Helioseismology: Implications for the Standard Solar Model

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Abstract

Helioseismology, the study of solar vibrations, has revealed a higher degree of homogeneity in the sun than is commonly assumed. This is contrary to the standard solar model (SSM), in which the sun is assumed to be segregated into a core region and radiative and convective regions which do not experience significant mixing with the core. Furthermore, a degree of solar homogeneity and concomitant mixing implies a lower core temperature than is typically assumed, which in turn means that significant helium production may not be occurring in the sun. Deuterium produced via hydrogen fusion therefore may not be consumed in producing helium. The deuterium abundance of the interstellar medium appears to be consistent with the possibility that deuterium is not consumed in the sun via helium production, but escapes into interplanetary space due to the sun's homogeneity.

Introduction

In the SSM, nuclear burning of hydrogen into helium is supposed to occur in the solar core. Neutrinos should also be produced as helium forms, but until 2001, several decades of solar neutrino detection efforts had consistently shown that neutrinos are not produced at the rate predicted by the SSM. This shortage was termed the "solar neutrino problem" (SNP). The SNP implied that the suite of nuclear reactions assumed in the SSM may not be occurring, with deuterium production from hydrogen fusion being possibly the only significant nuclear reaction in the sun. The core temperature implied by this reaction is on the order of 1 million K or less, in contrast to the 15 million K commonly assumed. In 2001, results from the Sudbury Neutrino Observatory (SNO) resolved the SNP by reportedly detecting the "missing" neutrinos. Since the announcement of the SNO results, the claim has been publicized that the SNP has been "cleared up" and that the SSM has been confirmed "with a 99% confidence level" (Seife, 2001, pp. 2227, 2228).

However, even before the SNO results reportedly confirmed the SSM, the SNP was not the only difficulty for the SSM. In the SSM the sun has a nuclear "burning" core which extends some 25 percent of the distance out from the center of the sun and is often assumed to include about 10 percent of the solar mass. The density of the core is usually described as having about 150 times the density of water, or roughly 15 times the density of lead. Traditionally the core has been modelled as physically isolated from the solar structure above it. The only transfer which occurs out of the core is that of radiative energy (except for the transfer of neutrinos). In recent years, however, the He-3 instability problem has generated speculation that there must be some mixing between the core and outer layers. But there is another phenomenon which indicates a high degree of mixing in the sun, namely, the existence of certain solar modes of oscillation. The study of solar oscillations, or helioseismology, began in 1960 with the discovery, from Doppler shift photospheric observations, of vibrations with periods of about 5 minutes. Such oscillations are now a well recognized aspect of solar behavior (Fix, 1999, p. 395).

Helioseismology Indicates that the Sun Is Somewhat Homogeneous

High frequency (short period) modes, such as the 5 minute oscillation, "resonate within the outermost parts of the Sun and give very little information about the interior. Longer wavelength modes... penetrate much more deeply into the Sun" (Fix, 1999, p. 395). Modes of sufficiently low frequency should be able to penetrate the sun's central region.

However, the presence of a large core as called for in the SSM would place a maximum limit of about one hour on the period for solar oscillations. Astrophysical theorist Keith Davies has noted that "oscillations greater than one hour would involve such enormous amounts of energy that they would result in the disruption of any large core

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that might be present in the Sun" (Davies, 1996, p. 2). Despite the implications of the SSM that such an oscillation should not exist, an oscillation with a period of 2 hr 40 min was observed in the sun during the 1970s. This discovery was discussed in two key articles, one written by Russian collaborators, and the other by a British team of scientists (Severny et al., 1976, pp. 87–89; Brooks et al., 1976, pp. 92–95).

