Stellar Atmospheres: A Contribution to the Observational Study of High Temperature in the Reversing Layers of Stars

Cecilia H. Payne

The classic for this month is the PhD thesis of Cecilia Payne. She worked on her thesis at Harvard Observatory and graduated in 1926. We reproduce a small selection of pages from the thesis to give you a flavour of its contents. Her thesis was published by the observatory as volume I of the *Harvard Observatory Monographs*.

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No. 1

 STELLAR ATMOSPHERES
A CONTRIBUTION TO THE OBSERVATIONAL
STUDY OF HIGH TEMPERATURE IN THE
REVERSING LAYERS OF STARS

BY

CECILIA H. PAYNE

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CONTENTS

PART I
THE PHYSICAL GROUNDWORK

I. THE LABORATORY BASIS OF ASTROPHYSICS . . . . . . . . 3
   Relation of physics to astrophysics.
   Properties of matter associated with nuclear structure.
   Arrangement of extra-nuclear electrons.
   Critical potentials.
   Duration of atomic states.
   Relative probabilities of atomic states.
   Effect on the spectrum of conditions at the source.
      (a) Temperature class.
      (b) Pressure effects.
      (c) Zeemann effect.
      (d) Stark effect.

II. THE STELLAR TEMPERATURE SCALE . . . . . . . . . . . . 27
   Definitions.
   The mean temperature scale.
   Temperatures of individual stars.
   Differences in temperature between giants and dwarfs.
   The temperature scale based on ionization.

III. PRESSURES IN STELLAR ATMOSPHERES . . . . . . . . . . 34
   Range in stellar pressures.
   Measures of pressure in the reversing layer.
      (a) Pressure shifts of spectral lines.
      (b) Sharpness of lines.
      (c) Widths of lines.
      (d) Flash spectrum.
      (e) Equilibrium of outer layers of the sun.
      (f) Observed limit of the Balmer series.
      (g) Ionization phenomena.

IV. THE SOURCE AND COMPOSITION OF THE STELLAR SPECTRUM . 46
   General appearance of the stellar spectrum.
   Descriptive definitions.
   The continuous background.
   The reversing layer.
   Emission lines.

V. ELEMENTS AND COMPOUNDS IN STELLAR ATMOSPHERES . . . . 55
   Identifications with laboratory spectra.
   Occurrence and behavior of known lines in stellar spectra.

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PART II

THEORY OF THERMAL IONIZATION

VI. THE HIGH-TEMPERATURE ABSORPTION SPECTRUM OF A GAS 91
   The schematic reversing layer.
   The absorption of radiation.
   Low temperature conditions.
   Ultimate lines.
   Ionization.
   Production of subordinate lines.
   Lines of ionized atoms.
   Summary.

VII. CRITICAL DISCUSSION OF IONIZATION THEORY 105
   Saha's treatment — marginal appearance.
   Theoretical formulae.
   Physical constants required by the formulae.
   Assumptions necessary for the application.
   Laboratory evidence bearing on the theory.
   (a) Ultimate lines.
   (b) Temperature classes.
   (c) Furnace experiments.
   (d) Conductivity of flames.
   Solar intensities as a test of ionization theory.

VIII. OBSERVATIONAL MATERIAL FOR THE TEST OF IONIZATION THEORY 116
   Measurement of line intensity.
   Method of standardization.
   Summary of results.
   Consistency of results.

IX. THE IONIZATION TEMPERATURE SCALE 133
   Consistency of the preliminary scale.
   Effect of pressure.
   Levels of origin of ultimate and subordinate lines.
   Influence of relative abundance.
   Method of determining effective partial pressure.
   The corrected temperature scale.

X. EFFECTS OF ABSOLUTE MAGNITUDE UPON THE SPECTRUM 140
   Influence of surface gravity on ionization.
   Influence of pressure.
   Influence of temperature gradient.
   Comparison of predicted and observed effects.
   Abnormal behavior of enhanced lines of alkaline earths.
## CONTENTS

### PART III

#### ADDITIONAL DEDUCTIONS FROM IONIZATION THEORY

**XI. The Astrophysical Evaluation of Physical Constants**
- Spectroscopic constants (Plaskett).
- Critical potentials (Payne).
- Duration of atomic states (Milne).

