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The steady vanishing of the three solar neutrino problems†

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Contents

Abstract. Three problems have been claimed for solar neutrinos. First, it has been said for over 20 years that the flux of high energy neutrinos was substantially less than that predicted from solar evolutionary models. Second, it was claimed that there were violent fluctuations in the high energy neutrino flux and that their periodicity was close to that of the sunspot cycle. Third, recently evidence was presented that low energy neutrinos may also have a flux deficit. The second problem is shown to be unreasonable and in disagreement with the more recent Kamiokande experiment. The other two problems of flux are shown to be vanishing with time. This is not from a single cause but from a series of improvements of the input data to the models, to a better appreciation of the errors which had sometimes been significantly underestimated, and also some of the experimental values have increased with time indicating a learning curve for some of these very difficult experiments with very low statistics. Finally it is concluded that the evidence for any solar neutrino problem is not compelling.

1. Introduction — the three problems

The conventional wisdom for some 20 years has been that there is a discrepancy between the predicted flux of neutrinos from the Sun and the measurements in a chlorine experiment. The predictions of Bahcall and co-workers for the flux measurements expected in the radiochemical experiment of Ray Davis using chlorine at the Homestake mine gave a serious discrepancy — since this involved mainly high energy neutrinos from the decay of boron-8; I shall call this first problem that of high-energy neutrinos. A major factor is the extrapolated cross section for the ^{7}Be(p, γ)^{8}B reaction, which has been steadily shifting to lower values, in particular by a new measurement at Riken in Japan, thus reducing the problem considerably.

In the 1980s, Davis et al. claimed that the large fluctuations observed in the neutrino flux as a function of time were strongly correlated with the inverse of the sunspot activity. This unexpected claim of a flux variation with the solar cycle will be called the second problem.

In 1990, experiments using gallium as a radiochemical detector began — they were important as they measured mainly low energy neutrinos which largely were produced in the basic proton – proton reaction. The very first result from the SAGE Collaboration gave a flux close to zero — this low energy neutrino flux problem will be called the third problem.

These three apparent disagreements with theory encouraged many to suggest explanations involving New Physics. Also many second-generation experiments are being prepared to obtain data with higher statistics and better quality to try and resolve these three problems. However, since 1990, a series of papers [1] have been presented showing that the evidence in favour of New Physics being required is 'not compelling'. In this paper, the theoretical estimates and experimental values will be examined critically and it will be shown that as new data and better calculations become available, theoretical and experimental values have converged, and also some theoretical errors have increased.

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Thus the evidence for the three problems has steadily decreased with time so that at present it is 'not compelling'.

Recently Kovetz and Shaviv [2] have made a new solar model calculation which may have some advantages over previous calculations. Dar and Shaviv [3] used these calculations and added some recent data to show that Standard Solar Models are consistent with the safest experimental measurements. This has been forcefully contested by Bahcall et al. in an electronic mail 'publication' [4] and this response has been answered equally strongly, with the use of the same media technique, by Dar and Shaviv [5]. Brief comments will be made on this new controversy, but it should be noted that the evidence in this present paper is previous to, and independent of, the Dar and Shaviv – Bahcall controversy. Thus the evidence for the existence of all three solar neutrino problems has been steadily vanishing and is 'not compelling' independently of these recent papers.

2. Solar evolutionary model

2.1 Introduction

In 1957 Schwarzchild [6] first introduced the Solar Evolutionary Model where the Sun's development is followed from its formation from gas clouds 4.5 Ga ago to the present. The model has made a fit to present-day values of the luminosity, L_0, mass, M_0, and radius, R_0. The composition of the Sun 4.5 Ga ago was estimated. A number of shells of different radii and a number of time intervals are taken, and the four equations giving continuity and balance across the boundaries are applied. (See Ref. [7] for a major, serious review). After 1964, this was called the Standard Solar Model, SSM, but it should be appreciated that there are many different calculations done under the umbrella name SSM — the real problem is the hard work in judging these carefully, and in deciding which should be used as a Reference Solar Model, RSM, which is most worthy for comparison with experimental measurements.

Since 1963 John Bahcall has been responsible for many calculations and improvements in models. For the predicted rate for chlorine, values were initially very high, but in papers with Shaviv in 1968, the rate dropped below 10 SNU and stayed there.

2.2 Errors

Since the 'problems' of high and low energy solar neutrinos come from a comparison of theory and experiment, a knowledge of errors, both experimental and theoretical, is essential.

It is sometimes hinted that the input data are only L_0, M_0, R_0, and the initial abundance of elements, but in fact there are an enormous number of pieces of input data plus a number of assumptions which are not always clearly indicated. Some of these assumptions are possible major sources of errors so that the theoretical error on an SSM prediction can be appreciably larger than the error coming from the experimental input values. This is important as the oft-used estimates of Bahcall and co-workers have unacceptably low errors essentially because of the unusual and unfortunate 'rule of thumb' [8] used to select theoretical errors. This is to look at the variation of each of the theoretical quantities with time and use that variation as an estimate of the errors — sounds fine but if the author inserts always the same theoretical hypothesis, then the resultant theoretical error will not vary and hence Bahcall and co-workers will assume the theoretical error is negligible, whereas the basic uncertainty made in the theoretical assumptions has not varied with time. This is the reason others, e.g. Turck-Chieze et al. [9], give larger theoretical errors because they worry about the uncertainty in, for example, which type of screening to use — also they state that their errors are minimal values since there could be other theoretical uncertainties — this is a much healthier and more realistic physics approach and these errors will be used here.

2.3 Early Sun, abundance of elements

Until recently, most SSM only started as a T Tauri star which rotated very quickly and then lost angular momentum quickly from its strong solar wind. Initially the Sun was believed to have a core.

The major problem of a SSM calculation is how does the heat from nuclear burning escape from the core? It does it almost entirely by photons which are emitted, interact, are absorbed many times — a typical diffusion time for information from the core to the surface is about τ years — this is the reason why so many were astonished at the idea that the neutrino flux from the core of the Sun could have fluctuations of the order of 10 a. This is a fundamental problem and is against any suggestion that the neutrino flux could vary with the sunspot cycle.

Two major problems are, first, to know the abundance of all the elements and their isotopes 4.5 Ga ago, and second, to evaluate their state of ionisation at different radii. The point is that the photons interact more with ions having electrons than those that have been stripped of electrons — and at the centre of the Sun all elements have no electrons attached except the very heaviest, such as iron. This question is referred to as the 'opacity' of the medium and is a very complex calculation — when it was realised in 1982 that the opacity in use then was most probably wrong, it took until 1992 before Livermore [10] issued new tables, which may still not be perfect. Almost all of the opacity comes from the heavy elements, especially iron, and it was a change in the abundance of iron as suggested by Courtaud et al. [11] that led to a reduction of about 15 to 20% in the predicted flux of ^{8}B neutrinos.

Determining the abundance of elements 4.5 Ga ago mainly by studying the present surface is a delicate matter and future surprises cannot be excluded (as for example the sudden increase by a factor of ten in the deuterium abundance from the Keck measurement [12] which, however, needs confirmation). However, a check can be made by careful studies of certain meteorites believed to date from a pre-Sun epoch — the agreement [13] is remarkably good except for ^{7}Li (off by a factor of 100), ^{9}Be (a factor of 2 too low) and ^{3}He (smaller effect).

2.4 Plasma effects

The centre of the Sun is a plasma with a temperature and pressure very different from what is normally studied on Earth, but plasma experts, V Tsytovich et al. [14], have suggested that collective effects and relativistic Doppler broadening and shifting of Raman resonances in scattering by electron polarisation clouds could be important. From first calculations, they concluded that these would make the Sun more transparent so that for a given temperature, the luminosity would be larger, or since the Sun's luminosity is fixed, the temperature would be lower. It should be recalled ([8], pages 149–151) that a lower temperature lowers the ^{8}B and ^{7}B fluxes according to T^{+18} and T^{+8}, but goes the other way with gallium, and would increase the neutrino flux according to $T^{-1.2}$. A full calculation is awaited on this important question.

