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90年代太阳模型和太阳震荡研究进展(I)：太阳模型研究进展

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摘 要

太阳模型的研究是了解太阳整体结构和性质的极为重要的手段。90年代以来太阳模型研究取得了进展。随着 MHD 及 OPAL 物态方程的引入，理论上的太阳振荡频率与观测值的差别已大为减小，而考虑湍流频谱分布的局域对流理论和三维流体动力学模拟结果可对太阳内部对流能量传输过程有更深刻的理解。以前所发现的理论模型与反演结果得到的初始氦丰度的差别已能由扩散过程加以解释，而太阳表面锂丰度亏损问题也可以由扩散过程或早期演化星风来加以解决，太阳中微子问题则似应由粒子物理而不是天体物理来解决。

关 键 词 太阳：太阳模型 — 太阳：振荡 — 太阳：内部

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Research on the Solar Model and Oscillation in 1990s (I): Progress in Solar Models

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Abstract

The study of solar models is the most important way for us to understand the global structure and properties of the Sun. Developments in solar modeling in 1990s are reviewed in

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this paper. The use of the MHD and OPAL equations of states and of the OPAL opacity has moved the theoretical solar oscillation frequencies much closer to the observed values. The introduction of turbulent spectrum in local convection theory and the 3D hydrodynamic simulation convection models have increased our knowledge of convective energy transportation, as well as its influence on the global Sun. The difference of surface helium abundance between models and inversion results has been filled by diffusion effect. Surface lithium may be depleted by turbulent diffusion or big mass loss. An astrophysical solution for the solar neutrino fluxes looks unlikely. A higher probability exists for a solution from particle physics.

Key words Sun: solar models—Sun: oscillations—Sun: interior

1 Introduction

The Sun is our nearest star and it is our most important energy supplier. This magnificent bright object in the sky has been constantly observed, from the time of our ancestors until today. With the advent of modern astronomy and physics, we are able to unravel the secrets of the Sun much beyond its appearance.

To study the Sun we can proceed in two ways. One is to regard the Sun as a global star whose most characteristics can be very well determined. This study will focus on its global structure, evolutionary processes and oscillation behaviors. Another way is to separate the Sun into small parts, and then investigate the dynamical events in each part, especially in the active regions. As the Sun is the only star that we can get its surface fine structure, we may get more details and constraints on our models. However, if we want to know the origin of those surface phenomenon, we'll have to go deeper inside. In this paper, we'll concentrate on what's happening in the whole Sun.

Already in the 1920s, scientists realized that the large amount of energy radiated from the surface of the Sun should come from the nuclear fusion in its deep interior. Once they knew that, they began to construct solar models based on mathematical equations that express fundamental physical laws, such as the balance between pressure and gravity or the energy flux production throughout the Sun. Nowadays the models made by theoretical astrophysicists can tell us both the inner and surface properties of the Sun in very high accuracy. At the same time, based on global observing networks, space satellites and other new technologies, we can observe the Sun uninterruptedly and precisely. The huge amount of out–coming data are bringing the study of oscillation frequencies and the solar model onto a much higher level.

Studying the global structure and oscillations of the Sun not only allows us to know the properties and processes in the inner part of the Sun, but also becomes a good testing stone of the entire theory of stellar evolution and pulsation. Meanwhile, the imperative demand on the knowledge of interaction among different particles gives scientists in atomic, nuclear, particle and statistic physics a good new opportunity to test some theories that can not be directly tested in

Earth-based laboratories.

Beyond these obvious successes, we should not forget the enigmas that have haunted us for decades, particularly the solar neutrino problem, the solar surface lithium abundance problem and the discrepancy in solar oscillation frequencies. We want to show here some important progress and controversies associated with solar modeling and helioseismology in the 90s. Given the enormous volume of work in the field, we can of course not cover everything. In the first part of this series we'll focus on solar structure, and in the second paper we'll discuss more about solar oscillation.

2 Construction of Solar Model

Because the Sun is just in the middle age of its main sequence life, its global structure is generally thought to be stable. Any global model of the Sun therefore assumes that the Sun is both in hydrostatic and thermal equilibrium [1]. Then, according to the theory of stellar structure and evolution [2], we obtain the boundary value problem of four nonlinear partial differential equations for the structure, and the initial value problem associated with the change of the local chemical compositions at all places in the Sun and at the all time during its evolution.

