VARIATIONS OF NEUTRINO FLUX FROM THE SUN

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ABSTRACT

It is suggested that very large solar flares and possibly phenomena in convective layers of the sun contribute to most of the observed flux of solar neutrinos. The steady flux from the core is at a barely detectable level (<1 SNU at 98% confidence level).

INTRODUCTION

We examine here the possible time variations indicated by the measured electron neutrino flux (ν_e)[1] from the sun. It is presumed in this analysis that all of the recorded electron neutrino flux, after correcting for cosmic ray background, is of solar origin. It is well known[2] that even under this assumption, the recorded flux is about a factor of three or four, below that expected from thermo nuclear reaction chain in the solar core on basis of the so-called 'standard' solar model[3]. There are several ideas put forward to explain this discrepancy, one of them being the instability of the ν_e *i.e.*, the ν_e changes its identity to other types of neutrinos on its path from the sun to the earth[4].

A more basic question addressed to the experimental result itself is whether the obtained data are compatible with the hypothesis of a steady flux of neutrinos. If there are indications of its variation, a new dimension to the subject will be added making untenable many of the ideas advanced to explain the low value of the flux from the sun.

ANALYSIS OF POSSIBLE TIME VARIATIONS IN THE RECORDED NEUTRINO FLUX

In figure 1 is shown the presently available data on the solar neutrino flux[5]. Each of the individual measurements has large error due to the small number of radioactive Ar atoms collected and their decay counted from an exposure for ~50 days. However, there is a correlation of the errors to the central values measured as shown in figure 2. The quoted mean for the set of 43 data points is 0.447 ± 0.05 atoms per day. The error represents a $\sigma = 0.32$ for the central value of measurement at 0.447 assuming that errors shrink as $\sigma/\sqrt{n-1}$ with $n=43$. This agrees with the $\langle\sigma\rangle = 0.33 \pm 0.03$ for the boxed set of data points in figure 2 corresponding to an average central value of 0.45. Therefore, we use a $\sigma(\text{expected}) = 0.33$ for the hypothesis of a constant flux of 0.45 in evaluating the χ^2.