**XII. Special Problems in Stellar Atmospheres**
- Class O stars.
- Class A stars.
  - The Balmer lines.
  - Classification of A stars.
  - Silicon and Strontium stars.
  - Peculiar Class A stars.
- C-stars.

**XIII. The Relative Abundance of the Elements**
- Terrestrial data.
- Astrophysical data.
- Uniformity of composition of stellar atmospheres.
- Marginal appearance.
- Comparison of stellar and terrestrial estimates.

**XIV. The Meaning of Stellar Classification**
- Principles of classification.
- Object of the Draper Classification.
- Method of classifying.
- Finer Subdivisions of the Draper Classes.
- Implications of the Draper system.
- Homogeneity of the classes.
- Spectral differences between giants and dwarfs.

**XV. On the Future of the Problem**

### APPENDICES

**I. Index to Definitions**

**II. Series Relations in Line Spectra**

**III. List of Stars Used in Chapter VIII**

**IV. Intensity Changes of Lines with Unknown Series Relations**

**V. Material on A Stars, Quoted in Chapter XII**

**Subject Index**

**Name Index**
CHAPTER I

THE LABORATORY BASIS OF ASTROPHYSICS

The application of physics in the domain of astronomy constitutes a line of investigation that seems to possess almost unbounded possibilities. In the stars we examine matter in quantities and under conditions unattainable in the laboratory. The increase in scope is counterbalanced, however, by a serious limitation — the stars are not accessible to experiment, only to observation, and there is no very direct way to establish the validity of laws, deduced in the laboratory, when they are extrapolated to stellar conditions.

The verification of physical laws is not, however, the primary object of the application of physics to the stars. The astrophysicist is generally obliged to assume their validity in applying them to stellar conditions. Ultimately it may be that the consistency of the findings in different branches of astrophysics will form a basis for a more general verification of physical laws than can be attained in the laboratory; but at present, terrestrial physics must be the groundwork of the study of stellar conditions. Hence it is necessary for the astrophysicist to have ready for application the latest data in every relevant branch of physical science, realizing which parts of modern physical theory are still in a tentative stage, and exercising due caution in applying these to cosmical problems.

The recent advance of astrophysics has been greatly assisted by the development, during the last decade, of atomic and radiation theory. The claim that it would have been possible to predict the existence, masses, temperatures, and luminosities of the stars from the laws of radiation, without recourse to stellar observations, represents the triumph of the theory of radiation. It is equally true that the main features of the spectra of the stars could be predicted from a knowledge of atomic structure and the
4. THE LABORATORY BASIS OF ASTROPHYSICS

origin of spectra. The theory of radiation has permitted an analysis of the central conditions of stars, while atomic theory enables us to analyze the only portion of the star that can be directly observed — the exceedingly tenuous atmosphere.

The present book is concerned with the second of these two problems, the analysis of the superficial layers, and it approaches the subject of the physical chemistry of stellar atmospheres by treating terrestrial physics as the basis of cosmical physics. From a brief working summary of useful physical data (Chapter I) and a synopsis of the conditions under which the application is to be made (Chapters II and III), we shall pass to an analysis of stellar atmospheres by means of modern spectrum theory. The standpoint adopted is primarily observational, and new data obtained by the writer in the course of the investigation will be presented as part of the discussion.

The first chapter contains a synopsis of the chief data which bear on atomic structure — the nuclear properties, and the disposition of the electrons around the nucleus. The origin of line spectra is discussed, and the ionization potentials corresponding to different atoms are tabulated. Lastly a brief summary is made of the effect of external conditions, such as temperature, pressure, and magnetic or electric fields, upon a line spectrum.

ATOMIC PROPERTIES ASSOCIATED WITH THE NUCLEUS

The properties determined by the atomic nucleus are the mass, and the isotopic and radioactive properties. The astrophysical study of these factors is as yet in an elementary stage, but it seems that all three have a bearing on the frequency of atomic species, and that future theory may also relate them to the problem of the source and fate of stellar energy. Moreover, up to the present no general formulation of the theory of the formation and stability of the elements has been possible, and it is well to keep in mind the data which are apparently most relevant to the problem — the observational facts relating to the nucleus. Probably the study of the nucleus involves the most fundamen-
CHAPTER XIII

THE RELATIVE ABUNDANCE OF THE ELEMENTS

The relative frequency of atomic species has for some time been of recognized significance. Numerous deductions have been based upon the observed terrestrial distribution of the elements; for example, attention has been drawn to the preponderance of the lighter elements (comprising those of atomic number less than thirty), to the "law of even numbers," which states that elements of even atomic number are far more frequent than elements of odd atomic number, and to the high frequency of atoms with an atomic weight that is a multiple of four.