2.5 The ^{7}Be(p, γ)^{8}B reaction, S_{17}

Neutrinos from boron-8 decay provide almost all the solar neutrinos detected by Kamiokande and about 80% of those detected by the chlorine experiment. Hence a knowledge of how often ^{8}B is formed is crucial. This is a small part of the solar chain of reactions, only a few parts per million, so that any change in the ^{8}B rate does not affect the Sun's luminosity significantly.

The essential point is that the reaction ^{7}Be(p, γ)^{8}B is not measured at the energy range of about 1 to 10 keV which is important in the Sun, but at much higher energies. The lowest energy measured is 117 keV where the cross section is only 3 nb and falling very quickly because of the barrier penetration factor as shown in Fig. 1. This makes extrapolation difficult, so the astrophysical S-factor is used which separates off the barrier penetration effect and leaves nuclear effects, which are hoped to vary slowly at these very low energies. For this reaction, it is called S_{17}.

A review by Johnson et al. [15] shows how complicated the situation is. Two of their plots for S_{17} are shown in Figs 1a and 1b where it can be seen that there is a strong resonance near 640 keV, and that the extrapolation to low energies must include both s-waves and d-waves as first introduced by Turck-Chieze et al. [16] in 1988, instead of s-waves alone. To avoid the effect of the resonance, Johnson et al. use only data below 500 keV, where there are only two series of experimental results, and give these results equal weight — this is inappropriate as the two experiments cannot be considered of equal worth. The Kavanagh experiment [17] was performed in 1969, 14 years earlier than that of Filippone et al. [18], and long experience [19] has taught that techniques change greatly over such a long time period; further and more importantly, it is a rule of data compilers [20] that only results fully described in refereed journals should be used in compilations, and the Kavanagh paper is only given in a 12-line abstract, whereas the Filippone work is very fully described. Since the two experiments are incompatible by more than three standard deviations, this makes a significant difference — following the rules and rejecting Kavanagh et al. lowers the extrapolated value from 22.4 eV b to about 20.0 eV b. It is important to note that Johnson et al. [15] say that their model is not satisfactory as it does not agree with some other experimental data.

A major reduction of S_{17} comes from a new measurement carried out at Riken by Motobayashi et al. [21]. They measured the inverse reaction ^{8}B(γ, p)^{7}Be, studying the Coulomb dissociation by impinging a beam of ^{8}B on a lead target where the exchange of a virtual photon gives ^{7}Be and a proton, which are detected. The multipole and partial wave contributions calculated for the reaction Be(p, γ)^{8}B are shown in Fig. 2. The magnetic dipole contribution, M1, which gives the resonance at 640 keV, does not contribute to the inverse reaction. The results of Motobayashi et al. are shown in Fig. 3. It may be seen that the values are lower than previous results (also the resonance is not observed).

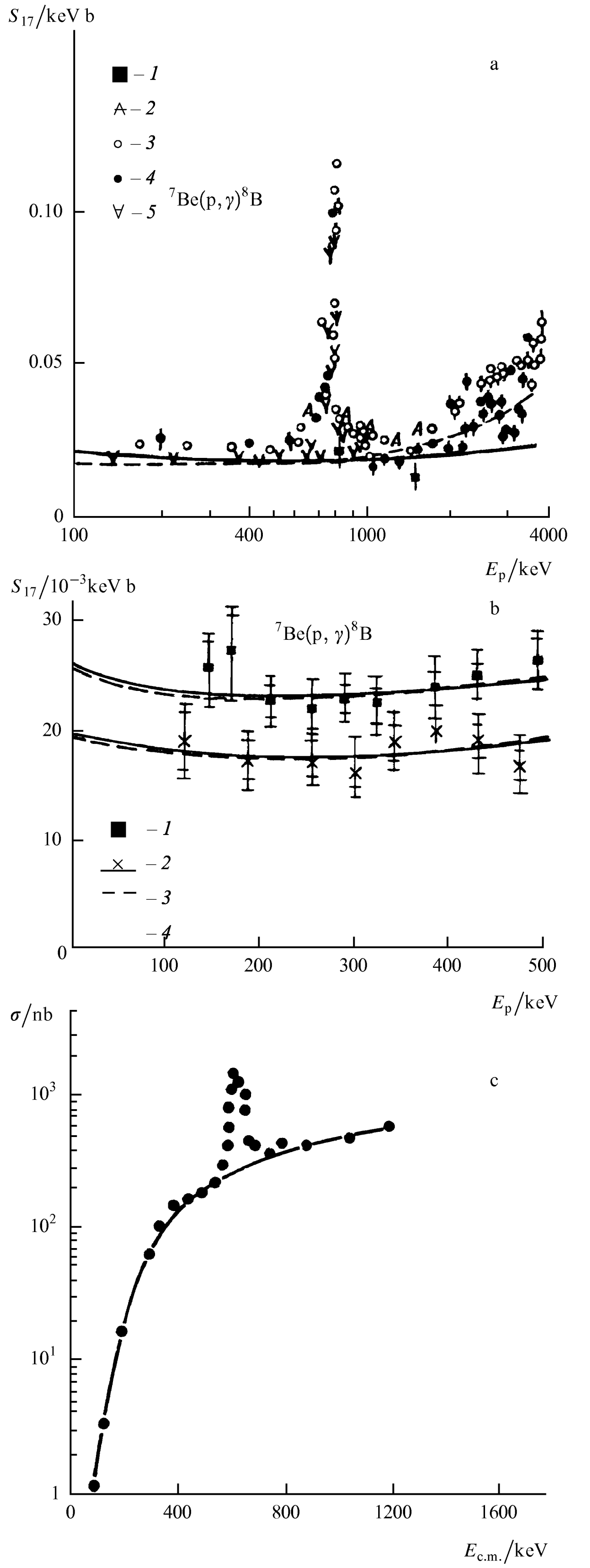

Figure 1. (a) Astrophysical S-factor, S_{17}, for the reaction ^{7}Be(p, γ)^{8}B. The solid line is for an s-wave fit to the data and dotted line an s-wave and d-wave fit, *1* — Kavanagh (1960), *2* — Parker (1968), *3* — Kavanagh et al. (1969), *4* — Vaughn et al (1970), *5* — Filippone et al. (1983); (b) as (a) for below 450 keV with two fits each to the data of Kavanagh [17] and Filippone [18], from Ref. [15]; (c) Cross section for the reaction ^{7}Be(p, γ)^{8}B.

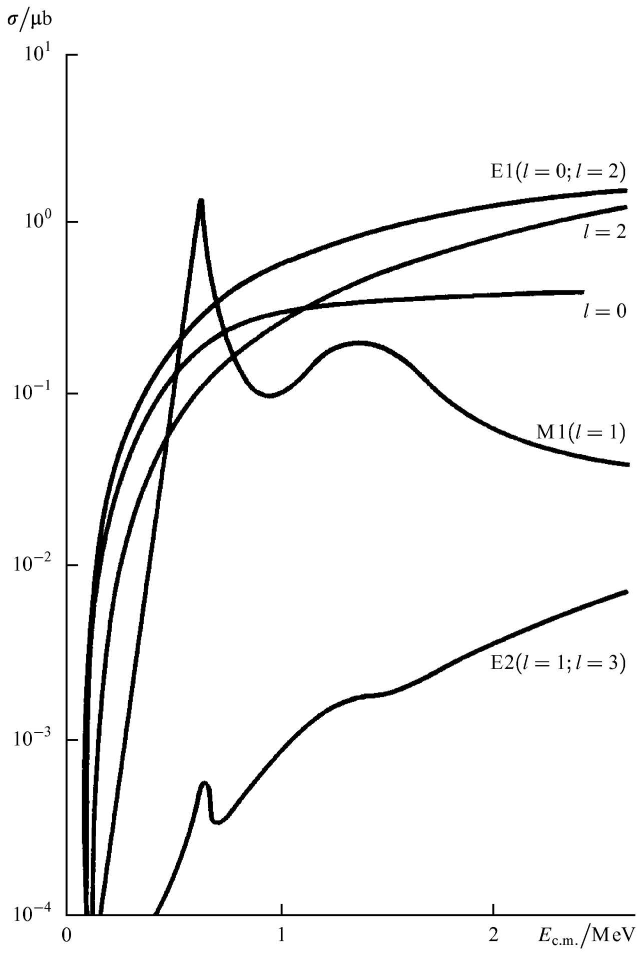

Figure 2. Multipole and partial wave contributions to the reaction $^7Be(p, \gamma)^8B$.

