Inside the Stars, IAU Colloquium 137
ASP Conference Series, Vol. 40, 1993
Werner W. Weiss and Annie Baglin (eds.)

BRIEF REVIEW OF SOLAR MODELS AND SOLAR NEUTRINO EXPERIMENTS

DOUGLAS R.O. MORRISON
CERN, Geneva, Switzerland

ABSTRACT Solar Evolutionary Models are briefly reviewed and while the models are robust, there are uncertainties in the input data which justify rather larger errors. The 1992 experimental results from GALLEX, SAGE II and Kamiokande are shown to be consistent with calculated fluxes of solar neutrinos whereas the Chlorine results continue to be significantly low though this experiment has a problem with the high variability with time of its results in contradiction to Kamiokande. It is concluded that the evidence for a solar neutrino problem is not compelling and New Physics are not demanded. Further experiments are essential to search for neutrino masses and to study the Sun.

CONVENTIONAL WISDOM

The Conventional Wisdom for 20 years has been that the experimentally measured flux of neutrinos from the Sun was very significantly less than that predicted by calculations of the Standard Solar Model, SSM. Further this neutrino flux varied with time according to the inverse of the sunspot activity (Bahcall, 1989).

For the Chlorine experiment in the Homestake mine (Lande, 1990), the neutrino flux was found to be 2.2±0.3 SNU whereas the SSM value calculated by Bahcall and Ulrich (1989) was 7.9 SNU. This result was confirmed in 1989, by the Kamiokande experiment (Hirata et al. 1989) using a different technique, who obtained the ratio;

$$Data/SSMvalue = 0.46 \pm 0.05 \pm 0.06 = 0.46 \pm 0.08 \qquad (1)$$

In 1990, the Soviet-American Gallium Experiment, SAGE, reported (Gavrin et al. 1990) results using a gallium target for which the predicted flux of 132 SNU (Bahcall and Ulrich, 1989) is much higher as this includes the fundamental proton-proton reaction. They found a best fit of 20 SNU and an upper limit of 70 SNU with 90% confidence - significantly less than predicted.

Thus in 1990 there was clearly strong evidence that there was a major problem. This belief is examined here - earlier and fuller examinations with drawings have been published (Morrison, 1992). This brief review was completed in July 1992.

However things are not so simple and clear. There is not one SSM calculation by Bahcall et al., but there have been many. Another important calculation available in 1990 was by the French-Belgian Collaboration (Turck-Chieze et al. 1988) who found for the Chlorine experiment a much lower value of 5.8 SNU instead 7.9 SNU and what is more important gave a much larger error of 22% instead of 11%. With this lower calculated value, the Kamiokande result is now

$$Data/SSM = 0.70 \pm 0.12 \qquad (2)$$

Recalculating (2) but now including also the theoretical error as well as the experimental error, gives;

$$Theory - Expt. = (1.00 \pm 0.22) - (0.70 \pm 0.12) = 0.30 \pm 0.25 \qquad (3)$$

Thus a significant result has become a non-significant 1.2 standard deviation effect. This shows that the errors on the model calculation are important and 10% effects must be seriously considered.

SOLAR EVOLUTIONARY MODEL

In 1957 Schwartzschild et al. (1957) calculated a model of the Sun where its evolution was followed from its birth from a protostar 4.5 Gyr ago to the present. Several hundred shells are taken and are followed for a series of intervals of time. The input is only the present luminosity, mass, and radius, plus the age and the abundance of the elements. The Sun is considered to have three main regions;

(1) the Core where the nuclear energy is produced,

(2) the Intermediate or Radiation Zone and

(3) an outer Convection Zone. The energy created in the Core is transferred to the Convection Zone essentially by radiation.

The convection in the outer zone is described by a single Mixing Length Parameter, α (it would be better to have more parameters but there is not enough pieces of input information).

Since radiation is dominant, it is essential to know the opacity. This requires a detailed knowledge of all the isotopes, their state of ionisation at each depth, and their energy levels. After a plea (Stone, 1982) to resolve a stellar problem in 1982, the opacity has been recalculated. The new calculation, called OPAL (Inglesias and Rogers, 1991), has resulted in better fits to stellar data and has also changed the neutrino fluxes.

The Solar Evolutionary Model, called the standard model, SSM, has a number of problems.

(1) the fractions of lithium and beryllium are 0.005 and 0.5 resp. of the predicted value.

