Overview of Solar Physics

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Abstract. The Sun has been aptly described as the Rosetta Stone of astronomy. Even though the interior of the Sun is not directly accessible to observations, it has been possible to unravel its internal structure with the help of equations governing the mechanical and thermal equilibrium along with the boundary conditions provided by observations of its mass, radius, luminosity and surface chemical composition. The external layers of the Sun display astonishingly rich dynamics with a host of energetic phenomena occurring at the surface and in the outer atmosphere. An interaction between solar differential rotation, turbulent convection and magnetic field seems to provide an effective mechanism that maintains the solar dynamo and drives the cyclic activity seen at the surface in the form of sunspots. The magnetic field appears to be the guiding force that can effectively supply the energy required for heating the chromospheric and coronal regions. The Sun thus turns out to be an ideal cosmic laboratory for testing atomic and nuclear physics, high-temperature plasma physics and magnetohydrodynamics, neutrino physics and general relativity.

1 Introduction

The Sun has played a major role in the development of physics and mathematics for the past several centuries. Thus, Kepler's laws provided the framework for describing motions of planets under the influence of the Sun's gravitational field. The Newtonian theory of gravitation explained the planetary and lunar motions with a remarkable degree of precision. The Newtonian theory has, in fact, successfully expounded the mechanics of planetary motions and the precession of their elliptical orbits. The measurements were refined by the end of the nineteenth century to the extent that the unaccounted precession of the orbit of planet Mercury was observed to be close to 43 seconds of arc per century. The excellent agreement between the prediction of general theory of relativity and the observed precession of the perihelion of Mercury was a great triumph for Einstein's geometrised formulation of gravitation. Another prediction of general relativity, namely, the gravitational deflection of light rays from a background star grazing the solar limb was measured during the total solar eclipse expedition of 1919, and found to be approximately the same as the predicted value of 1.75 arc seconds (precisely twice the Newtonian value). A longer transit time for radio waves propagating close to the solar body, across its deep gravitational potential well was also verified. It is clear our Sun has played a vital role in verification of general relativity (e.g., Weinberg 1972).

The Sun has been widely regarded as the Rosetta Stone of astronomy. This is a very apt description since our star has provided a readymade laboratory for

H.M. Antia, A. Bhatnagar, P. Ulmschneider (Eds.): LNP 619, pp. 1–26, 2003.

studying a variety of processes and phenomena operating both within and outside this object. Solar studies have also served as a valuable guide for the development of the theory of structure and evolution of stars in general and pulsating stars in particular. The proximity of our Sun has enabled a close enough scrutiny of its atmospheric layers and provided data of high spatial resolution of its surface features which is clearly not possible for other stars.

More than a century ago all that was known about the Sun was from the study of its face and the visible layers. Indeed, the early astronomers had noticed that the solar disk is dotted with dark blotches. These sunspots were, in fact, known to the Chinese and Greek astronomers, but it was Galileo who first made scientific observations of the march of these dark spots across the solar disk. The appearance of sunspots first in mid-latitudes ($\sim 30^\circ$) and then their migration towards the equator following a cycle with a period of approximately 11 years, has been systematically observed and encapsulated in the well-known "butterfly diagram" due to Maunder (e.g., Ambastha, Venkatakrishnan, this volume). Astronomers keep track of the spots appearing and disappearing on the visible disk of the Sun, hoping to gain insight into the processes that drive the solar cycle as well as to link solar activity with terrestrial climatic changes. Observational techniques and instruments used for solar observations are described by Bhatnagar (this volume).

There is a well-defined hierarchy of magnetic elements at the solar surface: magnetic flux tubes or fibrils, faculae, pores, plages and sunspots. Sunspots were the first significant markings observed on the face of the Sun, in the vicinity of which were also noticed the bright, irregular patches called faculae. Later observations made in chromospheric spectral lines revealed the presence of bright areas known as plages overlying the regions of enhanced magnetic fields. There are also widely separated concentrations of magnetic elements or fibrils with field strength of 1000–2000 G, over scales of the general order of 100 km.

The solar atmosphere displays a rich variety of features and complex phenomena which can be witnessed in their awesome splendour during the occurrence of a total solar eclipse. The chromosphere appears fleetingly just before and after totality as a fiery red ring around the disk and lingers for several seconds before disappearing. At totality the pearly white solar corona comes into view which changes its shape synchronously with the activity cycle, forming a jagged ring around the Sun at the peak of the activity cycle and transforming into trailing plumes and streamers by the end of the cycle. The corona is an extremely hot, tenuous and inhomogeneous region of the solar atmosphere consisting of complex loop structures with radiation emitted mainly in the UV and X-ray wavelengths (e.g., Ulmschneider, Dwivedi this volume).

Contrary to thermodynamic expectations, the outer atmosphere of the Sun is hotter than the visible photospheric layers from which much of the solar radiation is emitted. The temperature at the surface of the Sun where the particle density is about $10^{17}\,\mathrm{cm}^{-3}$ is approximately 5700 K, which decreases to a value of 4200 K at about 500 km above the photosphere and then rises up to a value of several tens of thousand degrees in the chromospheric layers made up of the network and active regions, at heights of around a few thousand km above the visible surface. The overlying coronal regions have temperatures approaching $(1–2)\times10^6$ K and are composed mainly of protons and electrons with number densities typically of order $10^8\,\mathrm{cm}^{-3}$ with an admixture of small amounts of heavier ions. Both the chromosphere and corona are observed to be highly structured and show clear evidence of association with the solar magnetic fields (e.g., Narain & Ulmschneider 1996). High resolution images from the Transition Region and Coronal Explorer (TRACE) spacecraft show that a large part of the corona has a fine-structure down to sub-arcsecond scale.

In the interior, it is the solar material that controls the magnetic field lines, while outside the solar body it is the magnetic field that dictates the behaviour of the plasma causing a variety of dynamic and transient phenomena. In fact, the magnetic field serves as an effective agent and provides a conduit to transport energy of the sub-photospheric motions and waves to the chromospheric/coronal regions and at other times acts as a detonator displaying spectacular events in the form of flares. Prominences of various kinds (e.g., quiescent, loop, hedgerow, eruptive, etc.) are seen to rise above active regions on the solar surface, providing striking evidence for the presence of magnetic fields in the outer atmosphere capturing and controlling the motion of the plasma along the field lines. It is evident that if the Sun were not to possess any magnetism, its external layers would not have presented such a spectacularly dazzling and explosive picture.

2 Composition and Structure of the Sun

More than a century ago all that was known about the Sun was by studying its visible layers and its surface markings. The early investigations in solar physics were largely devoted to an extensive collection of spectroscopic data for studying the surface temperature, density and chemical composition. Spectroscopy of the photospheric layers showed a spectrum dominated by the lines of elements such as carbon, silicon, sodium, iron, magnesium etc. Helium, even though relatively inconspicuous in the solar spectrum, was first discovered on the Sun before it was known in the laboratory. It was the spectroscopy of the chromosphere (with its somewhat higher temperature than that at the photosphere) which established, during a total solar eclipse, that hydrogen is the most abundant element in the Sun with helium being about one in ten atoms and heavier elements being present at the level of approximately 0.1 percent.

With a handle on the surface chemical composition, the attention of solar physicists turned to working out the internal structure of the Sun. For several centuries astronomers believed that the interior of the Sun and stars, shielded by the material beneath the visible surface, will never be accessible. This prompted the nineteenth century French philosopher, Auguste Comte to proclaim: “We can never learn their internal constitution”. It is, therefore, a triumph of the theory of stellar structure that one has been able to construct a reasonable picture of the Sun’s inside with the help of a set of mathematical equations governing its mechanical as well as thermal equilibrium and the nuclear energy generation, together with the boundary conditions supplied by observations. The earlier analytical efforts were mainly concentrated on the study of polytropic models for inferring the physical conditions inside the Sun. With the advent of high-speed computers, the structure equations were numerically integrated with the auxiliary input of physics, supplemented by appropriate boundary conditions. For this purpose, the Standard Solar Model (SSM) based on a minimum number of assumptions and physical processes was developed (e.g., Christensen-Dalsgaard et al. 1996; Bahcall, Pinsonneault & Basu 2001). In the SSM the Sun is taken to be a spherically symmetric object with negligible effects of rotation, magnetic fields, mass loss and tidal forces on its global structure. It is supposed to be in a quasi-stationary state maintaining hydrostatic and thermal equilibrium. The energy generation takes place in the central regions by thermonuclear reactions which convert hydrogen into helium mainly, by the proton-proton chain. The energy is transported outward from the core principally by radiative processes, but in the outer third of the solar radius it is carried largely by convection. There is supposed to be no mixing of nuclear reaction products outside the convection zone, except for the slow gravitational settling of helium and heavy elements by diffusion beneath the convection zone into the radiative interior. There is no energy transport by wave motion and the standard nuclear and neutrino physics is adopted for constructing theoretical solar models to obtain the present luminosity and radius by adjusting the initial helium abundance and the mixing-length parameter which controls the convective energy transport.