The British team developed a solar model which would produce the observed long-period oscillation, but in doing so, found that their model sun must be nearly homogeneous without a well-developed central core. Their model (Brookes et al., 1976, p. 94) indicated that a totally homogeneous sun would have an oscillation with a fundamental of 2 hr 47 min. The Russian team noted that a "most striking fact is that the observed period of 2 hours 40 minutes is almost precisely the same... as if the Sun were to be a homogeneous sphere" (Severny et al., 1976, p. 88). The British group stated a similar conclusion: "Current solar models predict a period of about 1 hour corresponding to a steep density increase in the solar interior, in marked contrast to the observed 2.65-hour period, which is consistent with a nearly homogeneous model of the sun" (Brookes et al., 1976, p. 94).

Of course, a nearly homogeneous sun would not support the extremely high core temperatures assumed to drive most of the fusion reactions of the SSM. With the mixing which homogeneity implies, He-3 production could take place with hydrogen brought into the core, except that the central temperature of the sun would be too low. Indeed, the only fusion reaction which appears to be occurring is hydrogen fusion at a low rate which supplies only a portion of the sun's luminosity. Thus the sun appears to be a young, relatively undifferentiated star which has not yet developed the massive and extremely dense core assumed by the SSM.

Astronomer Ian Nicholson recognized this challenge to the SSM, for he stated that if the observation of the 2 hr 40 min period were correct, the "standard model could not be correct" and that the "central temperature of the Sun would be less than half the conventional value" (Nicholson, 1982; Davies, 1996, p. 3). Other astronomers made similar comments, writing that it was "evident that a very drastic change in the solar model would be necessary" and that "it is unlikely that any such model can be found" (Christensen-Dalsgaard and Gough, 1976, p. 90)—at least, not any model that would support a 10 billion year main sequence chronology for the sun.

The implications for evolution of the 2 hr 40 min oscillation led to speculation that perhaps this oscillation might be a deep seated gravity wave or "g wave," discussed at more length below. Indeed, Christensen-Dalsgaard and Gough (1976, p. 90) opined that unless this were so, "a very drastic change in the solar model would be necessary to enable the 2 h 40 min oscillation to be interpreted as [a] fundamental radial mode," yet this was the very claim made by Severny et al. (1976, p. 89). In a similar vein, Van der Raay (1980, p. 535) noted that "the measured period of 160 minutes raised an immediate conflict with the standard solar model since if these were simple radial oscillations the longest period predictable was approximately 60 minutes." The way out of this evolutionary quandary, Van der Raay emphasized, would be for "the oscillations [to] be interpreted in terms of more complex g mode oscillations" (Van der Raay, 1980, p. 535). As will be discussed below, g-waves have not been detected in the sun to date, yet several years later the 2 hr 40 min period continued to be accepted as a genuine phenomenon (Grec et al., 1980, p. 544). Even later, Ando (1985, p. 177) expressed doubt that the 2 hr 40 min oscillation could be a g-wave, but rather was a radial wave, as had been originally proposed by Severny et al. (1976, p. 89).

Another possibility brought forth to avoid revising the SSM is to explain the 2 hr 40 min oscillation as a beat frequency resulting from "p-modes" near the 5 min period. This possibility, however, was shown to be invalid (Delache and Scherrer, 1983, p. 653). Scherrer and Wilcox (1983, p. 37) described this idea as "incorrect." Woodard and Hudson (1983, p. 67) stated that they did "not detect the 160-min oscillation," but acknowledged that such detection "might not have been expected in [the] data set" they employed, making their claim of non-detection moot.

It was also pointed out that 2 hr 40 min (160 min) is one-ninth of a 24-hr day, and "could therefore appear in [the solar] spectrum as a harmonic" (Scherrer and Wilcox, 1983, p. 37). This was ruled out by the improved observation that the so-called 160-min oscillation in fact had a period of 160.0095 ± 0.001 min, meaning that this oscillation was not a simple fraction of the day and was therefore not a harmonic. This conclusion was later confirmed by Hill et al. (1986, p. 560).

