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Solar Astrophysics: An Overview

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Abstract. In the last 20 years solar astrophysics has undergone a revolution with the measurement of solar oscillations and the development of helioseismology enabling us to probe the physical processes, internal structure and dynamics of the Sun. Further progress is imminent with the completion of the GONG network and the launch of SOHO. The oscillation frequencies give an increasingly tight constraint on the hydrostatic structure of the Sun, in reasonable agreement with models, but the low flux of solar neutrinos remains an outstanding problem, although, as I show, it is possible to obtain quite low neutrino fluxes from models that satisfy the helioseismic constraints.

Key words: Sun - astrophysics - stars - neutrinos.

1. Introduction

Solar astrophysics has undergone, and is undergoing a revolution. The growing wealth of data on oscillation frequencies of the Sun, and the development of helioseismology as a new tool with which to probe and diagnose the internal structure and dynamics, has opened a new era in solar astrophysics. 20 years ago when I gave a review on *The Internal Structure of the Sun and Solar Type Stars* at the IAU Colloquium in Prague (Roxburgh 1976), global oscillations of the sun had just been reported (Hill et al 1975) and helioseismology was in its infancy. 20 years is perhaps about the right interval of time over which to reflect on what we have achieved in the subject, which problems have been solved, which remain to be solved, and what new problems have been uncovered.

1.1 Why do we study the Sun?

The first answer is of course "because it is there"! It has been a source of mystery and worship for millennia, it is the source of energy for the Earth controlling the Earth's environment; without it we would not be here to ask the question.

But for the astronomer it is much more - it is the one laboratory for stellar physics accessible to detailed study. We study the detailed properties of the solar surface layers in increasingly high spatial and temporal resolution, the properties of convection, the chromosphere-corona, the magnetic structures. But we now have the additional tool of helioseismology - the study of solar oscillations which probe inside the sun - providing increasingly more accurate and detailed information on the structure and dynamics of the solar interior. This allows us to test and develop our ideas, theories and models of solar and stellar evolution.

I want to stress here the importance of studying the sun in the context of stellar evolution. Much of astronomy is dependent on our having a reliable theory of physical processes in stellar interiors that determine the structure and evolution of stars. Stars are used to determine the age and distance scale in the universe, through the dating of globular and open clusters with models of stellar evolution, the calibration of the distance scale depends on our having a reliable understanding of Cepheid variables and other very luminous stars, the chemical evolution of the galaxy is determined primarily through the processing of elements by nuclear reactions in the stellar interior, the subsequent dredge up of this material into the surface layers of stars and the ejection of this processed material back into the interstellar medium from which the subsequent generation of stars is formed. This chemical evolution determines the luminosity evolution of galaxies and thereby the determination of distance on the largest cosmological scales.

The empirical tests on stellar evolution theory are few. Probably the broad ideas are valid, stars are in hydrostatic equilibrium - pressure supports the star against self gravity, the stars are gaseous and hotter in the centre than the surface. Energy is produced in the centre by nuclear reactions and flows to the surface down the temperature gradient. The evolution of the star is due to the gradual conversion of light elements into heavier elements in the hotter central regions. Beyond this the shape of observed cluster H-R diagrams is similar to that predicted by evolutionary theory in which the star becomes chemically inhomogeneous - the helium produced by burning hydrogen in the central regions more or less staying there. One can - and many do - overstate the level of agreement between prediction and observation - the fact that cluster main sequences turn towards the red at higher luminosities and have bright cool giant stars is consistent with some degree of inhomogeneous evolution - fully mixed homogeneous models do not evolve to the red - but the quantitative agreement is poor. Indeed it is now part of the (increasingly) accepted modelling of stellar evolution that we need to include some extended mixing in stellar interiors, from convective penetration, to get reasonable agreement with observations of open clusters (Meynet et al 1993, Dowler et al 1995)

2. Solar Models

The first model of the sun was that of J Homer-Lane (1869) which was a polytrope of index 1.5, homogeneous throughout and fully convective. This model drew on the work of Kelvin (1862) on modelling the Earth's atmosphere, and was in fact produced to try to estimate the density of the surface layers of the Sun. The current models of the Sun are inhomogeneous, with a helium rich core and a convective envelope covering the outer 28% or so of the solar radius. Whereas in the Lane-Kelvin model the energy was transported by convection throughout the whole of the Sun, in the present solar model energy is considered to be carried by radiation in the inner 72% of the radius. The same physical processes are thought to operate in the interiors of all stars, although with different regions being convective, and the sun affords a unique laboratory for testing these ideas. Hopefully we will in the future have oscillation data from other stars - obtained both from the ground and from space.