In order to solve such a set of complicated boundary value and initial value problems, several assumptions and simplifications are needed. The usual basic assumptions include: global symmetry, no rotation, balance between pressure and gravity without acceleration, homogeneous initial composition, complete mixing in the convection zone, diffusion approximation for radiation and conduction, no mixing processes in the radiative zone, radiative opacity according to the hydrodynamic approximation, nuclear reaction rates extrapolated from experimental values, no mass loss or gain during the whole evolution, and finally, no magnetic field [3–4]. We then obtain the so-called "standard solar model (SSM)".

With the models we constructed, we can calculate the theoretical frequencies of these models. When compared these frequencies with millions of frequencies we get from observation, it is found that they can fit with each other in 0.3%. This is rather amazing, given the many assumptions that go into the calculations. It seems that the standard solar model is reasonable, and there's no obvious gross mistake existed [5,14].

Beyond the success, we need to notice that the existing difference between theoretical calculation and observation data is still much bigger than the error of the observation data themselves. This indicates that we still have some missed or oversimplified effects to be considered. While, when we want to improve our models, we know that there are so many factors to influence the Sun, and some of their effects will cancel. So we can not rule out that occasionally the total effect of more than one bad approximations will satisfy some of the observations much better. Therefore, the appropriateness of a given input physics can not alone be judged by its success with observed results [6]. A theory can be accepted only if it is reasonable and physically consistent, and if its use in the model provides a better fit with most observations and it is not in conflict with the others.

The physical theories that have significant influence on the solar model include parts from microphysics, such as the equation of state, opacity and nuclear reaction rates, and parts from macrophysics, such as energy transportation, convection, overshoot, diffusion, mixing in the solar core, magnetic fields, etc. [7]. In the following, we'll discuss recent progress and problems for each of these effects.

3 New Developments in the 90s

3.1 Equation of state

The equation of state used in solar models is to describe the characteristics and relationship of thermal dynamic quantities under different temperature, density and chemical compositions. In early equations of state only ionization equilibrium was considered with Saha equation. Afterward it is found that atoms will ionize when density is high enough, under the so-called "pressure ionization effect", and, as well, the Coulomb interaction between an atom and its surrounding background also can not be neglected, and, thus, the Debye–Hückel correction term, which represents such an interaction, is added in equation of state quantities. These two terms are usually called non-ideal effects in the equation of state. In late 80s, with more knowledge about atomic patterns and their interaction among each others, scientists developed two different sets of equations of state. They are the so-called MHD [6,8–13] equation of state, whose chemical picture treats properties of different kind of atoms differently, and the OPAL equation of state [9,15], developed at Lawrence Livermore National Laboratory, whose physical picture regards different atoms as only electrons and nuclei.

Modern equations of state are no longer several simple equations, but a full set of data which need to use supercomputers to carry out. In order to fit in with the needs of stellar evolution calculation, those data must cover wide range of density and temperature, as well as different chemical compositions, in relatively high accuracy [6]. Because of a great many of different broadening effects on spectrum lines, it is almost impossible to distinguish different equations of state in ground laboratories. The suitability of different equations of state in solar models and frequencies becomes one of the most important indirect way to determine its validity [6].

When non-ideal effects are added into simple equations of state in solar models, it is found that both neutrino fluxes, surface helium abundance, depth of convection zone and oscillation frequencies have more or less improvements when comparing with observations [16–21], while the use of the MHD equation of state can get similar but somewhat better results [5,7,17,18,22–24]. It seems that the use of very simple equations of states with Debye–Hückel correction is acceptable under some circumstance [25], and the addition of this correction is necessary only when we apply it into very deep interior of the Sun [26]. It is also found that the MHD equation of state must includes the contribution of all heavy elements [27], and the analytic solutions for second derivatives of thermodynamic quantities are needed so as to get more accurate frequencies [28].

However, Dziembowski [29] thought that some of the thermal dynamic quantities are not treated precisely, and the improvement of frequencies with the MHD equation of state might be limited to those seismic order l between $40 \leq l \leq 200$ modes [30].