It cannot be ruled out that the 2 hr 40 min oscillation may not be a permanent solar phenomenon. Indeed, it has been proposed that solar oscillations may be related to variable internal core rotations within the sun (Isaak, 1982, p. 131). Furthermore, although the sun is an "exceptionally stable" star (Seife, 1999, p. 15), it is gradually becoming recognized as somewhat variable in much of its behavior, a point first made some two decades ago due to the evolutionary questions raised by the SNP, helioseismology, and observations of solar shrinkage (Frazier, 1979, pp. 86–87). However, even the temporary existence of such a phenomenon as the 2 hr 40 min oscillation opens a window on the sun which reveals that the SSM is not accurate.

Solar Mixing May Reveal Internal Isotope Abundances

The evident near-homogeneity of the sun has the interesting implication that surface gas composition would be related to core composition. In the SSM this is held not to be true (Davis, 1994, p. 24), and all interior composition abundances must be modelled. In turn, the composition of surface gases and related phenomena such as solar flares and solar wind is taken to represent the primordial composition of the solar nebula (Bahcall, 1989, p. 174).

If the sun were generally recognized as homogeneous, then the surface composition could be taken as indicative of internal composition, but of course this is not conventionally done. Indeed, it has not been done since the early years of the twentieth century, when Saha derived a quantitative relationship between stellar spectra and temperature (1920, 1921), thus somewhat divorcing stellar spectra from intimations of composition (Eddington 1926, pp. 1–2, 345–346), and evolutionary astronomer A.S. Eddington assumed that stars like the sun undergo no convective transfer from the core to outer layers. It is generally assumed therefore that internal composition must be modelled. But in a totally homogeneous sun, internal He abundance, for instance, would equal surface abundance, and there would be no central depletion.

Let us assume the sun was created with no deuterium, and based on a solar neutrino detection ratio of about 1/2 (the detection rate acknowledged before the SNO results were announced), that hydrogen fusion to deuterium is supplying half of the sun's luminosity according to the reaction $H + H \rightarrow D + e^{+} + í_{e}$. Let us further assume that the deuterium produced is not consumed. Would the amount of deuterium thus produced at the lower rate over the biblical age of the sun (of the order of thousands of years) correspond to the measured abundance of deuterium in the sun today?

The sun has a luminosity of about 4×10^{26} J. The deuterium-producing reaction mentioned in the previous paragraph is thought to release 1.44 MeV of energy, or 2.3×10^{-13} J. Every second this reaction occurs 1.7×10^{39} times. Over the age of the sun, say, some 6000 yr or 1.89×10^{11} s, this reaction has occurred 3.3×10^{50} times. Each reaction produces one atom of deuterium, so 3.3×10^{50} atoms of D have been produced, or 1.1×10^{24} kg of D. The mass of the sun is about 2.0×10^{30}kg, so the present mass fraction of deuterium throughout the sun would be 5.3×10^{-7}, or 0.00005 percent, assuming that the sun is homogeneous. A deuterium mass fraction of 5×10^{-7} in the sun is equivalent to a homogeneous D/H ratio of 7×10^{-7}. For the interstellar medium (ISM), the D/H ratio is in the range 3×10^{-6} to 3.9×10^{-5} (Ferlet et al., 2000, p. 3). Thus the D/H ratio in a homogeneous sun is within an order of magnitude of the observed abundance of deuterium in the interstellar medium. For a slightly older sun, say on the order of 10,000 years, the agreement is improved with a solar D/H ratio of 1.2×10^{-6}. Further, if the SNO results can be taken to imply that perhaps deuterium production produces more than half the sun's luminosity, the agreement between the sun's surface deuterium abundance and that of the ISM would be improved yet again. One must be careful, however, not to infer from such a possibility that SNO has confirmed the SSM, since the presumed reactions of the SSM are contradicted by helioseismology.