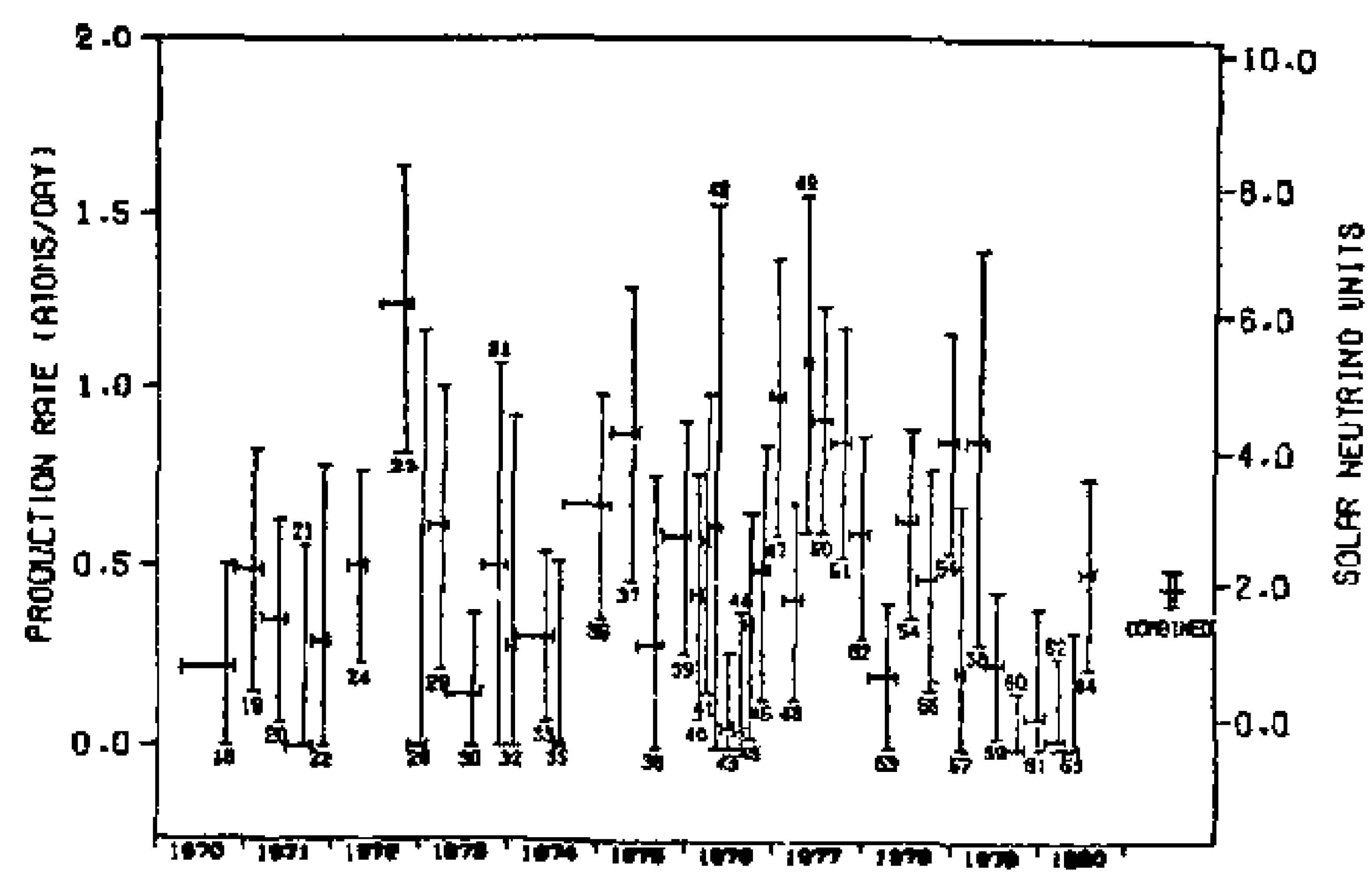

Figure 1. The distribution of measured flux of ν_e through the reaction $^{37}Cl(\nu_e, e^-)^{37}Ar$ by Davis, *et al.*, which is currently available[5]. The ordinate represents *β-active Argon atoms produced per day of exposure* of the tank containing chlorine atoms[1].

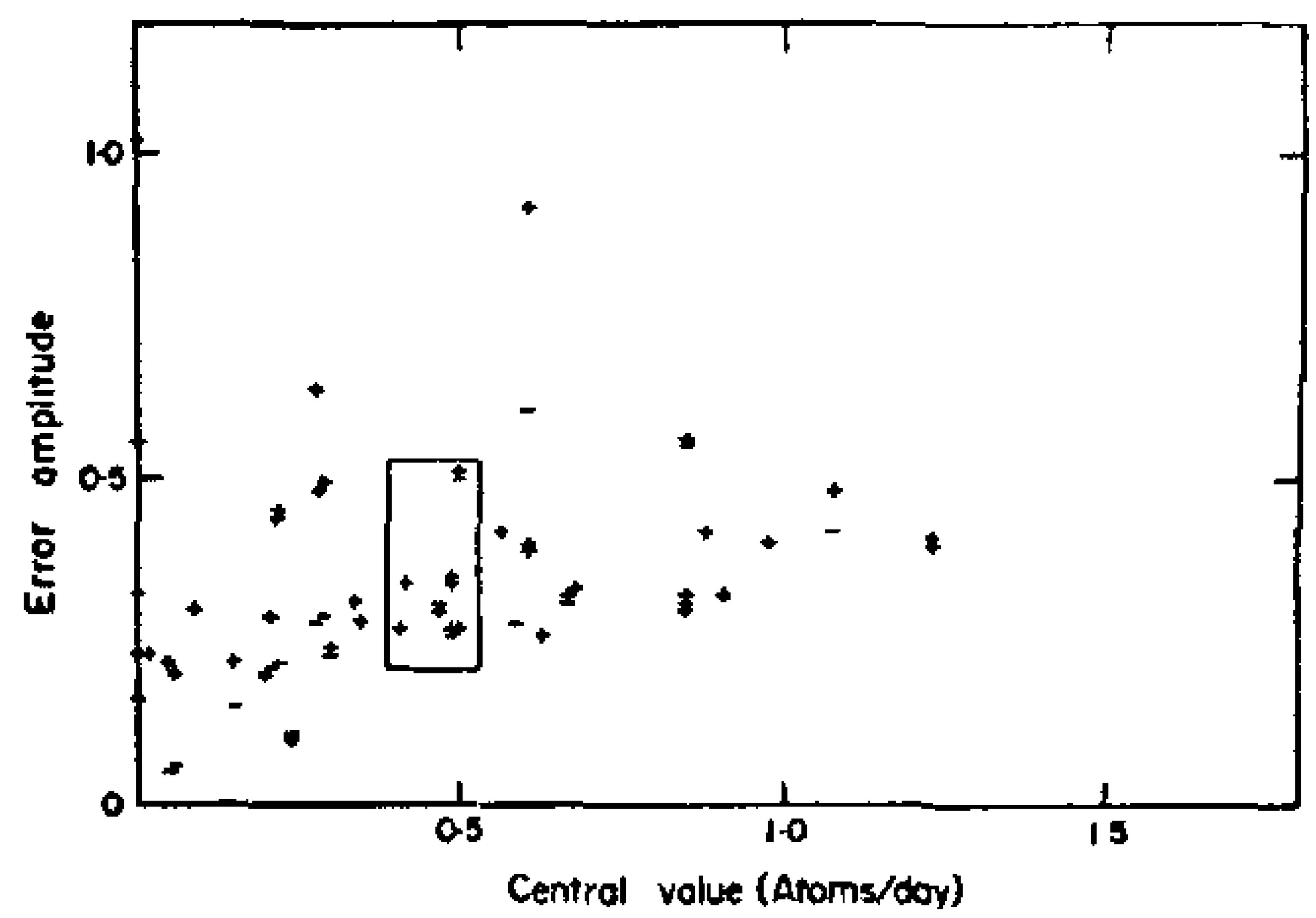

Figure 2. A scatter plot of the error bars versus the central value registered taken from figure 1. The + and − indicate positive and negative deviations in cases where they are different. Only + is plotted for cases of symmetric deviations. The boxed area represents errors that are averaged for the central value of 0.45 atoms/day which is the global mean shown in figure 1.