2.1 Fundamentals

When seeking to interpret observational data and to build models of the sun (and other stars) we make certain assumptions, some explicit some implicit. Fundamental amongst implicit assumptions are

The Universe is "lawlike"

That is that the structure and evolution of the Universe is governed by 'laws of Nature" everywhere and everywhen (at all times). For example we do not normally question the applicability of Newton's law of gravity (or Einstein's General theory of Relativity) inside the sun and stars, we believe that gravity behaves in the same way inside the stars as we find from experiment on Earth.

The constants of Nature that enter into these laws are the same everywhere and everywhen.

For example the strength of gravity is governed by the dimensionless coupling constant $\alpha_g = Gm^2/e^2$; we normally assume that this is constant in space and time. I say normally because from time to time this assumption is called into question. It is conceivable that α_g varies in time, it is a pure number and the value we measure now need not necessarily be the same as it was 5 10^9 years ago. Whether or not this is the case is an empirical question which must be addressed by experiment. Limits on the possible variation of α_g can be obtained from radar ranging to planetary orbits which give a time scale for any such change as longer than about 5 - 10 10^{10} years. However it should be pointed out that since the luminosity of the Sun is proportional to something like the 6th power of G, a 7% change in G over the solar lifetime corresponds to an 50% change in the luminosity, more than the change associated with the standard chemical evolution due to nuclear burning.

2.2 Model assumptions

Given that the laws and constants of Nature are constant, models of the sun are based on a number of hypotheses, some more strongly supported by observation than others.

The Sun is in hydrostatic equilibrium - pressure balances gravity

The Sun is in thermal equilibrium - the energy radiated is equal to the energy produced in the centre - save for a very small contribution from the thermal adjustment of the sun due to evolution

The energy source is hydrogen burning

Energy is carried solely by radiation except in regions which are convectively unstable where energy is also carried by the convection.

Convection can be adequately modelled by the mixing length "theory" (model!)

Chemical mixing only takes place in convective zones (possibly + diffusion)

Mass loss, rotation, magnetic fields are only small perturbations

The Sun was initially homogeneous and has an age of approximately 4.6 10^9 years

2.3 Building a "standard model"

Given these assumptions - and the assumptions that we know the relevant microphysics: opacities, equation of state, nuclear cross sections, ... we then construct a "standard solar model" by taking an initially chemically homogeneous sun, with the observed surface layer ratio of heavy elements to hydrogen, Z/X, the relative distribution of elements Z_i as found from meteorites and other solar system abundance studies, and an unknown initial helium abundance Y, and evolve this model for the solar age. The predicted values of the luminosity and radius depend on the assumed initial helium abundance Y, and the mixing length parameter in the theory of convection ℓ, these values are then adjusted to obtain agreement with the observed luminosity and radius. Given two parameters and two observables a fit can be found! Other effects are from time to time included in what one might call a reference model rather than a standard model, for example diffusion or gravitational settling of helium and heavy elements in the layers below the solar convective zone. Such gravitational settling might also be important in the atmosphere, for example it is puzzling that in the quiet solar wind the helium abundance is only 50% of that found from a standard solar model. Additional nuclear reactions are included in the energy producing cycles as they are found to be non negligible.

It is clear from the way the standard - reference model is constructed - that if we were to make different assumptions about the initial model, the mixing processes inside the sun, the microphysics, and even a time dependent gravitational constant - we could still produce model that had the observed luminosity and radius at the present age, adjusting Y and ℓ to give $L_\odot$ and $R_\odot$. So the model cannot be believed on the grounds that it fits the observations. Further tests are needed. Fortunately we now have a growing body of empirical data in the form of solar oscillations with which to test and improve our knowledge of the physical processes in the solar (and stellar) interior and to enable us to improve our theoretical models of the sun and stars.

2.4 Some problems and questions from 1975

It is interesting to look back 20 years and see what were the problems and questions at that time. Some of these problems were perceived to be:

The central temperature is of order 1.5 10^7 °K and the predicted Neutrino Flux was greater than values measure by the Homestake Chlorine Experiment (which is sensitive to neutrinos from the Be - B branch of the p-p chain).

Standard models predicted that the sun's luminosity increased monotonically from 0.7 to 1 $L_\odot$ - which was at that time difficult to reconcile with models of the evolution of the Earth's climate - which with such an evolution in luminosity predicted that the Earth should be covered with ice.