2.1 Equations of Stellar Structure

The central problem of solar structure is to determine the march of thermodynamic quantities with depth with the help of equations governing mechanical and thermal equilibrium. The mechanical equilibrium ensures that the pressure gradient balances the gravitational forces (e.g., Cox & Giuli 1968) and may be expressed as

$$\frac{\mathrm{d}P(r)}{\mathrm{d}r} = -\frac{Gm(r)}{r^2}\rho(r) \ , \tag{1}$$

$$\frac{\mathrm{d}m(r)}{\mathrm{d}r} = 4\pi r^2 \rho(r) \ . \tag{2}$$

Here $P(r)$ is the pressure, $\rho(r)$, the density and $m(r)$, the mass interior to the radius r, for a spherically symmetric Sun.

For maintaining thermal equilibrium, the energy radiated by the Sun, as measured by its luminosity, must be balanced by the nuclear energy generated throughout the solar interior,

$$\frac{\mathrm{d}L(r)}{\mathrm{d}r} = 4\pi r^2 \rho(r)\epsilon \ , \tag{3}$$

where ϵ is the energy generation rate per unit mass and $L(r) = 4\pi r^2(F_{\mathrm{rad}}+F_{\mathrm{conv}})$ is the luminosity. F_{rad} and F_{conv} are respectively, the radiative and convective energy flux (energy per cm^2 per s). The energy generation takes place in the central regions by thermonuclear reactions converting hydrogen into helium mainly by the proton-proton chain outlined in Table 1, where the numbers in the parentheses represent the energy of the neutrinos.

Table 1. pp Chain

	$p + p \rightarrow d + e^+ + \nu_e$	$(\leq 0.42\,\mathrm{MeV})$
	$p + e^- + p \rightarrow d + \nu_e$	$(1.44\,\mathrm{MeV})$
	$p + d \rightarrow {}^3\mathrm{He} + \gamma$	
pp-I:	${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$	
	${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$	$(\leq 18.8\,\mathrm{MeV})$
pp-II:	${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$	
	${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$	$(0.38,\ 0.86\,\mathrm{MeV})$
	${}^7\mathrm{Li} + p \rightarrow {}^8\mathrm{Be} + \gamma$	
	${}^8\mathrm{Be} \rightarrow 2\ {}^4\mathrm{He}$	
pp-III:	${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$	
	${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$	
	${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$	$(\leq 14.6\,\mathrm{MeV})$
	${}^8\mathrm{Be} \rightarrow 2\ {}^4\mathrm{He}$	

The Sun derives more than 98% of its energy from the proton-proton chain; there is an additional contribution of less than 2% from the CNO cycle reactions outlined in Table 2:

Table 2. CNO Cycle

${}^{12}\mathrm{C} + p \rightarrow {}^{13}\mathrm{N} + \gamma$	
${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^+ + \nu_e$	$(\leq 1.2\,\mathrm{MeV})$
${}^{13}\mathrm{C} + p \rightarrow {}^{14}\mathrm{N} + \gamma$	
${}^{14}\mathrm{N} + p \rightarrow {}^{15}\mathrm{O} + \gamma$	
${}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^+ + \nu_e$	$(\leq 1.7\,\mathrm{MeV})$
${}^{15}\mathrm{N} + p \rightarrow {}^{12}\mathrm{C} + {}^4\mathrm{He}$	
or	
${}^{15}\mathrm{N} + p \rightarrow {}^{16}\mathrm{O} + \gamma$	
${}^{16}\mathrm{O} + p \rightarrow {}^{17}\mathrm{F} + \gamma$	
${}^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O} + e^+ + \nu_e$	$(\leq 1.7\,\mathrm{MeV})$
${}^{17}\mathrm{O} + p \rightarrow {}^{14}\mathrm{N} + {}^4\mathrm{He}$	

The energy generated by these reaction networks is transported from the centre to the surface of the Sun from where it is radiated into the outside space. In about two-thirds of the solar interior the energy flux is carried by radiative processes and the radiative flux, $F_{\rm rad}$ is related to the temperature gradient by,

$$F_{\rm rad} = -\frac{4acT^3}{3\kappa\rho}\frac{{\rm d}T}{{\rm d}r} \ . \tag{4}$$

Here a is the Stefan-Boltzmann constant, c the speed of light and κ the opacity of solar material caused by a host of atomic processes involving many elements and several stages of ionisation (e.g., Rogers & Iglesias 1992; Iglesias & Rogers 1996). In the zone extending approximately one third of the solar radius below the surface, the radiative temperature gradient steepens because of the sharp rise in opacity while the adiabatic gradient drops in the ionisation zones. In such a situation the Schwarzschild instability criterion is readily satisfied and the energy flux is carried largely by convection and modelled in the framework of a local mixing-length formulation (Böhm-Vitense 1958) expressed as

$$F_{\rm conv} = -\kappa_t \rho T \frac{{\rm d}S}{{\rm d}r} \ . \tag{5}$$

Here κ_t is the turbulent diffusivity given by $\kappa_t \propto wl$, w being the mean vertical velocity, l the local mixing-length ($= \alpha H_P$, where H_P is the local pressure scale-height), S the entropy and α is a parameter of order unity. The mean convective velocity is given by

$$w = \left(\beta \frac{g}{H_P} Q l^2 (\nabla - \nabla_{\rm ad})\right)^{1/2} \ . \tag{6}$$

In this expression β is supposed to represent the effect of viscous breaking of the convective elements and the factor $Q = -\frac{T}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_P$ takes into account variation of the degree of ionisation in the moving elements. A value of $\alpha \approx 2$ seems to be indicated by time-dependent hydrodynamical simulation of stellar convection (Steffen 1992; Trampedach et al. 1997) as well as by a careful fitting of evolutionary tracks of the Sun with its present luminosity, radius and age (Schröder & Eggleton 1996; Hünsch & Schröder 1996).

An additional requirement is the knowledge of the thermodynamic state of matter throughout the solar body. For most parts except for the outermost layers, the material inside the Sun is essentially completely ionised and the perfect gas law is an adequate description of the equation of state which expresses the gas pressure as

$$P_g = \frac{k_B}{m_H \mu}\rho T \ , \tag{7}$$

where k_B is the Boltzman constant, m_H the mass of hydrogen atom and μ the mean molecular weight which is given by (Schwarzschild 1958)

$$\mu = \frac{1}{2X + \frac{3}{4}Y + \frac{1}{2}Z} \ . \tag{8}$$

Here X, Y, Z refer to the fractional abundance by mass of hydrogen, helium and heavy elements respectively. The perfect gas law description of the state of matter is clearly an idealisation. There are corrections, of course, amounting to a few per cent, to this ideal gas law arising from effects due to electron degeneracy, plasma screening, pressure ionisation and Coulomb free energy between charged particles (Eggleton, Faulkner & Flannery 1973; Mihalas, Däppen & Hummer 1988; Christensen-Dalsgaard & Däppen 1992; Rogers, Swenson & Iglesias 1996). In the sub-surface layers of the Sun, both hydrogen and helium undergo various stages of ionisation until temperatures upwards of 2×10^5 K are reached. The partial ionisation leads to a local decrease both in the adiabatic index, $\Gamma_1 = (\partial \ln P / \partial \ln \rho)_S$ and the logarithmic adiabatic temperature gradient, $\nabla_{\mathrm{ad}} \equiv (\partial \ln T / \partial \ln P)_S$. Note that Γ_1 dips to a value of 1.21 in the ionisation zone of hydrogen and singly ionised helium and to a value of about 1.58 in the second helium ionisation zone, thus showing departures from the ideal gas value of 5/3. Moreover, the superadiabatic gradient $(\nabla - \nabla_{\mathrm{ad}})$ (where $\nabla = \frac{\mathrm{d} \ln T}{\mathrm{d} \ln P}$ is the dimensionless temperatute gradient) has a pronounced peak in the ionisation zone near the surface.