The MHD equation of state seems to be accurate, hence further improvements on it have only very small observational effects [31]. The MHD and OPAL equations of state are found to fit so well with each other in most of the temperature and density region [32] that their discrepancy can be seen only when it's out of the effective range of Debye–Hückel correction [10,15,25]. Therefore, the difference with their application on oscillation frequencies and other observational results will be too small to identify [33]. However, it is said recently that the use of OPAL equation of state can get somewhat better sound speed profile when comparing with result from inversion than that of MHD equation of state [14,34,35].

3.2 Opacity

Till early 90s the most popular used opacities in solar models were from Los Alamos Astrophysical Opacity Library (LAAOL) [16,36,37]. Then, the significant effect of heavy elements, especially iron, on opacity [38], and its possible improvement in oscillation frequencies [39] are approved when Rogers *et al.* published their new OPAL opacity, which includes the contribution of iron atoms' M shell and, thus, the opacity increases up to 20% more than LAAOL opacity in (2–5)×10^6K region [40–42]. Such an increase is supported by lab experiments [43], although Charbonnel [24] suggested that it is more likely due to the improvement of chemical abundance but not from iron.

Using the OPAL opacity, or the modified LAAOL opacity, which includes the improvement contained in OPAL, it was found that the theoretical oscillation frequencies were significantly improved, although the discrepancy between theoretical and observational frequencies are still much bigger than observation error [17,18,22,29,44,45]. Further work pointed out that if the present OPAL opacity can be increased in 10% to 15% at the place just under convection zone, then most of the theoretical frequencies, but those very high degree ones, can fit much better with observation [17,26,31,46,47]. If the opacity in the center of the Sun can be increased, the solar neutrino flux will decrease [48].

Another opacity effort was pursued by an international consortium, the so-called "Opacity Project (OP)". The aforementioned MHD equation of state was developed as part of OP. The key difference to OPAL is that the interaction between atoms is dealt with quite differently [49–51]. Despite this, the resulting OPAL and OP opacity are surprisingly very close to each other for lower and intermediate densities. The somewhat larger difference at high density and temperature region has been regarded as the result of some neglected physical processes in the OP calculations [52]. Such a discrepancy, although it appears rather small in the opacity, was thought to have obvious effects on solar models [53]. No direct distinction between OPAL and OP opacity can be given out in laboratory, for the same reason as with equation of state [54]. Other effects, such as pressure ionization, may decrease solar center opacity, and thus reduce central temperature and expand the convection zone [55–56]. Some other possible mechanisms that may reduce the solar opacity are discussed by Tsytovich *et al.* [57]. While, the scattering of photons by free electrons in solar center may also increase opacity there [58].

Besides the atomic opacities, the contribution of molecules at the out envelope of the Sun where temperature is below $T < 10\ 000$ K, which is usually called low temperature opacity, may also influence the structure and frequency [59−62]. Although present values are thought to have little effects [36], the frequencies may be obviously improved if low temperature opacity is enhanced to be 3 times bigger [17,26,31].

3.3 Nuclear reaction

Because the energy threshold in present laboratory condition is still much higher than that of the solar nuclear fusion, the nuclear reaction rates we use in solar models all come from the extrapolation of experimental data, and, thus, have relatively big uncertainty [63,64]. Different authors select those combinations that they think to be more reasonable in their solar models[65,66], and some of them suggest an enhancement upon present values [67,68]. The ^{3}He non-equilibrium burning is thought to have very small influence [36]. The popularly used weak screening factors, which are considered to have influence on nuclear reactions from surrounding particles, are suggested to be replaced by strong screening factors [69−71].

As we know, solar neutrinos come from the nuclear reaction in the core of the Sun. Some people change the reaction rates to explain solar neutrino problems (see solar neutrino section). Other ideas, such as sub-nuclei fusion (nuclear reaction when the temperature is below the Gamow peak value) [72] and non-equilibrium burning in solar center [73], are also considered, while further evidence is still needed.

3.4 Convection and overshooting

The treatment of the convective motion is the most complicated question in stellar structure and evolution. The task of finding a solution for the three dimensional hydrodynamic fluid and implementing it consistently in a solar model is still far from being completed. Because of the lack of time dependent non-local convection theory in stellar modeling, local theories are still popularly used [74,75]. Comparing with traditional mixing length theory (MLT), Gabriel [28,46] finds that the use of temperature or depth dependent mixing length ratio $\alpha = \ell/H_{\rm p}$ (ℓ being mixing length, $H_{\rm p}$ pressure scale height) can not eliminate the existing discrepancy between theoretical and observational frequencies. Canuto [76], moreover, put forward an improved local theory whose convection energy transportation efficiency includes the spectrum distribution of turbulent elements, but not just a constant as in MLT. Such a consideration seems to improve the description of outer envelope of the Sun, and, thus, the calculated frequencies are closer to observations than those in MLT theory, although the gap is still not remedied [77−83]. The 3D simulation hydrodynamic convection models are also transferred to solar models [37,84,85]. The problem is that they need a fixed heat base, which should, but cannot so far, be determined by the model itself.

