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Dynamic Sun: an introduction

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1.1 Introduction

“A gaze blank and pitiless as the Sun”, was how W.B. Yeats evoked faceless doom in his poem *The Second Coming*. The glare of the Sun may still seem pitiless, but it is blank no longer - at least not to solar physicists. In spite of the stability of the Sun’s deep interior, the solar atmosphere is extremely active and dynamic. Observation reveals a wide-ranging repertoire of phenomena occurring at all times. Such phenomena are the consequence of magnetic flux emerging through the Sun’s surface from its interior, our understanding of which has been built up by theoretical modelling and observations, since they are beyond simulation in a terrestrial laboratory.

Although many exotic astronomical objects are available for study, the seemingly pedestrian Sun is the object of special study by large-scale ground-based telescopes and other facilities as well as by major spacecraft which were launched over the past twenty years by several space agencies around the world. One reason for this is of course the Sun’s proximity, which makes it a fundamental testing ground for virtually all astrophysical techniques. The signal-to-noise associated with the collection in one second of solar photons is comparable to that from a similar source at one parsec in 1000 years. Hence we are able to analyse solar data (in, e.g., the polarimetric, spectral, temporal, or spatial domain) to a very considerable extent. While we do not see surface details on any other star, we can resolve regions on the Sun as small as 150 km across, the size of a large city, using the latest ground-based instruments, and 700 km with spacecraft instrumentation, though recognizing it is likely to be even better soon. The success of solar observations has spawned studies in a wider context, e.g. atomic and nuclear spectroscopy in astrophysics, cosmic magnetometry,

neutrino astrophysics, and asteroseismology. Another example of the Sun's uniqueness for observational astronomers is the way in which it is possible, using particle detectors and magnetometers on spacecraft in orbits that take them far from the Earth's magnetosphere, to sample the solar wind which is the dynamic extension of the solar corona consisting of outward-streaming fully ionised plasma.

Despite the success of recent solar physicists in elucidating the workings of the Sun, there remain many challenges for our complete understanding. Some of the items include the filamentary structure of the photospheric magnetic field, the origin and behaviour of small magnetic bipoles continually emerging in supergranules, magnetic diffusion (which is so essential for understanding the solar dynamo), the Sun's peculiar internal rotation inferred from helioseismology, the energy source of the hot solar corona and the generation and acceleration of the solar wind, as well as the small but very important solar brightness variations with level of activity.

1.2 Main contents

In this book we present a modern, comprehensive and authoritative overview of the Dynamic Sun from its deep core to the outer corona, and the solar wind (see Figure 1.1), including a chapter on solar observing facilities. All the chapters have been refereed. They present an up-to-date account of the subject and list extensive references for further study. The main contents of each chapter is as follows:

Chapter 2: Solar models: structure, neutrinos, and helioseismological properties (Bahcall, Basu and Pinsonneault): Solar models remain at the frontiers of two different scientific disciplines, solar neutrino studies and helioseismology. After presenting the details of some state-of-the-art solar models, this chapter gives an overview of solar neutrino physics in some detail (helioseismology is covered in Chapters 3-5 of this book). The neutrino predictions from the set of solar models discussed have been contrasted with the results of the solar neutrino experiments. Finally, the structure of the solar models are compared with helioseismic results obtained using different data sets.

Chapter 3: Seismic Sun (Chitre and Antia): Helioseismology probes the internal structure and dynamics of the Sun with high precision. Frequencies of nearly half a million resonant modes of oscillations have been measured by the ground-based Global Oscillation Network Group (GONG) project and space-based Michelson Doppler Imager (MDI) on the SOHO spacecraft. Each of these modes is trapped in a different region of the solar interior and hence its frequency is sensitive to structure and dynamics in the corresponding region. Conversely, by combining the information from these large number of independent modes of solar oscillations, the inference is made of the structure and dynamics of the solar interior to unprecedented precision. These seismic data provide a test for solar models and theories of stellar structure and evolution.

