CHAPTER 1

RECENT ADVANCES IN SOLAR PHYSICS

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1.1. Introduction

For millennia, the Sun (and the universe) has been viewed in the visual light. As the bestower of light and life, the ancients made God out of the Sun. With the Babylonians, or with the multiple origins with the Chinese, Egyptians and Indians, quoting the Rig Veda: "All that exists was born from Sūrya, the God of gods.", we have come a long way to understanding the Sun. In the early seventeenth century, however, Galileo showed that the Sun was not an immaculate object. Thus began our scientific interests in our nearest stellar neighbour, the Sun (cf., Figure 1.1.), with its sunspots and the related solar activity. The observations of the Sun and their interpretations are of universal importance for at least two reasons: First, the Sun is the source of energy for the entire planetary system and all aspects of our life have direct impact on what happens on the Sun; and second, the Sun's proximity makes it unique among the billions of stars in the sky of which we can resolve its surface features and study physical processes at work.

Observations of the solar atmosphere led to the development of the theory of radiative transfer in stellar atmospheres and the discovery of the element helium. Moreover, the Sun is the principal magnetohydrodynamic (MHD) laboratory for large magnetic Reynolds numbers, exhibiting the totally unexpected phenomena of magnetic fibrils, sunspots, prominences, flares, coronal loops, coronal mass ejections (CMEs), the solar wind, the X-ray corona, and irradiance variations etc. It is the physics of these exotic phenomena, collectively making up variations of solar activity, with which we are confronted today. The activity affects the terrestrial environment, from occasionally knocking out power grids to space weather and most probably general climate.

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Beginning with the first solar ultraviolet light from space in 1946, X-rays in 1948, hard X-rays and γ-rays in 1958; many experiments have been conducted or being conducted using balloons, rockets and satellites (e.g., OSOs, Skylab, SMM, Yohkoh, SOHO, TRACE, RHESSI, Hinode and STEREO etc.). Artificial satellites have provided the unique opportunity to have uninterrupted observations of the Sun from the vantage points, such as the Sun-Earth Lagrangian point L_1 (e.g., SOHO), or from outside the ecliptic plane (e.g., Ulysses), or in stereoscopic modes using different orbits (e.g., STEREO). All these have provided a rich source of data, unlocking the secrets of the Sun and addressing some of its outstanding riddles (e.g., coronal heating, solar wind acceleration etc.)