They derive a value for S_{17} which is about 20% to 30% lower than the value of 22.4 eV b used by Bahcall and Pinsonneault [22] and Turck-Chieze et al. [9].

There is another major problem with the extrapolation of S_{17} from measurement values to solar energies. In nuclear physics, it has been established that nuclei which are rich in neutrons have a neutron halo, that is, the neutrons extend out further from the centre of the nucleus than expected. Rusager and Jensen [23] have pointed out that ^8B is proton-rich with 5 protons and only 3 neutrons, so it is to be expected that the proton wave function will extend to much larger values. The rms total radius of the ^8B nucleus is normally taken to be 2.51 fm but they calculate that the radius of the last proton is 3.75 fm. Since the radius for the main contribution for the reaction $^7Be(p, \gamma)^8B$ in the Sun is about 50 fermis, it is clear that the consequences of ^8B being proton-rich must be considered. The difficulty of knowing how to extrapolate is shown in Fig. 4 where the numbers marked on the curves are for different separation energies. They conclude that, starting from the points of Filippone et al. [18], the extrapolated value of S_{17} should probably be lower in the range 12 to 17 eV b, but the uncertainty is great and will not be easy to resolve. Note that this proton-rich effect is independent of the new Motobayashi et al. reduction and will reduce S_{17} still more.

In discussing the question of the constancy of input values to the SSM it is interesting to observe that the extrapolated value of S_{17} has changed by much more than the total error from all causes, of about 11% quoted by Bahcall et al. [24]. In successive papers in 1982, 1988, and 1992 Bahcall and co-workers have used values of 27, 24.3, and 22.4 eV b respectively whereas now the best value is about 17 eV b from Motobayashi and even lower when considering the proton-rich effect. Thus this one input factor alone has fallen by about 40 to 50%, much more than Bahcall's estimate for all input factors and for all theoretical uncertainties. This supports the arguments against Bahcall's 'rule of thumb' manner of estimating errors and justifies the contention of Turck-Chieze et al. [9] that 25% should be considered the minimum error value for ^8B neutrinos.

2.6 Diffusion

Diffusion effects expected inside the core and radiation zone of the Sun are of two types, turbulent and nonturbulent. The former are expected to decrease the neutrino rate while the latter are expected to increase it. Since Noerdlinger's work in 1977 [25], there have been several calculations of diffusion. Bahcall and Pinsonneault [22] have considered nonturbulent diffusion but not turbulent diffusion, thus increasing their predicted neutrino fluxes.

2.7 New evolutionary model calculation by Kovetz and Shaviv

Kovetz and Shaviv [2] have made a calculation of the Solar Evolutionary Model using a new code with a number of new features. They use many more shells in radius and time inside the Sun than most previous calculations. Kovetz and Shaviv followed all elements (other than trace elements) for diffusion and for nuclear reactions, unlike most previous calculations for diffusion which only followed hydrogen, helium, and heavy elements and assumed that the elements were completely ionised, which is not the case — this is important as the cross section for bound – bound and bound – free collisions are important.

A consequence of following each element is that Kovetz and Shaviv found that neutrinos from the CNO cycle (mainly from ^{13}N and ^{15}O) were fewer than predicted previously. This is because they did not assume equilibrium of the nuclear reactions as had most previous authors. It might be thought that this would give results for heavier stars where the CNO cycle was dominant in disagreement with observations, but the difference is that, while the CNO cycle of nuclear reactions is not in equilibrium in the Sun, it will be in equilibrium in heavier stars [26].

2.8 Dar and Shaviv paper

In a paper entitled "Has a standard physics solution to the solar neutrino problem been found?", Dar and Shaviv [3] have built on the Kovetz and Shaviv paper [2] to feed in several new 'best' values. These are the solar luminosity, (L_0) from the new Particle Data Group value, S_{17}, S_{34} [for the reaction $^3He(^4He, p)^7Be$], and the CNO cycle effects. The consequent changes are;

For boron-8 neutrinos:

L_0 goes from (3.86 to 3.826) $\times 10^{33}$ erg s^{-1} giving a reduction of 6%;

S_{17} goes from 22.4 to 17 eV b giving a reduction of 24%;

S_{34} goes from 0.533 to 0.45 keV b giving a reduction of 13%.