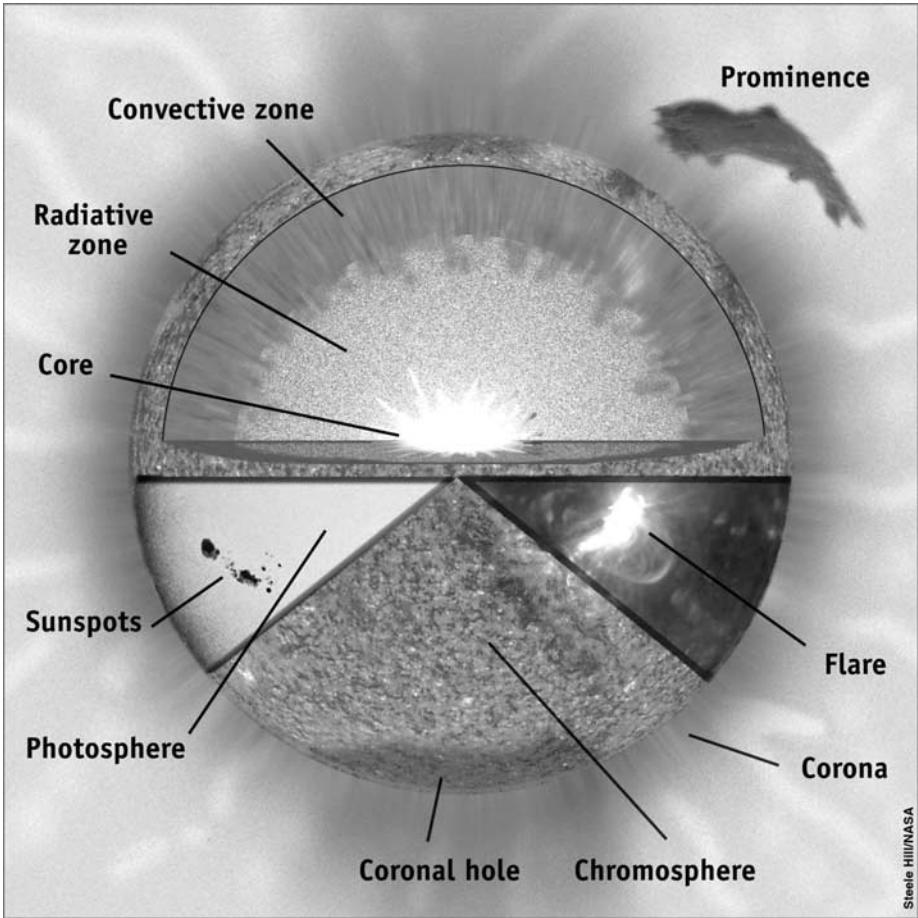


Figure 1.1. The chief parts of the Sun: This gives a basic overview of the Sun’s structure. The three major interior zones are the core (the innermost part of the Sun where energy is generated by nuclear reactions), the radiative zone (where energy travels outward by radiation through about 70% of the Sun), and the convection zone (in which convection circulates the Sun’s energy to the surface). The flare, sunspots and photosphere, chromosphere, corona, coronal holes, and the prominence are all clipped from actual SOHO images of the Sun. Courtesy of Steele Hill and SOHO/ESA-NASA.

Chapter 4: Rotation of the solar interior (Christensen-Dalsgaard and Thompson): Helioseismology allows us to infer the rotation in the greater part of the solar interior with high precision and resolution. The results show interesting conflicts with earlier theoretical expectations, indicating that the Sun is host to complex dynamical phenomena, so far hardly understood. This has important consequences for our ideas about the evolution of stellar rotation, as well as for models for the generation of the solar magnetic field. An overview of our current knowledge about solar rotation is given, much of it obtained from the SOHO spacecraft, and the broader implications are discussed.

Chapter 5: Helioseismic tomography (Kosovichev): Helioseismic tomography extends the capabilities of helioseismology by providing three-dimensional images of sound-speed variations and mass flows associated with sunspots, active regions, emerging magnetic flux, convective cells and other solar phenomena. The initial results reveal the structure of supergranulation and meridional flows beneath the solar surface as well as large-scale mass motions around sunspots and active regions, provide a clue for the mechanism of sunspots, and even show the presence of active regions on the far side of the Sun.

