

## A Statistically Significant Periodicity in the Homestake Solar Neutrino Data.

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(Received November 17, 1997)

Using the Empirical Mode Decomposition method developed by Huang, *et al.*, we have examined the time dependence of the solar neutrino fluxes measured by the Homestake <sup>37</sup>Cl experiment. Our analysis shows that a prominent feature in the Homestake data is the statistically significant peak found at a frequency of approximately  $0.1 \text{ y}^{-1}$ . A similar analysis has been applied to the Wolf Index on sunspot numbers. Possible correlation among the Intrinsic Mode Functions of the two analysed data sets can be achieved with a 3.5 year shift in phase.

PACS. 14.60.Pq – Neutrino mass and mixing.

PACS. 14.60.Lm – Ordinary neutrinos ( $\nu_e$ ,  $\nu_\mu$ ,  $\nu_\tau$ ).

### I. Introduction

Solar neutrinos have been detected by the underground neutrino experiments [1]. Those experiments, a triumphal achievement of mankind, have verified experimentally the fundamental concept of nuclear energy generation in stars. However, in interpreting these experimental results, we are confronted with two persisting solar neutrino problems: the deficit of solar neutrinos and the question of solar neutrino flux variation with time.

The deficit of solar neutrinos addresses the fact that none of these underground experiments has measured a solar neutrino flux as large as that predicted by the standard solar model (SSM) [2]. The current status can be summarized as [3]: "The measured solar neutrino fluxes,  $\phi(pp) \sim \phi^{SSM}(pp)$ ,  $\phi(^8B) \sim 0.4 \phi^{SSM}(^8B)$  and  $\phi(^7Be) \sim 0$ , where  $\phi^{SSM}$  denotes the SSM value of the solar neutrino flux." To explain such a discrepancy between experimental observations and the predictions of the SSM, new physics has to be put forward (for a review and references see [2]). One of the most promising solutions, concentrating on the properties of the neutrino itself, is the Mikheyev-Smirnov-Wolfenstein (MSW) matter mixing mechanism [4], in which a solar neutrino ( $\nu_e$ ) mixes with  $\nu_\mu$ ,  $\nu_\tau$  or  $\nu_x$  (or both) when traversing the sun. Hence solar neutrinos, the left handed  $\nu_e$ , may turn into a sterile form unseen by the underground detectors. Unfortunately, there is no convincing evidence for the existence of such a MSW effect anywhere other than those suggested by the solar neutrinos.

The question of the variation of solar neutrino fluxes with time is quite different, and has been considered to be an isolated controversial problem for quite some time. Speculative evidence for the existence of periodicities such as day-night, season-season, and the 11 year cycles, etc in solar neutrinos has been reported in literature, triggering many theoretical discussions and new experimental efforts [5]. The day-night and season-season oscillation have never received serious attention, presumably because, even if proven to be true, they could be explained in terms of neutrino oscillations or the MSW effect, etc. However, the possibility of having the solar neutrino capture rate oscillating according to an 11 year cycle, anti-correlated to the sunspot numbers, would be difficult to explain in the framework of the present standard theories. SSM suggests a steady rate of solar neutrino production with a time scale of billions of years. Evidence of correlation (or anti-correlation) between the  $^8B$  solar neutrino flux and the solar magnetic activity, if established, would have profound impact on both the understanding of the fundamental properties of the neutrinos and the constraints on the constructions of the standard solar model.

## II. Earlier treatments on solar neutrino time dependence

In 1986, Davis, et al compared the 5 point running averages of the  $^{37}Ar$  production rates in the Homestake data with the sunspot numbers and solar diameter measurements. A remarkable apparent anti-correlation was found between the measured solar neutrino fluxes and the solar activity during the onset of intense solar flares of solar cycle 21. In 1987, using  $\chi^2$  fitting and by scrambling the data points, Bahcall, et al. have analyzed the same data and concluded that statistically the anti-correlation with sunspot numbers is marginal and depends on a few low data points (for review of the subject see ref [5]). In 1991, in a second analysis, however, Bahcall, et al. concluded that the  $^{37}Ar$  production rate in the Homestake solar neutrino experiment is anti-correlated with the solar activity in the 1977-1989 region, but no significant correlation is substantiated in the early 1970-1977 region [6]. Using a maximum likelihood technique to analyze the Homestake data, Filippone and Vogel concluded in 1990 that [7]: "A capture rate anti-correlated with sunspot numbers gives a better fit to the data than a constant capture rate, but the goodness-of-fit for the two hypotheses is not significantly different. We also find that the statistical significance of the results are dependent on the confidence levels assumed for the very low capture rate runs." In 1996, Atsuto Suzuki, in a review paper for the 7th International workshop on Neutrino Telescopes [8], fitted the Data/SSM of Kamiokande taken between 1987 and 1995 to the sunspot numbers in the same period, and found that

$$\frac{Data}{SSM} = (9 \pm 7) \times 10^{-4} N_{sunspot} + (0.40_{-0.08}^{+0.09}).$$

He therefore concluded that there was no strong evidence for the existence of the anti-correlations.