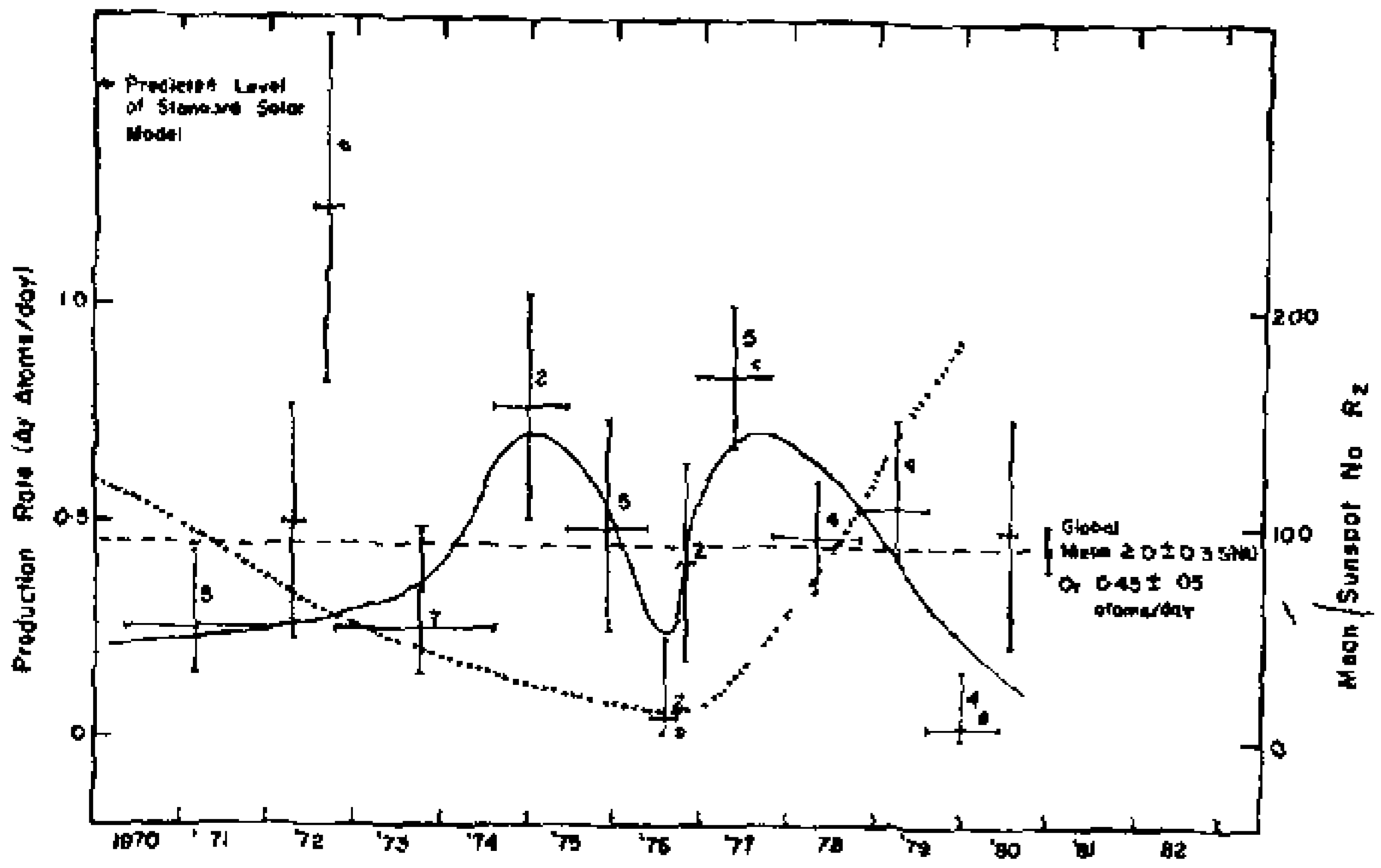

Figure 3. The data of figure 1 reduced to 13 points by averaging of adjacent measurements. The number close to the error bars indicate the number of sequential measurements used in the averaging, if greater than one. The points 'a' to 'd' are abnormally deviated from the mean steady rate indicated by the dashed line. The full line curve is a free hand sketch of possible time variation as indicated by the fluctuating points except 'a' which is attributed to the occurrence of a large solar flare. Portions of sunspot cycles 20 and 21 are shown by the dotted line.

