POSSIBLE ABSENCE OF SOLAR NEUTRINO PROBLEMS

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ABSTRACT

For the past 15 years it has been said that the experimental flux of solar neutrinos was significantly less than the flux predicted by the Standard Solar Model of Bahcall et al. and "New Physics" would be required. Evidence is presented that a more realistic evaluation of the theoretical flux, plus new results from the Kamiokande experiment, show that there is no significant disagreement. The suggestion that the solar neutrino flux varies with the inverse of the sunspot activity, is discussed and found unproven.

1. INTRODUCTION

The conventional wisdom is that the observed flux of neutrinos from the sun is significantly less than that expected [1]. This has led to great excitement and ingenious suggestions to resolve this discrepancy.

Many people have worked experimentally and theoretically on the sun [2]. In particle physics, particular attention has been given to the work of Bahcall and Collaborators who have proposed a Standard Solar Model (SSM), which they maintain gives a solar neutrino flux of 7.9 ± 2.6 SNU [3] where the SNU is the Solar Neutrino Unit which is the flux which would give one event per second for 10^{36} atoms of ^{37}Cl, whereas for the past 20 years Davis et al. [4] have observed an average value of 2.1 ± 0.3 SNU. Here this question is studied to see if there really is a significant discrepancy or not.

Further it has been suggested that the ^{37}Cl data of Davis et al. show an 11 year fluctuation closely correlated with the inverse of the sunspot activity. This "result" is also shown to be untrustworthy.

The sun is the star closest to us and gives an unrivalled chance to study with great accuracy and detail a quietly burning star. This is more than enough reason to justify major research programmes whether or not there is at present, a solar neutrino flux discrepancy or a correlation with sunspots.

2. SOLAR NEUTRINO MODELS

Over the last 20 years J.N. Bahcall has developed a Standard Solar Model (SSM). Essentially a model of the sun is chosen to give good fits to certain well-known parameters of the sun such as the mass, radius, lifetime, oblateness, luminosity plus the percentage of hydrogen, helium and "metals" (in a curious jargon, all elements heavier than helium are called metals – thus nitrogen and oxygen are "metals"). Reaction rates for the various nuclear interactions and decays are taken from experiments or assumed.

Further a certain number of assumptions are made (spherical symmetry, no magnetic effects, no turbulence, no convection, no rotation at any depth, no diffusion in the core, etc.).

However, new data are continually arriving and this has caused in the past, Bahcall to vary his flux between 10.2 and 4.7 SNU in the seventies, but in the eighties it has been remarkably stable near 7.9 SNU. An important point for the reader is that when Bahcall quotes 7.9 ± 2.6, he is giving a three standard deviation error, instead of the usual one standard deviation. Here we will follow the conventional scientific manner and hence will take the estimated flux value to be 7.9 ± 0.9 SNM. It may then be seen that an error of 11% is being given. In view of all the problems and assumptions given above, it might be considered astonishing that the error is only 11% and this question which is important for comparison with experimental data, will be considered.

To allow an estimate of the error on the SSM calculation, it is fortunate that an extensive calculation has been done in 1987 by the French–Belgian Collaboration of Turck–Chieze et al. [5] who quote a value of 5.8 ± 1.3 SNU, i.e.with an error of 22% – double that of Bahcall et al. They have found a non–scientific error of 10% [6] which then gives 6.4 ± 1.4 SNU. The basic parameters of the two SSM calculations are in excellent agreement, thus at the centre of the sun, the densities are 148 and 147.2 g/cm^3, the pressures are 2.29 E17 and 2.27 E17 dynes/cm^2 and most importantly, the central temperatures are 1.56 E7 and 1.55 E7 K respectively – this is critical as the neutrino fluxes vary as very high powers of the temperature (for the pp, 7Be, and 8B neutrino sources the powers of the temperature dependance are given [7] as 4, 11.5 and 24.5 respectively).

The most important errors and corrections will now be discussed.

3. REACTIONS CROSS SECTIONS; 7Be (p, gamma) 8B

Both SSM calculations use the same reaction cross sections except for 7Be (p, gamma) 8B. Here the problem is that the experimental values are for energies from 130 to 4000 keV whereas the astrophysical range is lower, typically 20 keV. Bahcall and several other authors use the 1965 extrapolation of Tombrello [8] who assumed only s–state whereas as can be seen from the data [9], a d–state is clearly required. This extrapolation has been done by Barker [10] and more recently Kajino [11]. Turck–Chieze et al. used this value. Hence the flux of Bahcall et al. should be decreased by 13% giving 6.9 ± 0.8 SNU.