Another related topic is whether there is an overshooting zone or not, and how big it is, if it exists. From the model calculation, some people don't believe the existence of overshooting zone [86−88], while, a 0.3 H_p overshooting zone is thought to be a very good candidate to analyse the depletion of lithium in solar surface [16,89,90]. Baglin and Lebreton [91], on the other hand, abandon overshooting model in the end, because they think that there must be a $0.7H_\mathrm{p}$ overshooting zone to burn the surface lithium, and it is somewhat too big to believe. When the influence of overshoot on frequency is taken into account, Gabriel [31] and Chaboyer [92] point out that the $0.1-0.2H_\mathrm{p}$ overshoot zone will have little influence on solar frequencies, while some others find the $0.05-0.2H_\mathrm{p}$ overshoot may improve the theoretical frequencies [89,90,93−95].

3.5 Diffusion

Diffusion effect, which includes gravity settling, thermal diffusion, chemical abundance gradient diffusion, and turbulent diffusion, becomes one of the most popular topics recently [96−101]. The most significant effect from diffusion is the change of surface helium abundance, so that the surface helium abundance from models can fit with those from inversion [22−23,102−105]. The oscillation frequencies which are sensitive to the condition of the bottom of convection zone may also improve when diffusion is included [22,86,87,106−109]. Results from inversion also support the introduction of diffusion [35,94]. Diffusion can also improve the depth of convection zone [110,111] and deplete the surface lithium [91,101,112].

The problem is how big those diffusion coefficients should be [21,106,113−115], and those used in the literatures seem to be overestimated [116]. Whether the composition gradient caused by diffusion just below the convection zone can be approved by observation is still a question [95], and the correlation among different diffusion mechanisms and the cancellation with other processes are also not fully considered [106,117−119]. The increase of solar neutrino fluxes in diffusion models are really a challenge [65,102,114,115], while Morel and Schatzman [120] find that the frequencies and neutrino problems can all be improved. Another question is that the improvement seems only to be effective to those diffusion sensitive intermediate degree frequencies but not high or low degree modes [92,121].

3.6 Numerical method and other parameters

The stellar structure is a set of so complicated nonlinear equations that no solution can be expressed analytically. In most solar model construction the Henyey method is used to get a numerical result, which calculates from chemically homogeneous zero age main sequence. The evolution from proto-star has also been considered [16], while it is thought that its influence is negligible [28]. The accuracy of numerical method is one of the most important factors for solar evolution and frequencies [7]. Berthomieu *et al.* [122] use B-spline collateration method to improve the accuracy from 2nd order to 4th order, and Reiter gives a much higher order accuracy by multi-point shooting method which is designed for parallel processors [123−126]. When same input physics is used, it is found that the difference between Henyey method and shooting method is less than 1 millionth on the sound speed in the Sun, and Henyey method is much stable in late stage evolution than other numerical methods [127].

Based on the assumption that the Sun and solar system have the same origin, usually the age of the Sun is 4.4 to 4.8 Gyr, while Elsworth *et al.* [109] find that if the Sun is 5.2Gyr old the model may be improved. The new isotope measurement suggests that the age of the Sun is 4.566Gyr [128]. The influence of age on solar model is thought not to be a main factor at present time [28,36,129].

If the gravity constant G is not a constant in the whole life of the Sun, it may also influence the solar evolution and oscillation. Investigation shows that the change of G in the Sun's whole life should be less than 2%, and thus the SSM is recommended [130,131]. The change of solar radius can not analyse the gap in frequencies, even measurement error is taken into account [132]. The change of brightness is much more likely to be related to surface magnetic field but not to interior structure [133,134], while, because of the difficult in absolute measurement, the system error between different authors should not be ignored [135,136]. The surface abundance of elements other than hydrogen and helium is also uncertain. When Z varies in its 0.02 ± 0.004 range [137], high degree modes will have bigger change, while in comparison with observation data it seems that the abundance in SSM has better result [138,139].