The techniques of using maximum likelihood or Fourier analysis or a linear fit such as that of Suzuki, namely by fitting  $\frac{Data}{SSM}$  of the  $^8B$  neutrino fluxes in terms of the sunspot numbers can only be justified if:

- neutrino capture rates are linear and stationary,

- experimental data, covering long enough periods of time, are characterized by decent statistics and precision,
- solar magnetic activity is the only source capable of modulating the rate of production of the  ${}^8B$  neutrinos in the solar core.

It is clear that none of the above is true. In this paper, we present result obtained based on an analysis of the Homestake solar neutrino data with the Empirical Mode Decomposition method which has been shown to be sensitive to non-linear and non-stationary data.

### III. EMD analysis on the homestake data

We have examined the time dependence of the solar neutrino fluxes measured by the Homestake  ${}^{37}Cl$  experiment based on an Empirical Mode Decomposition (EMD) method newly developed by Huang, *et al.* [9]. We focus our attention on the Homestake data because this is the only solar neutrino data covering long enough periods of time with the neutrino energy above 0.87 MeV which is sensitive to the  ${}^8B$  solar neutrinos.

#### III-1. The EMD method

The EMD method tries to find empirically a complete set of adaptive bases  $C_j(t)$ , the Intrinsic Mode Functions (IMF), of a given time series  $X(t)$ . The IMF's are required to be complete, orthogonal and admitting well behaved Hilbert transforms. With the Hilbert transform, the IMF yields instantaneous frequencies as a function of time that give sharp identification of the imbedded structure. In practice, the procedure involves the construction of two envelopes for the data: one based on all the local maxima, the other on all the local minima. From these envelopes, the mean of the envelopes,  $M_1(t)$ , is determined. We have:

$$X(t) - M_1(t) = C_1(t).$$

where  $C_1(t)$  is the first IMF, the first component of the basis function which can be used to reconstruct  $X(t)$  adaptively. Each IMF is required to satisfy the follow conditions:

- it has the same numbers of zero-crossing and extrema,
- The upper envelope constructed from all the maxima and the lower envelope constructed from all the minima are symmetric with respect to their mean.

When the above procedure is repeated on  $M_1(t)$ , we obtain:

$$M_1(t) - M_2(t) = C_2(t)$$

where  $M_2(t)$  is the mean of the upper and lower envelopes of  $M_1(t)$ , and  $C_2(t)$  is the second component of the adaptive basis, the second IMF. Repeating the the procedure till we reach:

$$M_n(t) - M_{n+1}(t) = C_n(t)$$

where  $M_{n+1}(t) = r_n(t)$ , either a constant, or a monotonic function without extrema, is no longer an IMF. By summing up all the decomposed components, we obtain

$$X(t) = \sum_{j=1}^n C_j(t) + r_n(t) \quad (1)$$

where  $C_j(t)$  is the  $j$ -th IMF of  $X(t)$ , and  $C_j(t)$  admits well behaved Hilbert transform defined by:

$$C_j(t) = \text{Re} \left( a_j(t) e^{i \int^t w_j(t') dt'} \right) \quad (2)$$

The instantaneous frequency  $w_j(t)$  can be obtained from the time derivative of the phase function of  $C_j(t)$  defined in Equ. (2). This accomplishes the Empirical Mode Decomposition of the  $X(t)$ . The basis functions,  $C_j(t)$ , form a complete set, they are almost orthogonal and adaptive. The orthogonality of the IMF's from EMD can be tested by evaluating the index of orthogonality, IO, defined by:

$$IO = \frac{1}{T} \sum_{t=0}^T \frac{\sum_j \sum_k C_j(t) C_k(t)}{X^2(t)} \quad (3)$$