Assuming all atoms to be in the ground state, the fraction of atoms ionised in the solar interior may be determined by using Saha's ionisation equation which relates the number densities of electrons, n_e and the number densities, n_i and n_{ii} of atoms in two successive stages of ionisation by the relation:

$$\frac{n_e n_{ii}}{n_i} = 2 \frac{u_{ii}}{u_i} \frac{(2\pi m_e k_B T)^{3/2}}{h^3} \mathrm{e}^{-I/k_B T} . \quad (9)$$

Here, u_i and u_{ii} are the partition functions of the two ionisation levels, m_e the electron mass, h the Planck constant and I is the ionisation potential of state i. This equation can be written for each stage of ionisation and all these equations can be solved to get the fractional abundance in each ionisation stage as well as the number density of electrons which are contributed by these ions.

In the standard solar model there is supposed to be no mixing of material outside the convection zone. But because of the momentum exchange between heavier and lighter elements, there is a slow gravitational diffusion of helium and heavy elements relative to hydrogen beneath the base of the convection zone into the radiative interior (e.g., Guzik & Cox 1993). In addition, the presence of a temperature gradient can cause thermal diffusion and so also can the radiation pressure acting on partially ionised or neutral atoms. It turns out for the solar conditions, the gravitational settling of helium and heavy elements relative to hydrogen is a more important process.

2.2 The Standard Solar Model

The structure equations supplemented by auxiliary input physics describing the thermodynamic state of the matter, the opacity and the nuclear energy generation rate are then numerically integrated to construct theoretical solar models which satisfy constraints, namely, the observed mass, radius, luminosity and ratio of chemical abundances by mass, Z/X. The resultant model profiles of temperature T, density ρ, pressure P, sound speed, adiabatic index Γ_1, hydrogen abundance X and helium abundance Y profiles through the solar interior are displayed in Fig. 1. The interior model is matched to the atmospheric model of Vernazza, Avrett & Loeser (1981) at the photosphere, above which the model profiles are calculated using this atmospheric model. The pressure decreases monotonically with increasing radius and the scale height of its variation becomes progressively small closer to the surface giving rise to a steep fall as we approach the surface. As we had noted earlier, the temperature reaches a minimum at about 500 km above the surface and then starts increasing towards the chromospheric and coronal regions. The density falls off monotonically with radial distance except in a very thin region just below the surface, where it increases as a result of a very strong superadiabatic temperature gradient prevailing in a narrow region. The occurrence of this feature which is referred to as the density inversion, depends on the treatment of convection and may be absent in some solar models. The sound speed also has a minimum at the temperature minimum and starts increasing as we move up to the chromosphere. The second dip in sound speed profile beyond the temperature minimum is due to steep fall in Γ_1 due to ionisation. The adiabatic index, Γ_1 has a value close to 5/3 when the solar material is either fully ionised as in the interior, or when there is no ionisation as in the region just above the surface.

It is customary in the theory of solar structure to assume the Sun has a homogeneous initial chemical composition, say, $X = 73\%$, $Y = 25\%$ with a small admixture of heavy elements, $Z = 2\%$, and its total mass, $M_\odot = 1.989 \times 10^{33}$ gm. The Sun is then evolved with a few adjustable parameters, to yield the present luminosity, $L_\odot = 3.846 \times 10^{33}$ erg s^{-1}, a radius $R_\odot = 6.9599 \times 10^{10}$ cm and a composition ratio $Z/X = 0.0245$ at the surface (Grevesse, Noels & Sauval 1996) after 4.6 billion years which is the estimated age of the Sun inferred from meteoritic data; for example, the Allende meteorite is dated to be 4.566 billion years old (Allégre, Manhès & Göpel 1995). These boundary conditions are generally satisfied by varying the initial composition and a parameter in the mixing-length formulation to calculate the convective flux in the convection zone. Thus, effectively there are no free parameters in the SSM, as all the unknown parameters are adjusted to satisfy the boundary conditions. Nevertheless, by varying input physics, like the opacities, the equation of state, the nuclear reaction rates or the diffusion coefficient it is possible to get different solar models. Further, it should be noted that the solar mass is not directly measured, but rather it is the product $GM_\odot$ which is accurately known from the study of planetary orbits. The solar mass is then determined from the knowledge of G, which is not known to very high accuracy. Thus the values of G and $M_\odot$ should be chosen to yield the correct value for the product $GM_\odot$.

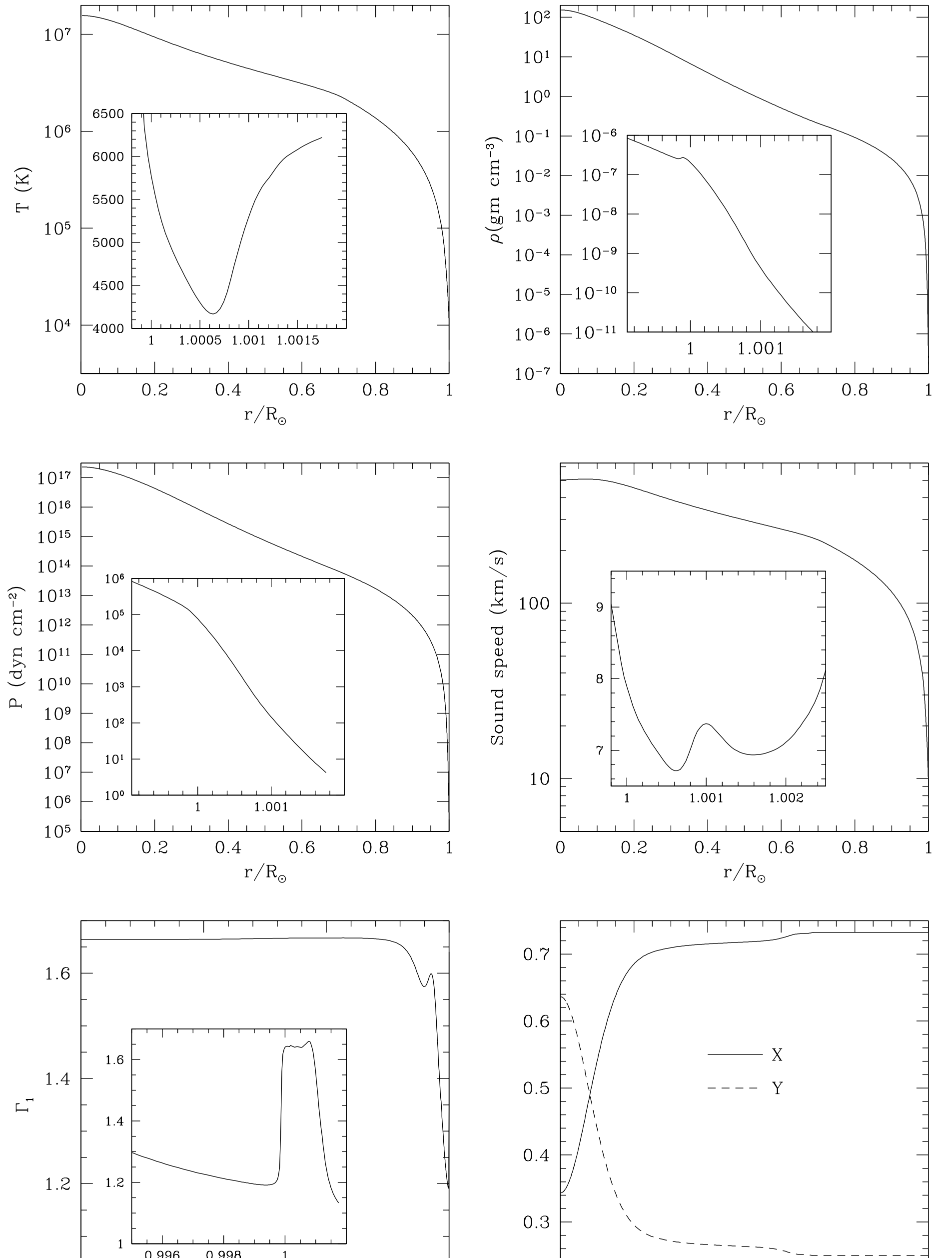

Fig. 1. The temperature, density, pressure, sound speed, adiabatic index, hydrogen and helium abundance profiles as a function of radial distance inside the Sun in a standard solar model of Brun, Turck-Chièze & Zahn (1999). The inset shows a blowup of the region close to the surface

