15. CONCLUSION

ACHIEVEMENTS AND PROSPECTS

L.E. CRAM
School of Physics
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Australia

1. Introduction

The scientific study of the topic of this Symposium, "Fundamental Stellar Properties," was in its infancy at the turn of the Century. As illustrated at this meeting, there has been significant progress in many directions over the past 100 years. Despite this progress, there are however many unsolved problems that will be addressed by theoretical and observational techniques that are emerging only now.

Some astronomers would argue that the investigation of fundamental stellar properties is a mature field, one in which only a few significant discoveries remain to be made. Indeed, there can be little doubt that new technologies are likely to stimulate rapid progress in other fields where exploration is particularly difficult (such as cosmology or in situ planetology). However, the central role of fundamental stellar properties in astrophysical research, combined with a number of significant unsolved problems, will ensure that the subject remains vigorous well into the next Century.

The presentations of many participants in this Symposium point to two particularly pressing classes of problem that will receive much attention in the future. The first can be described by the term 'stellar gas dynamics,' the study of (magneto-) gas-dynamic processes in and around stars. The second can be described by the term 'stellar populations,' the study of the relationship between stars as individuals and stars in groups sharing common characteristics.

In the first area, the study of stellar gas dynamic processes such as accretion and mass loss must be undertaken if we are to understand problems in late and early stages of evolution. These include the stellar initial mass function, stellar multiplicity, and the origin of (baryonic) dark matter, white dwarfs, neutron stars and black holes. For stars that are neither young nor old, the behavior of waves and convection in the stellar interior

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and atmosphere can influence structure and complicate spectroscopic diagnostics. Studies of waves may also open new ways to seek to verify theories of stellar structure. Although ever more powerful computers are enabling the investigation of hitherto intractable gas dynamic problems, there seem to be profound difficulties in establishing connections between gas-dynamic theory and spectroscopic observations of phenomena that take place on scales much smaller than the stellar radius.

In the second area, the classification of stars and their arrangement into populations is a subject with a long history. However, despite significant progress with our understanding of stellar populations and physical associations, we are far from a satisfactory understanding of the relationships between the properties of individual stars, and the collective behavior of groups of stars. The acquisition and exploitation of large-scale spectroscopic, photometric and dynamical data bases is likely to be a particularly important route to understanding the origins of stellar groups on scales ranging from associations to clusters of galaxies. A foundation of such research is a clear understanding of the relationship between theory and observation of fundamental stellar properties.

As we are approaching the end of a century of research on fundamental stellar properties, it seems to be opportune to use this closing address to review some of the achievements over this period. This will help me indicate some of the direction that the subject might take over the next few decades. Of necessity the survey will be brief and hence incomplete, but nevertheless we will be able to see how threads from the past lead us in certain directions to the future. It will be convenient to divide the review into three roughly equal time spans.

2. 1900–1935

At the turn of the Century, almost nothing was known about the source of stellar luminosity. Speculations regarding the possibility that nuclear reactions (or radioactivity) could power the stars were advanced as early as 1915 (by Eddington). However, it was only during the latter part of the 1930s that theories for nuclear fueling similar to those current today were developed. Without these theories it was not possible to discover the modern interpretation of the Hertzsprung-Russell diagram, and consequently their development was a major turning point in stellar astrophysics. Nevertheless, in the three decades leading up to this development, many remarkably resilient discoveries were made about the structure of stars, and about many of the basic features of stellar spectroscopic and photometric diagnostics.

Prior to the development of quantum mechanics and Saha's theory of ionisation ($\sim$1920), understanding of the effective temperatures of stars was relatively undeveloped despite the availability of Planck's essentially complete theory of radiation thermodynamics. However, it was recognised that the relationship between the sequence of spectral types and stellar colours (determined by photographic photometry and spectroscopy) provided an uncalibrated sequence ordered by effective temperature. The available refined techniques for measuring and conducting statistical error analyses of parallax measurements also allowed the inference of absolute magnitudes. The Hertzsprung-Russell diagram could thus be constructed. As the importance of this system of classification became widely appreciated ($\sim$1912–15), the rather subtle differences of spectral line shapes between giants and dwarfs were used to provide 'spectroscopic parallaxes' greatly extending the scope of the diagram. The astrophysical significance of this method, as well as the general behaviour of spectral lines in different spectral types, was explained by Saha's theory ($\sim$1920). By this time, the angular diameters of a few stars had also been measured, confirming the existence of the giant stars implied by the Hertzsprung-Russell diagram.