The temperature at the base of the convective envelope was predicted to be about 2.2 10^6 °K which is too low to explain the reduction in Lithium in the Sun and other solar type stars.

The Sun had been found to be oscillating in global modes (Hill and Stebbins 1975); what was the mechanism of excitation and what effect would they have on internal structure, particularly mixing and energy transport?

Do we really understand mixing in the interior? Was the initial composition homogeneous? Could Z be larger in the interior than in the surface layers?

Could internal waves contribute to energy transport in the interior?

The solar models became unstable to a low order g-mode driven by the build up of ^{3}He during evolution at an age of about 3 10^8 years. What does this instability do? Does it cause mixing - violent or slow?

Does the sun have a rapidly spinning core (or a large central magnetic field) that could change its structure, lowering the central temperature and "resolving" the neutrino problem?

Has the sun been mixed, or is it still being mixed by some turbulent-diffusive process driven by spin down of the surface layers from angular momentum loss in the solar wind?

Does convection driven in an unstable region penetrate deep into the surrounding stable regions?

3. Some Questions and Issues in 1995

Today we have more detailed measurements and more sophisticated diagnostic tools - in particular the rich data set of oscillation frequencies - but many of the questions remain the same.

3.1 Theory of convection

We still do not have an adequate understanding of the properties of convection, indeed still (mostly) use the same mixing-length model as in 1975. Some new approaches both theoretical and numerical have been developed and are being developed (see Canuto (1996), Nordlund and Stein (1996), Singh et al (1996), Toomre (1996)). But the problem remains - what is the structure of the non-adiabatic layer at the top of the surface convective zone? How can we generalise from the solar case to other stars? There is some hope of progress here in the sense of testing and calibrating models (I prefer to call them models rather than theories) using the observed oscillation frequencies to diagnose the structure of the upper layers. An analysis by Monteiro (1996) suggests that one obtains a better fit to the frequencies using a modification of the mixing length theory, such as the model by Canuto-Mazzitelli(1992), which is essentially equivalent to taking the mixing length as the distance from the boundary. But these models are clearly inadequate - numerical simulations - and common sense - suggests that the convection penetrates into the stable solar atmosphere, and whilst such "overshooting" is much studied in the solar and stellar interior it has not yet been incorporated in even simple theoretical models of the surface layers. More - the convective velocities can be quite large and the neglect of "turbulent pressure" is invalid and should be included. But even if this is done these theories - or models - are unlikely to give an adequate representation of the physics - they are not physical models in the sense that they approximate the actual physics: we do not know how to model the physics of turbulence.

Moreover it is clear from both observations and very simple estimates that magnetic fields can play an important role in surface layer convection, and although there are attempts to include these in numerical simulations we still have a long way to go.

A further observation - apparent from numerical simulations and from common sense - is that radiative losses are important in governing the properties of convection in the surface layers. These are just the layers from which radiation escapes so they cannot be adequately modelled by an optically thick diffusion approximation. Considerable advance has been made in studying these effects in numerical simulations.

But a word of caution about numerical simulations, unless - unknown to me - someone has solved the problem of turbulence, we cannot make fully realistic simulations of convection. We can do fully resolved calculations, but the parameters are very far removed from those in the sun and stars, or we can do large eddy simulations and make some closure approximation - or sub-grid modelling, to model the unresolved small scales of motion. But we do not know how to do this - if we did we would have solved the problem of turbulence! So look carefully at the claims made by large eddy simulators - what have they assumed for sub-grid modelling - and how do their answers depend on these assumptions? In some cases the answer to the first question is not clear - in almost all cases the second question has not been addressed.

For the interior structure of the sun and stars convective modelling is needed to determine the entropy S in the deeper adiabatic layers as a function of the surface properties, $S = S(X_i, T_{eff}, g, ...)$; such studies - through numerical large eddy simulations - are still in their infancy.

3.2 Abundance of the elements

Next we are still left with uncertainties about the abundance of the elements, especially of course the helium abundance but also the relative abundance of the heavier elements especially iron. These uncertainties propagate through to uncertainties in the opacity and hence radiative transfer of energy.