3 Probes of the Sun's Interior

It turns out from the theoretical calculations that there is a large variation of temperature from about 5700 K at the surface to upwards of 15 million degrees at the centre; likewise, the density varies from about 10^{-7} gm cm^{-3} to some 150 gm cm^{-3} between the surface and the core of the Sun. There is also a very steep variation of density and temperature through the overlying atmosphere. The principal questions concerning the structure of the Sun are: Is there any way of checking the correctness of these theoretical models? Are there any means of measuring the central temperature and finding out if the chemical make-up inside is the same as that at the surface? "What appliance can pierce through the outer layers of a star and test the conditions within?", asked Eddington (1926), in his classic book, The Internal Constitution of the Stars. As it happens, the Sun is, indeed, transparent to neutrinos released in the nuclear reaction network operating in the energy-generating core and also to waves generated through bulk of the solar body. These valuable probes complement each other and enable us "to see" inside the Sun. The deduced thermal and chemical composition profiles as well as rotation and magnetic fields prevailing in the solar interior can then be related to the phenomena occurring in the solar atmosphere. The internal and external layers of the Sun, it turns out, furnish an ideal cosmic laboratory for testing various branches of physics.

3.1 Solar Neutrino Problem

Historically, the measurement of neutrinos produced in the reaction network operating in the solar core was the first probe conceived to surmise the physical conditions in the deep interior. The neutrino fluxes are sensitive to the temperature and composition profiles in the central regions of the Sun. It was, therefore, hoped that the steep temperature dependence of some of the nuclear reaction rates involved in the production of neutrinos would enable a determination of the Sun's central temperature to better than a few per cent. "The use of a radically different observational probe may reveal wholly unexpected phenomena; perhaps, there is some great surprise in store for us when the first experiment in neutrino astronomy is completed", said Bahcall in 1967. There have been valiant efforts undertaken since the 1960s to set up experiments designed for the exceedingly difficult measurement of neutrinos from the Sun. Ray Davis's Chlorine experiment (Davis 1964) has been operating for well over 35 years and is sensitive to intermediate and high energy neutrinos released in the thermonuclear network. It has a tank containing 615 tons of liquid perchloroethylene, located some 1480 m underground in the Homestake gold mine in South Dakota, in which the Chlorine nuclei are the solar neutrino absorbers according to the reaction

$$^{37}\mathrm{Cl} + \nu_{\odot} \rightarrow {}^{37}\mathrm{Ar} + e^{-} \qquad (\mathrm{threshold} = 0.814\,\mathrm{MeV})\ . \tag{10}$$

The capture rate is dominated by the ^{8}B neutrinos contributing 5.9 SNU, with the ^{7}Be neutrinos making a contribution of 1.1 SNU. The sole motivation of the

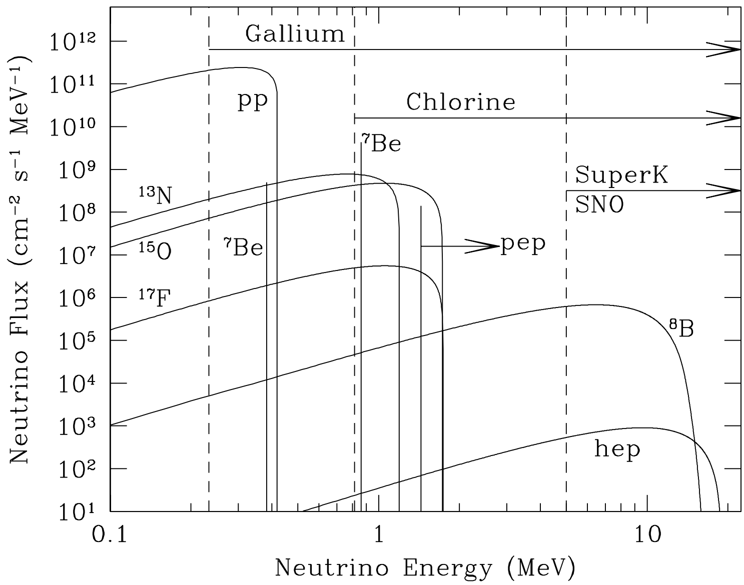

Fig. 2. The energy spectrum of neutrinos emitted by each of the 8 nuclear reactions that generate neutrinos in the solar core. For each curve the source of neutrinos is marked in the figure. The dashed vertical lines mark the threshold energy for each of the operating experiment as marked in the figure

Chlorine experiment was "to see into the interior of the Sun and thus verify directly the hypothesis of nuclear energy generation in stars". The Homestake solar neutrino experiment which is sensitive to intermediate and high energy neutrinos admirably fulfilled its objective. Unfortunately, over the years Davis has been reporting measurements of the solar neutrino counting rate of $2.56 \pm 0.23\,\mathrm{SNU}$ ($1\,\mathrm{SNU} = 10^{-36}$ captures per target atom per second), which is at variance with the counting rate of $7.6 \pm 1.2\,\mathrm{SNU}$ predicted by the standard solar model for the Chlorine experiment. This puzzling deficit in the neutrino counting rate, by nearly a factor of 3 over the SSM prediction, constitutes the solar neutrino problem which has been haunting the community for well over three decades. (e.g., Cleveland et al. 1998). Figure 2 shows the energy spectrum of neutrino fluxes from each of the 8 nuclear reactions that produce neutrinos in the standard solar model of Bahcall, Pinsonneault & Basu (2001). This figure also shows the energy threshold of all currently operating neutrino detectors. Only neutrinos above this energy are detected.

There have been a number of ingenious suggestions to account for the observed deficit in the solar neutrino flux: partial mixing in the solar interior which brings additional fuel of hydrogen and helium to the centre, thus maintaining the nuclear energy production at a slightly lower temperature; the presence of a small admixture of Weakly Interacting Massive Particles in the solar core which would effectively contribute to an increase in the thermal conductivity, in the process diminishing the temperature gradient required to transport the flux;

the rapidly rotating solar core; the centrally concentrated magnetic field; lower heavy element abundance. All such proposals lead to a slight reduction in the central temperature causing a lowering of the flux of high-energy neutrinos.

A Japanese experiment (Fukuda et al. 1996) consisting of a 680 ton water tank was located about 1 km underground in the Kamioka mine where charged particles are detected by measuring Cerenkov light through the elastic scattering reaction, $\nu_x + e^- \rightarrow \nu_x + e^-$ (threshold = 5.5 MeV). This and the upgraded SuperKamiokande experiment (Fukuda et al. 1999) are sensitive only to the high-energy ^{8}B neutrinos released by the pp-chain of nuclear reactions. The measured flux from the SuperKamiokande experiment is again deficient by about 50% over the total flux predicted by the standard solar model. The Homestake and SuperKamiokande experimental measurements are clearly inconsistent with the proposition of a cooler solar core being a viable solution for the solar neutrino problem. Such a reduction in the central temperature will lead to even larger suppression of the high energy ^{8}B neutrino flux to which the SuperKamiokande experiment is exclusively sensitive; this is because of the extremely high-temperature dependence of the ^{8}B neutrino reaction rate. Paradoxically, the Homestake experiment that detects the intermediate as well as high energy neutrinos shows an even larger reduction in the neutrino counting rate. Thus by reducing the core temperature it is not possible to get a solar model which simultaneously matches both the Homestake and SuperKamiokande measurements.

Besides these experiments there are three other radiochemical experiments (GALLEX, SAGE and GNO) that use a gallium detector with a relatively low threshold of 0.233 MeV and are capable of detecting the low-energy pp-neutrinos. The GALLEX, SAGE and GNO experiments (Hampel et al. 1999) report measurement of the solar neutrino counting rate of 74.7 ± 5.0 SNU, while the SSM prediction of the neutrino capture rate for the gallium experiments is 128 ± 8 SNU, again showing a deficit in the measured neutrino counting rate. Over the past three decades, experimental efforts and more refined theoretical models have only confirmed the discrepancy between the measured and calculated neutrino fluxes.