Chapter 6: The solar dynamo as a model of the solar cycle (Choudhuri): It is believed that the Sun's magnetic field is produced by the dynamo process, which involves non-linear interactions between the solar plasma and the magnetic field. Summarising the main characteristics of solar magnetic field, the basic ideas of dynamo theory are presented and its current status is discussed.

Chapter 7: Spectro-polarimetry (Stenflo): Spectro-polarimetry is our tool for remotely diagnosing the Sun's magnetic field. It deals with the wavelength variation of an observable vector quantity, the Stokes vector. The observational task is to map the Stokes vector both in the spectral and spatial domain with highest possible resolutions (spatial, spectral, temporal) and polarimetric accuracy. The interpretation or inversion of Stokes vector data to derive the magnetic and thermodynamic structure of the solar atmosphere must take into account the extreme structuring of the magnetic field, which extends to scales far smaller than we can resolve with present-day telescopes. With novel imaging Stokes polarimeters qualitatively new diagnostic tools like the Hanle effect and optical pumping are now available to complement the Zeeman effect in the exploration of the magnetized solar plasma on all scales.

Chapter 8: Solar photosphere and convection (Nordlund): An abrupt transition from convective to radiative energy transport at the solar surface results in a spatially and temporally very complex photosphere. The properties of the solar photosphere as well as its importance for both the sub-surface layers and for the chromosphere and corona above are now beginning to be understood in some detail. Progress has been made largely through the use and interpretation of numerical simulations of this region. Comparisons are made in a forward sense; synthetic observational data are generated from the numerical models, and are compared directly with corresponding observational data.

Chapter 9: The dynamics of the quiet solar chromosphere (Kalkofen, Hasan and Ulmschneider): Wave propagation in the nonmagnetic chromosphere is described for plane and spherical waves, and excitation by means of impulses in small source regions in the photosphere; excitation for flux tube waves in the magnetic network is described for large, single impulses and for a fluctuating velocity field. Observational signatures of the various wave types and their effect on chromospheric heating are considered. It is concluded that calcium bright points in the nonmagnetic

chromosphere are due to spherical acoustic waves, and that for the oscillations in the magnetic network, transverse waves are more important than longitudinal waves; they may penetrate into the corona, giving rise to some coronal heating.

Chapter 10: Heating of the solar chromosphere (Ulmschneider and Kalkofen): Overlying the photosphere is the chromosphere, a layer that is dominated by mechanical and magnetic heating. By simulating the chromospheric line and continuum emission, empirical models can be constructed that allow the energy balance to be evaluated. Several possible heating processes are discussed as well as the search is made for the actual heating mechanisms. It is found that dissipation by acoustic waves is the basic heating mechanism for nonmagnetic regions of the chromosphere, and MHD tube waves for magnetic regions.

Chapter 11: The solar transition region (Kjeldseth-Moe): What is the solar transition region like? The view of a static, thin transition region has long been left behind. Modern concepts are emerging, but a new model is not generally agreed upon. The observational facts and theoretical considerations, however, consistently point towards a strongly dynamic solar plasma. A comprehensive account of all this is presented here.

Chapter 12: Solar magnetohydrodynamics (Priest): The magnetic field exerts a force, stores energy, acts as a thermal blanket, channels plasma, drives instabilities, and supports waves. For many purposes the behaviour of the magnetic field and its interaction with plasma is governed by the equations of magnetohydrodynamics (MHD). This chapter gives a brief account of some of the basics of MHD, and summarises the simple properties of the different kinds of waves that are present in ideal MHD.