(2) screening effects are not well known and affect the choice of the Equation of State, and calculations of opacity and of nuclear reactions. The conditions of the Sun's plasma do not exist on Earth. These effects could give errors of about 15% on the neutrino flux for gallium and about 20% for the high energy neutrinos (Turck-Chieze, 1992)

(3) it is assumed that there is no rotation though initially the Sun was probably a T Tauri star, rotating strongly as mass was attracted to it from the rest of the protostar - this angular momentum and some mass would have been lost by a stronger solar wind than now; again this not in the SSM.

(4) diffusion exists at some level; recently Bahcall and Pinsonneault (1992) included 2 forms of diffusion (gravitational settling and thermal diffusion) which raised the neutrino flux estimates, but did not include turbulent diffusion which is expected to be important and which would lower the neutrino flux.

(5) some nuclear reaction rates are poorly known such as for the basic proton-proton reaction, ^{3}He-^{3}He and most importantly for high energy ^{8}B neutrinos, the ^{7}Be(p,γ)^{8}B reaction for which there is only one reliable measurement (see Morrison ref. b). A new measurement is being made at Riken by a Japanese-American collaboration. Thus there still exists considerable uncertainty even though the model is generally robust.

Early 1992, four new calculations were performed by Lopes and Turck-Chieze (1992), the Nice group of G. Berthomieu et al. (1992), the Yale group of Guenther et al. (1991) and by Bahcall and Pinsonneault (1992). Assuming the following standard conditions (best at this time); OPAL opacities, the astrophysical S(0) value for ^{7}Be(p,γ)^{8}B of 20.2 keV (see Morrison ref. 6b), age = 4.5 Gyr, low iron abundance in agreement with the meteorite value (see Morrison ref. 6b) and no partial diffusion, then the spread of neutrino rates are found to be:

(1) for chlorine targets, 5.8 to 6.4 SNU (Bahcall and Pinsonneault (1992) find 8.0 SNU which becomes 6.4 SNU for the standard conditions and 7.2 with the addition of their partial diffusion calculation).

(2) for gallium targets, the spread is 119 to 128 SNU (ref 12 gives 132 SNU which falls to 128 SNU under the standard conditions).

Overall the Stellar Evolutionary Models are surprisingly good and stable and the Yale group (Guenther et al. 1991) are even able by using 1800 shells, to fit the structure of the low ℓ, p-waves found in helioseismological measurements! However there are still some uncertainties and errors are probably larger than some models suggest, especially for the ^{8}B neutrinos.

EXPERIMENTS

Introduction

There are two experimental techniques used;

(1) a water Cerenkov detector where the neutrino elastically scatters on an electron which gives a ring of Cerenkov light detected by arrays of photomultipliers on the walls.

(2) chemical extraction experiments where a few atoms of a target of about 10^{30} atoms are converted by the neutrinos to a radioactive element which is extracted and the decays of these few atoms are counted.

The Kamiokande group are using a water Cerenkov detector; the threshold is high so that only the ^{8}B neutrinos are measured.

At the Homestake mine, the ^{37}Cl in a chlorine target can produce ^{37}Ar. The neutrinos are mainly from the higher energy ^{8}B decays in the Sun.

Gallium is used as a target where the ^{71}Ga isotope produces ^{71}Ge atoms. This has a low threshold so that the basic proton-proton reaction is a main contributor to the neutrino flux. Thus results from such experiments are of major importance whereas the ^{8}B neutrinos are from a minor branch of the chains of reactions in the Sun.

There are two gallium detectors - the Soviet-American Gallium Collaboration, SAGE, taking data in the Baksan Lab, and the GALLEX Collaboration in the Gran Sasso Lab.

The KAMIOKANDE Experiment

The Kamiokande experiment is run by a strong well-funded group and their experiment and results are fully described in refereed journals. Their first result called Kamiokande II, was based on 1040 days of operation where some 100 events were obtained above background, ie one event per 10 days. They observe a peak in the direction of the Sun confirming that the neutrinos are of solar origin. They found no variation with time, not with the sunspot number, nor with the season nor with the day/night cycle.

After improving their detector, the Kamiokande III run has begun and first results (Totsuka, 1992) from 220 days gave a ratio

$$data/SSM = 0.59 \pm 0.11 \pm 0.06 \tag{4}$$

which is slightly higher than previously but not significantly. The Cold Fusion cells of Steve Jones et al. at the centre of the Kamiokande detector have not seriously interfered with the neutrino work.

SAGE I

The first results for five runs of the SAGE detector with an average about 27 tons of gallium, between January and July 1990 were presented in August 1990. They (Gavrin et al. 1990) analysed their data using the method for low statistics of Cleveland et al. (1983) to obtain a best fit of 20 SNU which was substantially below a standard solar model calculation (Bahcall and Ulrich, 1989) of 132 SNU.

