Kodaikanal Obs Bull (1988) 9, 1 6

HOW WELL DO WE KNOW OUR SUN ?

S M Chitre
Tata Institute of Fundamental Research
BOMBAY

Abstract

The role of our Sun as a valuable astrophysical laboratory for testing theories of stellar physics is highlighted. The state of our knowledge concerning the solar interior and the possible probes for gaining insight into the internal layers of the Sun are discussed.

1 Introduction

The Sun has been aptly described as the "Rosetta Stone" of Astronomy, a description which is particularly appropriate as this star is sufficiently close to Earth for its surface phenomena to be closely scrutinized and its atmosphere to be probed in detail. The Sun provides us with data of high spatial resolution of surface structures that permits us to study solar atmospheric features and processes, that are clearly inaccessible for other stars. Many of these solar structures and physical processes are currently thought to be important in other stars; indeed, the evidence for chromospheres, coronae and winds for several stars of different spectral type is both compelling and growing rapidly with new techniques of observation (Linsky, 1981). The Sun gives only a snapshot of one star and other stars have to provide the rest of the story. Our Sun, it is hoped, could be used as an astrophysical laboratory for testing theories of stellar physics. This is the main reason why solar astronomers devote so much attention to a single star.

2 Hydrostatic Sun

Solar structure is that branch of astrophysics which is concerned with the physical conditions prevailing in the interior of stars. The inside of the Sun is clearly not accessible to observations, nonetheless it is possible to construct a reasonable picture of its interior. This is achieved through a combination of theory and observation. It is possible to construct a reasonable picture of the inside of the Sun by means of a set of mathematical equations governing the structure together with the boundary conditions provided by observation. The central problem of the theory of stellar structure is to determine the physical conditions such as the pressure, density, temperature prevailing within the star with the help of governing equations of stellar structure and the boundary conditions supplied by observations of its mass, radius, luminosity and chemical composition.

The mechanical equilibrium condition tells us that the pressure at any point in the interior is adequate to support the weight of the overlying layers. For thermal balance, the energy loss at the surface of the Sun as measured by its luminosity must be compensated by the energy released by nuclear processes in the stellar interior. The structure equations in the usual notation, may be written as

Mechanical equilibrium
$$\frac{dP(r)}{dr} = \frac{GM(r)}{r^2}\,\rho(r)$$

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r)$$

Thermal equilibrium: $\frac{dL(r)}{dr} = 4\pi r^2 \rho E$

$\text{Flux} = \frac{4acT^3}{3\chi\rho} \frac{dT(r)}{dr}$

Opacity $\chi = x(\rho\ T, X, Y, Z)$

Energy generation rate $\epsilon = \epsilon\ (\rho, T, X, Y, Z)$

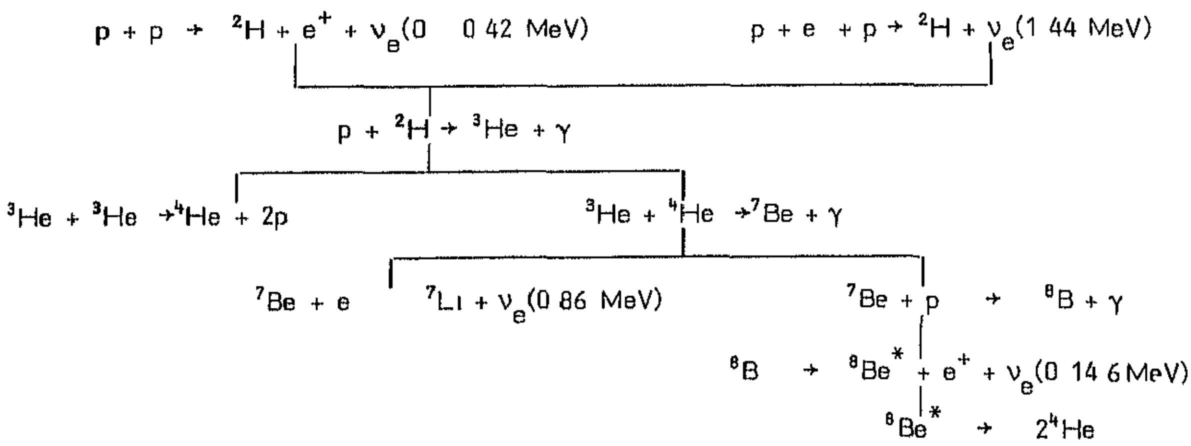
Equation of state $P = P(\rho, T\ X, Y, Z)$