Chapter 13: Solar activity (Švestka): What is the active Sun which is a very important factor in our life? Observations from SOHO and TRACE reveal the highly turbulent nature of Sun's surface and its atmospheric layers: all the time and everywhere we see brightness variations, loop formations and decays, plasma flows and ejections of gas. However, this is not what we call solar activity. The real processes called solar activity appear only in limited parts of the solar surface, and their occurrence varies quasi-periodically with time, creating 11-year cycles of solar activity whose main characteristics are described in this chapter. Particular attention is paid to coronal mass ejections, as the most important phenomenon affecting the Earth.

Chapter 14: Particle acceleration (Emslie and Miller): The acceleration of particles to high energies is a ubiquitous phenomenon at sites throughout the universe. Despite decades of observations in X-rays and gamma-rays, the mechanism for particle acceleration in solar flares remains an enigma. A comprehensive account of the Sun as a very efficient particle accelerator is presented in this chapter.

Chapter 15: Radio observations of explosive energy releases on the Sun (Kundu and White): This chapter is devoted to a discussion of the radio observations of explosive energy releases (normal flares and small-scale energy releases) on the Sun. Radio imaging observations of solar flares and coronal transients and the relationship of radio phenomena with those observed in hard and soft X-rays, and underlying physics are discussed.

Chapter 16: Coronal oscillations (Nakariakov): The detection of coronal waves provides us with a new tool for the determination of the unknown parameters of the corona - MHD seismology of the corona. The method is similar to helioseismology. But MHD coronal seismology is much richer as it is based upon three different wave modes – Alfvén, slow and fast magnetoacoustic modes. These MHD modes have quite different dispersive, polarization and propagation properties, which make this approach even more powerful. The delicate interplay of MHD wave theory and the observations of coronal waves and oscillations are presented, illustrating it with several examples.

Chapter 17: Probing the Sun's hot corona (Phillips and Dwivedi): The mega-Kelvin temperature of the solar corona has been recognized since the 1940s. While it is generally realized that the magnetic field is the underlying reason, the detailed heating mechanism still eludes solar physicists. This chapter reviews the main historical developments and discoveries right up to those from currently operating satellites such as SOHO and TRACE as well as the chief theoretical problems. An account of the two main competing ideas for coronal heating, nanoflares and MHD wave dissipation, is then given.

Chapter 18: Vacuum-ultraviolet emission line diagnostics for solar plasmas (Dwivedi, Mohan and Wilhelm): Observations of the solar vacuum-ultraviolet emission lines obtained by SUMER/SOHO and their interpretation in terms of atomic physics concepts are given. Electron temperature and density diagnostics of the low corona are described. Doppler line-of-sight measurements demonstrate an outflow at the base of the corona in the dark areas of coronal holes, which are seen as the source of the solar wind. Some aspects of the dynamics of the upper solar atmosphere, such as explosive events and sunspot oscillations, are mentioned as examples of the quiet-Sun activity, but spectral observations during solar flare are also shown with indications of plasmas with temperatures of several million Kelvins.

Chapter 19: Solar wind (Marsch, Axford and McKenzie): There are three major types of solar wind – the steady fast wind, the unsteady slow wind, and the variable transient wind. The fast streams are the normal modes of the solar wind. Their basic properties can be reproduced by multi-fluid models involving waves. After briefly reviewing the history of the subject and describing some of the modern theories of the fast wind, the boundary conditions and *in-situ* constraints are discussed which are imposed on the models, in particular by Ulysses at high latitudes.

Some of the results are then presented from SOHO observations that have brought a wealth of new information on the state of the wind in the inner corona as well as the plasma source conditions prevailing in the transition region and solar chromosphere. Finally, problem areas are identified and future research perspectives are outlined.

Chapter 20: Solar observing facilities (Fleck and Keller): An overview is given of current and planned ground-based solar telescopes and instruments, balloon-borne and suborbital solar telescopes, and solar and heliospheric space missions. These observing facilities operate in all areas of solar physics, from the solar interior to interplanetary space and from regimes of high energy to observations requiring high resolution. The next generation of solar telescopes and instruments promise us the ability to investigate solar processes on their fundamental scales, whether sub-arc second or global in nature.