Although the application of Planck's radiation theory to temperature determinations required Saha's theory to be fully effective, the theory could be applied to the problem of radiation transfer through a star. This commenced in $\sim$1905 with the work of Schuster and Schwarzschild. One thrust of this work was directed at the determination of stellar structure under the condition of radiative equilibrium, while another was directed at classical diagnostic problems such as the theory of solar limb darkening, the shape of the continuous spectrum, and the interpretation of the strengths and shapes of spectral lines. As a result of the long-running but erroneous underestimate of the hydrogen abundance (due mainly to incomplete understanding of the nuclear energy source and of the role of H^- as an opacity source) the quantitative results of spectroscopic diagnostic were often quite wrong. However, the foundations of such important procedures as curve-of-growth analysis and line profile fitting were laid at that time by Milne, Minneart, Menzel and others.

3. 1935–1965

As noted above, the discovery of the energy source of the stars in 1935–37 was a major advance shaping the future course of stellar astrophysics. Major research themes over the subsequent three decades (i.e, until the advent of a new generation of 4-metre class telescopes, solid-state panoramic detectors, space observatories and powerful computers) were naturally related to this discovery, particularly in relation to the abundances of the elements, the nature of stellar populations and the evolution of the stars.

Throughout the period 1935–65, the exploitation of photo-multipliers and other electronic devices opened up possibilities for observations to be made with improved precision and/or of fainter sources. Some of the most fruitful advances in instrumentation were applied to investigations of the Sun, which was studied from X-ray to radio wavelengths, and with even greater discernment of details in the optical wavebands. There was a vigorous exchange of people and ideas between stellar and solar astrophysics, providing insights and analogies that were particularly illuminating. Unfortunately, increased specialisation seems to have reduced the opportunities for such exchanges.

Discoveries made by solar physicists in this period included the convective origin of granulation and super-granulation, the five-minute oscillations, the high temperature of the corona, the compact nature of the chromosphere, and the ubiquity of magnetic flux tubes in the solar photosphere. Applications of the curve-of-growth and of line profile fitting provided estimates of the abundances of many elements, few of which have needed to be significantly revised. The techniques and concepts of non-LTE spectroscopic diagnostics were developed for solar applications at this time. Towards the end of the period, most of these areas of solar research were being directed also towards the stars.

Stellar astrophysicists discovered micro-and macro-turbulence (presumably the analogues of solar granulation and oscillations), began to explore magnetic stars and stellar chromospheres, and identified and provided preliminary accounts of the two great stellar populations. Significant advances were made in the absolute and relative measurement of stellar spectra and in the theory of stellar atmospheres. Together, these allowed a reliable link to be established between observations of the spectroscopic and photometric properties of stars and the fundamental quantities predicted and used by theory, such as effective temperature, luminosity and surface gravity.

The period 1935–65 saw not only the major nuclear reaction chains elucidated, but also the rapid development of methods for solving the equations of stellar structure. The importance of including convective energy transport was also discovered. With the resulting theory of stellar structure and evolution, it was possible to account for the relative abundances of many elements in various kinds of stars and stellar populations, and to explain the Hertzsprung-Russell diagram of field and cluster stars. The period also saw rapid developments in the theory of variable stars, including the theory of the Cepheid instability strip.

4. 1965–1996

New technology has stimulated rapid advances in the study of fundamental stellar properties over the past three decades. The construction of several

4-metre class telescopes combined with the application of panoramic solid-state optical and IR detectors has improved greatly the quality of ground-based observations. Space experiments, from those of the early days of Copernicus and Skylab to the recent spectacular results from Hipparcos and HST, opened up new spectral bands for accurate spectroscopy and photometry. This has provided a view of the stars as being far more 'dynamic' than hitherto recognised, stimulating many fruitful lines of research on fundamental stellar properties. During the same period, the increasing power of computers has allowed ever-more challenging problem in stellar astrophysics to be addressed.