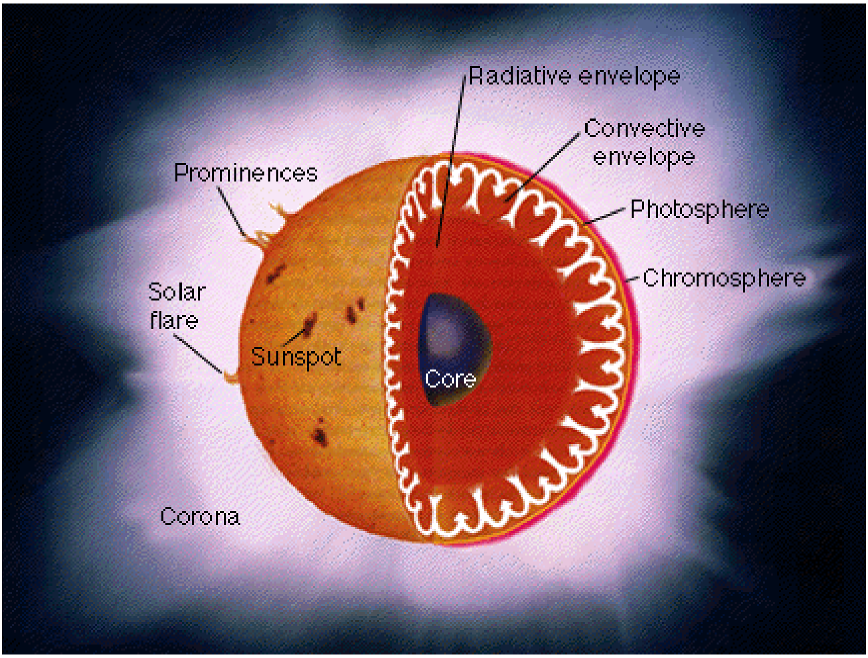

Figure 1.1. Brief view of the Sun: The Sun's energy derives from nuclear reactions that occur in its core which is at temperatures of 15 million degrees Kelvin. This energy moves outward, first in the form of electromagnetic radiation (e.g., X-rays and γ-rays) in the radiative zone. Energy then moves upward in photon-heated solar gas through convection in the convective zone (outer 200 000 km). Because of tremendous pressure, this energy is continually absorbed and re-absorbed and may take millions of years to reach the surface of the Sun. Convection motions in the Sun's interior generate magnetic fields, emerging at the Sun's surface as sunspots and loops of hot gas called prominences. Most solar energy finally escapes from a thin layer of the Sun's atmosphere called the photosphere, which is the part of the Sun observable to the naked eye. Image credit: NASA.

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Ground-based observations suffer from the effects of the Earth's atmosphere such as atmospheric extinction resulting in the limited radiative spectrum of the Sun, and turbulence resulting in image distortions. None the less, making use of adaptive optics system, solar images with resolution of about 0.13" (90 km on the Sun), or even smaller structures down to 60 km, have been obtained by the Swedish 1-meter Solar Telescope (SST) on La Palma. Neutrino detectors have provided a unique tool for probing the Sun's interior by comparing the emitted flux with the predictions of the standard solar models. Helioseismology from space and from ground (e.g., GONG) have revolutionised our understanding of the workings of the Sun.

Against this brief background, it is intended to bring some of these developments in a limited but pedagogical and updated way to help beginners pursue solar physics research.

1.2. Main Contents

This book contains 13 chapters beginning with a glance of main contents of each chapter as follows:

Chapter 2: Overview of the Sun (Hasan): This chapter begins with how solar physics is going through an exciting period, particularly due to new insights obtained from space and ground observations. These have contributed significantly to improving our understanding of fundamental processes occurring in the solar atmosphere, from the interior to the heliosphere. By combining the information obtained through observations with theoretical developments, a holistic view is slowly beginning to emerge of the physical mechanisms taking place on the Sun.

Chapter 3: Seismic view of the Sun (Chitre and Dwivedi): This chapter presents the solar seismology which probes the internal structure and dynamics of the Sun using hundreds of thousands of accurately measured frequencies of solar oscillations. With the accumulation of the helioseismic data obtained with Global Oscillation Network Group (GONG) and Michelson Doppler Imager (MDI) instruments over the past solar cycle, it is possible to study temporal variations that occur within the solar interior with the progress of the cycle.

Chapter 4: Solar Magnetism (Venkatakrishnan and Gosain): This chapter is basically divided into two parts. In the first part, the important properties of the solar magnetic field are summarized. The discussion begins with a simple introduction to solar magnetohydrodynamics, describing the current status of the solar dynamo theory. Some very curious and interesting results on magnetic helicity and force-free fields are then presented in very basic terms. Finally, the application of this theoretical frame-work to the problems of coronal heating, solar flares and coronal mass ejections are developed in a simple unified scheme, based on a hierarchy of physical conditions.

The second part of this chapter consists of a tutorial on magnetographs. It begins with a description of polarization of light from very fundamental notions of coherence of light. This is followed by simple but comprehensive explanations of the Zeeman and Hanle effects along with the necessary basic ideas of quantum physics of scattering of light. Then the working of a few important magnetographs is outlined, with special emphasis on a solar vector magnetograph developed for USO, to provide a "hands on" perspective. The chapter concludes with a few brief remarks on the possible future directions for research in the domain of solar magnetism.