1.3 Concluding remarks

SOHO and TRACE have produced a host of high-resolution observations that have already substantially improved our insights into the physics of the Sun itself as well as how the solar wind and coronal mass ejections influence the near-Earth environment. A new generation of satellites is expected to unravel further solar mysteries and to monitor space weather in a similar way to its terrestrial counterpart. The scientific future of solar physics thus offers exciting prospects for the simple reason that the Sun presents more and more mysteries giving opportunities to learn new physics. And as Yeats says elsewhere, “I’ll . . . pluck till time and times are done . . . the golden apples of the Sun”, I hope the intended readership (graduate students, and researchers in solar physics, astrophysics, and astronomy) will find each chapter of this book, a ‘golden apple’ of the Dynamic Sun and as a whole an indispensable guide. This has been possible with the kind support of all my co-authors, and I can hardly thank them enough.

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Solar models: Structure, neutrinos, and helioseismological properties

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2.1 Introduction

Why are new calculations of standard solar models of interest? After all, solar models have been used to calculate neutrino fluxes since 1962 (Bahcall *et al.* 1963) and solar atmospheres have been used to calculate p-mode oscillation frequencies since 1970 (Ulrich 1970; Leibacher and Stein 1971). Over the past four decades, the accuracy with which solar models are calculated has been steadily refined as the result of increased observational and experimental information about the input parameters (such as nuclear reaction rates and the surface abundances of different elements), more accurate calculations of constituent quantities (such as radiative opacity and equation of state), the inclusion of new physical effects (such as element diffusion), and the development of faster computers and more precise stellar evolution codes.

Solar models nevertheless remain at the frontiers of two different scientific disciplines, solar neutrino studies and helioseismology. In an era in which many major laboratory studies are underway to study neutrino oscillations with the aid of very long baselines, $\sim 10^3$ km, between accelerator and detector, solar neutrinos have a natural advantage, with a baseline of 10^8 km (Pontecorvo 1968). In addition, solar neutrinos provide unique opportunities for studying the effects of matter upon neutrino propagation, the so-called MSW effect (Wolfenstein 1978; Mikheyev and Smirnov 1985), since on their way to terrestrial detectors they pass through large amounts of matter in the Sun and, at night, also in the earth.

The connection with ongoing solar neutrino research imposes special requirements on authors carrying out the most detailed solar modeling. Precision comparisons between neutrino measurements and solar predictions are used by many physicists to refine the determination of neutrino parameters and to test different models of neutrino propagation. Since the neutrino experiments and the associated analysis of solar neutrino data are refined at frequent intervals, it is appropriate to reevaluate and refine the solar model predictions as improvements are made in the model input parameters, calculational techniques, and descriptions of the microscopic and macroscopic physics.

In this paper, we provide new information about the total solar neutrino fluxes and the predicted neutrino event rates for a set of standard and non-standard solar models. We also present the number density of scatterers of sterile neutrinos. These quantities are important for precision studies of neutrino oscillations using solar neutrinos.

At the present writing, the Sun remains the only main-sequence star for which p-mode oscillations have been robustly detected. Thus only for the Sun can one measure precisely tens of thousands of the eigenfrequencies for stellar pressure oscillations. The comparison between the sound speeds and pressures derived from the observed p-mode frequencies and those calculated with standard solar models has provided a host of accurate measurements of the interior of the nearest star. The solar quantities determined by helioseismology include the sound velocity and density as a function of solar radius. The excellent agreement between the helioseismological observations and the solar model calculations has shown that the large discrepancies between solar neutrino measurements and solar model calculations cannot be due to errors in the solar models (cf. Figure 2.3). In this paper, we present a refined comparison between our best standard solar model and measurements of the solar sound speeds obtained using oscillation data from a number of different sources.

The interested reader may wish to consult the following works that summarize the solar neutrino aspects of solar models (Bahcall 1989; Bahcall and Pinsonneault 1992, 1995; Berezinsky, Fiorentini, and Lissia 1996; Castellani *et al.* 1997; Richards *et al.* 1996; Turck-Chièze *et al.* 1993; Bahcall, Basu, and Pinsonneault 1998) and the helioseismologic aspects of solar models (Bahcall and Ulrich 1988; Bahcall and Pinsonneault 1995; Christensen-Dalsgaard *et al.* 1996; Guenther and Demarque 1997; Guzik 1998; Turck-Chièze *et al.* 1998; Brun, Turck-Chièze, and Zahn 1999; Ricci and Fiorentini 2000).