However as pointed out in Morrison (1992), the Cleveland method assumes that if the run data give a negative amount of ^{37}Ar atoms, then this is unphysical and the value is put to 0.0. Three of the five runs were given values of 0.0 SNU. Looking at the counts as a function of time, as shown in Morrison (ref 6a,b), it can be seen that the counting rates are so low that it is better to assume that the best fit to the five runs is zero.

There can be two main explanations of this null result - either this is New Physics or there is some unexpected problems with the extraction of a few atoms of ^{71}Ge from some 10^{30} atoms of ^{71}Ga. The SAGE Collaboration plan to calibrate their detector and extraction process by exposing it to a mega-curie source of neutrinos - probably late in 1993.

GALLEX

The GALLEX Collaboration spent considerable time preparing their experiment and announced that they would not publish until they had performed all calibrations and had sufficient statistics. In June 1992 they presented (Anselmann et al. 1992) the results of 14 runs with 30 tons of gallium, where they found

$$83 \pm 19 \pm 8 \text{ SNU} \tag{5}$$

which is 1.3 to 2 standard deviations from the four recent SSM calculations and indicated there was no significant disagreement with the models.

They observed peaks in the electron energy spectrum at 10.3 and 1.3 keV which is what would be expected from decays from the K and L shells. They had a total of 65 counts attributable to ^{71}Ge which corresponded to about one count per 5 days. They also plan to calibrate their detector with a strong neutrino source.

SAGE II

In June 1992, the SAGE Collaboration presented (Gavrin, 1992) the preliminary results of five runs in 1991 - for the four later runs, the mass of gallium was doubled to 57 tons. They obtained rates of 27, 300, 48, 75 and 93 SNU. This would appear to be consistent with the expectations from SSM calculations, but the authors say that these results are preliminary, so did not combine the five runs nor draw any conclusions from this experiment which is called SAGE II.

The CHLORINE Experiment

The Chlorine experiment has been running since 1967 but the first three years data were excluded as it was found that by requiring the pulse of the ^{37}Ar count to have a fast rise-time, the background was suppressed and more reliable results were obtained (if there is a decay in the counter, the ions produced are clustered close together and hence reach the wire in a short interval of time giving a fast rise-time to the pulse whereas if a background cosmic ray particle traverses the counter, the ions produced are dispersed and give a slow pulse rise-time).

Since 1970, the Homestake mine experiment has given rates which have stayed close to the latest value (Lande, 1992) of 2.25 ± 0.3 SNU which is significantly less than the recent SSM values of 5.8 to 6.4 (or 8.0). This series of results have been the basis of the Solar Neutrino Problem.

However there is a major worry about these results - this is their extreme variability. Thus after a prolonged shut-down to replace pumps, the results were for some time generally close to the Kamiokande II values (see Morrison ref 6b) This variability has been interpreted in terms of the solar sunspot cycle of 11 years though the best fit is obtained (Filippone and Vogel, 1990) with a 4.5 year cycle. Perhaps the fullest analysis using Poisson statistics, has been made by Filippone and Vogel who found that if one assumed a constant flux the probability of the fit was 3.9% whereas if one assumed there was a variation with the inverse of the sunspot number, the fit had a 8.3% probability. On the other hand another analysis (Davis, 1987) gave a 5 standard deviation effect. Another worry is the abnormal number of runs with zero or one count which is inconsistent with the claimed average of 5.6 counts per run (from 1970 to 1984 there were (Bahcall, 1989) 339 counts of ^{37}Ar in 61 runs giving one count per 15 days).

However in 1992, the data have been re-analysed (Fiorini, 1992) with wider selection criteria and almost all values have been changed and it is claimed that there are 8.1 counts per run. For 93 runs there are now only 6 zeros, but this number still seems high.

It is intended to start a new experiment with iodine which should give a substantially higher counting rate(about 5 times) - one awaits their results with interest.

NEUTRINO MASS

There is no reason to exclude neutrinos from having masses theoretically. Neutrino masses would be welcome, in particular they could be an important component of Dark Matter in the Universe, for example a value of 7 eV as suggested by the COBE data (Smoot et al. 1992). The errors of the theory and of the experiments are at present, both sufficiently large so that neutrino masses of up to about 10 eV are possible.