This value of 6.9 SNU is now in good agreement with the value of 6.4 ± 1.4 SNU of Turck–Chieze et al., though the Bahcall error is still too small.

(Most authors simply assume that all experimental results are equally good and should be combined by their given errors, but as a long–time compiler of cross sections for the CERN–HERA reports, have found that as techniques and knowledge improve, more reasonable values are obtained by rejecting or lowering the weight of older data but keeping the more modern data).

4. HEAVIER ELEMENTS (METALLICITY) – PROBLEM OF IRON

Although the "metals" constitute only 2% of the sun's material, they are important for the opacity, giving 40% near the centre and 90% in the neighbouring intermediate zone. Thus they are important for the neutrinos who are produced near the centre. The percentage composition of the outer part of the sun, photosphere, is assumed to be the same as the interior of the sun. While many of the elements can be measured in the photosphere, helium cannot and has to be obtained by subtraction from 100%. A check of sorts can be made by comparing the fractions of 20 "metals" measured in the photosphere with the composition of meteorites (see table 1 of ref. [12]). In general there is reasonable agreement – except for iron which has an important role. The point is that in the central region, all the elements are completely ionised except iron. This means that iron has more processes which can contribute to the opacity (i.e. to the photon absorbtion spectrum) so that iron contributes about 20% of the total opacity. The opacity controls the energy flow in the radiative region of the star. This changes the central temperature and hence the flux of neutrinos Courtaud et al. [12] have calculated that if the photospheric value of Fe/hydrogen = (4.68 ± 0.33) 10^{-5}, is taken the neutrino flux will be 5.8 SNU whereas if the meteoric value of (3.24 ± 0.075) 10^{-5} is used the neutrino flux is 4.6 SNU.

After correction this would imply a flux of 5.1 ± 1.0 SNU for Turck–Chieze et al. while the Bahcall et al. flux would change from 6.9 ± 0.8 to 5.5 ± 0.6. This large change of almost two standard deviations illustrates that Bahcall et al. have much too small an error.

An interesting point is that only neutral iron can be measured in the photosphere and this is only 5% of the total amount of iron – this illustrates the potentially large error when the photospheric value for iron is used.

Further problems come from the light elements not included in the 20 "metals" considered above. Thus the value of lithium coming from the SSM model is in serious disagreement with that observed experimentally on the surface of the sun which is a factor of 100 lower – as is observed in many young stars, Boesgaard [13]. In addition ^{3}He has a small excess and ^{9}Be is a factor of 2 too low. As lithium and beryllium burn at 2.5 and 3.5 million degrees respectively these discrepancies indicate a problem in the convective zone. It is not clear whether this will affect the centre of the sun and hence the neutrino flux, though Schatzman [2] suggests it may.

It may be concluded that the SSM needs further development to fit all these data and that it would be wise to increase the errors on flux estimates.

5. HELIOSEISMOLOGY

Measurements of acoustic oscillations on the surface of the sun are giving important new input data. The p (for pressure) modes of 5 minutes period, indicate that the convective zone is 30% of the radius and not 25% as derived from the SSM.

Gough and Kosovishev [14] have deduced from low degree p modes, the density and adiabatic sound speed as a function of radius and then the temperature. The central temperature is much lower than with the SSM giving a neutrino flux that could be a factor two lower.

Again this indicates that the errors on the SSM estimates of the neutrino flux should be increased.

Very recent data by Elsworth et al. [15] and Libbrecht and Woodart [16] which is reviewed by Gough [17], show that there is some evidence for an 11–year variation as with sunspots. They find that this activity is concentrated in the very outer layers of the sun indicating that the sunspot activity is unrelated to the neutrino flux which has its origin in the central region of the sun. Libbrecht and Woodard's measurements were accurate to one part in 10 000.

6. ESTIMATE OF THE THEORETICAL SSM ESTIMATE OF THE SOLAR NEUTRINO FLUX

Using the SSM approach, as corrected above, favours taking the average of the Turck–Chieze et al. and the Bahcall et al. values giving 5.3 SNU. The error is difficult to estimate as there seems to be large possible sources of error which are not determined. The error of 11% of Bahcall is clearly too low. The error of 22% proposed by Turck–Chieze et al. may also be too low, but will be adopted for the present giving 5.3 $\pm$ 1.2 SNU.

7. EXPERIMENTAL RESULTS

So far there are only two mature experiments that have given results plus one with preliminary results, but more are expected soon.