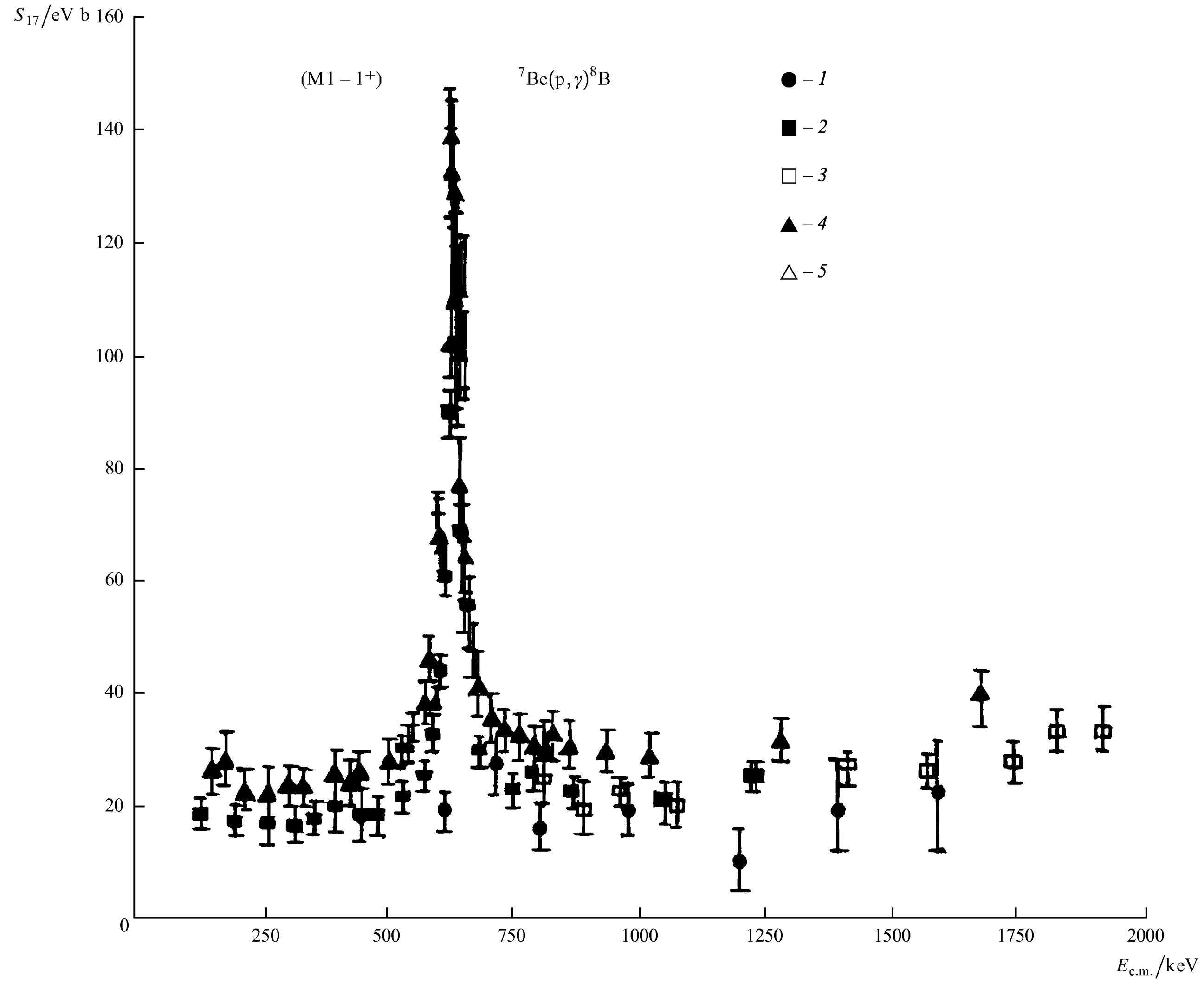

Figure 3. Comparison of the values of S_{17} obtained from the Coulomb dissociation reaction by Motobayshi et al. [21] with other data: *1* — Motobayashi et al. (1993), *2* — Filippone et al. (1983), *3* — Vaughn et al. (1970), *4* — Kavanagh et al. (1969), *5* — Parker (1966).

Combining these three reductions would give a total reduction of 38% compared to Ref. [9] and Ref. [22] for ^8B neutrinos.

Dar and Shaviv give a predicted chlorine rate of 4.2 SNU.

Note that if as a rough check we take the Turck-Chieze et al. [9] value of 6.4 SNU for chlorine and reduce this by 38% this would give 4.0 SNU (approximate, as ^8B neutrinos contribute only 80%, but the ^7Be neutrinos are decreased by 19%).

For gallium experiments: Dar and Shaviv suggest reductions in the number of ^8B, ^7Be, and CNO neutrinos giving a production rate of 113 SNU to be compared with 132 SNU for the Bahcall and Pinsonneault prediction [22] and 122.5 SNU for the Turck-Chieze and Lopez [9] prediction.

Dar and Shaviv do not seem to have yet made a serious evaluation of their errors, so it is probably wise to use the errors of Turck-Chieze and Lopez for the present — these are 25% for Kamiokande, 22% for chlorine, and 6% gallium, and all are lower limits.

The paper of Dar and Shaviv has been very strongly criticised by Bahcall et al. [4]. This criticism was posted electronically and had a swift response, similarly posted electronically, from Dar and Shaviv [5]. It may be that Bahcall et al. have not fully understood the Dar and Shaviv paper. Also they make the elementary mistake that, when they compare theory and experiment, they only take the experimental error and do not include the theoretical error — this is a major mistake as the theoretical error is bigger than the experimental in some cases. By this technique, they found that the chlorine result was 14 standard deviations from their model prediction. This will be discussed later in Section 3.4, and a somewhat smaller number of standard deviations deduced.

At the recent Neutrino 94 conference, one awaited the detailed Bahcall et al. reply to the Dar and Shaviv response, but it was lacking. However, one did learn that the Kovetz and Shaviv calculation deduces a fraction of 29% for helium-4 which is rather high.

It is not intended to enter fully into the Bahcall – Dar debate, but it should be emphasised that the conclusion of this present paper that there is 'no compelling evidence' for any of three solar neutrino problems is independent of this debate.

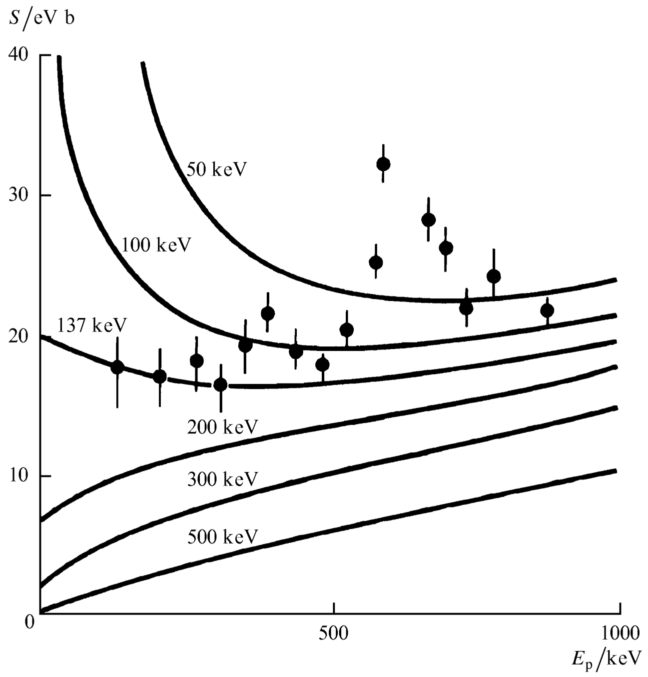

Figure 4. S_{17} factor for the reaction $^7Be(p, \gamma)\,^8B$ as a function of the energy of the system for different separation energies of ^8B (as marked on curves). The calculations include both s-waves and d-waves but not the resonance capture at 640 keV [23].

2.9 Choice of reference model and of errors

If one wishes to look for a discrepancy between a solar evolutionary model and experimental values, it is essential first to choose the best possible model.

At present this is not too easy. The models of Bahcall et al. should be rejected because of their abnormally small errors, rising with time from 10 to 14% for Kamiokande. The errors of Turck-Chieze and Lopez [9] seem reasonable and they are wisely given as lower limits because of lack of knowledge of theoretical uncertainties — these errors will be adopted. They are 6%, 22%, and 25% for gallium, chlorine, and Kamiokande respectively.

Because of the Bahcall – Dar debate, it would be unwise at present to consider either yet as a reference model.

Hence while awaiting progress, I will adopt the Turck-Chieze and Lopez values [9], but with a single correction — the 25% lower value for the Motobayashi experiment [21] for the chlorine and Kamiokande experiments.

Probably other corrections are needed (e.g. S_{34}, L_0, diffusion), but they will not be included yet.

Thus the values preferred for the moment are:
gallium $= 122.5 \pm 7$ SNU,
chlorine $6.4 - 1.6 = 4.8 \pm 1.1$ SNU,
Kamiokande $(4.4 - 1.1) \times 10^6 = (3.3 \pm 0.8) \times 10^6\ \mathrm{cm^{-2}\ s^{-1}}$,
again noting that these errors are minimum values.

2.10 Flux versus rate — thresholds

There is sometimes a tendency to write (e.g. Bahcall [27]) that the neutrinos seen by the chlorine experiment are of much lower energy that those seen by Kamiokande. This is based on the statement that the threshold for the chlorine detector is 0.8 MeV while for Kamiokande the lowest published threshold is almost an order of magnitude higher at 7 MeV. Although correct, this statement could be misleading as it is not made clear if the difference in

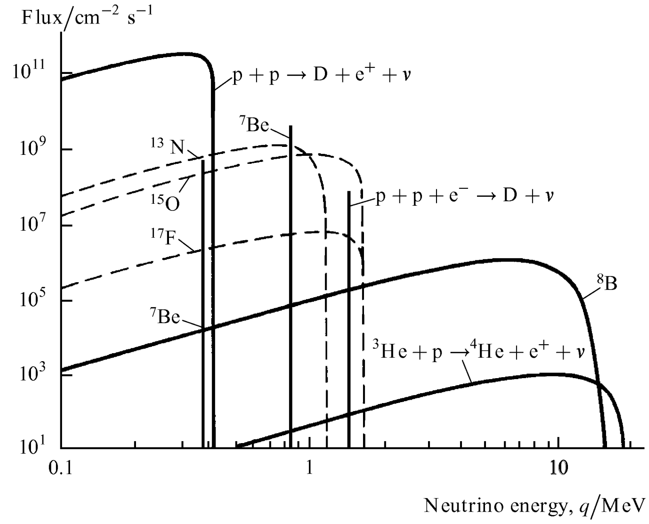

Figure 5. Energy spectrum of solar neutrinos predicted by Bahcall and Ulrich [24]. Note, the $^3He + p$ values should be reduced by a factor of six [22].