One way to seek to determine the helium abundance, and the entropy, in the adiabatic deeper convective zone is through the signature in the oscillation frequencies caused by the depression of the adiabatic exponent Γ. A number of attempts have been made to do this but they are in my view overwhelmed by uncertainties in the equation of state. That is the values one gets are dependent on assumptions about the equation of state - and since we have no independent constraint in the equation of state we cannot obtain reliable estimates of the helium abundance. Another direct way to determine the helium abundance is through in-situ measurements in the solar wind. Such experimental determinations - on the space mission Ulysses - give a result very substantially different from other estimates and from our prejudices - namely about 0.13 (Feldman 1996). This is difficult to reconcile with estimates ranging from 0.23 to 0.28 found from solar model fitting and from studies of the oscillation frequencies, especially since the Z/X ratio in the quiet solar wind seems to be similar to the photospheric values.

3.3 Depth of the convective zone and overshooting

Another question that was raised in 1975 on which some progress has been made is the depth of the solar convective zone and constraints on convective penetration into the deeper stable layers. This problem has been addressed by theory, comparing models with observations, using the characteristic signature in the frequencies due to the rapid scale of variation of the derivatives of the sound speed, and by numerical simulation. But there is still no consensus - not that truth is determined by consensus! Comparison of models of convective envelopes with the oscillation frequencies indicates a depth of the convective envelope of 0.283 $R_\odot$ (Christensen-Dalsgaard et al 1991), although too much weight should not be put on the number of significant figures since it depends on assumptions about the models, and in particular the structure of the layer just beneath the zone where overshooting will occur. The analysis of overshooting by myself and Sergei Vorontsov (Roxburgh and Vorontsov, 1994) found that the present observations could not rule out an overshoot layer whose thickness was 0.25 times a pressure scale height- or 10% of the depth of the zone - a more recent analysis by Monteiro et al (1994) places a more stringent limit on this penetration depth but also confirmed our result that small penetration distances are in some sense "disguised" - that is it is very difficult in practice (although not in principle) to differentiate between modest and no overshooting. Numerical simulations tend to give greater penetration depths, and the sharp change found in theoretical models tends to be smoothed. Whether this is a real effect or due to coarse spatial resolution remains to be answered.

3.4 Rotation

Helioseismology has also yielded information on the rotation of the sun from measurements of the rotational splitting of the frequencies. The rotation in the outer convective zone is found to be such that the surface differential rotation continues throughout most of the zone - being almost constant on radial lines. This was somewhat of a surprise to those whose background was in incompressible non-turbulent hydrodynamics who naively thought that the rotation would be constant on cylinders - but less of a surprise to those of us who had sought to model the differential rotation in a turbulent rotating shell. Reconciling the observed (or rather deduced) differential rotation with simple models of the dynamo generation of the solar magnetic field remains a problem. But perhaps the simple (α, ω) dynamo models are far from the real world, they are based on an assumption that one can separate the dynamics into two scales - a mean flow and field and a small perturbation about these mean fields - this is not actually a valid separation given the observed properties of the solar surface layers. And of course any mean field turbulent model has the problem of modelling the small scale motion and fields which cannot be resolved in a numerical simulation - this is probably even more of a problem for magneto-fluid turbulence than for convection.

The splitting data for the solar interior show that the differential rotation in the convective envelope merges into an essentially radial rotation rate $\Omega = \Omega(r)$ in a relatively thin transition layer - how thin has yet to be resolved. In the central core the situation is not yet totally clear - with different groups obtaining different values from the splitting of low ℓ frequencies (see Elsworth 1996, Fossat 1996), some claiming a small inward increase in the central $\Omega(r)$ others claiming a small decrease. My own view is that all the data is compatible with uniform rotation throughout the bulk of the solar interior - what one might expect if the interior is threaded by even a weak magnetic field. I should make one point, if the sun were uniformly rotating at an early stage of its evolution, then angular momentum loss from the surface - through a magnetically dominated solar wind, and the contraction of the central core due to the increase in density with evolution, should lead to the core spinning more rapidly that the surface layers, rather than slower. Evolution gives an increase in central density by a factor of about 2 leading to a central rotation that is 60% larger than the rotation at the base of the convective envelope. But this would be removed by even a small magnetic field. From time to time there have been hints that perhaps something unusual is happening at a radius of around $0.3R_{\odot}$, perhaps a differentially rotating belt, it is worth noting that this is in the region of the peak of the distribution of ^{3}He and perhaps the instability driven by this distribution might play an as yet not understood role (Roxburgh 1985).