If one takes a summed χ^2 value, one obtains 40.6 for the 43 data points representing 42 degrees of freedom which is a fairly reasonable fit to the hypothesis of a steady neutrino flux at the mean value with a confidence level of 50%. However, the above test does not recognise correlations between adjacent data points. If the data points vary purely statistically, any sequentially averaged set of data points with quadratic compounding of errors should not degrade the quality of fit to the steady flux hypothesis. It appears that one set of such sequentially averaged data points (figure 3) is not compatible with the hypothesis of a steady neutrino flux.

There are four data points in figure 3 deviating from the mean expected by about 2 or more standard deviations given by $0.33\sqrt{n}$ where n is the number of measurements averaged in the group. These are marked 'a' to 'd'. The overall χ^2 for the 13 data points is 28.4 which makes the hypothesis of steady flux improbable. For the 12 degrees of freedom this χ^2 represents 0.3% probability. There is another way to look at the deviations shown in figure 3. One expects 4.6% probability for a deviation more than 2σ in a normal distribution of the measured values. One should expect not more than one data point among the 13 in figure 3 to exhibit at 2σ or more deviation. We have here in all 3 excluding point 'b' which is just under 2σ. In the absence of any systematically accountable effects in the experiment which affects a sequence of independent measurements (for example the point 'd' represents the averaging of a string of 4 sets of data points), the variations seen in figure 3 must be attributed to variations in the source.

Test of Significance of the Correlations with Randomly Generated Data

In figure 4 we show a set of data points generated by a flat distribution of fake 'events' using a computer to randomise the 'events' into 49 bins. The grouped averages shown in figure 5 for this distribution exhibit the usually expected behaviour. Just one point out of the 10 shows a 3 standard deviation effect. The χ^2 for the 9 degrees of freedom is 16.1 giving 8% as the probability of compability with a constant 'event' rate which is the input in the beginning.

It may be mentioned here that in figure 5 equal number of data bins taken from figure 4 have been averaged to show the agreement with the constant