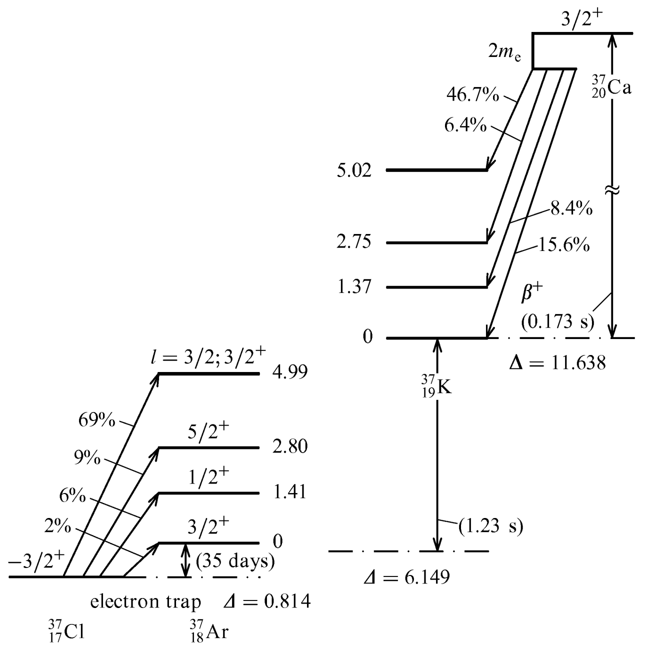

Figure 6. Energy levels of the $A = 37$ system, chlorine, argon, potassium and calcium, units in MeV.

threshold is the only factor and if there are other factors — as there are. This threshold difference would be clear if there was not a confusion between flux and rate.

The flux as calculated by Bahcall and Ulrich [24] is shown in Fig. 5. However, the rate is the product of the flux and the cross section. For the Kamiokande experiment, the rate varies smoothly with energy, but not for the chlorine experiment since there has to be an excited state in the ^{37}A nucleus to receive the neutrino. The excited states in the reaction $^{37}Cl\,(\nu, e)\,^{37}A$ cannot be measured directly, so they are studied experimentally in the isobaric analogue states from the beta-decay of ^{37}Ca to ^{37}K. The main results are shown in Fig. 6. The latest experiment, performed by Garcia et al. at CERN [28] gave 11 more excited states, increasing the rate by 0.3 SNU.

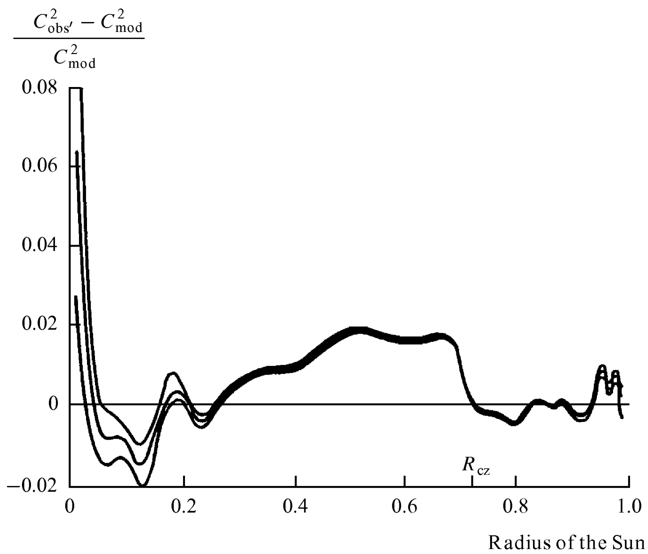

Figure 7. Difference between the observed sound velocity squared, C^2, and the calculated one as a function of the radius of the Sun. R_{cz} is the radius at the boundary between the convection zone and the radiation zone [9].

It may be seen that there are very few excited states near the threshold of 0.8 MeV and also that they give low rates. The reaction mainly (69%) proceeds through the excited state at 4.99 MeV which means neutrinos of 5.8 MeV, which is not so far removed from the Kamiokande range of 7 MeV and upwards. Thus it is possibly misleading to quote thresholds only and not consider rates and excited states.

2.11 Helioseismology

The Sun is a resonant cavity with millions of modes of which some tens of thousands have been measured with great accuracy, e.g. Liebrecht and Woodward [29]. The oscillations have a period of about 5 minutes and are caused by pressure waves, or p-waves as they are called. They allow the velocity of sound, C, to be measured as a function of the radius. From this, an inversion calculation can be performed (with reasonable assumptions) to derive temperatures and pressures as a function of the radius — good agreement is obtained with values from solar evolutionary models. An example is shown in Fig. 7 where the measured value of C^2 is compared with the predictions of Turck-Chieze et al. [9]. It is found that the boundary between the convection zone, where turbulence is important, and the radiation zone where there is relatively little movement, is at a radius of $0.715R_0$ in good agreement with the models. Unfortunately the p-waves give little information on the core of the Sun where the neutrinos are produced, but the overall agreement gives strong independent support to stellar evolutionary models. Attempts are being made to measure gravity waves, or g-waves, as they will give information about the core, but this will be very difficult.

2.12 Conclusions

The overal conclusion is that solar and stellar evolutionary models work very well and independent confirmation of this comes from helioseismology. There are still a number of problems such the ^{7}Li abundance being wrong by a factor 100 and the ^{9}Be abundance by a factor of 2 (there are at least three different theories to explain these discrepancies).

Solar neutrino fluxes from different models agree to better than a factor of two. For the channel of neutrinos from ^{8}B which is of little importance, 0.3% overall, whether there is a disagreement or not may depend on which assumptions and calculation are chosen to be compared with experiment. There is clearly a difference between taking a 10% error or a 25% error in comparing with an experiment which has an error of about 10%. The values of various pieces of input data such as S_{17} continue to vary with time – also, S_{17} gets steadily lower. There is considerable uncertainty about a number of pieces of theoretical input, in particular screening effects.

A new factor which may be important is collective effects in plasma which might change the theoretical predictions and improve the agreement with experiment.

3. Experiments

3.1 Four experiments

There are four experiments which have directly measured solar neutrinos. Three are radiochemical where a neutrino gives a (ν, e) reaction and the element created then decays. For chlorine, ^{37}A is formed and decays with a half-life of 35 days, by emitting an electron of 2.8 keV. Ray Davis led a pioneering experiment which observed such a decay and thus should be congratulated for being the first to observe solar neutrinos directly. The two gallium experiments, SAGE and GALLEX, observe the decay of ^{71}Ge with a half-life of 11.4 days which gives either a single electron of 10 or 1.3 keV (K-shell or L-shell respectively) or a low energy electron (1.1 or 1.2 keV) plus x-rays from the K-shell decay. Since the gallium threshold is low, 0.2 MeV, this means that these experiments are measuring neutrinos from the basic p – p reaction.

The fourth experiment is performed by Kamiokande with a 300 ton water Cerenkov detector, and observes neutrino – electron scattering. The background is high but a distinct peak is seen towards the direction of the Sun — this is the only experiment which has such a directional signal.

In total, it is clear that solar neutrinos are being observed and measured.