In contrast to these conclusions, the sun is typically assumed to be depleted in deuterium at present due to production of He-3, and the primordial D/H ratio is usually taken as 2×10^{-5} (Hubbard, 1984, p. 10; Ouyed et al., 1998, p. 371). This value is loosely inferred from the D/H ratio now existing in the Jovian planets on the assumption that planetary deuterium represents the primordial abundance in the solar nebula (Hubbard, 1984, p. 8). However, planetary abundances of deuterium do not agree well with the putative primordial D/H ratio (Hubbard, 1984, pp. 244, 272, 284), and planetary D/H ratios themselves are not uniform. In a biblical creationist framework, this putative ratio never existed, and the perceived difficulty of squaring planetary abundances of deuterium with that of the sun disappears.

Thus the D/H ratio in the sun after some thousands of years of hydrogen fusion would be nearly comparable to the observed D/H ratio in the ISM. In the SSM (and in stellar evolution models in general), it is assumed that deuterium is continuously consumed within the stellar core to produce He-4, and that deuterium in the ISM and in the intergalactic medium (IGM) is primordial material produced in the Big Bang.

One would therefore expect that the D/H ratio would be more or less uniform throughout the cosmos if this were true. That is not at all the case. Instead, the D/H ratio is found to vary within the solar system as mentioned above, but also within galaxies, and even within the IGM in ways that evolutionary models cannot predict. Discoveries of unexpected D/H ratios are often described as a "surprise." Regarding the D/H ratio in the solar system (Saturn), Griffin (2000, p. 1) calls it a "big surprise." The D/H ratio outside the solar system (in Orion) to Schilling (1999, p. 1) is also a "surprise." The low D/H ratio in Orion (50 percent of that predicted) may be explained by the fact that only molecular D and H were detectable, and undetected atomic D and H may make up the deficiency. However, the evolutionary prediction did not take this possibility into account, and this possibility was formulated only after the original evolutionary prediction had failed.

If the sun were homogeneous, and had generated deuterium since creation via hydrogen fusion, the deuterium would eventually mix with surface gases, some of which would leave the star to form the ISM. The resemblance between the sun's D/H ratio, and that of the ISM, would seem to imply that this may be the case. Other stars in the galaxy would similarly contribute to the IGM.

Let us consider the D/H ratio in the ISM from a creationist perspective. We cannot go back to observe the original sinless state of the universe, but we have the biblical record to guide us in visualizing that condition. Genesis 1:14–18 states that the stars were created to be time tellers, which would require that they be easily visible. Furthermore, Genesis 1:31 tells us that the sinless creation was very good, meaning among other things, that the ordained purposes of each part of the creation were fulfilled without obstruction or diminution. A possible conclusion is that there may have been originally little or no ISM or IGM to result in the extinction of starlight travelling to earth.

This last statement is buttressed by the fact that the ISM is now believed to have come primarily from the stars themselves, which means that when the universe was extremely young, there would have been little accumulation of ISM. Fix (1999, pp. 505–513) presents an overview of the ISM which confirms this analysis. He estimates that 20 percent of the Milky Way is ISM (Fix, 1999, p. 505), presents the typical scenario of stars evolving in certain interstellar gas structures, but then also describes the formation of interstellar dust grains from material flowing into space *from* stars. The acknowledgment that dust grains originate from stellar material is a change from what was believed among evolutionists in the past. Dust grains in the past were assumed to be formed directly from primordial material. However, the improbability of generating dust grains in this manner was eventually recognized. Slusher (1980, pp. 17–19) presents a summary of the problems associated with the alleged formation of primordial ISM.

Coupled with this assessment is the fact that planetary and stellar catastrophes are known to generate dust and debris. In the solar system, collisions between planetary ring debris, or between asteroids, are commonly acknowledged to form dust (though of course different in composition from the ISM). Likewise, it is commonly acknowledged that unstable stars of various sorts add material to the ISM and to the IGM. Furthermore, all stars produce a stellar wind which adds to the ISM/IGM. These known facts are in direct contrast to the evolutionary belief that the ISM/IGM is somehow primordial and is the source from which all the structure of the universe arose.