The oral, poster and written contributions at this Symposium have provided an impressive picture of many of the most significant outcomes of this research. For example, we have seen that there has been great progress in measuring stellar parallaxes and proper motions in the galaxy. The technical barriers to interferometric determinations of stellar angular diameters are finally breaking down. These measurements, combined with a raft of new determinations of stellar masses from refined studies of binary systems, will provide new and tight constraints on models of stellar structure and evolution. Calibrations of absolute flux measurements in the near UV, visual and IR spectral regions are approaching 1% uncertainty, providing significant challenges to the most refined models of stars. Spectroscopic observations interpreted using refined diagnostic techniques are providing relative and differential abundance estimates with uncertainties believed to be smaller than a factor of two. Observations of stellar oscillations and pulsations are providing new ways of probing the internal structure of stars.

As our understanding of 'normal' stars improves, so attention turns increasingly to the early and late stages of stellar evolution where both theory and observation is more difficult. The genesis of stars and of any planetary systems that they might possess is increasingly amenable to observational and theoretical investigation. The origin and evolution of stellar chromospheres and coronae, and of magnetic phenomena in general, are becoming increasingly clear. The importance of mass-loss, especially in the late stages of stellar evolution, is readily acknowledged, and there has been steady progress in understanding the phenomenon.

On the theoretical side, powerful and flexible codes now include millions of absorbing species and quite complex models of important physical processes to yield remarkably refined predictions of stellar spectra. Models of stellar evolution are based on ever-sounder determinations of data on nuclear reaction rates and opacities, and methods are available to deal with evolution so rapid that hydrodynamic effects become important. Significant progress has been made with theories that combine gas-dynamic models of radiation pressure driven mass-loss with self-consistent non-LTE predictions of spectra, allowing new interpretations of observations of stars at critical stages of their evolution. Increasing attention is also being directed at sophisticated models of internal gas-dynamics, including the (non-linear) interaction between convection, rotation, pulsation and magnetic fields. These are providing new and valuable insights that help to identify the processes that control the observed differences in structure and evolution from star to star.

5. Prospects

There are a number of profound questions about the formation and structure of the universe that turn on topics that lie in the province of fundamental stellar astrophysics. For example, it is widely acknowledged that there is the need for a great deal more work on the relationships between age, kinematic behaviour and abundances of stars and star groupings in the Galaxy to elucidate some of the basic processes involved in galaxy formation and structure. As another example, despite quite rapid recent progress the relationship between the nature of dark matter and the outcomes of stellar evolution remains poorly understood. On the very large scale, the interpretation of the spectra of external galaxies rests squarely on the understanding of the spectra of the individual stars (and populations) that contribute to the integrated light, and many crucial linkages still remain to be made in this field. On a much smaller (but no less interesting) scale is the desire and improving capacity to explore the environs of stars, to understand better the formation and properties of companions, winds, planets and so forth.

These topics, and many others, will be the subject of future research in the field of fundamental stellar astrophysics. However, while it seems clear that the field offers important and tractable research opportunities, several speakers at this Symposium have displayed caution and concern about the future of the subject. Much of this appears to have its origins in a problem shared by some other fields of research: a recognition that progress seems to demand increasing attention to the details, combined with an uncomfortable feeling that the subject could become constipated through preoccupation with just these details.

There is, I believe, no easy answer to this dilemma. It can be exemplified by an important theme emerging from this Symposium, namely the prospects for major developments in computer-based theories of convection and waves in stellar atmospheres. We recognise that these are likely to represent significant advances in our understanding of micro-and macroturbulence and other motions in stellar atmospheres, which are certainly unsatisfactory aspects of contemporary diagnostic practice. Furthermore, we suspect that temperature inhomogeneities and temperature/velocity correlations could be leading to significant systematic errors in determinations of abundances and line shifts. However, it is extremely difficult to see how the wealth of details and the multitude of parameters that will characterise refined hydrodynamic modelling are going to be incorporated into a theory of the gross behaviour of stars. Presumably, researchers should aim to concentrate on those details that do indeed influence (or probe) the gross properties of stars, and to forge linkages between theory and observation so that observable consequences can be identified and critical tests can be devised.

This Symposium has provided a timely and wide ranging overview of a branch of science whose birth coincided with the turn of the Century, and which has witnessed remarkable progress of the past 100 years. Its prospects for the next few decades took equally intriguing.