3.2 Can an experiment be wrong?

I was brought up in the Rutherford school where experimental results were everything and had to be trusted — this is a comforting belief. However, it took some time and experience for me to realise that not all experimental results are correct. For example, several experiments in different laboratories found evidence for the existence of a 17 keV neutrino and papers were written which used it to explain the solar neutrino problem. However, second generation experiments found no effect, the original proposers then found mistakes in their own experiments and retracted, so it is now agreed that there is no 17 keV neutrino [30].

It is not uncommon to have a situation where there is disagreement between theory and an experiment, and where the theory is well-established on the basis of a large number of experiments. It is often useful to apply Ockham's razor [31], and to decide that the simplest solution is to consider that one experiment is incorrect while the large number of experiments on which the theory is based are correct — ^{6}He is an example.

For pioneering neutrino experiments, it has often been observed that the numerical value found did not stand the test of time, and frequently needed serious modification. This does not take away the credit of being a pioneer from the experimenters, but does suggest that some caution should be used in dealing with pioneering numerical values.

3.3 Is there a variation of the neutrino flux with the solar cycle?

It has been claimed that there are significant fluctuations of the neutrino flux measured in the chlorine experiment and these were identified as correlating with the inverse of the sunspot activity. It was said this was a five standard deviation effect.

As explained in Section 2.3, this periodicity of some ten years appeared to be in contradiction with other knowledge.

Apart from graphs, it was said that the rates at the solar minimum of solar cycles 21 and 22 were 4.1 ± 0.9 and 4.2 ± 0.7 while at the solar minima, they were 0.4 ± 0.2 and 1.2 ± 0.6. The value of 0.4 ± 0.2 for the runs 61 to 66, that is, a year's running, is surprisingly low — it can be compared to the average value from 1970 to 1992 [32] of 2.55 ± 0.25 SNU and it can be seen that the difference is 2.15 ± 0.30, which is a seven standard deviation effect for this year alone. If this year is compared with the average for the period 1986 – 1988 to 1992 – 1994 when the rate has been given [33] as 2.81 ± 0.38 SNU (but according to a graph in Ref. [32], may be 2.9 SNU now), then the difference is 2.41 ± 0.38 SNU which is again some six (or seven) standard deviations.

It should also be noted that after two years running the chlorine experiment was reported [34] to have an upper limit of one SNU — again this seems in contradiction with either of the values 2.55 ± 0.25 or 2.81 ± 0.32 SNU.

Now the Kamiokande experiment has been running since 1987 and no evidence of any significant variation of flux has been found, not with the solar nor on any other time scale. Furthermore they have not observed such low values as the chlorine experiment claims.

Given that the neutrinos are of approximately the same energy, as shown in Section 2.10, there appears to be a contradiction in the results.

There is a choice:

(a) Assume that the Kamiokande results are wrong. As the experiment is performed by a powerful well-funded group who appear to have carried out many checks, this seems unlikely. Also if one assumes there is a cycle of period 10 years, then one needs a miracle, because as is explained in Section 2.3, the normal time is more like 10^7 years. Such explanations seem to be missing.

(b) Assume that the Kamiokande experiment result is correct and that there are intermittent problems with the chlorine experiment. This would not then require any unusual theoretical explanations.

Once more, as a result of wielding Ockham's razor, solution (b) seems by far the more likely.

Thus it is concluded that the evidence in favour of problem number two, of large fluctuations of flux with a period about that of the solar cycle, is 'not compelling' and indeed is very unlikely.

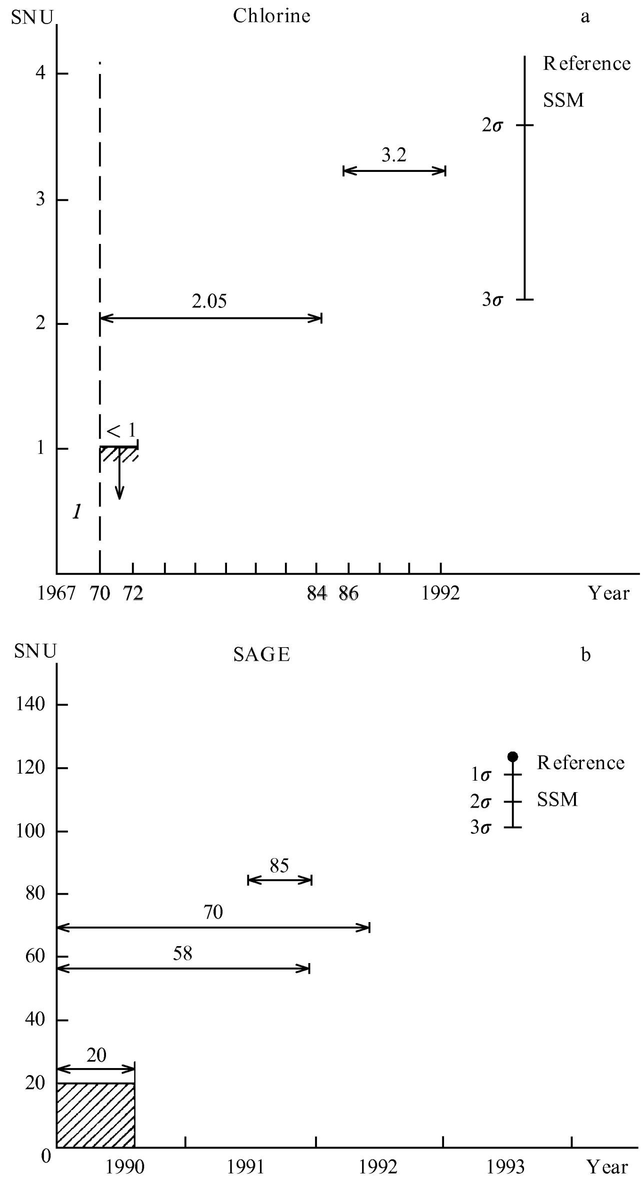

Figure 8. Variation of the measured solar rate in SNU as of March 1994, for (a) the chlorine experiment, (b) the SAGE experiment. A com-parison is made with Turck-Chieze and Lopez [9] as reference model.

3.4 The chlorine neutrino rate

There have always been some unexpected features of the SNU rates quoted by the chlorine experiment. The first few years' data, 1967 – 1970, were eliminated as it was found that the background could be greatly reduced by using a fast rise of the pulse as a selection to reduce background which would give a slow rise of the pulse in the counter for a passing cosmic ray. In 1972 the value given [34] was an upper limit of one SNU. Over the period 1970.8 to 1984.3, the average rate [33] was 2.08 ± 0.25. At this time there was a stop due to pump failures. From 1986.8 to 1992.4, the rate was 2.81 ± 0.32 [34]. These rates are shown graphically in Fig. 8a. The graph looks like a learning curve.

Also on Fig. 8a are the predictions of the Turck-Chieze and Lopez model where 2σ and 3σ are the two and three standard deviation values. It may be seen that the data for the last five and a half years are not incompatible with this model calculation.

If instead the conservative reference rate of 4.8 ± 1.1 SNU recommended in Section 2.9 had been taken, then the difference of 2.25 ± 1.1 SNU is about two standard deviations. It may be noted that this is rather less significant than the 14 standard deviations proposed by Bahcall et al. in Ref. [4].

The essential difference is that if one assumes the fluctuations claimed do exist, it is concluded that the experiment has some normal and some intermittent low values, so that the average is low. These fluctuations seem to have been reduced after the shutdown for the pump valves. But the conclusion is that while the chlorine experimenters can be praised for being the first to observe solar neutrinos, the balance of their data suggests that there have been some intermittent problems in achieving consistent rate measurements (this would account for the fluctuations claimed), so that on averaging, systematic low values are obtained. In other words, the experimental data indicate that it is not entirely safe to use the chlorine data before the 1984 – 1986 shutdown.