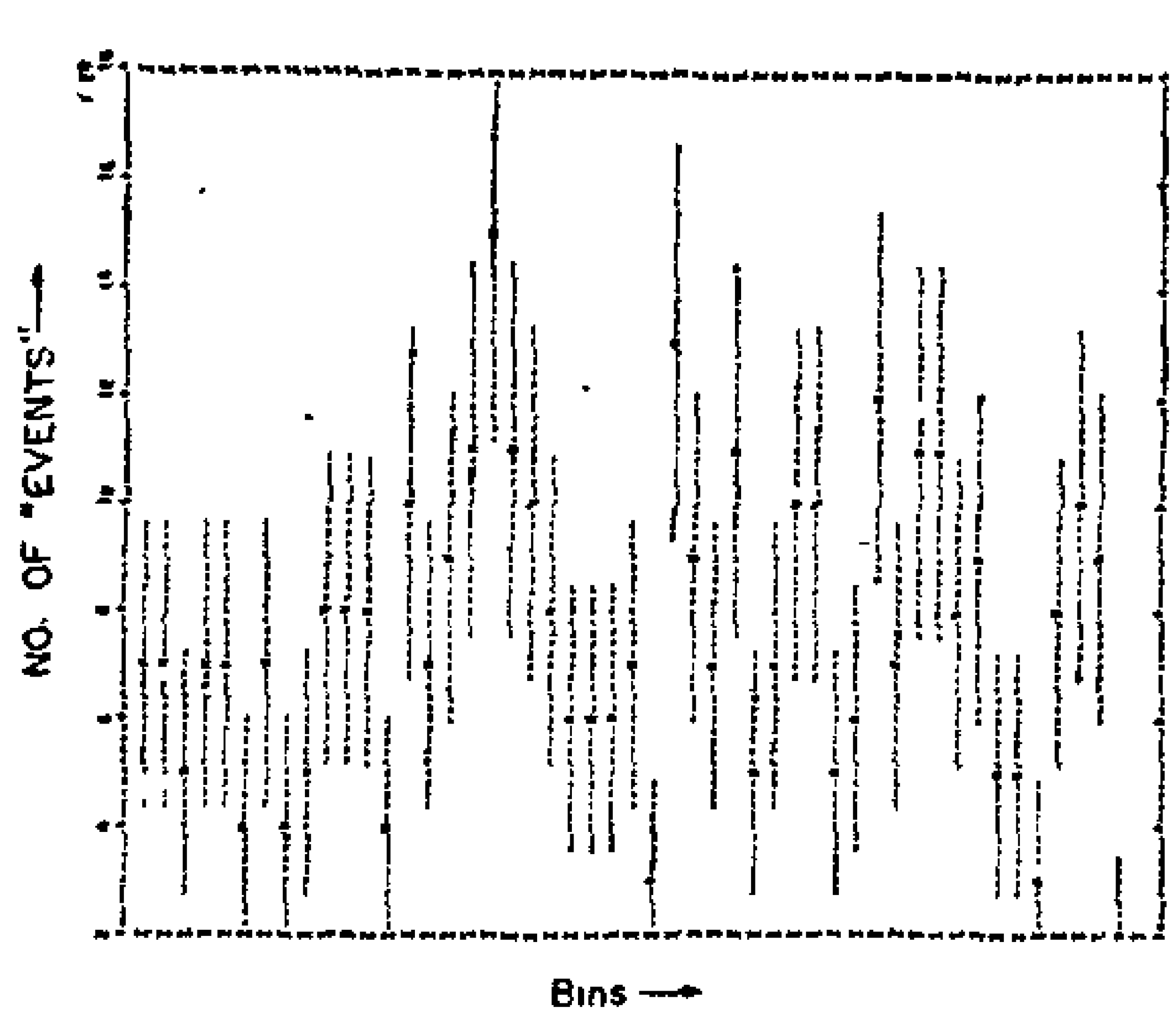

Figure 4. A computer generated flat distribution with an average per bin of 7.6 'events'. Though the statistical fluctuations are large. Similar to those in figure 1, the adjacent bin correlations are quite different from the case of figure 1.

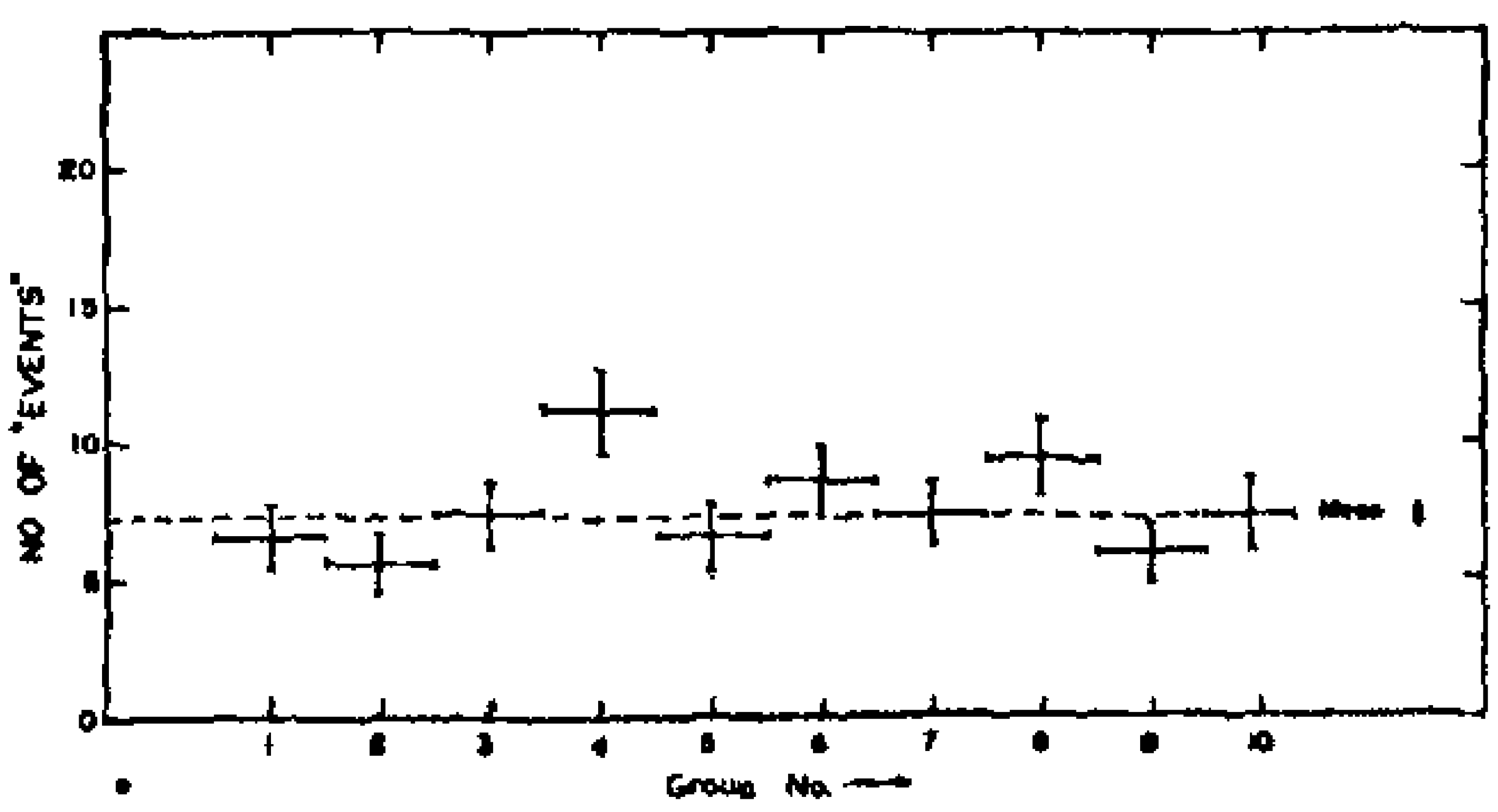

Figure 5. The adjacent bin averaged (usually 5 except the last which has 4) distribution of 10 data points from the 49 available in figure 4. There is only one data point deviating by 2 or more standard deviations. The entire distribution is as expected.