Chapter 5: Waves and Oscillations in the Solar Atmosphere (Erdélyi): This chapter introduces waves and oscillations in the solar atmosphere in a lucid manner. Recent satellite and ground-based imaging and spectral instruments have observed a wide range of wave and oscillatory phenomena in the visible, EUV, X-ray and radio wavelengths in the solar atmosphere. Because in most cases these waves and oscillations are tied to the complex magnetic structure of the solar atmosphere, these oscillatory and wave phenomena are interpreted in terms of magnetohydrodynamic (MHD) waves. Waves and oscillations are crucial in the understanding of the diagnostics and dynamics of the magnetised solar atmosphere, as these periodic motions contain information about the medium they occur in. Using undergraduate tools of applied mathematics, the basic properties of MHD waves and oscillations are described. The theoretical description is then strongly linked to the latest observational findings with applications to the wealth of MHD wave phenomena present in the solar atmosphere.

Observed MHD waves propagating from the lower solar atmosphere into the higher, often very dynamic regions of the magnetized corona, have the potential to provide an excellent insight into the physical processes at work at the coupling point between these apparently different regions of the Sun. High-resolution wave observations combined with advanced forward MHD modelling can give an unprecedented insight into the connectivity of the magnetized solar atmosphere, which further provides us with a realistic chance to reconstruct the structure of the magnetic field in the solar atmosphere. This type of solar exploration is termed as atmospheric magneto-seismology. Some new trends in the observational study of waves and oscillations, discussing their origin, and their propagation through the atmosphere are summarised. Finally, the role of the leakage of photospheric motions, whether coherent (e.g., p-modes), random (e.g., granular buffetting), or casual (e.g., footpoint nano-scale energy release) on the dynamics present in the solar atmosphere is addressed.

Chapter 6: VUV Spectroscopy of Solar Plasma (Mohan): Electron densities, temperatures, elemental abundances and emission measures of the space plasma are the basic parameters to give the informations regarding the generation and transport of mass, momentum and energy. The fundamental property of hot solar plasmas is their inhomogeneity. Using the spectroscopic diagnostic techniques for the temperature and density structures of hot optically thin plasmas, the solar atmosphere and its composition have been thoroughly examined. As an illustration, the potential for plasma diagnostics of forbidden transitions from ground levels in the nitrogen-like ions has been presented. Some of the lines considered in the present chapter have been measured by SUMER for the first time. Also using the SUMER spectra, electron density, temperature and abundance anomalies in the off-limb solar corona are discussed. In particular, the behaviour of the solar FIP (first ionization potential) effect with height above an active region observed at the solar limb is presented.

Chapter 7: Active Region Diagnostics (Mason and Tripathi): Recent observations from SOHO, Yohkoh and TRACE clearly demonstrate the complex and dynamic nature of the solar atmosphere. In order to explore the nature of solar active regions, it is important to determine the local plasma parameters (electron density, temperature, emission measure distribution, element abundances, flows, non-thermal line broadening etc.). This can only be reliably achieved using simultaneous imaging and spectroscopic observations. The Hinode and STEREO spacecrafts, launched in autumn 2006, are providing some spectacular new observations and insights. This chapter focuses on what has been learnt about active regions in particular from recent observations using spectroscopic diagnostics in the UV and X-ray wavelength ranges.

Chapter 8: Hall Effect and Ambipolar Diffusion in the Lower Solar Atmosphere (Krishan): This chapter highlights the realistic importance of incorporating multi-fluid system in the Sun's atmosphere to understand the physical processes in operation. The lower solar atmosphere is a partially ionized plasma consisting of electrons, protons and predominantly hydrogen atoms. The discrete structures such as the sunspots, the prominences and the spicules also consist of the three main species of particles. This essentially forms a three fluid system and therefore, it is mandatory to go beyond the single fluid magnetohydrodynamic studies. One must include the Hall effect which arises from the treatment of the electrons and the protons as two separate fluids and the ambipolar diffusion arising due to the inclusion of neutrals as the third fluid. The Hall effect and the ambipolar diffusion have been shown to be operational in a region beginning from below the photosphere up to the chromosphere. In this three fluid system, the magnetic induction is subjected to the ambipolar diffusion and the Hall effect, in addition to the usual resistive dissipation caused by the electron-proton and electron-neutral collisions. These effects produce novel modifications in the equilibrium configurations of the flows and the fields, the wave phenomena and the magnetic field transport processes. A first principle derivation of these effects in a three fluid system along with an account of their role in the characterization of the lower solar atmosphere is given in this chapter.