Helium abundance is another interesting topic. Although helium was first detected in the solar spectrum, the formation of the helium lines is so complex that observation gives no precise information about its abundance [14]. It seems that we need to determine Y value in theoretical studies. This adjustable parameter in solar modeling is found to be from 0.25 to 0.28, and it may be influenced by heavy element abundance, the existence of mass loss, or interior opacity [3,36,140−142]. However, it is obvious that this value is bigger than the estimated value from big bang. From inversions, the helium abundance is found to be only $Y = 0.23 - 0.25$, less than that of standard solar models [23,100,143,144]. Consequently, diffusion was introduced to explain the reduced surface helium abundance [35,108,110,118,145].

3.7 Surface lithium and beryllium abundance

Although the abundance of all the elements on the surface of the Sun is supposed to be the same as that in the early formation period of the solar system, which can be measured from meteoritic abundance, the lithium in the solar surface is found to be 150 times less than what we predicted, and beryllium is 2 to 3 times less, too. The burning of lithium and beryllium by nuclear reaction will happen at 2.5×10^6K and 3.3×10^6K, respectively, while from structure study it is thought that even the hottest part of solar convection zone, which locates at its bottom, has never reached such a high temperature in the Sun's whole life. There must be some other mechanisms [14].

One possible solution is that there's an overshooting zone just beneath the convection zone, and, thus, the surface lithium and beryllium are brought inside and burned in the high temperature interior. The problem is that the need of $0.3H_\mathrm{p}$, or sometimes even $0.7H_\mathrm{p}$ of overshooting zone to burn lithium and beryllium [16,89−91] is too big to believe. The existence of turbulent diffusion when the Sun's surface differential rotation changes to interior's solid body rotation can also bring surface lithium and beryllium inward and burn them [104,112,145,146]. However, Schatzman [147] points out that such an effect may cause a rotation related surface lithium abundance, which is not supported by observation. Furthermore, he suggests that the gravity inner wave produced by the random motion of turbulence at the low edge of convection zone is the next candidate.

Another solution is from the mass loss in pre-main sequence or early main sequence phase of the Sun. If there is mass loss of $0.1M_\odot$ in relatively short period of time (< 0.2 Gyr), the surface lithium may be depleted, and the frequencies of the model will also not conflict with observations [86,118,142,148–150]. However, Dearborn [137] finds no evidence for such big mass loss from other low mass stars.

3.8 Solar neutrinos

The solar neutrino problem refers that only one third to half of the predicted neutrinos from standard solar models have been observed. It has turned out to be one of the most difficult problem in solar modeling and particle physics. Since some of the conditions in the solar neutrino detection, such as the far distance from the neutrino emission source in the Sun to Earth, the neutrino energy that is lower than we can get in laboratories, and the massive solar mass for the neutrinos to travel through before they reach the Earth, can not be reached in ground-based laboratories, the possibility of changes in the neutrinos before they hit the instruments should be considered [151].

First let's see what we know from SSM study. The neutrino fluxes detected are (2.55 ± 0.25) SNU for ^{37}Cl detector, and (79 ± 12) SNU for ^{71}Ga detector [152–155], while in SSM the fluxes are 7 – 9 SNU for ^{37}Cl and 115 – 135 SNU for ^{71}Ga. The uncertainty in SSM comes from the difference of nuclear reaction rates, heavy element abundance, opacity and the absorption cross section of the detectors [18,140], and the influence of pre-main sequence evolution is less than 1% [156]. As all the neutrinos come from the nuclear reactions in the solar core, the change of fusion rates may sometimes improve the observed neutrino fluxes [72,157,158]. Castellani *et al.* [159] suggest that the deduction of p-p reaction S33(0) factor to 3 times may get the observed value, and Dar and Shaviv [136] also think that the improvement of both nuclear reaction rates and opacity can analyse the observed solar neutrino fluxes. But Berezinsky [160] and Wolfsberg [161] point out that the change of nuclear reaction rates will be too bigger than experimental errors when we want to fit the observed neutrinos, and the change of opacity to achieve this goal is also difficult [69]. The probability of getting both observed neutrinos and present solar luminosity is less than 3% in present SSM [162], and the inversion results support the predictions of neutrino fluxes from SSM, too [116,163]. The introduction of mass loss [142] and diffusion [65,99,110,111] will even increase the theoretical neutrinos, and the diffusion have got some support from helioseismology [164]. It does not look like that we can solve it in SSM theory.