3.5 Excitation and damping of oscillations

Our understanding of the excitation and damping mechanism of solar oscillations is in its infancy. It is now widely accepted that the oscillations are stochastically excited by the turbulent convection (although I remark again that truth is not determined by a vote amongst the community!), with the κ - mechanism playing a negligible or small role. I am not wholly convinced by these arguments - and harbour a view that the observed variation in line widths with frequency may be related to the location of excitation and damping from the κ - mechanism within the convective envelope. Some progress has been started on the problem of relating line profiles to excitation and damping mechanisms, (Roxburgh and Vorontsov 1995) but radiative losses and damping in the solar atmosphere has yet to be adequately incorporated in these calculations. I anticipate that this will become an important area of research as we obtain better data from GONG and SOHO, and that it will hopefully enhance our limited understanding of turbulent convection.

3.6 Mixing and diffusion

The other area that I think is still open to question is the degree of mixing (or anti-mixing ie gravitational settling) in the solar interior. Such mixing could be by weak turbulence driven by the instability due to the build up of a steep gradient in ^{3}He during solar evolution (Christensen-Dalsgaard et al 1974). In my view this problem has not been satisfactorily resolved and is usually forgotten! To remind the reader, this nuclear driven instability arises when the ^{3}He profile is sufficiently steep and capable of exciting a low order g-mode. Many calculations support the conclusion that this instability sets in when the sun was 2 - 3 10^8 years old, the issue is what then happens. One possibility - suggested by Dziembowski is that the unstable mode is in resonance with a set of other damped modes which prevents the mode from growing in amplitude and that it therefore has no effect on solar evolution. An alternative hypothesis - advanced by myself 20 years ago (Roxburgh 1976, 1984) is that it breaks down into mild turbulence, the slow mixing by this turbulence transporting the ^{3}He into the hotter interior where it is burnt; the system having a feed back mechanism then stays on the edge of instability. Such mild turbulence would also cause some mixing of hydrogen and thereby affect solar evolution and the neutrino flux.

Another mechanism, suggested by Press (1981), and developed by Evry Schatzman and co-workers (see Schatzman and Montbalan 1995) is mixing due to gravity waves generated by the convection at the base of the convective zone. These wave propagate into the interior and can cause some degree of mixing. There is some debate about the efficacy of this mechanism but it needs to be explored in greater detail.

In the layers beneath the solar convective zone there are many mechanisms that may be effective in causing some mixing. Differential rotation beneath the zone - where the differential rotation in the envelope adjusts to the almost radial distribution in the interior - may drive circulation or be unstable, causing some mixing. Gravity waves may be effective in this layer; this may be the seat of a turbulent dynamo with some consequential mixing from turbulence and instabilities. Convective penetration may be more effective than deduced from theory or observations of the oscillation frequencies - due to the "high velocity tail" in the convection: strong downdrafts which can penetrate deep into the stable region. The role of gravitational settling - or anti-mixing may also be important. Estimates suggest that this is indeed the case and it is now included in reference solar models, which it is argued then give better agreement with the observed frequencies. I am not convinced by these arguments, since a change in the opacity can produce similar results, and it is not obvious that we know the opacity of stellar material to sufficient accuracy to make a deduction about gravitational settling. Moreover it seems to me that there will be some form of mixing in these layers (turbulent, circulation, waves) and that one needs to include all these effects.

3.7 Microphysics

I have said little about the microphysics in the solar interior - opacities - equation of state, nuclear reactions - but there are uncertainties here. It seems to me highly unlikely that the present set of opacity calculations is the final word on the subject - one would have to ignore the historical development in this area to take such an optimistic view!

4. A Solar Acoustic Model

Before turning to the long standing Solar Neutrino Problem I wish to emphasise what we learn and do not learn from helioseismology. In a spherically symmetric star the adiabatic oscillation frequencies depend only on its acoustic structure; that is on the run of pressure P, density ρ and adiabatic exponent Γ inside the star. They do not depend explicitly on the temperature or composition. The frequencies can therefore only yield the values of P(r), $\rho(r)$ and $\Gamma(r)$. They cannot be used directly to infer the temperature T(r) or the hydrogen profile X(r). With an assumption that we understand the equation of state in the solar interior (eg approximately an ideal gas) then we can determine T/μ where $\mu = 4/(3+5X)$ but not T and X separately. To place constraints on the thermal structure we need to invoke assumptions about radiative energy transport which requires a knowledge of the opacity, and of the role played by other possible transport mechanisms (waves, turbulence, instabilities, ...). But this is just what we wish to test.