Our complete understanding of the solar structure is based upon a series of auxiliary assumptions concerning the opacity, energy generation rate, the equation of state and the mean molecular weight The conventional approach in evolutionary calculations is to adopt a homogeneous initial chemical composition and the mass, and then evolve the Sun to yield the present luminosity and the radius after 4 7 billion years The hope is, for the Sun, we can partially check the validity of these assumptions Had we discovered that the conventional theories of solar structure adequately describe the Sun, we would have left the Sun alone The agreement is tantalisingly close in many respects, but it fails on some counts

During the past several decades extensive computations have been performed and numerical techniques have been developed to handle the non linear differential equations governing the solar structure For evolving the Sun, best available data on nuclear cross sections has been used and energy generation rates calculated by Bethe have been adopted Astrophysicists then began to ask the questions Is there any way of checking the evolutionary calculations? Is there a way of looking into the thermonuclear furnace hidden deep in the core of the Sun' As it happens, there is a particle the neutrino, released by the network of thermonuclear reactions in the solar interior, that is capable of streaming out practically unhindered from the central regions to the surface and escaping into space outside for us to measure here on Earth Table 1 shows thi proton proton chain operating inside the solar core

Table 1

Proton proton chain



Davis and his collatorators at Brookhaven have set up a tank with 615 tonnes of C_2Cl_4 (tetrachloroethylene in which ^{37}Cl nuclei are the solar nutrino absorbers according to the relation :

$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e$$

The solar neutrinos are expected to convert some of the ^{37}Cl nuclei into ^{37}Ar and Davis counts these ^{37}Ar atoms by an ingenious device. The measured ^{37}Ar production rate is 0.36 ± 0.05 ^{37}Ar atoms/day = (2.07 ± 0.25) SNU (1 SNU = 10^{-36} per target nucleus/sec), while the standard solar model predicts a capture rate of (5.8 ± 2.2) SNU (Bahcall and Davies, 1984). Clearly we have a discrepancy of a factor of 3 to 4 between theory and measurement. The feature that was immediately localised was that the central temperature T_c needs to be reduced slightly in order to bring down the extremely temperature sensitive flux of neutrinos from ^{8}Be and ^{8}B decays. From the Virial theorem, we know

$$kT_c \sim \frac{GM_\odot}{R_\odot} m_H$$

i.e. the internal energy and the gravitational energy are in equipartition which must be if the thermal pressure is able to overcome the gravitational attraction. But if we were to add some external force like rotation or magnetic field contributing to the central pressure then

$$kT_c + \text{centrifugal force} + \text{magnetic force} \sim \frac{GM_\odot}{R_\odot} m_H$$

In this way the central temperature can be reduced but not enough unless one incorporates an excessive amount of rotation or magnetic field which will conflict with the observed oblateness of $< 5 \times 10^{-5}$. What then is the solution of the problem of the missing solar neutrinos? Is there some deficiency in standard solar models or is the nuclear physics not adequately described or do we not understand the neutrino physics well enough? To make the problem more intriguing Davis (1987) has recently announced that measurements between 1977 and 1985 show that ^{37}Ar production rate anticorrelates with sunspot number, i.e. with solar activity, and that there seems to be an apparent increased rate of ^{37}Ar production during large solar flares. This has prompted solar physicists to look for some independent means to determine conditions in the Sun's interior.