DETAILED CONCLUSIONS

a) There are many Standard Solar Model calculations who broadly agree for the same input, however there are important uncertainties so that errors of 15 to 20% at least must be considered in comparing with data.

b) The Kamiokande rate is consistent with most SSM calculations. No time variation is observed.

c) The SAGE I experiment found essentially no evidence for solar neutrinos or had extraction problems

d) the GALLEX experiment is consistent with all SSM calculations within 1.3 to 2 standard deviations

e) The SAGE II preliminary results appear to be consistent with the SSM

f) The rate found by the Chlorine experiment is significantly lower than SSM estimates, however the data show a disturbing variability with time.

g) Extraction experiments with gallium or chlorine, are difficult.

GENERAL CONCLUSIONS

- The History of Science is full of cases where a first pioneering experiment opened the way but the result was controversial. Later experiments built on the pioneering one and also corrected the problem.
- In the past there may have been a Solar neutrino Problem. In the future there may a Solar Neutrino Problem. But today the evidence for a Problem is not compelling - not for a rate problem nor for a time variation.

- There is still considerable space for Neutrino Masses.
- It is essential to KEEP SEARCHING - for neutrino masses and to study the Sun which is the only star near us

ACKNOWLEDGMENTS

It is a pleasure to acknowledge helpful discussions with Drs. J.N. Bahcall, G. Berthomieu, T. Bowles, V.N. Gavrin, W. Hampel, K. Lande, A. Maeder, M.H. Pinsonneault, A. Suzuki, Y. Totsuka, S. Turck-Chieze, D. Vignaud, and J.F. Wilkerson, though the responsibility for the content is the author's.

REFERENCES

Anselmann P. et al. Phys. Lett. B283(1992)376 and 390.

Bahcall J. N., 'Neutrino Astrophysics', CUP, Cambridge (1989).

Bahcall J. N. and Pinsonneault M. H., a) Princeton preprint IASSNS-AST 92/10 (1992) and to be publ. in Rev. Mod. Phys.; b) to be publ. Astrophys. J. (1992).

Bahcall J. N. and Ulrich R. K., Rev. Mod. Phys. 60(1989)297-372.

Berthomieu G. et al., subm. to Astrom. and Astrophys. (1992).

Cleveland B. T., Nucl. Instrum. Meth. 214(19783)451.

Davis R. Jr., Proc. Informal Conf. on Status and Future of Solar Neutrino Research, Ed. E. Friedlander, (1987), BNL report No. 50879 Vol. 1 p.1.

Filippone B. W. and Vogel P., Phys. Lett. B246(1990)546.

Fiorini E., Workshop on Neutrino Telescopes, Ed. M. Baldo-Ceolin, Palazzo Loredan, Venice, (1992), to be publ. and K. Lande, priv. comm., (1992).

Gavrin V. N. et al, Phys. Rev. Lett. 67(1990)3332.

Gavrin V. N., Particle Astrophysics Colloq. Blois, June 1992.

Guenther D. B. et al. Astrophys. 46(1991)377-393.

Hirata K. S. et al. Phys. Rev. Lett. 63(1989)16, 65(1990)1297, 65(1990)1301 and Phys. Rev. D44(1991)2241.

Inglesias C. A. and Rogers F. J., Astrophys. J. 371(1991)L73; 371(1991)408 and Rogers F. J. and Inglesias C. A., to appear in Astrophys. J. Suppl.(1992).

Lande, 25th Intl. Conf. on High Energy Physics, Singapore, 1990, Eds. K.K. Phua and Y. Yamaguchi.

Lande K., Particle Astrophsics Colloq. Blois 1992.

Lopes I. and Turck-Chieze S., IAU Colloquium 137 'Inside the Stars' Vienna, April 1992, and sub. to Astrophys. J. (1992).

Morrison D. R. O., a) CERN-PPE/92-109; b) Particle World, 3(1992)30-39; c) Joint Intl. Lepton-Photon Symp. and Europhysics Conf. on High Energy Physics, Geneva, 1991, Eds. S. Hagerty, K. Potter, and E. Querigh, World

Scientific, Singapore (1992) Vol. I p599. d) Int. Conf. on High Energy Physics, Singapore, 1990, Eds K.K. Phua and Y. Yamaguchi.

Schwartzschild M. et al., Astrophys. J. 125(1957)233.

Smoot G. F. et al., subm. to Astrophys. J. (1992).

Stone N. , Astrophys. J. 260(1982)L87.

Totsuka Y., Particle Astrophysics Colloq., Blois, June 1992.

Turck-Chieze S., talk at at Moriond Workshop on Massive Neutrinos and Tests of Fundamental Symmetries, Jan. 1992.