mines of information.

(*b*) *Classification from Objective Prism Spectra.* While the basis of the ultimate physical classification must rest on detailed analysis of the brighter stars, the adopted system must at the same time be applicable so far as practicable to the faintest stars which can be reached by any spectroscopic method. Spectrophotometric methods give promise that both these conditions may simultaneously be fulfilled. Thus, for example, at the present time it is possible to classify existing Harvard objective prism spectra on a basis of observed colour temperature and degree of ionization—a physical classification separating two important variables. By an application of the methods developed by Miss Payne and Hogg the intensity-distribution in the continuous spectrum may be measured from objective prism plates with a satisfactory degree of accuracy and consistency. This intensity-distribution in the Harvard types A to M is a sensitive indicator of the colour temperature which might be made a parameter in the hypothetical classification. Again, from the ratio of line intensities, simultaneously determined spectrophotometrically, the degree of ionization in the spectrum may be found.

Thus, on such a system, a gKo star might be found to have a class 4·0 (7) and a dKo, 4·8 (6), where the first figures give the colour temperature in units of a thousand degrees and the bracketed figures the degree of ionization in volts.

The determination of colour temperature is admittedly insensitive for stars hotter than Ao and inaccurate for late type stars on account of the partial obliteration of the continuous background in short dispersion spectra. How insensitive and how inaccurate are questions which can only be answered after detailed analyses of high dispersion spectra have been carried out. Once such analyses have been made, however, a correction could be applied to the types thus defined and measured on the objective prism plates.

2. From Mt Wilson (Adams and Russell).

The number of parameters involved in any fairly complete specification of a spectrum, from the standpoint of line intensities alone, appears to be large. In this connection a brief report upon some work now in progress at Mount Wilson may be used to illustrate some of the aspects of the problem.

(*a*) Through a comparison of the Rowland intensities of solar spectrum lines belonging to the same multiplet with the relative numbers of atoms which theoretically should be engaged in the transitions, a calibration of the Rowland scale has been obtained. This permits of the conversion of Rowland's estimates of intensity into estimates of the relative numbers of atoms which are acting throughout the solar atmosphere (per square centimetre of surface) in the production of neighbouring lines. The gradation of Rowland's intensities with the increase in the number of atoms acting is steeper in the red than in the violet, and in neither case can the absolute number of atoms present as yet be estimated. The results for the relative numbers of atoms involved in the production of different lines, however, are in good agreement for many elements, both neutral and ionized, and it appears that about 500,000 times as many atoms are operative in producing a line of Rowland intensity 30 as for one of intensity 000.

(*b*) The extension of this empirical scale to stellar spectra photographed with high dispersion leads to estimates of the relative numbers of atoms N and N^1 which operate in producing the same line in the sun and a given star. From thermodynamic theory it follows that for the lines of a given neutral element

$$\log \frac{N^1}{N} = A + BE,$$

where E is the excitation potential for the line in question, A represents the relative abundance of neutral atoms in their normal state ($E = 0$) in the star's atmosphere as compared with the sun's, and B is connected with the atmospheric temperature by the equation

$$B = 5040\left(\frac{1}{T} - \frac{1}{T^1}\right).$$

The application of this equation to α Orionis, α Scorpii, α Boötis, γ Cygni, α Persei, and α Canis Minoris gives values of the temperatures in excellent agreement with those derived from other data, while the values of A indicate that the atmospheres of these stars, with the exception of α Canis Minoris, are far more extensive than that of the sun.

(c) The lines of an ionized atom give a similar equation, with the same value for B but a different one for A', the latter now representing the relative abundance of ionized atoms in the star and sun. If the atmosphere were all at one pressure this quantity, together with the abundance of neutral atoms, would determine the pressure; but actual tests show that for such stars as α Orionis the computed pressure is absurdly low—of the order of 10^{-6} that in the sun's atmosphere. In these stars radiation pressure is strong in proportion to gravity: and they appear to have very extensive and rarefied chromospheres, in which the ionization is high, despite the low temperature.

The above are the results of only a preliminary study. They indicate that for a numerical specification of the behaviour of the lines of a single element in a stellar spectrum three quantities are necessary:

1. A quantity B depending on the temperature.
2. A quantity A depending on the abundance of neutral atoms.
3. A quantity A^1 depending on the abundance of ionized atoms.

The constants A and A^1 appear to differ considerably, but not greatly, for different elements.

Much further work will be required before it will be possible to determine what elements are of similar behaviour, and what stars—dwarfs, giants, or super-giants—may best be chosen as theoretically "typical". It is already evident, however, that a complete numerical specification of the characteristics of a stellar spectrum, even if only relative to that of a standard star, will not be a wholly simple matter.