3. Dynamic Sun

Recently, solar physicists have developed a new and powerful tool to probe the Sun's interior with extraordinary precision. The tool is provided by a rich spectrum of velocity fields observed at the solar surface. To a casual observer, the surface of the Sun appears quiescent, but in reality the Sun is quite dynamic, vibrating in an agitated manner. The observed velocity field has two main components: a non-oscillatory part which is believed to be a manifestation of the convective motions in the sub-surface layers of the Sun (Beckers 1979) and an oscillatory component with a period predominantly centred around 5 minutes (Toomre 1986). one of the striking properties of the observed convective motions on the Sun is the discrete spectrum of their horizontal scales. The basic question we must seek to answer is why do there exist only three preferred length scales: granulation with a characteristic cell size ~ 2000-3000 km with an average lifetime of the order of 8-15 minutes, the supergranulation with an average diameter ~ 30,000 km and lifetime of 1-2 days, and giant cells which are comparable in size to the total thickness of the solar convection zone and lasting for several months. Then there is the solar rotation with a period of about 27 days at the equator and nearly 30 days at higher latitudes. How does the rotation field vary with depth? Is the interior of the Sun rotating more rapidly than the surface layers? What is the period of rotation in the solar core? Amongst the oscillatory motions, the five-minute oscillations are the most extensively documented since their discovery by Leighton, Noyes and Simon (1962). The surface layers of the Sun resemble the ocean surface with its up and down motion of the waves. The major complexity arises from the fact that there are a million ways in which the Sun can simultaneously pulsate. This feature has received special attention recently when it was realized that the solar oscillations reveal information in much the same manner as the study of seismic waves (geoseismology), generated by earthquakes, and has helped us to learn about the interior of the Earth In geoseismology, by measuring the time taken by seismic waves to traverse the distance from the earthquake site to the seismographs, we can deduce the internal structure of the Earth The speed of waves, for example, is controlled by the composition of the terrestrial material they encounter during the propagation Likewise, the seismic waves seen at the solar surface allow us to measure conditions in the deep interior of the Sun, since the properties of these waves will be expected to depend on the medium through which they travel

This new tool of helioseismology provides a complementary probe to the solar neutrinos for diagnosing the interior of the Sun

Solar oscillations may be regarded as a superposition of many standing waves and their frequencies depend on the average internal physical properties like the temperature, density and chemical composition of the solar material There are two main classes of waves sound (or acoustic) waves which are controlled by pressure fluctuations, and gravity waves for which the major responsible force is the Sun's gravity Broadly speaking, pressure fluctuations operating at the high frequency end produce acoustic waves while buoyancy forces dominate the low frequency gravity waves What have we learnt from the rich spectrum of modes provided by helioseismology? The most straightforward way to use the oscillation data was to compare the observed oscillation frequencies with the theorietical eigenfrequencies of a variety of theoretical models This would enable us to deduce the depth of the outer solar convection zone which comes out to be about 200,000 km and to estimate the initial helium abundance to be 25% by mass in accordance with the ideas of cosmological nucleosynthesis It has also been possible to deduce the variation of sound speed through much of the interior of the Sun It also appears that a substantial degree of small scale of mixing of the products of the nuclear reactions with the non reacting environment has <u>not</u> occurred, although small amount of mixing cannot be excluded In fact any effective energy transport mechanism that can reduce the central temperature T_c without extensive mixing might in principle resolve both the solar neutrino problem and the obseved g made period spacing (cf Faulkner Gough and Vahia, 1986) The acoustic modes of short wavelength are confined largely in the outer layers of the Sun and are valuable in shedding light on the nature of the solar convection zone The gravity modes are mainly trapped in the interior and just as acoustic waves are important for understanding the temperature stratification inside the Sun the internal gravity waves are highly useful in revealing the density stratification that prevails in the central regions of the Sun This is evidently a very promising diagnostic tool to probe the very central region of the Sun