One of the primary goals of contemporary solar neutrino experiments was to understand the physics of thermonuclear reactions operating in the Sun and more importantly, to constrain the properties of neutrinos. It became clear that none of the measurements of neutrino fluxes by the Chlorine, Water and Gallium experiments were consistent with each other, provided one makes the following assumptions: neutrinos have standard physical properties, namely, no mass and hence no magnetic moment and no flavour-mixing during transit and that the Sun is in thermal equilibrium generating a constant luminosity. There are considerations based on fairly general arguments independent of any underlying solar model which can be demonstrated to lead to unphysical situations such as a negative flux of beryllium neutrinos. A possible resolution of this conundrum is to endow neutrinos with a tiny mass and permit oscillations of neutrino flavours during propagation. The electron neutrinos could get transformed into neutrinos of a different flavour along their flight path through the interior of the Sun and the Earth, or through space between the Sun and Earth. A fraction of electron neutrinos exclusively produced in the Sun's nuclear reaction network would then go undetected in some of the solar neutrino experiments. This raises the exciting possibility of nonstandard neutrino physics being responsible for the deficit in the measured neutrino fluxes and for the need to go beyond the Standard Model of Particle Physics. The first compelling evidence for such neutrino oscillations came a few years ago from the SuperKamiokande's analysis of the data on the high-energy cosmic ray neutrinos from the atmosphere. The SuperKamiokande experiment measured the difference in the up and down fluxes of neutrinos produced by cosmic ray interaction with the terrestrial atmosphere to show that neutrino oscillations, indeed, take place. This asymmetry in the up and down fluxes arises because upward moving neutrinos have to pass through the solid material of the Earth, while the downward moving neutrinos, coming from overhead and being generated afresh in the Earth's atmosphere are less likely to undergo any flavour oscillations.

The recent results from the Sudbury Neutrino Observatory (SNO) have claimed convincing evidence that the solar neutrinos, indeed, change from one flavour to another during their journey from the Sun to Earth. (Ahmad et al. 2001). The SNO experiment located at a depth of over 6000 meters of water equivalent in Sudbury uses 1000 tons of heavy water containing the deuterium isotopes of hydrogen for detecting solar neutrinos, while the SuperKamiokande detector contains ordinary water for capturing the neutrinos. In both heavy and ordinary water neutrinos can elastically scatter electrons to produce Cerenkov radiation, but such electron scattering can be caused by any of the three neutrino flavours: electron-, muon- and tau-neutrino. The Sudbury Neutrino Observatory is capable of measuring the ^{8}B neutrinos through the following reactions:

$$\nu_e + d \rightarrow p + p + e^- \qquad \text{(charged current)} , \tag{11}$$

$$\nu_x + e^- \rightarrow \nu_x' + e^- \qquad \text{(elastic scattering)} \qquad (x = e, \mu, \tau) , \tag{12}$$

$$\nu_x + d \rightarrow \nu_x' + p + n \qquad \text{(neutral current)} \qquad (x = e, \mu, \tau) . \tag{13}$$

SNO's heavy water detector is capable of isolating electron neutrinos, because that flavour alone can be absorbed by a deuterium nucleus to produce two protons and an electron. The neutral current (NC) reaction is equally sensitive to all neutrino flavours, while the elastic scattering (EC) has significantly low sensitivity to mu- and tau-neutrinos. SNO has reported the elastic scattering count rate which equals the SuperKamiokande event rate, to within experimental errors. However, SNO's count of the charged current reaction which is sensitive exclusively to the electron-neutrinos is lower than the SNO/SuperKamiokande event rate of all flavours. This difference in the ^{8}B flux deduced from the charged current and elastic scattering rates, at the level of 1.6σ, provides reasonably firm evidence that some of the Sun's electron-neutrinos are transformed into mu- or tau-neutrinos by the time they reach the experimental setup on Earth. Recently, the neutral current reaction results have been announced by SNO reporting the flux of mu- or tau-neutrino at 5.3σ level (Ahmad et al. 2002). Furthermore, the total ^{8}B neutrino flux as measured by the NC reactions is $(5.09 \pm 0.62) \times 10^6$ cm^{-2} s^{-1}, in agreement with that predicted by the standard solar model of Bahcall, Pinsonneault & Basu (2001). The neutrino oscillations have been further confirmed by the KamLAND experiment (Eguchi et al. 2003) which has detected oscillations in anti-neutrinos produced by nuclear reactors. The KamLAND results combined with results from other solar neutrino experiments have succeeded in determining the parameters governing mixing of neutrino flavours in favour of the large mixing angle (Bahcall, Gonzalez-Garcia & Pena-Garay 2003; Bandyopadhyay et al. 2002), thus effectively solving the solar neutrino problem. These results reassure solar physicists that the theoretical models of the Sun's internal structure are essentially correct and that the resolution of the solar neutrino puzzle should be sought in the realm of particle physics. It has also prompted the community to explore an independent, complementary tool to probe the physical conditions inside the Sun and this was provided by helioseismic studies.

3.2 Helioseismology

The surface of the Sun undergoes a series of mechanical vibrations which manifest themselves as Doppler shifts oscillating with a period centred around 5 minutes (e.g., Leighton, Noyes & Simon 1962; Antia, this volume). These have now been identified as acoustic modes of pulsation of the entire Sun representing a superposition of millions of standing waves with amplitude of an individual mode of the order of a few cm s^{-1} (Ulrich 1970; Leibacher & Stein 1971; Deubner 1975). The frequencies of many of these modes have been determined to an accuracy of better than 1 part in 10^5. The accurately measured oscillation frequencies provide very stringent constraints on the admissible solar models. The determination of the mode frequencies to a high accuracy, of course, requires continuous observations extending over very long periods of time and this is achieved with the help of ground-based network observing the Sun almost continuously. The most prominent amongst these networks is the Global Oscillation Network Group (GONG) which comprises six stations located in contiguous longitudes around the world (Harvey et al. 1996). Satellite-borne instruments have also been observing the solar oscillations and particularly, the Michelson Doppler Imager (MDI) on board the Solar and Heliospheric Observatory (SOHO) with its higher spatial resolution has been able to study solar oscillations with small associated length scales (Scherrer et al. 1995).

Despite considerable progress in the field of helioseismology over the past 25 years, the basic mechanism responsible for the excitation of solar oscillations is still not adequately understood. The acoustic modes may be either intrinsically overstable, or they could be stochastically excited by nonlinear interactions with other motions. In the solar envelope, except for the top several tens of kilometres, convection is responsible for transporting a major fraction of the heat flux. The turbulent conductivity also far exceeds the corresponding radiative conductivity for most part of the convection zone. The convective turbulence and radiative exchange are, therefore, expected to control both the excitation and damping of solar p-mode oscillations.

The linear growth rates of five-minute oscillations for realistic solar models were studied by Ulrich (1970), Ando & Osaki (1975) and Antia, Chitre & Narasimha (1982) using a highly simplified description of radiative transfer and incorporating mechanical and thermal effects of convective turbulence in an approximate manner. It was demonstrated that many of the p-modes in the five-minute period range could be overstable. However, there are many uncertainties in these calculations such as the diffusion approximation for radiative transfer which breaks down near the surface layers, inadequacies of our knowledge of the atmospheric opacity and its derivatives and the lack of knowledge to treat the pulsation-convection coupling. In any case the observed amplitudes of p-modes are extremely small and if these modes were indeed overstable, there should be present some nonlinear amplitude-limiting mechanism. It is difficult to imagine any nonlinear mechanism which becomes effective at such small amplitudes. The linear stability of solar p-modes is rather sensitively dependent on the interaction of pulsation with radiation and convection and many studies have found all modes to be stable (e.g., Balmforth 1992). It turns out, the mechanism of stochastic excitation by turbulent convection, on the other hand, yields amplitudes of individual modes that are in rough agreement with observations (e.g., Goldreich & Keeley 1977; Christensen-Dalsgaard & Frandsen 1983).

The coupling of solar convection with acoustic oscillation was studied by Kumar & Goldreich (1989) by assuming the p-modes to be stable and driven by acoustic emission from turbulent convection. The outstanding question concerns the basic energy source for driving these oscillations. The reservoir of energy available in the form of radiation and convection is certainly quite adequate for the purpose of exciting the p-modes to observed levels. Unfortunately, all the proposed mechanisms for extracting energy from such a reservoir necessarily involve overstable modes which would lead to an unacceptably large build-up of mode amplitudes for the Sun.

