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The solar granulation

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The Solar Chromosphere, R. J. Bray & R. E. Loughhead (London: Chapman & Hall, 1974)

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The solar granulation

R. J. BRAY, R. E. LOUGHHEAD
AND C. J. DURRANT

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PREFACE

When examined with a sufficiently powerful telescope under conditions of good atmospheric seeing the surface of the Sun reveals a fine structure consisting of an irregular cellular pattern of polygonal bright elements – granules – separated by narrow dark lanes. Over the whole surface there are some four million granules, whose average diameter is only about $1''.3$–$1''.4$ of arc ($\sim$1000 km). The observation of such small structures is not easy, and only in the last twenty-five years or so has the application of high-resolution techniques (both from the ground and from high-altitude balloons) given us a detailed picture of the properties and mode of origin of the granulation. Since the publication of the first edition of this book in 1967, the pace of advance has quickened: granule observations of higher resolution, covering longer periods of time, have been obtained and powerful computers are opening the way to realistic numerical simulations of the complex hydrodynamic processes involved. Our aim in this revised and expanded edition is to present a comprehensive and updated account of existing observational and theoretical knowledge.

Serious interest in the fine structure of the solar surface dates back to the beginning of the nineteenth century, and in a brief historical introduction (Chapter 1) we trace the changing ideas concerning the nature of the granulation resulting first from visual examination and, later, from photographic and spectroscopic observations, during the period 1801–1957. The latter date marks the beginning of the modern era, and in Chapter 2 we give a detailed account of the knowledge derived since then of the morphology, evolution, and dynamics of the photospheric granulation. In addition, we digress slightly in order to consider the corresponding properties of the supergranulation, which bears a certain resemblance to the ordinary granulation and may have a similar mode of origin.

Up to the present, our knowledge of the granulation has been based solely on observations from either ground-based or balloon-borne telescopes. However, many of the problems still confronting us require observations lying at or beyond the limit of the technically feasible. It is true that towards the late 1980s we can look forward to higher-resolution instruments carried on satellites, e.g. NASA's 1.25-m Solar Optical Telescope (SOT). Nevertheless, for quite some time to come we shall continue to rely very heavily on observations from the ground. Thermal disturbances in the Earth's atmosphere impose fundamental limitations on such observations and therefore we begin Chapter 2 with a brief review of solar seeing and its implications for solar observing.

Modern observations show unmistakably that the photospheric granulation is basically a convective phenomenon, each granule and its surrounding dark material representing a single convection cell. In fact, the granules are the visible manifestation of subphotospheric convection currents which contribute substantially to the outward transport of energy from deeper layers and thus help to maintain the energy balance of the Sun as a whole. Actually, they play an even wider role since, in the upper levels of the convection zone, they are believed to give rise to waves which are partially, if not wholly, responsible for heating the overlying chromosphere and corona. A discussion of the various possible types of waves lies beyond the scope of this book, but a detailed account can be found in a companion monograph (*The Solar Chromosphere*, R. J. Bray & R. E. Loughhead, London: Chapman & Hall).

A knowledge of the modern theory of fluid convection is evidently an essential pre-requisite to an understanding of convection in the Sun and stars and therefore to a proper interpretation of the solar granulation. Accordingly, in Chapter 3 we give an introduction to this theory, laying emphasis on those aspects of particular relevance to astrophysical systems. The topics covered include the basic hydrodynamic equations, the anelastic and Boussinesq approximations, the classical Rayleigh problem and its extension to stratified fluids, and laboratory convection. Although most laboratory experiments have been restricted to incompressible fluids, they can nevertheless provide valuable insight into the onset of convection in *compressible* fluids and into the processes involved in the transition to developed and ultimately, at very high Rayleigh numbers, turbulent convection. The chapter ends with a discussion of the so-called 'ice–water' experiment which, paradoxically, provides illuminating insight into the overshooting of the convective motions at the top of the solar convection zone into the stably stratified layer above.

In Chapter 4 we turn from laboratory to astrophysical convection and consider the theory of developed convection in a *stratified* gas. We start by describing different versions of the well-known mixing-length theory, which has been widely used to provide zeroth-order models of stellar convection zones. Next we consider more rigorous theories, seeking 'exact' solutions to the non-linear hydrodynamic equations which describe the flow pattern in detail. In so doing we have to recognize that solar convection is turbulent in character and therefore an understanding of the interplay between the large-scale ordered motions and the small-scale turbulence is vital. As one rises through the granulation layer the solar gas changes from being optically thick to optically thin and radiative smoothing of temperature differences between different parts of the gas becomes increasingly effective. Accordingly, our treatment of the theory of astrophysical convection ends with a discussion of radiative energy transfer in such an inhomogeneous medium.