The existence of these general relations for the atoms that occur in the crust of the earth is in itself a fact of the highest interest, but the considerations contained in the present chapter indicate that such relations also hold for the atoms that constitute the stellar atmospheres and therefore have an even deeper significance than was at first supposed. Data on the subject of the relative frequency of the different species of atoms contain a possible key to the problem of the evolution and stability of the elements. Though the time does not as yet seem ripe for an interpretation of the facts, the collection of data on a comprehensive scale will prepare the way for theory, and will help to place it, when it comes, on a sound observational basis.

The intensity of the absorption lines associated with an element immediately suggests itself as a possible source of information on relative abundance. But the same species of atom gives rise simultaneously to lines of different intensities belonging to the same series, and also to different series, which change in intensity relative to one another according to the temperature of the star. The intensity of the absorption line is, of course, a very complex function of the temperature, the pressure, and the
relative abundance of the elements

variation will probably not be very large. The reorganization
time of an atom appears to be an atomic constant, and to be of
the same order for all atoms hitherto examined in the laboratory
or in stellar atmospheres. As a working assumption, then, the
equality of the atomic absorption coefficients is assumed with

<table>
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<th>Atomic Number</th>
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<th>Log $\sigma_r$</th>
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<td>Ba+</td>
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some confidence in the discussion of observed marginal appear-
ances.

As stated above, the relative abundances of the atoms are
given directly by the reciprocals of the respective fractional con-
centrations at marginal appearance. The values of the relative
abundance thus deduced are contained in Table XXVIII. Suc-
cessive columns give the atomic number, the atom, and the
logarithm of the relative abundance, $\sigma_r$.

Comparison of Stellar Atmosphere and Earth's Crust

The preponderance of the lighter elements in stellar atmos-
pheres is a striking aspect of the results, and recalls the similar
feature that is conspicuous in analyses of the crust of the earth.\(^6\) A
distinct parallelism in the relative frequencies of the atoms of
the more abundant elements in both sources has already been
suggested by Russell,\(^7\) and discussed by H. H. Plaskett,\(^8\) and the

\(^7\) Russell, Science, 90, 701, 1914.
data contained in Table XXVIII confirm and amplify the similarity.

A close correspondence between the percentage compositions of the stellar atmosphere and the crust of the earth would not, perhaps, be expected, since both sources form a negligible fraction of the body of which they are a part. There is every reason to suppose, on observational and theoretical grounds, that the composition of the earth varies with depth below the surface; and the theory of thermodynamical equilibrium would appear to lead to the result that the heavier atoms should, on the average, gravitate to the center of a star. If, however, the earth originated from the surface layers of the sun, the percentage composition of the whole earth should resemble the composition of the solar (and therefore of a typical stellar) atmosphere. But the mass of the earth alone is considerably in excess of the mass of the reversing layer of the sun. Eddington, quoting von Zeipel, has pointed out that an effect of rotation of a star will be to keep the constituents well mixed, so that the outer portions of the sun or of a star are probably fairly representative of the interior. Considering the possibility of atomic segregation both in the earth and in the star, it appears likely that the earth’s crust is representative of the stellar atmosphere.

The most obvious conclusion that can be drawn from Table XXVIII is that all the commoner elements found terrestrially, which could also, for spectroscopic reasons, be looked for in the stellar atmosphere, are actually observed in the stars. The twenty-four elements that are commonest in the crust of the earth, in order of atomic abundance, are oxygen, silicon, hydrogen, aluminum, sodium, calcium, iron, magnesium, potassium, titanium, carbon, chlorine, phosphorus, sulphur, nitrogen, manganese, fluorine, chromium, vanadium, lithium, barium, zirconium, nickel, and strontium.