The standard - or reference - solar models agree well with the observed frequencies but this does not prove that the models are correct, only that the run of P(r), $\rho(r)$, $\Gamma(r)$ are in good agreement with observations. But since the models are in hydrostatic equilibrium, and $\Gamma = 5/3$ in the bulk of the interior, there is only one function, say $u(r) = P/\rho$, that is actually determined by the oscillation frequencies and here there is good, but not perfect, agreement between the predictions of the standard (or reference) models and observation. The disagreement is largest in the surface, centre and in the layers beneath the solar convective zone. Whilst the observed frequencies are already of sufficient accuracy to rule out some alternative models (such as those with WIMPS) in my view insufficient effort has been devoted to studying the range of model uncertainties that are compatible with the observations. A further observation is that the standard - or reference - models of the Sun have been "improved" over the years, that is they have been modified, new values of opacities, cross sections, additional physical process - have been incorporated in the model - driven by the aim of improving the agreement between prediction and observation. Whilst this is a reasonable way to advance scientific enquiry there is a danger that one only includes those effects that improve the agreement and not those that work in the opposite way. With a selective approach to inclusion of additional effects it is not that sound to then say - look - our new improved model agrees with the observational data so it must be correct. For example the effect of the ^{3}He instability is ignored, the disagreement between prediction and observation of the flux of neutrinos is transferred to particle physics rather than astrophysics. Perhaps one could produce alternative models - and an evolutionary scheme - that equally agreed with the observations. I am not claiming that this is the case but just urging a little caution!

5. The Solar Neutrino Problem

The Solar Neutrino Problem is the longest running outstanding problem in solar astrophysics - at least in terms of the internal structure and evolution of the Sun. Prior to the development of helioseismolgy, observations of the neutrino flux by the Homestake mine $^{37}C\ell$ experiment was the only test on solar models - and the models failed this test. Understanding whether or not this is a problem in stellar modelling or in particle physics remains a major - I would say the major - problem in Solar Astrophysics. If the problem is that we have got our models wrong then this has an impact on the whole of stellar evolution theory, with consequences for much of astrophysics.

5.1 What is the problem?

There are now 4 experiments measuring the flux of neutrinos in different energy ranges that fall on the Earth: all of them measure fluxes that are less than that predicted by standard - reference - solar models. The predictions vary from one reference model to another but all agree that the predictions are substantially in excess of the observations.

Table 1. Solar Neutrino Fluxes: Observations and Predictions

Experiment	Observation	1σ	Prediction
Homestake	2.55	0.35	8.3
GALLEX	77	14	132
SAGE	69	16	132
Kamiokande	2.75	0.6	6.1

There are several problems rather than just the one that existed 20 years ago.

1. The flux as measured by GALLEX and SAGE Gallium experiments is essentially the flux of all neutrinos and is compatible with the energy being produced by nuclear burning of Hydrogen but not with the (^{3}He,^{4}He) branching ratio predicted by standard solar models. These results suggest that either or the centre of the sun is much cooler than in the standard models - and therefore the hydrogen content much larger, or that the (^{3}He,^{3}He) cross section is underestimated, or the (^{3}He,^{4}He) cross section is overestimated, or any combination of the three.

2. The Kamiokande experiment measures the energetic neutrinos from the ^{8}B decay. This result suggests that whilst we may not have the (^{3}He,^{4}He) branching ratio correct it is not that wrong.

3. The Homestake experiment measures the flux from both the Be and B reactions and therefore should be in excess of that predicted solely from the measured flux of B neutrinos, whereas it is less.

This latter problem is referred to as the Beryllium problem and in my view is somewhat overstated. Of course if one takes the observations at face value then, since the ratio of observed to measured B neutrinos is 0.46, and since the B neutrinos constitute 90% of the flux in the Homestake experiment, the ratio of observation to theory should be 0.41, even with no Beryllium neutrinos, whereas it is 0.3. But I think this is putting too much weight on both the claimed accuracy of the measured flux of neutrinos and the theoretical predictions. Further the disagreement between Kamiokande and Homestake is exaggerated by taking the average from the Homestake experiment over its duration of 25 years. It was pointed out by Davis (who built and ran the Homestake experiment) (Davis and Cox 1991, Davis 1993), that if one just compared the measured values for the period when both experiments were running, then the disagreement was reduced.

A further problem is that even if one can reconcile the Homestake and Kamiokande experiments within their uncertainties - they both detect a non negligible flux of neutrinos which come from the (^{3}He,^{4}He) branch of the (p,p) chain. This then predicts a substantial flux of Be neutrinos contributing to the SAGE and GALLEX measurement which cannot be reconciled with the measured low values.