Another source of energy for driving p-modes is provided by the mechanical energy of fully developed turbulent convective motions. The theory of acoustic emission from homogeneous turbulence was developed by Lighthill (1952) and it is well known that turbulent flow field can generate sound waves with frequency bandwidth equal to the inverse of the energy cascade time. The acoustic emission could arise from a monopole, dipole or quadrupole sources (e.g., Ulmschneider, this volume). The equipartition between mode energy and the kinetic energy of a resonant eddy for compressible turbulence was derived by Goldreich & Keeley (1977), by taking into account the quadrupole emission and absorption due to Reynolds stresses. In the solar case, the mechanism responsible for exciting turbulence can itself cause acoustic emission and absorption (e.g., Kumar & Goldreich 1989). It turns out the acoustic emission associated with the buoyancy forces is, in fact, more efficient compared to Reynolds stresses by (Mach no.)$^{-2}$, and there is a monopole emission when, near the surface of the Sun, there is a loss of heat by radiation. However, the contributions from monopole and dipole radiation can cancel each other for energy-bearing eddies, with a residue left that is comparable with the quadrupolar emission from Reynolds stresses. It would thus, appear that the forcing of p-modes through coupling with acoustic noise generated by turbulent convection is a viable mechanism for their excitation to the desired amplitude level.

The accurate helioseismic data of oscillation frequencies may be analysed in two ways: i) Forward method; ii) Inverse method (e.g., Antia, this volume). In the Forward method, an equilibrium standard solar model is perturbed in a linearised theory to obtain the eigenfrequencies of solar oscillations, and these are compared with the accurately measured mode frequencies (e.g., Elsworth et al. 1990). The fit naturally is seldom perfect, but a comparison between the observed and theoretically computed frequencies indicated the thickness of the convection zone to be close to 200 000 km and the helium abundance, Y in the solar envelope to be 0.25. It was noted that an improved treatment of convection due to Canuto & Mazzitelli (1991) led to a significantly better accord between calculated and observed p-mode frequencies (Basu & Antia 1994). The forward method has had only a limited success. A number of inversion techniques have, therefore, been developed using the equations of mechanical equilibrium to infer the acoustic structure of the Sun (Gough & Thompson 1991).

One of the major accomplishments of the inversion methods was an effective use of the accurately measured solar oscillation frequencies for a reliable inference of the internal structure of the Sun (Gough et al. 1996; Kosovichev et al. 1997). The profile of the sound speed can now be determined through the bulk of the solar interior to an accuracy of better than 0.1% and the profiles of density to a somewhat lower accuracy. The agreement between the sound speed profile deduced from helioseismic inversions and the SSM is remarkably close except for a pronounced discrepancy near the base of the convection zone and a noticeable difference in the energy-generating core. The hump at the base of the convection zone may be attributed to a sharp change in the gradient of the helium abundance profile on account of diffusion. A moderate amount of rotationally-induced mixing immediately beneath the convection zone, can smooth out this feature (Richard et al. 1996; Brun, Turck-Chièze & Zahn 1999). The dip in the relative sound speed difference in the core may be due to ill-determined composition profiles in the SSM, possibly resulting from the use of inaccurate nuclear reaction rates.

From the recently available seismic data, the helium abundance in the solar envelope is deduced to be 0.249 ± 0.003 (Basu & Antia 1995) and the depth of the convection zone is estimated to be $(0.2865 \pm 0.0005)R_\odot$ (Christensen-Dalsgaard, Gough & Thompson 1991; Basu 1998). It has also been possible to surmise the extent of overshoot of convective eddies beneath the base of the convection zone. The measured oscillatory signal is found to be consistent with no overshoot, with an upper limit of $0.05H_P$ (H_P being the local pressure scale height) (Monteiro, Christensen-Dalsgaard & Thompson 1994; Basu, Antia & Narasimha 1994; Basu 1997).

The seismic structure of the Sun discussed so far is based on the equations of mechanical equilibrium. The equations of thermal equilibrium have not been used because on oscillatory time scales of several minutes, the modes are not expected to exchange significant amounts of energy. The frequencies of solar oscillations are, therefore, largely unaffected by the thermal processes in the interior. However, in order to determine the temperature and chemical composition profiles one needs to supplement the seismically inferred structure, obtained through primary inversions, by the equations of thermal equilibrium, together with the auxiliary input physics such as the opacity, equation of state and nuclear energy generation rates (Gough & Kosovichev 1990; Antia & Chitre 1998; Takata & Shibahashi 1998). It turns out that the inverted sound speed, density, temperature and composition profiles, and consequently the neutrino fluxes, come pretty close to those given by the SSM. In general, the computed total luminosity resulting from these inverted profiles would not necessarily match the observed solar luminosity. The discrepancy between the computed and observed solar luminosity, $L_\odot$ can, then be effectively used to provide a test of the input nuclear physics; in particular, it can be demonstrated that the cross-section for the proton-proton reaction needs to be increased slightly to $(4.15 \pm 0.25) \times 10^{-25}$ MeV barns (Antia & Chitre 1998). Note this cross-section has a crucial influence on the nuclear energy generation and neutrino fluxes, but it has not been measured in the laboratory. Indeed, it can be readily shown that the current best estimates (Adelberger et al. 1998) for the proton-proton reaction cross-section and metallicity, Z are only marginally consistent with the helioseismic constraints and probably need to be increased slightly by a few per cent (Antia & Chitre 1999a). The extent to which the proton-proton reaction cross-section needs to be increased also depends on the treatment of electron screening (e.g., Antia this volume). With the use of intermediate screening treatment due to Mitler (1977) the theoretically computed cross-section is essentially consistent with helioseismic constraints (Antia & Chitre 2002).

The seismic models enable a determination of the central temperature of the Sun which is found to be $(15.6 \pm 0.4) \times 10^6$ K, allowing for up to 10% uncertainty in the opacities (Antia & Chitre 1995). It turns out that it is possible to determine only one parameter specifying the chemical composition and we assume the heavy element abundance, Z to be known and attempt to surmise the helium abundance profile, Y. The inferred helium abundance profile is in fairly good agreement with that in the SSM which includes diffusion, except in the regions just beneath the convection zone where the profile is essentially flat (Antia & Chitre 1998). This is suggestive of some sort of mixing, possibly arising from a rotationally-induced instability. Interestingly, the temperature at the base of the solar convection zone is 2.2×10^6 K, which is not high enough to burn lithium. However, if there is some amount of mixing that extends a little beyond the base of the convection zone to a radial distance of $0.68 R_\odot$, say, temperatures exceeding 2.5×10^6 K will be attained for the destruction of lithium by nuclear burning, and this may explain the low lithium abundance observed at the solar surface.

The remarkable feature that emerges from these computations is that even if we allow for arbitrary variations in the input opacities and relax the requirement of thermal equilibrium, but assume standard properties for neutrinos, it turns out to be difficult to construct a seismic model that is simultaneously consistent with any two of the three existing solar neutrino experiments within 2σ of the measured fluxes (Roxburgh 1996; Antia & Chitre 1997). It has been suggested that mixing of ^{3}He in the solar core can alter the neutrino fluxes significantly (e.g., Cumming & Haxton 1996). However, such a modification of the standard solar model can be ruled out on the basis of helioseismic constraints (Bahcall et al. 1997). It is unlikely that any substantial mixing can take place in the solar core, as, otherwise, the chemical composition profile will need to be fine-tuned to reproduce the helioseismically inferred sound speed profile. This argument is applicable to any general type of mixing process. On the other hand, it is conceivable that ^{3}He abundance may not have been estimated correctly in the solar interior which will, of course, not affect the mean molecular weight and hence the sound speed because of the very low ^{3}He abundance compared to ^{4}He and H. But it can be demonstrated that the solar neutrino problem is unlikely to be solved with an arbitrary redistribution of ^{3}He or arbitrary heavy element abundance or any non-Maxwellian equilibrium energy distribution, provided the observed luminosity constraint is maintained (Antia & Chitre 1999b). This suggests that the persistent discrepancy between measured and predicted solar neutrino fluxes is likely to be due to non-standard neutrino physics. In this sense, helioseismology may be regarded to have highlighted the importance of the Sun as a cosmic laboratory for studying the novel properties of neutrinos.