The most abundant elements found in stellar atmospheres,
RELATIVE ABUNDANCE OF THE ELEMENTS

also in order of abundance, are silicon, sodium, magnesium, aluminum, carbon, calcium, iron, zinc, titanium, manganese, chromium, potassium, vanadium, strontium, barium, (hydrogen, and helium). All the atoms for which quantitative estimates have been made are included in this list. Although hydrogen and helium are manifestly very abundant in stellar atmospheres, the actual values derived from the estimates of marginal appearance are regarded as spurious.

The absence from the stellar list of eight terrestrially abundant elements can be fully accounted for. The substances in question are oxygen, chlorine, phosphorus, sulphur, nitrogen, fluorine, zirconium, and nickel, and none of these elements gives lines of known series relations in the region ordinarily photographed.

The \(^{18}\text{O} - \text{m} \text{P}^{5}\) "triplets" of neutral oxygen, in the red, should prove accessible in the near future; the point of disappearance of these lines would not be difficult to estimate, and they would furnish a value for the stellar abundance of oxygen. The lines of ionized oxygen, which have not yet been analyzed into series, are conspicuous in the B stars,\(^{14}\) and the element is probably present in large quantities.

Sulphur and nitrogen both lack suitable lines in the region usually studied; the analyzed spectrum of neutral sulphur is in the green and red,\(^{15}\) or in the far ultra-violet,\(^{16}\) and the neutral nitrogen spectrum has not as yet been arranged in series. Both sulphur and nitrogen appear, in hotter stars, in the once and twice ionized conditions,\(^{17}\) and are probably abundant elements in stellar atmospheres.

For the remaining elements, phosphorus, chlorine, fluorine, zirconium and nickel, series relations are not, as yet, available. No lines of phosphorus or the halogens have been detected in stellar spectra, but these elements have not been satisfactorily analyzed spectroscopically, and their apparent absence from the stars is probably a result of a deficiency in suitable lines. Nickel

\(^{14}\) H. C. 256, 1924.
\(^{15}\) Fowler, Report on Series in Line Spectra, 170, 1922.
\(^{16}\) Hopfield, Nature, 432, 1923.
\(^{17}\) H. C. 256, 1924.
and zirconium will probably be analyzed in the near future; they are both well represented in stellar spectra, and nickel especially is probably abundant.

The relative abundances, in the stellar atmosphere and the earth, of the elements that are known to occur in both, display a striking numerical parallelism. Table XXIX gives the data for the sixteen elements most abundant in the stellar atmosphere. Successive columns give the atomic number, the atom,

<table>
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<th>Atomic Number</th>
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<th>Stellar Abundance</th>
<th>Terrestrial Abundance</th>
<th>Abundance Stony Meteorites</th>
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<td>Crust.</td>
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the relative stellar abundance, the relative terrestrial abundance (both for the lithosphere, hydrosphere, and atmosphere, and for the whole earth), and the relative abundance in stony meteorites. The figures in the fifth column are derived from Clarke's estimates of the percentage composition of the earth. The composition of the earth has been variously estimated by different

---

investigators, and the resulting figures depend upon theories that cannot be discussed here. The order given by Clarke is based on the assumption of a nickel-iron core.

The numbers expressing the stellar abundance are percentages, calculated on the assumption that the stellar and terrestrial elements form the same fraction of the total material present. This reduces the two columns of numbers to a form in which they are directly comparable, but no great importance is attached to the absolute percentages in the third column.

The method that has here been used is subject to inaccuracy and uncertainty, especially in the estimates of the exact spectral class at which a line is first or last seen. The most that can be expected is that the results will be trustworthy in order of magnitude. It may be seen that the only element for which the stellar and terrestrial values are not of the same order is zinc. Further, it appears that when the estimates for the percentage composition of the whole earth are used in the comparison with the stellar values, the agreement is improved in the case of silicon, magnesium, aluminum, manganese, chromium, and potassium; it is about the same for calcium and titanium, is less close for sodium, and markedly poorer for iron. * In the stellar atmosphere and the meteorite the agreement is good for all the atoms that are common to the two, but several important elements are not recorded in the meteorite.