'event' rate hypothesis. Many other equal or unequal bin averaging can be resorted to. However, it has been found not feasible to create a set of averaged points somewhat strikingly similar to that obtained in the real data averages shown in figure 3 with unequal bin averaging. With no correlation allowed in generating figure 4, no striking patterns are expected no matter how the bin averages are taken. Obviously, the averaging process takes advantage of adjacent bin data correlation patterns. It is claimed through figure 3 that in the solar neutrino flux data (figure 1), adjacent bin correlations suggest overall time variations whose periods are ~ year or more, *i.e.*, larger than individual data gathering times of ~70 days. As remarked earlier, in the absence of a definite *a priori* hypothesis concerning the pattern of variations, resort to unequal binning has been made to reduce figures 1 to 3 in order to point out a possible pattern of variation. All we would like to point out by the above discussion is that any unequal bin averaging would not necessarily bring out a statistically significant correlations pattern out of truly uncorrelated data. We would get the pattern shown in figure 3 by merely examining the data points shown in figure 1 and arrive at the grouping scheme shown in figure 3 in one or two trials only. The chance that this pattern can be produced from the constant source following uncorrelated statistical fluctuations in data recording, is as stated earlier 0.3% from the χ^2 analysis.

Possible Physical Mechanisms Causing Variation of the Solar Neutrino Flux

In an earlier note [6] an attempt was made to relate the variations of solar neutrino flux to solar activity, *i.e.*, sunspots and solar flares. Although there is no theory as yet of mechanisms of neutrino production associated with solar activity, the correlation sought was purely empirical with certain additional motives not discussed here. There have been references to thermonuclear phenomena[7] in solar particle flares. The recently discovered γ-ray lines from solar flares indicate a variety of nuclear reactions taking place there[8]. In the earlier analysis, it was noted that deviation of point 'a' could be ascribed to one of the largest solar flares in the last two decades which produced cosmic rays besides other effects[9]. In fact, this was the major correlation with solar neutrino flux one could isolate easily when one compares[6] the geomagnetic indices* of the flares.

* It is not clear what the correct index is for best correlation with total energy release in a flare. Polar cap absorbption (PCA) seems to be the strongest of all the various indices characterising the August 4, 1972 event[9].

It is important to note that only the very large solar flares which accelerate protons to relativistic energies could perhaps contribute to a detectable perturbation in the recorded neutrino flux as shown in Appendix I. These large flares occur[9] at a rate of the order of not more than a few per 11 year solar cycle. The correlation with the flares in the earlier work[6] was sought with this criterion of large flares in mind. It has been pointed out in Appendix I that neutrino generating mechanism from phenomena underlying the production of large fluxes has to be extremely efficient (by a factor ~10^5 or more) compared to the feeble Boron decay process embedded in the envisaged chain reactions listed in Appendix II. *A totally new neutrino emitting process is called for in the flare generating mechanism, if indeed some large solar flares can perturb the observed solar neutrino flux.* It is obvious that we have to go out of conventional nuclear physics framework to think of a suitable basic reaction process that could be responsible for the flare correlated neutrino flux variation.

There is a gross correlation of all solar flares with the sunspot cycle and there is no evident sunspot cyclic variation seen in figure 1 or 3. This has been pointed out by Lanzerotti and Raghavan[10]. In the earlier work[6] the possibility of phase shift in the solar activity cycle represented by the sunspot and the neutrino flux