It is this combination of solar neutrino problems that has convinced some that the problem is one of neutrino physics rather than astrophysics. The argument goes that since the standard solar models agree with helioseismology, and since the observed neutrino fluxes do not agree with the predictions of these models - and also have internal contradictions - then we need new physics - the MSW effect - or vacuum oscillations - or a magnetic moment of the neutrino - or ....

Before necessarily accepting this argument I prefer to further explore the astrophysical problem. How close to the observed values can we get whilst still staying within the constraints imposed by helioseismology?

5.2 Solar models with low neutrino fluxes

I accept as a constraint that the model of the present sun must satisfy the helioseismic constraints. That is P(r), $\rho(r)$, must consistent with the measured frequencies.

I also accept as a constraint that the nuclear energy generation must balance the solar luminosity, that is the sun is in thermal equilibrium. This is not a necessary constraint, the thermal diffusion time from the centre to the surface is of the order of 10^7 years so there could be a thermal imbalance which takes this long to manifest itself at the surface.

But the hydrogen abundance in the interior is taken as unknown. It is a consequence of an evolutionary scenario and of energy transport and mixing processes that I will consider unknown. One might argue that one should impose a constraint that the total hydrogen consumed in nuclear reactions over the lifetime of the sun should balance the total energy lost. This is a sound argument but not one that can be imposed unless one has a knowledge of the degree of mixing - in particular whether or not the sun was fully mixed at some stage.

Now given P(r), $\rho(r)$ I explore the predicted values of the neutrino fluxes for different assumptions about the hydrogen abundance X(r) in the central core. In fact as far as the energy generation is concerned the hydrogen abundance in the outer 60% of the mass is unimportant and if desired could be adjusted so that the total hydrogen burnt was such as to have fuelled the sun for the solar lifetime. The nuclear parameters were as used in Bahcall and Pinnsoneault (1992), the equation of state was relatively simple - perfect gas with radiation pressure, partial degeneracy, and a Debye-Huckel correction. The routine reproduces the values from the GONG model (Christensen-Dalsgaard 1995).

Three acoustic models were used - the GONG reference model - which agrees reasonably well with the observed frequencies, and two acoustic (or hydrostatic) models obtained using the run of sound speed c(r) obtained by Sergei Vorontsov (1996) from inversions using the frequencies (and errors) as measured by the LOWL experiment (Tomczyk and Schou 1996). Table 2 lists the predictions of these models with the hydrogen profile X(r) taken from the GONG reference model. Since the LOWL models differ slightly from the GONG model, X(r) was scaled in the inner part of the models so as obtain a models that had the observed luminosity. As can be seen from Table 2 the LOWL models give somewhat smaller neutrino fluxes than the GONG model.

Table 2. Solar Neutrino Fluxes: Standard Model Predictions

Model	X_c	T_c	ρ_c	$F(C\ell)$	F(Ga)	F(B)
GONG	0.338	15.7	154	8.3	132	6.1
LOWL	0.364	15.5	152	5.9	120	4.2
LOWL2	0.380	15.3	153	4.5	112	3.1

In Table 3 we take the hydrogen abundance (X_c) in the core to be constant out to 0.5 $R_\odot$. I should emphasise again that these models necessarily agree with the oscillation frequencies, and they have the observed solar luminosity (and radius).

Table 3. Solar Neutrino Fluxes: Homogeneous core

Model	X_c	T_c	ρ_c	$F(C\ell)$	F(Ga)	F(B)
GONG	0.530	13.3	154	2.4	107	1.2
LOWL	0.578	12.9	152	1.4	97	0.5

Finally Table 4 gives the results from varying the nuclear cross sections for the "best" LOWL model. In this exercise the (p,p) cross section was scaled by a factor fS01 and the (Be,e) capture by fS07, this latter is equivalent to scaling the (Be,e):(Be,p) branching ratio. In the first set of models the hydrogen profile was taken from the GONG reference model and scaled so that the models had the solar luminosity, the last 2 models are with constant hydrogen abundance in the solar core. The variation in the (p,p) cross section is within the quoted uncertainties and values estimated in recent years. The reduction in the (Be,e) capture rate is well outside current estimates of the uncertainty of this process, although since Be is not completely ionised at temperatures of 13 10^6 °K some uncertainty surrounds the determination of this capture rate.