The outstanding discrepancies between the astrophysical and terrestrial abundances are displayed for hydrogen and helium. The enormous abundance derived for these elements in the stellar atmosphere is almost certainly not real. Probably the result

* Professor Russell believes that iron is much more abundant, at least in the sun, than calculated above. He writes: "More than half of all the strong winged solar lines are iron lines, and the strength and evident saturation of even the faint satellites in the iron multiplets is remarkable. . . . There are a great many multiplets of nearly equal strength arising from the low triplet F level in iron. . . . Nothing like this happens for the D lines, or for H and K, although it may hold true for the Mg triplets. I should consequently favor multiplying the percentage for iron by a factor of at least 3 and probably 5 — which would put it where it obviously belongs."
may be considered, for hydrogen, as another aspect of its abnormal behavior, already alluded to; and helium, which has some features of astrophysical behavior in common with hydrogen, possibly deviates for similar reasons. The lines of both atoms appear to be far more persistent, at high and at low temperatures, than those of any other element.

The uniformity of composition of stellar atmospheres appears to be an established fact. The quantitative composition of the atmosphere of a star is derived, in the present chapter, from estimates of the "marginal appearance" of certain spectral lines, and the inferred composition displays a striking parallel with the composition of the earth.

The observations on abundance refer merely to the stellar atmosphere, and it is not possible to arrive in this way at conclusions as to internal composition. But marked differences of internal composition from star to star might be expected to affect the atmospheres to a noticeable extent, and it is therefore somewhat unlikely that such differences do occur.

Chapter V, p. 56.
CHAPTER XIV

THE MEANING OF STELLAR CLASSIFICATION

It is not necessary to discuss the possibility or desirability of classifying stellar spectra. Both have been adequately demonstrated by Miss Cannon in the Henry Draper Catalogue,¹ which contains the classification that has been accepted as standard.² The catalogue will undoubtedly long remain the authoritative source of spectral data for the major part of the stars bright enough to be accessible to the spectroscopist. The uses of the material that it contains are so numerous and so direct that the basis and meaning of the classes seem to deserve attention.

In classifying a number of objects, an attempt should be made to select criteria that will distribute the material into the most natural groups. A classification devised with one point of view will not necessarily appear natural from another, and the best that can generally be done is to select the standpoint that seems to be the most important. From all other standpoints the classification is empirical, and must be treated as such. It seems necessary to emphasize this empiricism with regard to the classifying of stellar spectra, for reference is often made to the Henry Draper Classification as though it had a theoretical, even an evolutionary, basis, whereas it is essentially arbitrary. It is true that a classification based on theoretical principles is very desirable, but at present there is no adequate physical theory on which to found one.

The essential feature of the Draper classification is that it aims at classing together similar spectra, relying on general appearance, and not on the measurement of any one line or group of lines. This has the advantage of distributing the material in the most natural groups possible, and a disadvantage in that

HOMOGENEITY OF CLASSES

of A. Fowler,7 "... the typical stars not only increase in redness in passing through the sequence, but successive Draper classes correspond to nearly equal increments of redness as measured by the color index."

The preceding eight chapters review the arguments and the observations that have established the connection between the spectrum of a star and its temperature. From an examination of the data there given it becomes clear that what the Draper system classifies is essentially the degree of thermal ionization. A. Fowler, in fact, makes the illuminating distinctions of "arc" (N to G), "spark" (F to A), and "superspark" (B onwards) stars.

The table that follows contains, in concise form, the chief features by which the type stars of each class are to be recognized, although it is again emphasized that these were not actually measured as criteria for the Draper classes. The lines characteristic of each class serve, however, to specify its degree of thermal ionization.

The homogeneity of the spectra in a given class is striking, and the fact that large numbers of stars display exactly similar spectra has a significance — considered in another chapter 8 — to which the classification problem cannot do more than call attention. The similarity of the spectra becomes the more striking when it is remembered that the range of conditions embraced within any one class is very wide; the ratio in mean density may be as great as $10^9$ between stars of the same class but of differing absolute magnitude.10

The close spectral similarity between giants and dwarfs, in spite of the great differences in physical conditions, should not, however, be misinterpreted. The observed facts are in exact accordance with what might have been anticipated. In the first place, thermal ionization is governed by the surface gravity, and only indirectly by the mean density.11 It is shown in Chapter III that the range in surface gravity is far smaller than the