The subject matter of Chapters 3 and 4 is inherently difficult and complex, but we have tried to develop the account in such a way as to make the subject accessible to solar physicists and astrophysicists with no expert knowledge of modern fluid mechanics and to theoretical hydrodynamicists with little or no previous contact with solar physics.

It must be admitted that the modern theory of astrophysical convection still suffers from certain deficiencies, e.g. the absence of a comprehensive treatment of the non-linear interactions leading to stochastic behaviour in the small-scale motions. Nevertheless, its application to the Sun has significantly advanced our understanding of the physical nature of the solar granulation and the solar convection zone. In the final chapter, Chapter 5, we confront the theory with the results of the extensive observations described in Chapter 2 wherever this is both possible and fruitful. The topics discussed include the mean cell size, lifetime, granulation near the extreme limb, height of overshoot, convective heat flux, direction of cellular motion and turbulence spectrum.

The comparison between observation and theory (Chapter 5) is effected by the construction of inhomogeneous models, taking account of the horizontal and vertical variations in the various hydrodynamic and thermodynamic quantities. This approach has advanced to the stage where, with the aid of modern large computers, a start has been made on the time-dependent numerical simulation of the granulation phenomenon. With the coming generation of computers such simulations should become increasingly realistic. But already a consistent picture of the granulation has emerged. This is important, not least because a convincing numerical simulation of the solar convection zone would constitute almost the sole astrophysical test of the basic theory of convection in highly stratified fluids.

The Sun is in no sense a peculiar star: a dwarf of spectral class G2 it is – as far as we know – a typical member of the lower main sequence of the Hertzsprung–Russell diagram. If we were able to examine the surfaces of other stars of similar spectral class, we would presumably see the phenomena of the granulation and supergranulation in much the same form. In fact, stars covering a wide range of spectral class are believed to possess convective envelopes similar to that of the

Sun. G, K and M stars have a hydrogen convection zone of considerable thickness, while A stars have a thin zone at the base of the atmosphere, the transition from a thick to a thin zone occurring at class F. The early B stars possess, instead of a hydrogen convection zone, a weak thin helium convection zone which carries only negligible heat. Among red stars, both giants and dwarfs have a deep convection zone, which in the extreme case of a late M dwarf extends all the way to the star's centre. In general, a convective core is associated with a strong concentration of the thermonuclear energy generation toward the centre, which is typically the case in early-type stars; the Sun is believed not to have a convective core.

On the other hand the Sun is the only star on which we are ever likely to see resolved granules. Therefore, information about stellar granulation can come only from Fraunhofer line profiles integrated over the stellar disk. Two promising diagnostics for the presence of stellar convection are discussed at the end of Chapter 5, based on our knowledge of the asymmetries and shifts of solar lines. Although the effects are small and refined measuring techniques are required, attempts to exploit them are in progress. In fact, we are witnessing the birth of a new era in stellar physics: more rigorous theories of astrophysical convection are being applied to the calculation of stellar models and, for the first time, the effects of convection in stellar atmospheres are being observed and compared with theory.

R.J.B. R.E.L. C.J.D.

Note by C. J. Durrant

This edition was conceived in mid-1979 when I was invited by the authors of the first (1967) edition to prepare a revision which would involve updating the observational parameters, reworking the discussion of convective theory and excising material which appeared dated or had been superseded. None of us then appreciated quite how much had been published in the intervening years, not only in terms of sheer volume but also in range of content. As a result, the framework of the book had to be enlarged in order to accommodate a treatment that would do justice to recent developments. Thus the reader will find two chapters devoted to convective theory in place of one previously; these are balanced by a chapter on the observed properties of the granulation which has been considerably enlarged to take account of its statistical as well as individual characteristics. The theoretical and observational material is drawn together in the final chapter to provide as complete a physical description of the granulation phenomenon as is possible today.

The bulk of this new material has been drafted by myself but the final text represents the outcome of an extended reworking by all three authors. To end on a personal note, I would like to express my warmest thanks to my coauthors. Not only did they encourage me to proceed with a more radical revision than was originally envisaged, but they were a constant source of material, advice, criticism and tact. The collaboration was most stimulating and rewarding; I hope that the reader will discern in the text some traces of the pleasure that the preparation of this edition has provided.

C.J.D.

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