7.1 KAMIOKANDE 2

The large water detector at Kamiokande in Japan has presented results at the Neutrino '90 conference [18]. After 1040 days of operation, they found a neutrino flux which was 0.46 $\pm$ 0.05 $\pm$ 0.06 of the SSM prediction of Bahcall et al. [3]. If we reduce the Bahcall flux from 7.9 to 5.3 SNU as discussed above i.e. by a third, then the Kamiokande ratio becomes 0.69 $\pm$ 0.17 and this is to be compared with a theoretical value of 1.00 $\pm$ 0.22. This gives a difference of 0.31 $\pm$ 0.28. That is, there is no significant difference from the Standard Solar Model. Note that here we have taken the 22% error proposed by Turck–Chiez et al., but as shown above, this is probably an underestimate.

This calculation is not quite correct, as the 8B neutrino flux only should be considered, but as this is most of the flux (Bahcall gives 6.0 SNU) the conclusion is unchanged.

During the period January 1987 to January 1990, the neutrino flux measured by the Kamiokande experiment was effectively constant. No indication of a variation with the sunspot activity was observed even though the sunspot rate changed greatly over this period. As the Kamiokande statistics are still low (164 events after correction and derived from about 100 events) they write that a correlation cannot be definitely ruled out, but it is clearly very strong evidence against.

7.2 Chlorine experiment of Davis et al.

Secondly there is the Davis et al. [4] experiment where 37 Chlorine is converted into 37 Argon which after a period of ten days, is swept out of the detector and the decay of the ^{37}A is measured. The first run of the experiment was in 1970 and this was a lonely pioneering work for many years. For the first 7 or so years the rates were roughly constant, but then fluctuations in the rate were indicated and more recently it has been suggested [19] that one was observing an effect related to the inverse of the sunspot activity with an 11–year period.

It is hard to evaluate the reliability of this experiment. The Kamiokande experiment has to some extent, been calibrated by its brilliant results on the flux of neutrinos from Supernova 1987A. But there is no such calibration for the chlorine experiment. Although one would expect an experiment which has been running for 20 years to have good statistics, the number of actual counts seem small. An example of the problem is a description given where the experiment was run for 50 days and production of 50 Argon atoms was expected but after extraction and delay and decay of the argon atoms, only 2 to 4 counts were obtained. The cosmic ray background is said to be small, 0.08 ^{37}A atoms per day.

The average value of the flux from the Chlorine experiment is 2.1 $\pm$ 0.3 and this has to be compared with 5.3 $\pm$ 1.2. This gives a value which is 2.5 standard deviations low, but as said above, the theoretical error is probably too low.

The neutrino flux is a poor fit to a constant value but the fit to the inverse of the eleven year sunspot–type variation is also not a good fit.

7.3 Preliminary results from the SAGE experiment

If a gallium detector is used, the threshold energy for neutrino detection is much lower so that other reactions giving neutrinos can also be detected. Thus the neutrino flux detected by gallium should be about 20 times greater than detected by chlorine. However, the two new gallium experiments will initially have 30 tons of gallium which is 1/20 of the mass of chlorine in the Davis et al. experiment. The result is that both types of experiment will give the same data acquisition rate of roughly one event per week [19].

The Soviet–American Gallium experiment, SAGE, has started to take data and preliminary results have been presented [20], suggesting that the most likely neutrino flux was zero and that the SSM value of Bahcall et al. of 132 SNU was two standard deviations from their data. In view of the difficulties of the experiment and its newness, these preliminary data like the helioseismological data, have not been included in the conclusions (Note, they point in opposite directions).

8. CONCLUSIONS

It is shown that the Standard Solar Model has considerable uncertainties so that the errors on it should be considerably increased. Corrections are made to estimates of the neutrino flux. It is found that the flux measured by the Kamiokande experiment is in good agreement with the new SSM estimate of 5.3 $\pm$ 1.2 SNU. The Chlorine experiment measurement is about 2.5 standard deviations lower than this.

Evidence is given that the neutrino flux should not be correlated with the sunspot activity. The Kamiokande experiment finds no evidence for any correlation. The chlorine experiment gives a poor fit to a constant flux and while indicating a correlation with the inverse of the sunspot activity, gives a poor fit to this hypothesis. The helioseismological results and the expectation that it takes 10^4 years for the centre of the sun to communicate with the surface – which is much greater than the 11 years of the sunspot cycle – is further evidence against any correlation between the solar neutrino flux and sunspot activity.

It is concluded that there is no compelling evidence at present which suggests that there is a serious discrepancy between theory and experiment and which would require an introduction of "New Physics".

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