Studies of present-day processes such as deuterium fractionation in interstellar dust grains will ultimately shed no light on the origins of the universe, because the ISM and the IGM do not have to do with the origin of the universe. They have to do with stellar decay. Furthermore, it can be expected that missions such as the Advanced Composition Explorer (ACE) which are measuring solar wind composition will continue to reveal more questions than answers, as long as the solar wind is believed to represent primordial composition.

Modern Helioseismic Data Confirm a Degree of Solar Homogeneity

How has evolutionary philosophy dealt with the implications of the 2 hr 40 min oscillation? The oscillation is acknowledged to exist, but the implications are ignored, and the SSM continues to be taught and applied as if it were reality. Astronomer John D. Fix (1999, p. 396) presents a typical treatment. Fix does not deny that the 2 hr 40 min oscillation exists. Indeed, a diagram is used to show that "long wavelength oscillations probe the deep interior of the Sun" (Fix, 1999, p. 396). Fix does not misrepresent that very low frequency oscillation in any way confirms the SSM. He is merely silent on the matter.

Yet Keith Davies points out that new evidence continues to indicate that the sun is at least somewhat homogeneous. One such finding is that "the temperature at the center of the Sun seems to be varying over a period of several months. This is extremely hard to understand if the Sun has a huge central core with a resulting enormous heat capacity. However, such rapid temperature changes are explicable if the Sun is young and homogeneous" (Davies, 1996, p. 2; Chown, 1995, p. 16). Such temperature variation may also be related to the oscillatory neutrino flux found by experiments such as GALLEX.

In total contrast to the assertions of Keith Davies, it is commonly stated that helioseismology actually supports the SSM. A typical statement is the following: "In recent years acoustic oscillations of the sun's surface have been used to investigate its internal structure; the frequencies of the oscillations calculated from the standard model agree with the thousands of observed values to better than 1 percent" (Bahcall, 1990, p. 56). How can two such opposite positions be true simultaneously? Of course, they cannot. Indeed, there is a type of circular reasoning involved in analyzing helioseismological results to bring about a fit with the SSM: "Theorists turn to current models of the sun to differentiate and analyze the various acoustic modes; the modes, in turn, help to refine the standard model of the sun" (Bartusiak, 1990, p. 25). Such model-fitting is based ultimately on the assumption of high opacity for the radiative region of the sun. But the assumption of high opacity is ultimately based on the assumption that the sun cannot be younger than the evolutionary age of the earth. The high opacity has never been observationally verified, only modelled.

Nevertheless, with the assumption of high opacity and the corresponding low rate of thermal energy transmission, one can assume that solar modes transfer energy adiabatically throughout most of the radius, therefore resulting in little or no mixing, and in turn preserving the conventional picture of the sun with its high thermal gradient and segregated core. Along this line of thought, Bartusiak (1990, p. 29) has noted, "Estimating the sun's opacity... affects how modal frequencies are calculated from the Doppler information." Thus, the computed frequencies are model-dependent.

In a similar vein, Christensen-Dalsgaard et al. (1996, p. 1288) state, "In almost the entire solar interior, the thermal time scale is so long, compared with the periods of oscillation, that the oscillations can be regarded as adiabatic." They then write:

> The adiabatic approximation breaks down near the surface. Here the full energy equation for the oscillations must be considered, including the perturbation in the radiative flux and the highly uncertain perturbation in the convective flux. [One suspects that these conditions ought to be assumed for the deeper interior as well.]... [Below the surface layers] we consider only the adiabatic oscillations and generally treat convection according to the simple mixing-length prescription, neglecting effects of turbulent pressure [i.e., large-scale mixing is ruled out]; it is then straightforward to compute numerically precise frequencies for a given solar model (Christensen-Dalsgaard et al., 1996, p. 1288).