3.3 Rotation Rate in the Solar Interior

Helioseismology has also made it possible to determine the rotation rate in the interior from the accurately measured rotational splittings (e.g., Antia, this volume). The first order effect of rotation yields splittings which depend on odd powers of the azimuthal order. These odd splitting coefficients can be used to deduce the rotation rate as a function of depth and latitude. It is found that the surface differential rotation persists through the solar convection zone, while in the radiative interior the rotation rate appears to be relatively uniform (Thompson et al. 1996; Schou et al. 1998). A transition region near the base of the convection zone (the tachocline) is centred at a radial distance, $r = (0.7050 \pm 0.0027) R_\odot$ (Basu 1997). The seat of the solar dynamo is widely believed to be located in this tachocline region. There is also a shear layer present just beneath the solar surface extending to $r \simeq 0.94 R_\odot$ where the rotation rate is found to increase with depth. It will be instructive to examine its role in sustaining a secondary dynamo.

It may be recalled, an important aspect of solar internal rotation is that it can provide a crucial test of Einstein's general theory of relativity. The test is based on the measurements of planetary orbits which should be elliptical under Newton's inverse square law. In practice, however, on account of the mutual gravitational interaction between planets, the orbits are somewhat different. After correcting for these perturbations, the residual orbit of planet Mercury, for example, was found to be a rotating ellipse that precesses about the Sun at 43 seconds of arc per century. The excellent agreement between the theoretical prediction of general relativity and observed precession of the perihelion of Mercury was heralded as a great triumph for the theory of relativity. The prediction of Einstein general theory is, of course, based on the crucial assumption that the Sun is a spherically symmetric body. The presence of both rotation and magnetic field in the interior is liable to cause a bulge at the equator and a flattening at the poles, in the process contributing a higher order term to its gravitational potential. Such an oblateness would modify the Sun's gravitational field in a way to induce the observed precession of Mercury's orbit from purely Newtonian effects. It turns out in order to account for full precession of 43 arc second per century the Sun would have to rotate much faster than what is inferred from helioseismic inversions. The helioseismically inferred rotation rate is, indeed, consistent with the measured solar oblateness of approximately 10^{-5} (Kuhn et al. 1998). The resulting quadrupole moment turns out to be $(2.18 \pm 0.06) \times 10^{-7}$ (Pijpers 1998), implying a precession of perihelion of the orbit of planet Mercury by about 0.03 arcsec/century, which is clearly consistent with the general theory of relativity. The even order terms in the splittings of solar oscillation frequencies reflect the Sun's effective acoustic asphericity and can provide a valuable handle to probe the presence of a large-scale magnetic field or a latitude-dependent thermal fluctuation in the solar interior.

It has now been well demonstrated that the frequencies of solar oscillations vary with time and that these variations are correlated with the solar activity (e.g., Bhatnagar, Jain & Tripathy 1999). It is expected that these frequency variations should result from structural changes in the layers close to the solar surface for explaining fluctuations over timescales of order 11 years. With accumulating GONG and MDI data over nearly seven years during the rising phase of solar cycle 23, it has, indeed, been possible to study temporal variations of the solar rotation rate and other characteristic features associated with the solar envelope. In fact, helioseismic inversions have revealed small temporal variations of the rotation rate in the subsurface layers. These alternating bands of fast and slow rotation appear to migrate towards the equator as the solar cycle progresses, reminiscent of the torsional oscillations detected at the solar surface, but extending to a depth of at least 60 Mm (e.g., Antia, this volume).

The frequencies of fundamental, or f-modes which are surface modes, are largely determined by the surface gravity and thus provide a valuable tool to probe the near-surface regions as well as an accurate measurement of the solar radius. An important application of the accurately measured f-mode frequencies is their potential use as a diagnostic of solar oblateness and of magnetic fields just beneath the solar surface, in addition to studying the solar cycle variations of these quantities.

The ongoing efforts in helioseismology will hopefully, reveal the nature and strength of magnetic fields present inside the Sun and will also help in highlighting the processes that drive the cyclical magnetic activity and also locate the seat of the solar dynamo. The accumulating seismic data during the ascending and descending phases of cycle 23 will enable us to study the temporal variations of mode frequencies and amplitudes which should be indicative of the changes in the solar structure and dynamics. In the process, we may also learn how the magnetic field of the Sun changes with the solar cycle and what causes the solar irradiance to vary synchronously with the sunspot cycle. Finally, an unambiguous detection of buoyancy driven gravity modes would furnish a powerful tracer of the energy-generating regions of our Sun!

4 Magnetically Controlled Solar Phenomena

The existence of magnetic fields on the Sun was established by Hale from the Zeeman splitting of spectral lines in sunspots, indicating magnetic fields of order 2000–3000 G in the dark central regions of the spot. The general background magnetic field in the Sun, detected with sensitive magnetographs, was shown by the Babcocks to have an average strength of about 10 G. The overall magnetic field structures are oppositely directed in the northern and southern hemispheres, and the reversals in the field polarities are observed to take place near the maximum phase of the sunspot cycle. It is now widely believed that the global magnetic field of the Sun is not uniformly spread over its surface, but rather the field is distributed in separate clusters of magnetic flux tubes (fibrils) with field strength $\sim$ 1000–2000 G and diameters of order 100 km (e.g., Hasan, this volume). The active regions with which the sunspots and large flaring events are normally associated are found to lie in the midst of extended bipolar regions of $\sim$ 100 G fields. The outstanding question that is continuing to puzzle the solar astronomers is the origin and seat of the solar dynamo and the nature of the mechanism that drives the activity cycle with such a regularity. The observed nonuniform rotation of the Sun, namely, faster rotation at the equatorial latitudes than near the polar regions continually shears the dipole magnetic field to generate a toroidal component, while the cyclonic turbulent convection interacting with the toroidal loops reinforces the dipole field configuration (e.g., Venkatakrishnan, this volume). It is fair to say that the issues relating to the formation of sunspots, their emergence at the surface, their evolution and decay and in fact, the basic underlying mechanism responsible for the origin of the solar activity cycle are not adequately understood.

The Sun has evidently a large reservoir of free magnetic energy available, but the process for its explosive release is not altogether clear. The generally accepted mechanism for sudden energy release is a process called magnetic reconnection which involves splicing and rejoining magnetic lines of force. Thus, the flare phenomena occurring in the vicinity of active regions are evidently hydromagnetic manifestations which involve a rapid conversion of magnetic free energy into fast particles and hot plasma.

The production of prominences also results from the strong, large-scale magnetic fields existing in active regions playing a major role. The solar plasma is guided along the lines of force condensing into regions of higher density and lower temperature and raining down back towards the photosphere. The solar flares are observed on various scales ranging from the largest with energy $\sim 10^{32}$ erg over dimensions of 10^4 km down to the limit of detection with energy $\sim 10^{25}$ ergs over 100–1000 kms (microflares). The basic mechanism seems to involve rapid diffusion and reconnection of magnetic field lines (e.g., Ambastha, this volume). The prominent feature associated with magnetic fields embedded in a plasma and undergoing continuous deformation would be the occurrence of current sheets with steep magnetic field gradients. These current sheets provide the sites for fast reconnection and explosive dissipation of magnetic energy. The recent results from the SUMER instrument aboard the SOHO satellite provide plausible evidence for magnetic reconnections on the Sun from the formation of bi-directional outflow jets at these sites.

The outer solar atmosphere presents a rich variety of designs and complex structures for close scrutiny in a cosmic setting. The chromosphere and corona are observed to be highly structured with a clear evidence of association with magnetic fields. Thus, the chromospheric network closely coincides with the network of locally strong and mainly vertical magnetic field with strength $\sim$10–20 G (e.g., Ambastha, this volume). An indication of magnetic activity in the solar atmosphere is the presence of plages, (incandescent bright regions of gas with a higher density than the surrounding atmosphere), which are caused by enhanced magnetic fields. It has also been observed that the tenuous gas above the strong ($\sim$ 100 G) bipolar fields of active regions is heated to temperatures of $\sim 4 \times 10^6$ K, while the broad regions of weak (5–10 G) fields are heated to temperatures of 1.5×10^6 K. The active region corona is thus appreciably hotter than that associated with the quiet regions (e.g., Dwivedi, this volume). The solar corona is a magnetically structured region consisting of X-ray bright points, coronal loops and coronal holes with open streamer structures. The coronal loops are closed magnetic structures spread over a wide range of scales with their footpoints anchored in the surface layers. The large loops interconnecting active regions are likely to be responsible for the diffuse coronal emission, while the smallest loops probably form the X-ray bright points. It appears that most of the loops are heated within about 10 000–20 000 km of the solar surface and the upper atmospheric layers of the Sun probably respond to the evolution of magnetic fields that are anchored in the photosphere. The existence of coronal holes as persistent depression in the coronal intensity has been known from the ground-based coronagraphic observations since the 1950s. Later satellite observations from the Skylab and Yohkoh further established that high-speed solar winds approaching velocities of order 800 km s^{-1} originate in coronal holes where field lines are open to interplanetary space (e.g., Manoharan, this volume). The classical solar wind model of Parker is based upon thermally driven effects, but the mechanism for the acceleration of high-speed winds in coronal holes is still not clear, as are the agents responsible for the coronal mass ejections.