Chapter 9: On Solar Coronal Heating Mechanisms (Pandey and Narain): The million degree temperature of the solar corona has been an outstanding astrophysical problem since 1943. A number of mechanisms, such as accretion of intergalactic matter, acoustic waves, magnetoacoustic waves, Alfvén waves, currents/magnetic fields, spicules, magnetic flux emergence, velocity filtration etc have been offered as possible explanation. Alfvén waves may heat coronal holes as well as coronal loops in the solar corona. These structures can also be heated by currents/magnetic fields (as nano- and micro-flares) generated by slow photospheric foot point motions. The expected behaviour of X-ray and EUV intensities from Alfvén waves and nano- and micro-flares are quite similar. Only suitable experimental techniques can discriminate between the two main mechanisms. Velocity filtration does not require any source of energy but it requires the existence of highly energetic particles (mechanism still not known) at the base of corona. Other mechanisms do contribute to the energy budget of the solar corona but they cannot resolve the coronal heating problem individually.

Chapter 10: Coronal Mass Ejections (CMEs) and Associated Phenomena (Srivastava): Coronal mass ejections are spectacular expulsions of mass from the Sun that display a three-part structure comprising a leading edge, a dark cavity and a bright knot. Since the discovery of coronal mass ejections (CMEs) in 1970s, our knowledge about CMEs has improved considerably. This is largely due to multi-wavelength observations with several instruments dedicated to the observations of the Sun both from ground and space. Our understanding of CMEs took a giant leap with the unprecedented observations obtained by several instruments aboard SOHO designed to probe different layers of the Sun. This chapter expounds physical and kinematic properties of CMEs and associated phenomena, such as flares, eruptive prominences, sigmoids and EIT waves. It also examines the links between these phenomena and the physical processes that lead to eruption of CMEs. Finally, the observations of CMEs from the recently launched STEREO and Hinode are highlighted and the problems that these missions might be able to address and resolve.

Chapter 11: The Radio Sun (Manoharan): Solar radio observations from ground-based and space-based instruments have contributed a unique perspective on the physical phenomena occurring on the Sun. In particular, radio observations have played a key role in probing the different altitudes of the corona and provided the possibility to trace the three-dimensional structure of the coronal magnetic field. Moreover, the comparison of radio observations with other multi-wavelength data (e.g., X-ray, EUV, and optical) has clearly shown specific advantages and allowed for a deeper understanding of solar flares and coronal mass ejections and the physics behind the fundamental processes of the solar radio emission mechanism. This chapter gives the overview of radio observations of the quiet and active Sun and physics of the explosive energy release.

Chapter 12: The Solar Wind (Manoharan): This chapter reviews the evolution of the solar wind, with the particular emphasis on the properties of the solar wind within about 1 AU of the Sun. To start with, a brief discussion of coronal heating is given followed by the energy balance in the solar atmosphere and the formation of the solar wind. The solar wind measurement using the interplanetary scintillation technique is explained in detail. The results on the large-scale properties and long-term changes of quasi-stationary structures of the solar wind are presented. The solar wind disturbances resulting from the solar phenomena and their heliospheric evolution in space and time are reviewed based on radio scintillation technique. The solar cycle changes of the solar wind in the three-dimensional heliosphere are reviewed in the aspect of space weather effects of the solar wind. The final part also includes the turbulence characteristics of the quasi-stationary and transient solar wind.

Chapter 13: The Sun-Earth System: Our Home in Space (Lean): The concluding chapter of this book addresses the Sun-Earth system and our home in space. Energy flowing from the Sun heats the Earth, structures its atmosphere and organizes the surrounding space environment. Changes in this energy occur continually, with myriad terrestrial impacts, some of which have societal consequences involving climate change, the ozone layer and space-based enterprise.

1.3. Concluding Remarks

A pedagogical updated modern view of the Sun from its interior to its exterior as well as the Sun-Earth system in this book by eminent solar physicists present a rich menu to motivate graduate students who wish to pursue solar physics research career.

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