Concerning the assumption of adiabatic behavior, Gough et al. (1996b, p. 1299) state, "Except in the surface layers of the sun, the characteristic cooling time is much longer than the periods of the seismic waves, so the wave motion is essentially adiabatic." But the condition of long cooling time, or long thermal time-scale, is only an assumption based on the prior assumption of high opacity.

However, modifications of the SSM to fit helioseismological modes do not fit other solar characteristics. Douglas Gough and colleagues have written,

> Immediately beneath the convection zone and at the edge of the energy-generating core, the sound-speed variation is somewhat smoother in the sun than it is in the model. This could be a consequence of chemical inhomogeneity that is too severe in the model... or to neglected macroscopic motion that may be present in the sun (Gough et al., 1996b, p. 1296).

In other words, there is a degree of mixing in the solar interior, as discussed above, but which the SSM has typically ignored.

Gough et al. have proposed that core mixing with outer solar layers may in fact constitute a resolution to the SNP:

> The discrepancy in the energy-generating core might also be a symptom of macroscopic motion, which transports the products of the nuclear reactions from their sites of production. That would modify the neutrino emission rates and thereby change the status of the solar neutrino problem... (Gough et al., 1996b, p. 1299).

Other researchers have also recognized the probability of core mixing with outer solar layers. Newkirk (1983, p. 431–432) has discussed several models which would alleviate the SNP by mixing time scales of the order of 10^5 years or more. From a biblical creationist perspective, however, lengthy time scales do not exist, and it is significant that both Homestake and GALLEX neutrino researchers have proposed internal solar mixing over shorter time scales as a way of explaining the deficiency of both high energy neutrinos (Homestake) and low energy neutrinos (GALLEX) (Davis, 1994, p. 30; Kirsten, 1994, p. 34). It remains to be seen whether this possibility will continue to be considered, with the SNO results having reportedly confirmed the SSM. To ignore this possibility, however, would be to ignore the divergence between the SSM and helioseismology.

Other data confirm that a relatively high degree of mixing may be occurring in the sun. The high angular momentum of the planets compared to the sun has been a long-standing problem for evolutionary models of solar system origins. It has become accepted that the sun, which allegedly possessed high angular momentum acquired from the solar nebula, has undergone a process of angular momentum transfer to the planets mediated by the solar magnetic field. This model of the sun's relatively low angular momentum leads to the expectation that the sun would now have a relatively small internal rotation. Over 4.5 billion years "it is therefore believed that the sun has been losing angular momentum over its lifetime through its magnetized wind, thereby spinning down its outer convection zone and probably the bulk of its interior" (Thompson et al., 1996, p. 1300).

Contrary to this expectation, helioseismic observations imply the existence of a relatively high spin rate in the solar interior (Claverie, et al. 1981, p. 443; Isaak, 1982, p. 130). Such a conclusion imposes constraints on the alleged 4.5 billion year age of the sun, since evidently the sun has not had so much time to spin down. But more to the point, the relatively high internal spin rate implies significant internal shear and mixing, two conditions consistent with a degree of homogeneity. Although in a biblical creationist model spin down over 4.5 billion years has not occurred, there is nevertheless "rapidly rotating plasma deeper in the convection zone" than previously believed (Thompson et al., 1996, p. 1301).

Interpreting such plasma motion as an artefact of spin down, GONG (Global Oscillation Network Group) researchers have acknowledged that, "The spin down to the present state... may have involved material motion or instabilities, leading to mixing in the solar interior and thus affecting the structure of the present sun..." (Christensen-Dalsgaard et al., 1996, p. 1287). The rotation rate of the core is not certain at this time (Thompson et al., 1996, p. 1301). However, it is thought that perhaps the core rotation rate may be "considerably faster than that of the solar surface" (Thompson et al., 1996, p. 1304), a conclusion echoing the earlier claim of Claverie et al. (1981, p. 443) that the core rotation is "2–9 times [faster] than the observed surface rotation," a point which further indicates solar homogeneity.