The importance of magnetic fields in supplying the energy for heating the solar atmosphere is being widely recognised. The presence of kilogauss magnetic fields at the boundaries of supergranules, the detection of coronal loops and bright points in soft X-ray photographs have served to highlight the dominant role of magnetic fields in controlling the energetic phenomena in outer layers of the Sun.

The temperatures in the outer atmosphere of the Sun exceed that at the surface by about one to two orders of magnitude. But the nature of the mechanisms responsible for heating the chromospheric and the coronal layers to such high temperatures has continued to be intriguing (e.g., Ulmschneider, this volume). It is known that the sub-photospheric turbulent convection in the Sun generates waves of different kind: acoustic, gravity and hydromagnetic (Alfvén) waves. Biermann (1946) and Schwarzschild (1948) were the first to suggest a mechanism for heating the solar atmosphere by sound waves generated in the sub-surface turbulent convection zone, steepening into shock waves during their propagation outwards. It is now generally believed that the dissipation of acoustic waves is perhaps important only for the lower chromospheric regions for which the heating needed for the energy-balance is about 4×10^6 erg cm^{-2} s^{-1} (Withbroe & Noyes 1977). Alternatively, acoustic waves impinging on the chromospheric magnetic canopy can be resonantly absorbed and subsequently dissipated in narrow layers by resistive effects (e.g., Chitre & Davila 1991). In the overlying corona, however, the required heating is only about 3×10^5 erg cm^{-2} s^{-1} for the quiet regions and 5×10^6 erg cm^{-2} s^{-1} for active regions. But basically, both the chromosphere and corona of the Sun are heated by some mechanical input of energy and the underlying mechanism for heating the upper chromosphere and corona is very likely to be of magnetic origin. The observational support for the acoustic heating of the lower solar atmosphere comes from the profiles of spectral lines which are broadened by the presence of some nonthermal motions (e.g., propagating sound waves) that appear to increase in magnitude outward.

Several different mechanisms have been proposed for heating the solar corona. There are two main contenders capable of supplying the requisite amount of energy: hydromagnetic waves generated by the sub-photospheric turbulence propagating outwards and getting damped in the upper layers of the chromosphere and corona and formation of current sheets and small-scale reconnection leading to an explosive release of energy for coronal heating (e.g., Dwivedi, this volume).

A fresh insight into the nature and location of the process responsible for heating the solar corona has been provided by the recent observations from the SOHO and TRACE missions (Dwivedi & Mohan 1997). The inhomogeneously structured corona is seen to be made up of a large number of loops of different sizes down to a few hundred kilometres wide loops revealed by TRACE imagery. There is an evident relationship between such loops and the large-scale coronal arches with the photospheric magnetic fields. The earlier theoretical studies envisaged a fairly uniform heating extended over the whole length of the coronal loops (Rosner, Tucker & Vaiana 1978). The X-ray observations of the diffuse corona seem to validate such a model with the uniform distribution of energy describing the observed temperature variations along large loops (Priest et al. 1998). The recent TRACE images of active regions reveal a continual localised brightening indicating dynamic events occurring near the footpoints of the small active region loops (Aschwanden, Nightingale & Alexander 2000). This would place the source of coronal heating in the lower atmosphere of the Sun within about 10 000 km of the surface. Earlier balloon-borne measurements by Lin et al. (1984) had reported the detection of impulsive, bursts of X-ray emission (microflares). With Yohkoh data on active regions, Shimizu (1995) also found numerous small brightening events associated with active region loops. It is plausible that part of the coronal heating responsible for the presence of X-ray bright points results from the process of reconnection of magnetic loops which are driven by the motions of their footpoints by the sub-surface convection. The diffuse coronal emission is likely to arise from regions of in-situ heating that is uniformly distributed along the large-scale loops. The dissipation of long wavelength Alfvén waves by the mechanism of resonant absorption was previously thought to be a promising candidate for heating large coronal loops. Such a heating process tends to be non-uniformly distributed and is, therefore, unlikely to explain the observations.

A viable mechanism that is currently in favour for heating the coronal plasma is the Ohmic dissipation of many narrow current sheets. It appears that the energy input for the coronal holes and the associated high-speed solar wind may be supplied mainly by microflares occurring among the magnetic fibrils that are present on the surface of the Sun. The dense X-ray corona is heated to temperatures in excess of a few million degrees by even smaller flares (nanoflares) that take place in the small current sheets produced in the stronger ($\sim$ 100 G) bipolar magnetic regions by continuous shuffling and buffeting of the footpoints of the field by the sub-surface convective motions. The measurements with the extreme ultraviolet imaging telescope on board the SOHO satellite have also highlighted the role of numerous tiny flaring events (nanoflares) as plausible feeders of energy into the extended loops to heat the corona to temperatures of the order of a few million degrees. However, a major theoretical problem with any coronal heating mechanism involving magnetic fields is the requirement of an efficient diffusion process followed by the reconnection of field lines, and also distribution of the heat from the small volume where the energy dissipation occurs to the larger coronal regions. The recent observations with SOHO and TRACE have provided evidence for the outward transfer of magnetic energy from the solar surface up to the coronal regions. The presence of a magnetic carpet made up of loops is probably responsible in heating the corona to its temperature of several million degrees. These magnetic concentrations are spread all over the surface with their foot points anchored in the photosphere. Each of these magnetic loops carries substantial amount of energy so that when they interact, they cause electrical and magnetic short circuits. The strong electric currents that are produced in these thin sheets can then release adequate amount of energy to heat the solar corona to high temperatures.

It used to be thought that the solar wind streamed outwards from points on the solar surface in all directions. The observations from spacecrafts have revealed the solar corona to be highly structured by magnetic fields. In some places the magnetic field lines form large loop-like structures trapping the solar plasma within them, while at other places on the Sun where the field lines are open, the unconfined coronal plasma flows out into space at high speed as solar wind. SOHO observation have shown that the plumes near the polar caps of the Sun are found within coronal holes which are sites of denser and possibly cooler streams of solar wind. The high speed solar wind ($\sim$ 800 km s^{-1}) associated with open field lines occupies most of the Sun during the phases of solar minimum, and it seems to carry the imprint of the 27 days (synodic) rotation period of the Sun. The coronal holes, in fact, appear to display rigid rotation as if they are attached to the solar body. The slow solar wind ($\sim$ 400 km s^{-1}) is limited by the closed magnetic field lines and its velocity increases polewards from $\sim$ 400 km s^{-1} in the equatorial regions to $\sim$ 600–700 km s^{-1} in the polar latitudes.

The polar regions may be the seats of plumes and coronal holes, but it is the great streamers and huge eruptions called coronal mass ejection (CMEs) that dominate the solar wind pattern in the equatorial latitudes. The CMEs are huge clouds of solar material lifting off from the corona and travelling out into interplanetary space like great blobs of plasma. These outbursts are occasionally seen to travel in opposite directions, nearly simultaneously, resembling ejections girdling the equatorial belt. Observations of the solar corona with Large Angle and Spectrometric Coronagraph (LASCO) and Extreme ultraviolet Imaging Telescope (EIT) instruments aboard the SOHO should provide an opportunity to study CMEs from their initiation to gain an understanding of the sources regions from which they originate and their association with active regions on the surface of the Sun.

It is no exaggeration that the internal and external layers of our Sun furnish unlimited opportunities to study various branches of physics in the cosmic environment. Equally, some of the violent events occurring in its atmosphere have profound implications for the life here on Earth.

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