3.5 The Kamiokande experiment

The Kamiokande group have presented very consistent results which have been carefully checked.

However, when they first presented their results, these appeared to show a major significant disagreement with the model. They were given as:

(Data)/(SSM) $= 0.46 \pm 0.08$.

Expressing this as

Data $-$SSM $= 0.54 \pm 0.08$

this would appear to indicate about a 7 standard deviation effect.

Here the SSM was taken from the 1988 paper of Bahcall and Ulrich [24] who gave 7.9 SNU with an 11% error. But the above calculation only considers the experimental error of 17% and neglects the theoretical error. If this theoretical error is now included, one obtains:

Data $-$ SSM $= (1.00 \pm 0.11) - (0.46 \pm 0.08) = 0.54 \pm 0.15$, which is about 3.6 standard deviations.

If one now were to take the 1988 value of Turck-Chieze et al. [16] of 5.8 SNU with an error of 22%, then the ratio of 0.46 found becomes 0.70 and

Data $-$ SSM $= (1.00 \pm 0.22) - (0.70 \pm 0.11) = 0.30 \pm 0.24$ and this is not significant as it is less than 1.3 standard deviations.

This shows the importance of including all errors, theoretical as well as experimental.

More recent data from 627 days of running Kamiokande III with higher efficiency and lower threshold have given

(Data)/(SSM) $= 0.54 \pm 0.85$,

where the SSM is again the 1988 Bahcall and Ulrich value.

If, instead, all the errors are included and the 1992 Turck-Chieze and Lopez value [9] is taken, then the difference is 1.5 standard deviations.

The most recent value [35] for 1670 days, from January 1987 to July 1993 is:

$$\left(2.89^{+0.22}_{-0.21}\right) \times 10^{6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ ,$$

and this is about half a standard deviation away from the reference value of $(3.3 \pm 0.8) \times 10^{6}\ \mathrm{cm}^{2}\,\mathrm{s}^{-1}$.

Note, they also express their result [35] as (Data)/(SSM) $= 0.54 \pm 0.04 \pm 0.06$ where the SSM is now the Bahcall and Pinsonneault value [22] and there the important theoretical error has not been included nor the lower S_{17} value. These errors perhaps explain why Bahcall et al. [4] state "the ^{8}B flux in the five well-calibrated solar models is between 4σ and 6σ from the Kamiokande result" which is in contradiction with the half σ difference calculated above.

3.6 The SAGE experiment

The Soviet American Gallium Experiment, SAGE, first ran in 1990 when runs during the months of January, February, March, April and July were considered acceptable. The result [36] of 20 SNU with an upper limit of 72 SNU created great surprise. This could be considered major evidence for a new solar neutrino flux problem — now at low neutrino energy. However, the value was so low that it was inconsistent with all models and even with a very minimal calculation which takes the luminosity and assumes it comes from the p – p reaction. It is interesting to consider the raw results for each of the five months separately – they are shown in Fig. 9. In this figure are marked the 1τ, 2τ, and 3τ values where τ is the ^{71}Ge half-life of 11.4 days. One expects a flat background and a falling count rate from ^{71}Ge decays, but inspection of the five plots does not show this. Indeed, three of the months (January, April and July) show negative rates but it was decided that negative rates were unphysical and hence the rates were given as zero — whereas many would consider that statistical fluctuations were possible and negative numbers should be accepted — in this case the 5 months' combined data appear to have a zero SNU rate. The month of February was also unusual in that a single count was recorded on the first day and no further counts were recorded for the subsequent 61 days. Later the data were re-evaluated and the rates for February and March were increased to 94 and 109 SNU respectively whereas the other three runs were kept at zero SNU. A second re-evaluation [36] now gives 80 and 100 SNU and a total for the five runs of 40^{+31}_{-38} SNU. Although this appears to double the rate, it is quite within the errors (the re-evaluation involved changing the acceptance windows in the plot of rise time versus electron energy).

Further runs in 1991 and 1992 gave values of about 85 SNU and the known results in March 1994 are summarised in Fig. 8b — again there would appear to be a learning curve.

However, in May 1994 a new data set was presented [36] with values for 1991, 1992, and 1993, of (100^{+31}_{-38}) SNU, (62^{+29}_{-27}) SNU, and (76^{+26}_{-19}) SNU giving a combined value for 1990 to 1993 of 74^{+13}_{-12} (stat.) $^{+5}_{-7}$ (syst) SNU.

As there is no longer any need for an explanation for the abnormally low values (upper limit of 72 SNU) found in the pioneering run in 1990, it is not necessary to wield Ockham's razor and suggest that the run be ascribed to a learning period and with the greater data sample; one can now simply accept the value of ^{51}Cr SNU.

The SAGE experimenters plan to insert a ^{51}Cr neutrino source later in 1994 to check.

3.7 The GALLEX experiment

The GALLEX experiment is a strong well-funded collaboration operating under almost ideal conditions at Gran Sasso. The two sets of runs give [37] almost identical