The introduction of weakly interactive massive particles (WIMPs) into non- standard solar model is another possible solution for the solar neutrino problem. It is suggested that WIMPs, such as Cosmions, which are accreted into the center of the Sun, may transport some of the energy from the nuclear burning core outward, and, as a result, enhance the net energy transport capacity in the center of the Sun. They would therefore lower the temperature of the solar core, and thus reduce the neutrino fluxes [165,166]. However, the efficiency of their energy transportation is still not so sure [167], and the bad influence on solar frequencies, which move the theoretical values further away from observation, is so big that a lot of people refuse to accept such a theory [21,100,113,137,168–172].

The same situation will happen to those artificial enhancement of solar central Hydrogen abundance or reduction of central heavy elements abundance hypothesis [173], which are also doubted [101,115,137,151,172]. The condensation of central iron to reduce center opacity is difficult to accept, too, because of the lack of evidence [21,174,175], and so is the effect of big amplitude oscillation of low degree g-modes theory [176]. The non-homogeneous formation of the Sun, which suppose the existence of a metal rich core in the Sun when it is formed [177,178], is still to be tested on its effect on the frequencies.

Now we have more methods in different energy threshold value to detect solar neutrino fluxes, while troubles also come. If the standard neutrino theory is correct, the ^{7}Be neutrino from SSM will always be twice as much as that from observation [162,179–181], and no SSM can get observed ^{37}Cl and ^{8}B neutrino flux simultaneously [182,183], even the increase of ^{3}He to solar core from some unknown mechanism may reduce ^{7}Be/^{8}B neutrino flux ratio and ^{8}B neutrino [184] is considered. The most serious problem is that the observed value from ^{37}Cl detectors, which include all the ^{8}B neutrinos and part of ^{7}Be, pep, CNO neutrinos, is only 2.55SNU, while that from Kamiokande experiment, which contains only total ^{8}B neutrinos, is as big as 3.2SNU. How can we imagine the contribution from the other three reactions are negative? It is more likely that standard electroweak theory and standard neutrino model should be modified [151,185,186]. The astrophysical solution of solar neutrino problem seems to be more and more unlikely [68,79,109,164,187].

If we abandon the assumption of stable and massless neutrino model in standard electroweak theory, the possible solution for solar neutrino problems could be neutrino vacuum oscillations, the so-called Mikheyev-Smirnov-Wolfenstein (MSW) effect, neutrino magnetic momentum, neutrino decay or the interaction between neutrinos and gravity field [151,161,188]. If neutrinos have magnetic momentum of $10^{-11} - 10^{-10}\mu B$, then they will be influenced by solar magnetic field [161], while the dependence of neutrino flux to solar cycle is not obviously observed. Neutrino decay hypothesis has already been ruled out [189]. The neutrino vacuum oscillation theory implies that the emitted neutrinos from the center of the Sun will change from the detectable electron neutrinos to more difficultly detected μ or τ neutrinos in vacuum when they travel from the Sun to the Earth, due to the mass difference among different neutrinos whose mass are around $10^{-6} - 10^{-5}$eV [158,190]. The MSW effect [191,192] refers to the resonant oscillation between electron neutrinos and electrons in solar materials which may change electron neutrinos to other eigenstates such as μ or τ neutrinos. For such an effect neutrinos should be as massive as $10^{-4}\text{eV} \leq m \leq 10^{-2}\text{eV}$ [72,113,183,193,194]. It is still difficult to determine whether the neutrino vacuum oscillation, the adiabatic or non-adiabatic solution of MSW effect can fit observation better [195,196], while vacuum oscillation is sometimes doubted [72], and non-adiabatic resonant solution is sometimes preferred [197,198]. Dar and Shaviv [136], on the other hand, dispute the MSW effect as not being able to get necessary support from other neutrino experiments. The coupling of neutrinos and gravity field, which needs no mass for neutrinos, may be another possible solution [152].