There are other implications of the apparent homogeneity of the sun. If the sun is nearly homogeneous, then a highly segregated, dense core as predicted in the SSM would not exist. Oscillations of the sun which are detectable from Doppler shifting at the surface are called "p-modes." If the sun's core were dense, it should support the existence of gravity waves or "g-modes" (Bartusiak, 1990, p. 26). However, "no internal gravity wave has yet been unambiguously seen" (Gough et al., 1996a, p. 1201). The absence of g waves seems to imply that the solar core may not be as dense as typically expected. GONG scientist Christensen-Dalsgaard has indicated his hope that g waves will be detected, because "they would really allow us to nail down the conditions in the core" (Hellemans, 1996, p. 1265). He apparently expects that the detection of g waves would verify the existence of the dense core assumed in the SSM, a verification which has not yet happened.

Helioseismology has not confirmed the SSM, but has revealed further discrepancies between the SSM and reality. The SSM has been modified to enlarge the convection zone to some 30 percent of the solar radius, compared with the 20 to 25 percent it was assumed to occupy before the advent of helioseismology (Bartusiak, 1990, p. 28; Christensen-Dalsgaard et al., 1996, p. 1287). Nevertheless, the SSM most likely cannot be made to fit the helioseismic discoveries discussed above while simultaneously satisfying the SNP. Christensen-Dalsgaard et al. (1996, p. 1290) state, "No solution of the neutrino problem can be found by modifying the computation of solar models while at the same time preserving agreement with the helioseismic data..."

Of course, if the restrictive and unrealistic assumptions of the SSM were dropped, and a realistic solar model developed, consistency would appear among solar properties, solar neutrino data, and helioseismic data. However, abandoning the SSM would mean abandoning the evolutionary chronology for the sun. Rather than taking that route, Christensen-Dalsgaard et al. (1996, p. 1290) opine that the lack of agreement between the SSM and real data strengthens "the case for a solution involving the properties of the neutrinos." Neutrinos have typically been assumed to be massless, but if the neutrino mass were not zero, it is felt that the SNP might be resolved if it could be shown that such neutrinos might transform or "oscillate" into other forms in a phenomenon known as the Mikheyev-Smirnov-Wolfenstein (MSW) effect. The sun produces "electron neutrinos" (í$_e$), but there also are thought to exist mu neutrinos í$_i$ and tau neutrinos í$_ô$.

According to the neutrino oscillation theory, í$_e$ generated in the sun might "oscillate" before arriving at earth, becoming virtually undetectable í$_i$ or í$_ô$, and thus explaining the solar neutrino shortage (Bahcall, 1989, pp. 28–32, 258–284). It is believed that massless neutrinos could not experience such a transformation, however, thus neutrinos must have a non-zero mass for the MSW effect to explain the SNP. Before the announcement of the SNO results, this idea had not been confirmed (Antia, 1998, p. 155; Normille, 1999, p. 1910), but the SNO results reportedly confirmed the MSW effect (Seife, 2001, p. 2227). The irony since the announcement of the SNO results is that the discrepancies between the SSM and helioseismology are still unexplained. The implication of these discrepancies is that rather than using the SNO results as a window to see what is really happening in the sun, the MSW effect has served more as a vehicle for "saving" the SSM in particular and evolutionary chronology in general.

Conclusion

Recent experiments in helioseismology such as GONG and SOHO have not resolved the discrepancies between the SSM and the implications of helioseismology concerning the internal structure of the sun. The helioseismic implications of reports published in the 1970s remain essentially true today, namely, that the sun is somewhat homogeneous with a relatively low core density. Such conditions limit the maximum core temperature for the sun, imply a relatively low opacity, and are consistent with the implication of the SNP as understood before the publicizing of the SNO results, namely, that hydrogen fusion into deuterium is occurring at a temperature of some 1 million K or less in the core.

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