Summarizing the result of these and other suggestions, it appears that physical parameters of three types have been recognized:

(1) *Temperature.*

(a) Colour temperature determined from the distribution of intensity in the continuous background.

(b) Ionization temperature, determined from the maximum intensities of spectral lines, as by the method of R. H. Fowler and Milne.

(c) Temperature determined from the relative intensities of lines of different excitation potential.

Existing evidence shows that the "Temperatures" (a) and (b) are fairly consistent for the general run of the stars but differ widely in some cases (for example P Cygni).

(2) *Ionization* as suggested by Harvard and Mt Wilson. This parameter is closely connected with the atmospheric pressure.

(3) *Abundance* representing the amount of material present in the star's atmosphere.

It appears, therefore, that at least four different parameters, capable of numerical expression, can be derived from a study of a given stellar spectrum.

Whether special correlations exist between them, so that the number of *independent* parameters is smaller, or whether it is actually greater is a matter for future investigation. If all the parameters turn out to be independent, astrophysics will be the richer.

Research is at present active both in theory and observation.

The development of a rational physical theory and classification of stellar spectra is therefore to be hoped for within a few years, but any attempt at specifying it to-day would be premature.

RECOMMENDATIONS

O-Type Stars

1. For O-type stars which show a definite absorption spectrum, whether or not accompanied by bright lines or bands, H. H. Plaskett's decimal system of classification should be adopted. The classes for which criteria are given range from O5 to O9. The upper subdivisions are left for future discoveries, O0 denoting the theoretical limit of a star so hot that it shows no spectral lines at all. Such objects may perhaps be found among the nuclei of planetary nebulae.

2. Stars which show bright lines of hydrogen, and in some cases of metals, resembling those in types B0e–B3e should be denoted by the suffix e.

Example: H.D. 60848, O8e.

3. Stars showing the characteristic Wolf-Rayet emission lines or bands, and in which the absorption spectrum can be classified as above, should be denoted by the suffix ew. When the bands are conspicuous they should be described as ew!.

Examples: 9 Sagittae, O7ew,
H.D. 193793, O6ew!.

4. For stars in which the Wolf-Rayet bands are prominent and the absorption spectrum cannot be classified, the notation of the Draper Catalogue, Oa, Ob, Oc, Od, should be retained pending further investigation.

It may prove possible to classify these stars on the basis of the excitation potentials of the bright bands, but a detailed study of the correlation between the degrees of excitation indicated by emission and absorption when both are present will be necessary before these stars can be connected with the general sequence. J. S. Plaskett's investigation* of this question has led him to the conclusion that any such correlation is very doubtful, and that Wolf-Rayet bands may make their appearance at any stage of the absorption spectrum.

5. If it is desired to describe both the absorption and emission spectra the letters a, b, c, d, being the notation of the Draper Catalogue, may be added to the suffix ew according to the appearance of the Wolf-Rayet bands.

Examples: ζ Puppis, O5ewd,
γ Velorum, O6ew!a.

Peculiar Spectra

Certain suggestions which have been received too late for formal submission to the members of the Committee appear to be of sufficient merit to justify their provisional recommendation, subject to such action as the Committee may please to take at the Leiden meeting.

6. Newall and Baxandall note the fact that the chief peculiarities of many spectra classed as peculiar in the Draper Catalogue relate to particular sets of lines of known or unidentified origin. For such spectra they suggest that the symbol of the element most affected be added in parenthesis, unidentified lines being designated as Un.

Examples: α Andromedae, A0p (Mn II, Un),
61^1 Cygni, dK8 (Ca IIe).

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The modern notation Mn II, Ca II, instead of Mn^+, Ca^+, is recommended, the absence of a roman numeral indicating that the arc spectrum is understood. Merrill suggests that the presence of "forbidden" lines (arising from transitions involving metastable states in the atom), such as occur in the spectra of gaseous nebulae and η Carinae, be denoted by the symbol of the element in square brackets.

Example: Boss 5650, gM2ep [*Fe* IIe].

7. According to a suggestion by Miss Payne spectra in which bright metallic lines are fairly conspicuous in addition to the usual bright hydrogen lines may be denoted by the suffix em.

Example: γ Cassiopeiae, Bo em,
ο Ceti, Mv em v + Bp em p.

8. The following modifications are suggested by Newall in the nomenclature for Novae (report of this Committee 1922):

For Qc read: Absorption spectrum of metallic lines, oxygen, nitrogen, and helium, enhanced metallic lines predominating.

Add a new class Qd, the spectrum containing the same lines as Qc, but with the gaseous lines predominating.

General

9. In view of the development of spectrophotometric methods, the Commission formally recognizes the value of spectrophotometry as an aid to stellar classifications.

10. It is recommended that the name of this Commission be changed to *Commission on Stellar Spectra.*

W. S. Adams
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