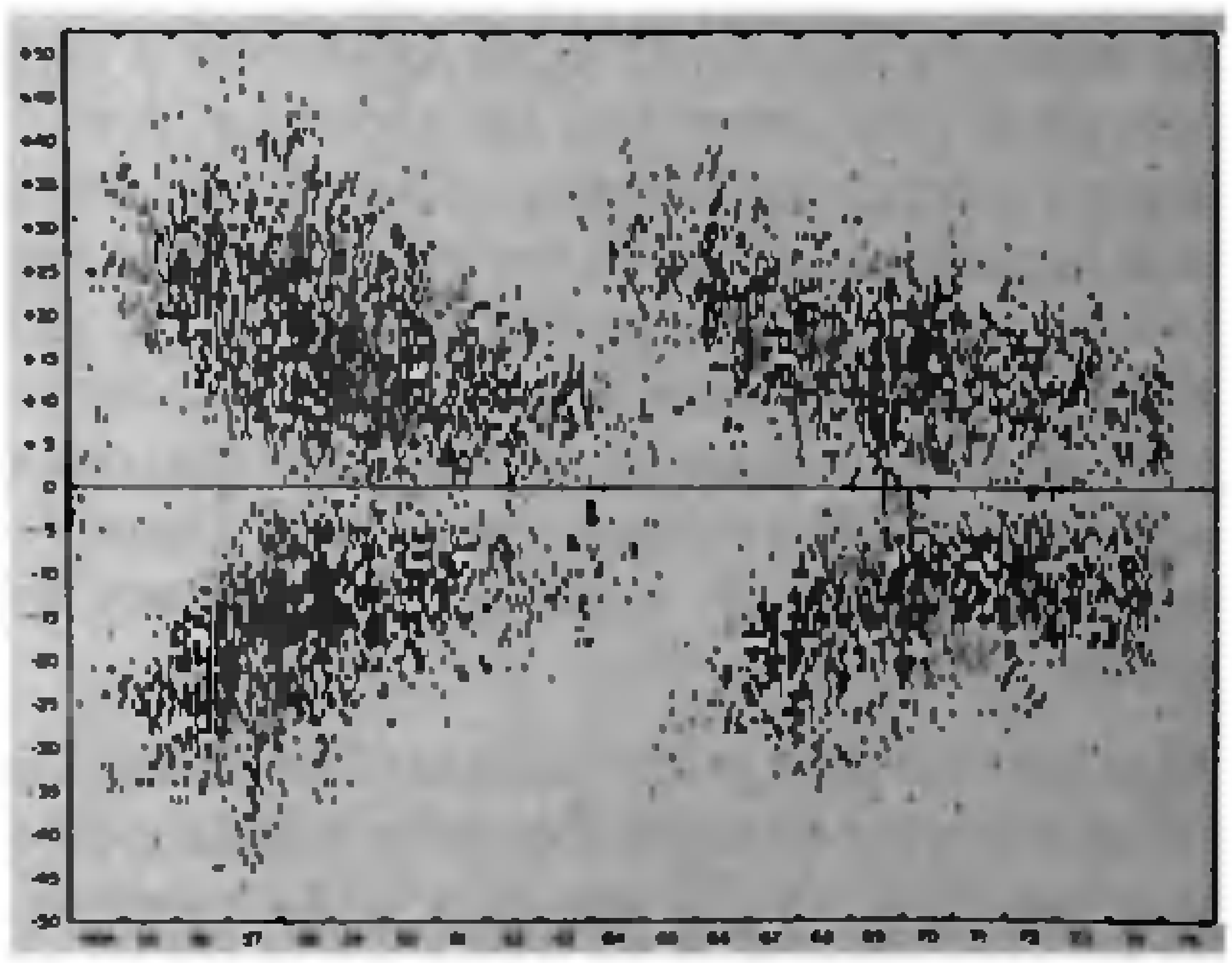

Figure 6. The 'butterfly' diagram of solar latitude distribution of sunspot groups as they progress through the years. The gross sunspot numbers go through a minimum at the region where there is the discontinuity in the lattitude. The old cycle sunspots disappear near the minimum and new spots of next cycle begin to appear at the higher lattitudes. The variation in neutrino flux suggested in figure 3 may have a broad enhancement correlated to this discontinuity. The discontinuity shown here for the previous cycle 20 occurred in 1964 and would correspond to a similar discontinuity in 1976 for the cycle 21 applicable to figure 3.

APPENDIX I

The energy release in large solar particle flares where relativistic protons are accelerated and ground level effects are seen (GLE events) is typically $\sim 10^{32}$–10^{33} ergs, or $\sim 10^{38}$–10^{39} MeV. We can expect neutrino generation at not more than one neutrino for every 10 MeV of energy release as an extreme limit which puts upper limits of $\sim 10^{37}$–10^{38} neutrinos leading to an integrated flux at the earth of 10^{10}–$10^{11}/cm^2$ in ~ 100 secs. a typical duration for the intense portion of a flare. One can compare this to the steady flux of $10^{10.8}\ cm^{-2}.\ sec^{-1}$ for the pp reaction neutrinos from $10^{33.6}$ ergs. $sec.^{-1}$ energy output from the sun or $10^{6.7}\ \nu_e\ cm^{-2}.\ sec^{-1}$ from the 14 MeV Boron decay (see the envisaged chain reactions in Appendix II) expected in the standard solar model[3]. Since typical collection times are ~ 50 days (4×10^6 sec) in the Cl–Ar experiment[1], we need a highly efficient neutrino emission process underlying the flare mechanism in order that the monitored flux in the Davis *et al.* experiment can perceptibly be affected. For *e.g.*, the equivalent neutrino flux corresponding to point no. 27 in figure 1 has to be $\sim 10^{13}$ $cm^{-2}/(\sim 10^{40}$ at the sun) which would necessitate energy release in that event to be at least $\sim 10^{41}$ MeV or 10^{35} ergs. Flares with energy output substantially less than the above, though they may occur more often, are unlikely to perturb the recorded neutrino flux in the above experiment. Triggering of the neutrino efficient process, whatever that may be, probably does not occur in every flare.

data was envisaged because sunspots are presumably manifestations of convective layer activities just below the photosphere. If we remove the point 'a' as flare affected, the remainder of the points are barely compatible with a steady flux. The χ^2 for the 11 degrees of freedom drops to 22.8 and yields a probability of 1.5% for the steady flux hypothesis. These 12 points could exhibit a 11 year cyclic variation with a broad peak around the year 1977 which is 3 years earlier than the peak of sunspot cycle 21. This 3 years of advanced phase tantalisingly corresponds to the discontinuity in solar latitude seen in the 'butterfly' diagram of sunspot occurrences[11] (figure 6). In order to establish any such correlation of the neutrino flux conclusively, one needs prolonged observations over at least two decades covering two solar cycles.