Helioseismology is proving its worth in revealing the distribution of angular velocity with depth In the absence of rotation one of the many resonant mode which the Sun can exhibit is a standing wave For a completely spherical distribution, the eastward and westward moving waves would have identical frequencies and would, as a result be indistinguishable The rotation breaks the spherical symmetry by bringing about a deviation which influences the two types of standing waves in a different manner, depending on whether the wave is travelling with the direction of the solar rotation or against it This results in a slight difference in the frequencies of the waves, called the rotational splitting The amount of this frequency difference depend on the rotational velocity of the Sun, and since the oscillatory modes pervade a large part of the solar interior, they would clearly experience the rotation field pervading the entire solar body The measurement of rotational splitting of many different waves would give a weighted average of the rotational velocity with depth The Sun certainly seems to rotate faster in the interior, but the details of the distribution of angular velocity throughout the Sun are still unclear At any rate the mean angular velocity of the core appears to be anywhere between about two or four times that at the surface Duvall and Harvey (1984) have deduced the internal profile of the angular velocity field, which is almost constant down to 0 6 $R_\odot$ and then decreases to a minimum between 0 3 $R_\odot$ and 0 2 $R_\odot$ before rising in the inner regions to a value that is about twice four times that of the surface value Brown (1985) concluded that the solar interior rotates less differentially than the photosphere However, Duvall and Harvey maintain that the latitudinal differential rotation persists at least down to the base of the convection zone and below the convection zone, the angular velocity is perhaps constant on spheres

A knowledge of the rotation of the solar interior plays a vital role in understanding the mechanisms for driving the sunspot cycle, but more interestingly, it provides a crucial test of Einstein's GRT This test is based on the measurement of the orbit of planet Mercury whose orbit after correcting for planetary interactions may be represented by a rotating ellipse which precesses about the Sun at a tiny value of 43 seconds of arc per century. Einstein's GRT explains this precession of the orbit of Mercury remarkably well, but this explanation is based on the Sun being a completely spherically symmetric body The solar rotation would lead to a slight flattening at the poles, which is liable to modify the gravitational potential and will give rise to a quadrupole moment This modified gravitational field of the oblate Sun could also cause the orbit of planet Mercury to precess in the way that is observed However, in order to explain the whole of the procession of 43 seconds of arc per century would require the Sun to be far more distorted at the equator than it is observed to be It is staightforward, from the knowledge of the internal angular velocity profile, to calculate the oblateness produced by the rotational forces at the surface and it turns out that the contribution, from the centrifugal flattening of the Sun to the precession of the orbit of the Mercury is not even one per cent So we can fairly conclude that there is no particular need to alter the original formulation of Einstein s GRT

4. Sun as a Star

A good working definition of a sun like star is one which has a (turbulent) magnetic field sufficiently strong to control the dynamics and energetics of its outer atmospheric motions An outstanding feature of the solar stellar connection is that magnetic fields and their interaction with fluid motions are the basic factors controlling the solar and stellar activity Clearly the magnetic pressure must exceed the thermal and turbulent pressure to have a controlling influence on the motion It is generally believed that the activity originates a magnetic dynamo powered by the interaction of solar rotation and convection This interaction produces a differential rotation with the solar convection zone which together with the convective motions, amplifies the internal magnetic field and is also responsible for the transport and dissipation of surface magnetic fields and the 22 year magnetic cycle Similar processes could occur in other sun like stars

Accepting the foregoing working definition of sun like stars, the most reliable method for identifying solar type stars is, of course to directly measure their magnetic fields, especially the strong facular or starspot magnetic fields Thus, many dwarfs G, K and M type are sun like and systematic studies of the correlations of field variations with different signatures of activity cycle would be valuable in finding its dependence on stellar charactristics like the depth of convection zone, effective temperature, gravity, rotation and age Most widely used indicator of stellar activity is the flux in the CaII H and K like cores In fact, the strength of core omissions of the CaII H and K and MgII h and K flux profile correlate well with the total plage area which is controlled by solar activity (Sivaraman 1986) Wilson (1978) has reported the results for activity cycle of 91 stars of F, G, K and M main sequence stars Out of these about 40% show evidence of a cycle, while another 40% exhibit short term variability The cycles are probably signatures of 'old" stars, whereas young stars are characterized by short term variability