4 Discussion

As there are so many developments in almost all of the input microphysics and macrophysics processes, different authors may choose those combinations they prefer, and one would think that the resulting solar models would turn out to be different. However, if the input physics is consistently normalized, the results seem to be virtually the same [199]. This leads to the conclusion that despite some different simplifications and treatments in the various models the standard solar model is still believable.

One should be aware though that the uncertainty in this input physics may still play a critical role. As it is difficult to consider many different chemical elements under all kinds of extreme conditions, some simplification or ignoring in the calculation are needed, and this could have very serious consequences in some evolutionary stages of stars. The differences appearing in the input physics can often not be studied in ground-based laboratories. For these situations the Sun plays an important role of a physics laboratory.

From the present study it seems that there is no evidence for a very strong magnetic field in the solar core [143], nor for WIMPs, a central hydrogen enhancement from outside, artificial reduction of the central temperature, or the central iron condensation hypothesis [24,109,173]. These additional hypotheses would cause serious shifts of the solar p-mode frequencies, which can be detected with very high accuracy.

Although rotation may be helpful for surface chemical abundance and solar sound speed profile analysis [83,200], it can not solve neutrino or surface lithium abundance problem alone [77]. The $0.1M_\odot$ mass loss during pre-main sequence or early main sequence stage in very short time scale (< 0.2Gyr) may analyse the depletion of surface lithium abundance [83,118,142,148,200], while further evidence from other low mass stars is needed to prove the existence of such kind of solar wind [101].

From present standard or non-standard solar models we know that the solar convection zone is $R_{\rm con} = 0.7 - 0.73R_\odot$, and the initial helium abundance is $Y_{\rm init} = 0.26 - 0.29$, while the surface helium is reduced to $Y_{\rm surface} = 0.23 - 0.25$ due to diffusion. The neutrino flux from models will be $6 - 9$ SNU for ^{37}Cl detector, and $115 - 135$ SNU for ^{71}Ga detector, which are much bigger than the observed values.

The rapid development in solar modeling gives us a good view of what happens in the Sun, while some problems are still not solved. The next step may be to examine the validity of hydrostatic hypothesis [201], and there are some researchers who are introducing the usually ignored acceleration terms into the evolutionary study. Sometimes some dynamical processes are impossible to be analysed from only hydrostatic study, and the dynamic consideration is valuable.

How to consider differential rotation in our standard model is still a question. From inversions we find that below the convection zone the Sun rotates more like a solid body, while outside it is a complex differential rotator. The interaction between rotation and turbulent convection is a complicate process, and it may seriously influence all those present assumptions about element diffusion processes. There is not a single model which can consistently include both rotation and diffusion available right now. What happens at the bottom of the convection zone, where the rotation profile changes, and the diffusion process occurs, is very important for us to understand more precisely. We are interested in the impact on the global solar structure.

The existence of global magnetic field, and the non-spherical effect on magnetic field, abundance and thermal dynamic equilibrium [202,203], are some problems to be considered, too. It is out of question that the magnetic field will have some effect on solar structure, but how to consider its effect in our model construction is still an unsolved problem.

The solar neutrino puzzle has puzzled us for decades. From section 2 we can find that the possibility of explaining the observed solar neutrino flux without changing the global structure of the solar model is very difficult. Most assumptions for neutrino flux analyses have very bad effects on solar p-mode frequencies, and are thus unacceptable. The observed neutrino fluxes even conflict with each other. A non-standard neutrino model might be favored [151], although particle physicists do not yet see sufficiently strong evidence to accept such a conclusion.

The uncertainty in some input parameters [204], nuclear reaction rates [72], opacity [83,205], and influence of solar atmosphere [45,206] should also be considered. But, as we know, some of them are quite difficult to solve, and the development will build upon our knowledge on atomic physics.

What will the excellent solar model looks like, then? It seems that the model needs to fit the following observational constraints [101]:

(1) observed luminosity $L_\odot$ and radius $R_\odot$ at given mass and age
(2) p-mode frequencies
(3) g-mode frequencies
(4) rotation profile fit both surface differential rotation and interior result from inversion
(5) depletion of surface lithium to 150 to 200 times
(6) depletion of surface beryllium to 2 to 5 times
(7) solar oblateness
(8) increase of surface ^{3}He to 15%
(9) increase ^{13}C/^{12}C to 7%
(10) solar magnetic field
(11) solar neutrino fluxes (maybe this is the only exception)

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