SUGGESTION OF A LOW STEADY NEUTRINO FLUX FROM THE SUN

The significant result one would like to infer from figure 3 is based on points 'b' and 'd' which indicate that during certain periods the neutrino flux is consistent with being zero. In fact, it was suggested in the earlier analysis[6] that the 'quiet sun' flux could be near zero. The average value for points 'c' and 'e' is $0.04 \pm^{0.11}_{0.04}$ which is consistent with zero since the cosmic ray background is expected to be 0.08 ± 0.03. The difference of $-0.04 \pm^{0.11}_{0.04}$ sets an upper limit of 1 SNU (0.18 atoms/day*) at 98% confidence level.

If, in fact, there are periods (of the order of one year for data point 'd') during which neutrino flux plunges to zero, it indicates that any steady component of neutrinos from the sun must be barely detectable.

Thus, there will be room to assume that the thermonuclear chain in the solar core, which presumably cannot change in time scales less than $\sim 10^6$ years[12], does not progress up to the 'B' decay level (see Appendix II) at a sufficient rate. That could indicate lower core temperatures and unburnt He^3 diffusing from core to envelope regions, as has been suggested in the literature[13].

On the basis of the variations seen in figure 3, we are forced to ascribe the fluctuating neutrino flux to happenings in the convective zones in the sun, since the time scale of changes in the core regions are usually expected to be millions of years[12]. However, a model due to Hoyle[14] envisages fast convective motions in the core and only as little as 0.5 SNU of steady neutrino flux from the core. There may be internal bursts of thermonuclear reactions in the convective zone with a 11 year periodicity. The depth at which these bursts occur can perhaps be decided from the phase relationship between the 11 year sunspot cycle and the neutrino flux variations at a later date when extended observations are available. However, we are not suggesting that it may be possible to generate from known thermonuclear reaction processes (Appendix II) adequate neutrino flux to be associated with any internal convective motion induced temperature fluctuations and enhanced reaction rates. We have already pointed out the need for a new extremely efficient neutrino generation process associated with an underlying mechanism of solar flares. The same reaction process might be involved in this suggested convective origin of neutrino flux also. It is not suggested that abnormally large temperature variations in convective process and conventional nuclear reactions alone could be responsible for the neutrino flux variations.

* This is in the detector of Davis *et al.*[1] 1 SNU = 10^{36} captures per ^{37}Cl atom in the detector per second.

Appendix II

The pp chain ending in He^4 with three alternate channels denoted as I, II and III below is supposed to take place in the solar core as follows[15] releasing neutrinos in some of them:

	Reaction	Neutrino energy (MeV)	Flux at earth cm^{-2} sec^{-1}	Capture rate in $^{37}Cl \times 10^{36}$ sec^{-1}
	$p(p, e^+ + \nu_e)d$	0–0.42	6×10^{10}	below threshold
	$p(p + e^-, \nu_e)d$	1.44	1.5×10^8	0.26
	$e^+(e^-)\gamma$	—	—	—
	$d(p, \gamma)\, ^3He$	—	—	—
I)	$^3He(^3He, p+p)\, ^4He$ (85%)	—	—	—
II)	$^3He(^4He, \gamma)\, ^7Be$ (15%)	—	—	—
	$^7Be(e^-, \nu_e)\, ^7Li$	0.86	4.5×10^9	1.31
	$^7Li\, (p, \alpha)\, ^4He$	—	—	—
III)	$^7Be\, (p, \gamma)\, ^8B$ (0.05%)	—	—	—
	$^8B(, e^+ + \nu_e)^8Be^*$	0–14	5.4×10^6	7.3
	$^8Be^* \rightarrow 2He^4$	—	—	—

Conclusion

In conclusion, evidence has been presented to show that the neutrino flux from the sun shows large variations, the minimum values touching zero indicative of a lack of detectable steady flux. The data points indicate a broad enhancement roughly in anti-correlation with sunspot cycle which goes through a minimum around 1976. The dip at point 'c' in 1976 is not yet compelling. If these results are indeed true, a modified scheme of nuclear burning chain in the sun which perturbs the standard steady state model would be called for. Certain solar transients connected with large solar flares or the 11 year cycle accounting for a fraction of the steady energy output of the sun seem to be efficient (by several orders of magnitude) generators of neutrino fluxes of energy $\gtrsim$ few MeV. A totally new nuclear process would perhaps have to be called for if the suggested neutrino flux variations are established.

Acknowledgements

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