Another indicator of stellar magnetic activity is the soft X ray flux The X ray flux from lower main sequence stars is found to be tightly dependent on the rotation Thus, both chromospheric and coronal emission clearly tracks stellar surface magnetic fields The chromospheric structures seem in the CaII H and K lines serve a good indicators of the photospheric magnetic structures and they reflect morphological changes in the surface magnetic features associated with the solar cycle Similar changes occurring in other solar type stars could be profitably used as a diagnostic of surface activity An unambiguous indicator of stellar magnetic activity is provided by starspots Starspots have been extensively studied in late dMe stars and rapidly rotating RS CVn stars both of which show spot coverage very much larger than the Sun Another piece of evidence is provided by flaring which is generally thought to be an indicator of strong magnetic fields in the stellar atmosphere as the rapid heating presumably results from the conversion of magnetic energy into non thermal particles and eventually heat The flaring is exhibited by pre main sequence and T Tauri stars

The Sun is a star in the Galazy which, with its planetary system, is voyaging around the galactic disc through a varying cosmic environment If the solar system had been dissociated from the rest of the Galaxy then the solar luminosity would have remained sensibly constant, and the terrestrial climate would have evolved securely without any events like glaciations What is the effect of solar motion on its luminosity and possibly its magnetic activity cycle?

The future studies will hopefully answer some of the following questions

What is the resolution of the problem of the missing solar neutrinos?

What really are the conditions like in the core of the Sun?

Is there a diffusive mixing of the nuclear products generated in the thermonuclear furnace with the overlying cooler regions?

Is there an additional mode of energy transport, besides the radiative process in the solar core which could affect its central thermal structure?

Is there an accumulation of the magnetic field at the base of the convection zone which controls the 11 year solar cycle?

Does the solar core harbour a significant amount of magnetic field?

Does the solar luminosity vary with time?

We hope the clues to these intriguing and outstanding problems will be partly provided, in the next few years The first major task is to get over the day night cycle and to obtain a long, continuous record of solar oscillations Clearly observations from a single station cannot achieve this objective except from the polar regions, which is naturally not a very feasible proposition An international community of scientists have, therefore, proposed a network of identical solar telescopes to be located around the globe in contiguous longitudes for an uninterrupted view of the Sun The Udaipur Solar Observatory in the Indian longitudes is a potentially attractive site for participating in such a joint venture (GONG project) initiated by an international group of solar physicists This ground based network will have to be supplemented by a satellite borne solar telescope for the accurate measurement of modes with short wavelength, which get severely affected by atmospheric seeing distortions The space borne observations along with the ground based network will, hopefully, push the helioseismological tools to their limits and produce some unexpected surprises about our Sun

References

Bahcall, J N and Davis, R 1984, in Solar Neutrinos and Neutrino Astronomy (ed M M Cherry, K Lande and W Fowler AIP)
Beckers, J M 1979, IAU Colloquium 51 (ed D F Gray and J L Linsky Springer Verlag) p 85
Brown, T M 1985, nature, 317 591
Duvall T L Jr and harvey, J W 1984, Nature, 310, 19
Davis, R 1987, Proc Int Cosmic Ray Conference, Moscow
Faulkner, J, Gough, D O and Vahia, M N 1986, Nature, 321, 226
Gough, D O 1985, Adv Space Res 4, 85
Leighton, R B, Noyes, R W and Simon, G W 1962, Astrophys J 135, 474
Linsky, J L 1981, in Solar Phenomena in Stars and Stellar Systems (ed R M Bonnett and A K Dupree D Reidel Publishing Company) p 99
Sivaraman, K R 1986, Kodaikanal Obs Bull 6, 11
Toomre, J 1986, in Seismology of the Sun and the Distant Stars (ed D O Gough D Reidel Publishing Company) p 1
Wilson, O C: 1978, Astrophys J 226, 379