Table 4. Solar Neutrino Fluxes: Effect of changes in cross sections, LOWL models

fs01	fs07	Scale	X_c	$F(C\ell)$	F(Ga)	F(B)
1.000	1.00	1.08	0.364	5.9	120	4.2
1.003	1.00	1.17	0.396	3.1	104	1.9
1.050	1.00	1.27	0.427	1.8	96	0.9
1.050	0.50	1.27	0.427	2.7	98	1.8
1.075	0.10	1.45	0.489	2.7	93	2.0
1.078	0.05	1.49	0.501	3.8	95	3.0
1.050	0.10	*const*	0.657	1.7	90	1.0
1.075	0.02	*const*	0.692	3.0	92	2.4

As can be seen from these tables the divergence between observations and predictions for the neutrino fluxes, from solar models that satisfy the constraints of helioseismology is not that large. With sufficient dexterity one can readily find models that lie within 2σ of the experimental results.

Of course these models have not been produced from a coherent picture of solar evolution but it is not beyond the imaginative powers of either the readers, or the author, to produce such a picture. Essentially one needs some slow diffusive mixing in the interior and a change in the opacity or other contributions to energy transport that will yield the acoustic structure as a consequence of an evolutionary scenario. Indeed, in my review of 20 years ago (Roxburgh 1976), I concluded with a conjectured model for the sun which had slow mixing driven by the ^{3}He instability out to 0.56 $R_\odot$, and a wave contribution to energy transport in the core!

6. Conclusions

The advent of helioseismology has revolutionised our ability to probe and diagnose the solar interior, giving increasingly tight constraints on the acoustic structure of the solar interior, and on the interior rotation. A combination of modelling, simulation, and fitting of the frequencies, offers the prospect of an enhanced understanding of convection. The Solar Neutrino Problem remains although perhaps is not as serious as usually assumed. The new data from GONG and SOHO should lead to further advances in our understanding.

References

Bahcall J., Pinnsoneault M.H., 1992, Rev Mod Phys, 64, 885

Canuto V., 1996, this volume

Canuto V., Mazzitelli I., 1992, Astrophys J, 389, 724

Christensen-Dalsgaard J.,1995, (private communication)

Christensen-Dalsgaard J., Dilke F.W.W., Gough D.O., 1974, Mon Not R A S, 169, 429

Christensen-Dalsgaard J., Gough D.O. and Thompson M.J., 1991, Astrophys J, 378, 413

Davis R., Cox A.N., 1991. *Solar Interior and Atmosphere*, eds Cox A.N., Livingstone W.C., Mathews M.S., 51, Univ. Arizona Press

Davis R, 1993 *Frontiers of Neutrino Astrophysics*, eds Suzuki Y., Nakamura K., 47, Univ Acad Press Inc, Tokyo

Dowler P., van den Bergh D., 1995, (private communication).

Elseworth Y., 1996, this volume

Feldman W., 1996, (private communication)

Fossat E., 1996, this volume

Hill H.A. Stebbins R. T., 1975, Annals New York Acad Sci, 262, 472

Kelvin Lord, 1862, Mathematical and Physical Papers, 3, 255.

Lane, Homer J, 1869, Amer J Sci, 2nd Series, 50, 57

Meynet G., Mermilliod J-C., Maeder A., 1993, Astron & Astrophys Supp, 98, 477.

Monteiro M, PhD thesis, University of London, 1996.

Monteiro M., Christensen-Dalsgaard J., & Thompson M.J., 1994, Astron & Astrophys, 283, 247

Nordlund A. Stein R.F., 1996, this volume

Press W.H., 1981, Astrophys J, 245, 286

Roxburgh I W , 1976, *The Internal Structure of the Sun and Solar Type Stars, Basic Mechanisms of Solar Activity*, eds Bumba V., Kleczek Z., 453, Reidel, Dordecht.

Roxburgh I W , 1984, *Observational Tests of the Stellar Evolution Theory*, eds Maeder A., Renzini A., 519, Reidel, Dordecht.

Roxburgh I W , 1985, *Present Problems of the Solar Interior*, Solar Physics, 100, 21-51, published as *Progress in Solar Physics*, eds de Jager C., Svestka Z, Reidel, Dordecht, 1986

Roxburgh I.W., Vorontsov S.V., 1994, Mon Not R A S, 268, 880

Roxburgh I.W., Vorontsov S.V., 1995, Mon Not R A S, 272, 850

Schatzman E., Montalban J., 1995, *Physical Processes in Astrophysics*, eds Roxburgh I.W., Masnou J-L., p, 171, Springer Verlag.

Singh H.P., Roxburgh I.W., Chan K. L., 1996, this volume

Tomczyk S., Schou J., 1996, this volume

Toomre J., 1996, this volume

Vorontsov S.V., 1996, (private communication)