7 Observatory, 38, 381, 1915.
8 Chapter XIII, p. 178.
9 Observatory, 38, 381, 1915.
10 Chapter III, p. 36.
11 Chapter III, p. 35.
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<tr>
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<td>H Ca+</td>
</tr>
<tr>
<td>G0</td>
<td>H Ca+</td>
</tr>
<tr>
<td>K0</td>
<td>H Ca+</td>
</tr>
<tr>
<td>Ma</td>
<td>H Ca*</td>
</tr>
<tr>
<td>Mb</td>
<td>H Ca*</td>
</tr>
<tr>
<td>Md</td>
<td>H Ca*</td>
</tr>
</tbody>
</table>

The division into “are,” “spark,” and “superspark” is clearly shown by the table. Maxima of the lines which are used as criteria of class are marked with an asterisk.
CHAPTER XV

ON THE FUTURE OF THE PROBLEM

The future of a subject is the product of its past, and the hopes of astrophysics should be implicit in what the science has already achieved. Astrophysics is a young science, however, and is still, to some extent, in a position of choosing its route; it is very much to be desired that present effort should so be directed that the chosen path may lead in a permanently productive direction. The direction in which progress lies will depend on the material available, on the development of theory, and on the trend of thought.

The material already at hand is far from exhaustively analyzed, and it is perhaps premature to contemplate collecting more. But as a science progresses it is often possible to direct the way "by showing the kind of data which it is especially important to improve," and particularly is this the case for astrophysics. In the improvement of the old data, by far the most important requirement is some method of standardizing the intensities of spectrum lines, and of measuring their width, energy distribution, and central intensity. This involves a very difficult and necessary piece of photographic photometry. The problem is an old one that has defied attack for a long time past. It is none the less urgent, and until the attack has been successfully made, many questions, such as are discussed in Chapter III, and other questions, which, for lack of data, we have not been able to discuss at all, must await their precise answers.

Much patient labor, on types of investigation that have already been well worked, still remains to be done. The identification of lines in the spectra of the sun and stars must necessarily be of a laborious nature, but the fact that more than two thirds of the lines in Rowland's table are still unidentified shows how
necessary and how large a piece of work this is. One of the things that would greatly assist progress would be a revision of Rowland’s table in the light of the recent analysis of the arc and spark spectra of the metals, insertion of the series relations, when known, and the reduction of the wave-length system to International Angstroms.

Another line of work, which lies upon the borderland between astrophysics and pure physics, is the analysis of spectral series. For most of the astrophysically important lines, series relations are already known, but some of the more difficult spectra, such as the spectrum of nitrogen, remain unanalyzed. The analysis of all such spectra is necessary to the advance of astrophysics.

The investigation of stellar spectra has been confined, for the most part, to the region lying between 3900 and 5000, although work on special stars has been carried into the red and the ultra-violet. The use of special dyes should permit work to be carried to about 7900 in the red, and a wave-length of 3500 appears to be accessible in the ultra-violet. There appears to be a large field for an extension of the analysis of stellar spectra into regions of the spectrum that are comparatively unexplored, and the writer hopes in the immediate future to undertake work in this direction.

The types of investigation hitherto mentioned are amplifications of work already in progress. New fields are not easy to predict, but they may be suggested by examining the extent to which present investigation is covering the possibilities of the data. The line position and intensity data are in full use at the present time. The form and energy distribution of individual lines, and the study of asymmetries, are among the urgent future problems. The measurement of the polarisation of the light received from the stars has enormous possibilities, but so far very little success has attended such attempts.

The future progress of theory is a harder subject for prediction than the future progress of observation. But one thing is certain: observation must make the way for theory, and only if it does so can the science have its greatest productivity.
ON THE FUTURE OF THE PROBLEM

Observational astrophysics is so vigorous a science that the progress of theory is almost completely determined by the progress of observation.

The most important of the three factors contemplated at the opening of the chapter is perhaps the trend of thought. It is owing to the tendency towards laying stress on observation, and to the general lessening of the distrust of large dimensions, that astrophysics has become possible as a science. The surprising growth of the subject during the last forty years is in great measure the result of this happy chance. The growth of the subject during the next forty years will depend on the coming trend of thought.

The prospect appears encouraging. At the present time the tendency is towards mutual toleration of point of view and to understanding of limitations among the sciences, and a consequent increase of correlation. If the breadth of conception thus engendered develops in the future as it has done in the immediate past, there is hope that the high promise of astrophysics may be brought to fruition.