2.2 Standard solar model

By ‘the Standard solar model’ (henceforth SSM), we mean the solar model which is constructed with the best-available physics and input data. All of the solar models we consider, standard or ‘deviant’ models, (see below) are required to fit the observed luminosity and radius of the Sun at the present epoch, as well as the observed heavy

element to hydrogen ratio at the surface of the Sun. No helioseismological constraints are used in defining the SSM.

Naturally, Standard models improve with time, as the input data are made more accurate, the calculational techniques become faster and more precise, and the physical description is more detailed.

Our SSM[†] is constructed with the OPAL equation of state (Rogers, Swenson, and Iglesias 1996) and OPAL opacities (Iglesias and Rogers 1996), which are supplemented by the low temperature opacities of Alexander and Ferguson (1994). The model was calculated using the usual mixing length formalism to determine the convective flux.

The principal change in the input data is the use of the Grevesse and Sauval (1998) improved standard solar composition in the OPAL opacities (see <http://www.phys.lnl.gov/Research/OPAL/index.htm>) and in the calculation of the nuclear reaction rates. The refinements in this composition redetermination come from many different sources, including the use of more accurate atomic transition probabilities in interpreting solar spectra. The OPAL equation of state and the Alexander and Ferguson opacities are not yet available with the composition recommended by Grevesse and Sauval 1998.

The nuclear reaction rates were evaluated with the subroutine `exportenergy.f` (cf. Bahcall and Pinsonneault 1992), using the reaction data in Adelberger *et al.* (1998) and with electron and ion weak screening as indicated by recent calculations of Gruzinov and Bahcall (1998); see also Salpeter (1954)[‡]. The model incorporates helium and heavy element diffusion using the exportable diffusion subroutine of Thoul (cf. Thoul, Bahcall and Loeb, 1994; Bahcall and Pinsonneault 1995)[§]. An independent and detailed treatment of diffusion by Turcotte *et al.* (1998) yields results for the impact of diffusion on the computed solar quantities that are very similar to those obtained here. We have used the most recent and detailed calculation (Marcucci *et al.* 2000) for the S_0 -factor for the ${}^3\text{He}(p, e^+ + \nu_e){}^4\text{He}$ reaction: $S_0(\text{hep}) = 10.1 \times 10^{-20}$ keV b, which is a factor of 4.4 times larger than the previous best-estimate [see §2.4.2, Bahcall and Krastev (1998), and Marcucci *et al.* (2001) for a discussion of the large uncertainties in calculating $S_0(\text{hep})$]. For values of $S_0(\text{hep})$

[†] To simplify the language of the discussion, we will often describe characteristics of the Standard model as if we knew they were characteristics of the Sun. We will sometimes abbreviate the reference to this Standard model as BP2000 or Bahcall-Pinsonneault 2000.

[‡] Other approximations to screening are sometimes used. The numerical procedures of Dzitko *et al.* (1995) and Mitler (1977) predict reaction rates that are too slow for heavy ions because they assumed that the electron charge density near a screened nucleus is the unperturbed value, $en_e(\infty)$. This assumption seriously underestimates the charge density near heavy ions. For example, it is known that a screened beryllium nucleus under solar interior conditions has charge density near the nucleus $\approx -3.85en_e(\infty)$ (Gruzinov and Bahcall 1997; Brown and Sawyer 1997; all quantum mechanical calculations give similar results, see Bahcall 1962, and Iben, Kalata, and Schwartz 1967).

[§] Both the nuclear energy generation subroutine, `exportenergy.f`, and the diffusion subroutine, `diffusion.f`, are available at the Web site www.sns.ias.edu/~jnb, menu item: neutrino software and data.