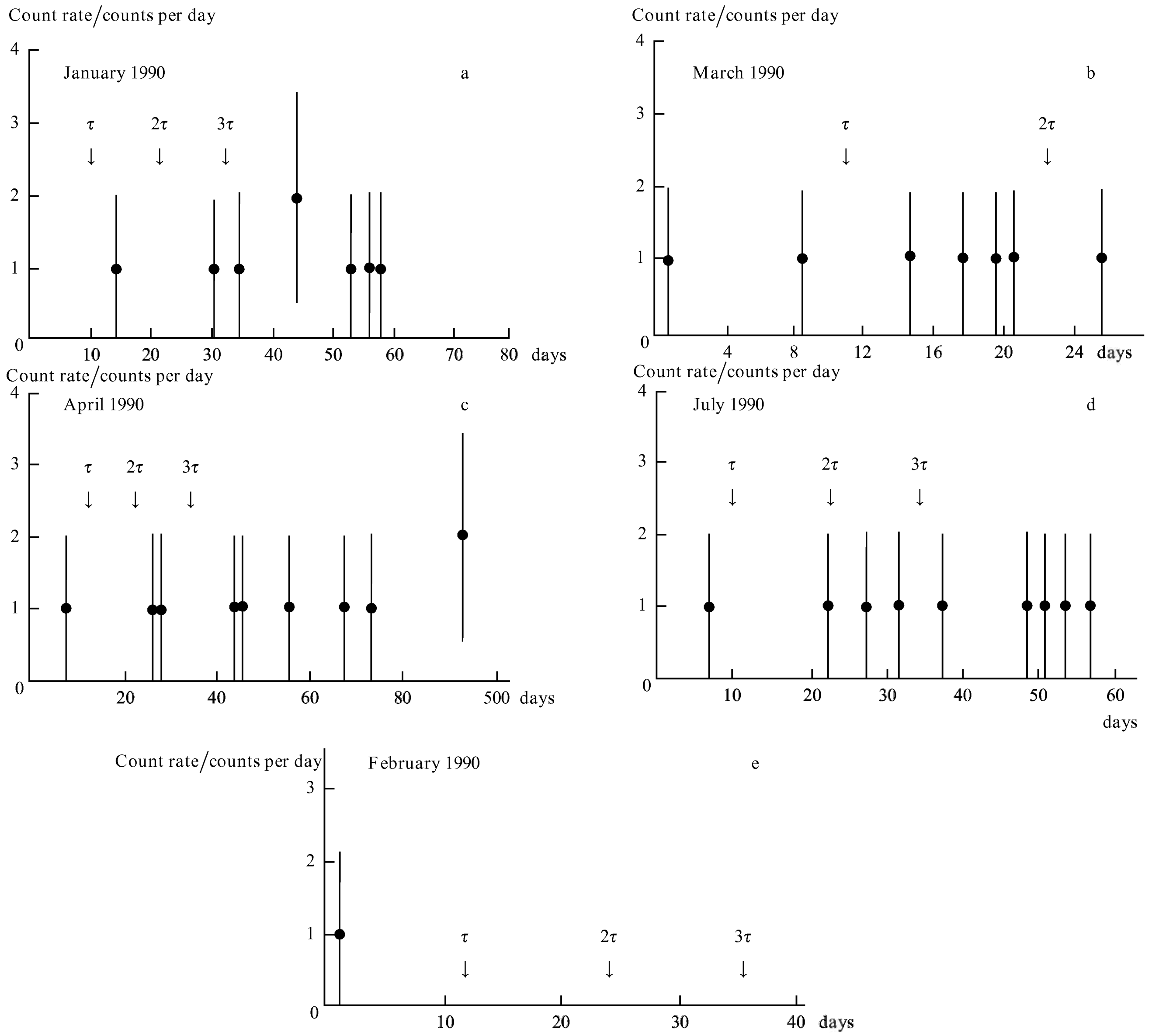

Figure 9. Counts recorded by the SAGE Collaboration during their accepted five runs in 1990. The arrows correspond to one, two and three half-lifes, τ, of 11.4 days.

rates (81 and 78 SNU) giving an average of $79 \pm 10 \pm 6$ SNU.

Although they have only 30 tons of gallium, they can measure electrons not only of 10.3 keV as at SAGE, but also electrons of 1.1, 1.2, and 1.3 keV which gives them a relatively high counting rate. A very commendable feature of the experiment is that they have performed many (19) blank runs.

As they find fewer than all solar model calculations suggest, an important check will be a control with a neutrino source. At the end of June, it is intended to insert a ^{51}Cr source of a megacurie into the detector.

3.8 Comparison of gallium experiments with models

If the GALLEX experiment is compared with the reference model value of 122.5 ± 7 SNU given in Section 2.9, then the difference is 2.9 standard deviations. For SAGE the effect is similarly about three standard deviations. Thus for low energy neutrinos, the evidence is ‘not compelling’, but it is close to becoming interesting and the results of the tests with the ^{51}Cr source are eagerly awaited. However, the choice of the best theoretical value is still uncertain and a resolution of the Bahcall–Dar difference is necessary.

4. Conclusions

(1) The experiments are difficult and the statistics are often very small.
(2) There are indications of experimental learning curves.
(3) The second problem of a possible fluctuation with the period of a solar cycle of about ten years appears excluded.
(4) There are experimental indications of intermittent low flux measurements in the chlorine experiment before 1985 and this makes the flux values unsafe for this period.

(5) The neutrino flux from each of the four experiments is not by itself significantly different from the best available model values, though the gallium experiments are being followed attentively.
(6) The difference between theory and models is steadily vanishing with time.
(7) All experiments give lower values than the model values. There are still considerable uncertainties in the models — one possible explanation could be coherence effects with plasmas, but this needs much further study before any firm conclusion can be drawn.
(8) Today, evidence for any of the three possible solar neutrino problems is ‘not compelling’.
(9) Better statistics, which are certainly coming with second generation experiments, would be welcome. Apart from any solar neutrino problem, the Sun is the only star near us and it is important to study it as thoroughly as possible.

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References

1. Morrison D R O *International Conference on High Energy Physics* (Eds K K Phua, Y Yamaguchi) (Singapore: World Scientific, 1990) 676–680; *Particle World* **3** 30 (1992); *Intl. J. Mod. Phys.* **D1** 281 (1992); CERN-PPE/93-196; XXIII International Symposium on Multiparticle Dynamics, Aspen, Sept. 1993; 3rd Nestor Workshop, Pylos, October 1993
2. Kovetz A, Shaviv G *Astrophys. J.* in press
3. Dar A, Shaviv G *Phys. Rev. Lett.* in press
4. Bahcall J N et al., E-mail; Inst. for Adv. Studies, Princeton preprint, IASSNS-AST 94/13
5. Dar A, Shaviv G, E-mail; Technion preprint
6. Schwarzchild M et al. *Astrophys. J.* **125** 233 (1957)
7. Turck-Chieze S et al. *Phys. Rep.* **230** 57 (1993)
8. Bahcall J N *Neutrino Astrophysics* (Cambridge: Cambridge University Press, 1989) p. 319
9. Turck-Chieze S, Lopez I *Astrophys. J.* **408** 347 (1993)
10. Roberts F J, Inglesias C A *Astrophys. J. Suppl.* **79** 507 (1992)
11. Courtaud D et al. *Solar Phys.* **128** 49 (1990)
12. Sonagalia et al. *Nature (London)* **368** 599 (1994)
13. Anders E, Grevesse N *Geochim. Cosmochim. Acta* **53** 197 (1989)
14. Tsytovich V N et al., ‘‘Collective plasma effects in the radiative transport in solar interior’’, in *Proceedings of the International Topical Workshop on Solar-Neutrino Problem* (Eds V Berezinsky, E Fiorini) (Gran Sasso, 1994)
15. Johnson C W et al. *Astrophys. J.* **392** 320 (1992)
16. Turck-Chieze S et al. *Astrophys. J.* **355** 415 (1988)
17. Kavanagh R W et al. *Bull. Am. Phys. Soc.* **149** 1209 (1969)
18. Filippone B W et al. *Phys. Rev. Lett.* **50** 412 (1983); *Phys. Rev. C* **28** 2222 (1983)
19. Baldini A, Flaminio V, Morrison D R O, Moorhead W G ‘‘Total cross sections for reactions of high energy particles’’ *Landolt-Bornstein New Series* **12a**; **12b** (1987); Ezhela V V et al. ‘‘Electron-positron interactions’’ *Landolt-Bornstein New Series* **14** (1992)
20. Particle Data Group *Phys. Rev.* **D45** (11) Part II (1992)
21. Motobayashi T *Phys. Rev. Lett.* (1994) (in press)
22. Bahcall J N, Pinsonneault M H *Rev. Mod. Phys.* **64** 885 (1992)
23. Russager K, Jensen A S Aarhus preprint, IFA-93-1 (1993)
24. Bahcall J N, Ulrich R K *Rev. Mod. Phys.* **60** 297 (1988)
25. Noerdlinger P D *Astron. Astrophys.* **57** 407 (1977)
26. Shaviv G (private communication)
27. Bahcall J N, Inst. for Adv. Studies, Princeton preprint IASSNS-AST 93/69 (1993)
28. Garcia A et al. *Phys. Rev. Lett.* **67** 3654 (1991)
29. Liebrecht K G, Woodward M F *Nature (London)* **345** 779 (1990)
30. Morrison D R O *Nature (London)* **366** 29 (1993)
31. William Ockham (c 1280–1349), ‘‘Pluralites non est ponenda sine necessitate’’, translated by the *Encyclopaedia Britannica* as ‘‘Multiplicity ought not to be posited without necessity’’ or more colloquially, ‘‘Don’t assume New Physics if known ideas will explain’’
32. Lande K Conference ‘‘Neutrino 94’’ (Eilat, May 1994)
33. Lande K February 1994 (private communication)
34. Ref. [8] p. 319
35. Suzuki Y Conference ‘‘Neutrino 94’’ (Eilat, May 1994)
36. Gavrin V N et al. (SAGE) *Phys. Rev. Lett.* **67** 3332 (1990)
37. Gavrin V N (SAGE) Conference ‘‘Neutrino 94’’ (Eilat, May 1994)
38. Anselmann P et al. (GALLEX) *Phys. Lett.* **B327** 377 (1994)
39. Christensen-Dalsgaard J ‘‘Seismology of the Sun and Sun-like stars’’ (Ed. E J Rolfe) ESA SP-286, 431 (1988)