Covariances between different individual IMF's can be calculated by evaluating:

$$IO_{j,k} = \frac{1}{T} \sum_t \frac{C_j C_k}{C_j^2 + C_k^2}. \quad (4)$$

A set of perfect orthogonal IMF's will give zero values of IO and  $IO_{j,k}$ 's. But in practice, we accept solutions for those with IO and  $IO_{j,k}$ 's smaller than 0.1. With decomposition and Hilbert transform, one can define the Hilbert spectrum,  $H(w, t) = X(t)^2$ . Integrating  $H(w, t)$  over time, we obtain the marginal Hilbert spectrum,  $h(w)$ , defined below in Equ. (5):

$$h(w) = \int_0^T H(w, t) dt. \quad (5)$$

The marginal Hilbert spectrum offers a measurement of the strength or the energy of contributions from each of the frequency values. The EMD analysis differs from that of the traditional Fourier analysis in a fundamental way: time dependence of the amplitudes and frequencies. In Fourier analysis the data is considered to be linear and stationary. Analogous to Equations (1 and 2), it can be represented by:

$$X(t) = \text{Re} \left( \sum_n a_n e^{i n w_o t} \right). \quad (6)$$

Since both the amplitude and frequency of each component in Equ. (6) are constants, the only information a Fourier spectrum can provide is the marginal spectrum. It becomes a sequence of  $\delta$  functions (the fundamental and the higher order harmonics) located at frequencies  $n \times w_o$ , for  $n = 1, 2, 3, \dots$ , where  $w_o$  is the fundamental frequency. The spectrum offers a beautiful mathematic presentation, yet lacks physics meaning.

#### 111-2. Simple classical examples

Consider, for instance, a non-linear wave form:

$$X(t) = \cos(\omega t + \epsilon \sin 2 \omega t) \quad (7)$$

for  $\epsilon = 0.3$ , and  $\omega = \frac{2\pi}{64}$ . Applying EMD to Equ. (7), we found:

$$X(t) = C_1(t) + r_1(t)$$

where  $C_1(t) = X(t)$  is the only needed IMF basis, and  $r_1(t) = \text{Constant} = 0$ . The profile of  $C_1(t)$  as shown in Figure 1 consists of sharpened crests and troughs, a characteristic often found in a pure sinusoidal wave modulated by harmonic distortions. Figure 2 shows the Hilbert spectrum of  $X(t)$ , indicating that the system is oscillating with a frequency limited to a narrow band centered around  $\omega_o = \frac{2\pi}{64} = 0.016 \text{ Hz}$ , the assumed fundamental frequency. Frequency dependence of the wave's energy is shown by the color code of the spectrum. It is clear that most of the energy of the wave defined in Equ. (7) is dissipated at the limiting frequencies, 0.011 and 0.021 Hz, as shown in Figure 2. The solid curve in Figure 3 shows the marginal Hilbert spectrum of the wave, indicating that  $X(t)$  has a non stationary frequency varying in the neighborhood around  $\omega$ . Superimposed on the solid curve, the dashed curves, are the fundamental and higher harmonics of  $X(t)$  obtained from a Fourier analysis. The higher harmonics centered around  $3\omega_o, 5\omega_o, \dots$  provided a beautiful mathematical representation of the wave without real physics meaning.

For further demonstration of the power of EMD analysis, we consider a simple example with the classical Duffing equation:

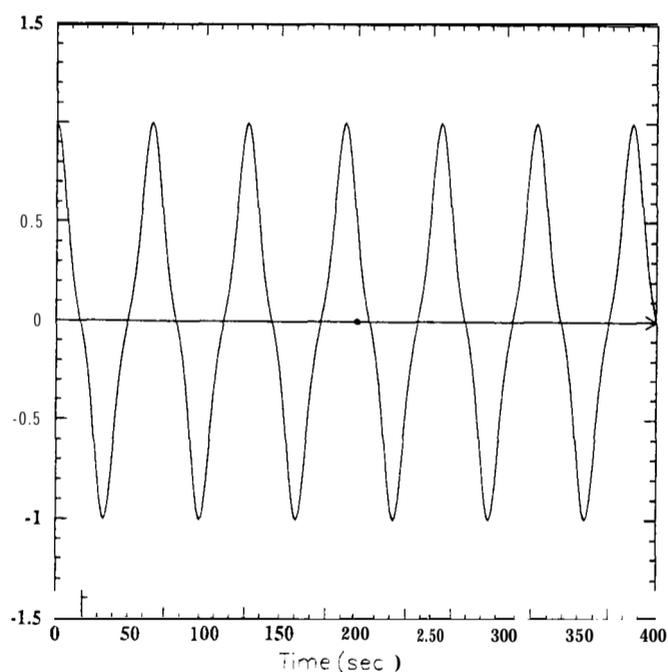


FIG 1. Profiles of  $X(2) = \cos(\omega t + \epsilon \sin 2\omega t)$  for  $\epsilon = 0.3$ , and  $\omega = \frac{2\pi}{64}$ . In the end,  $X(2)$  itself is the only IMF needed for the representation of  $X(t)$  under EMD analysis.

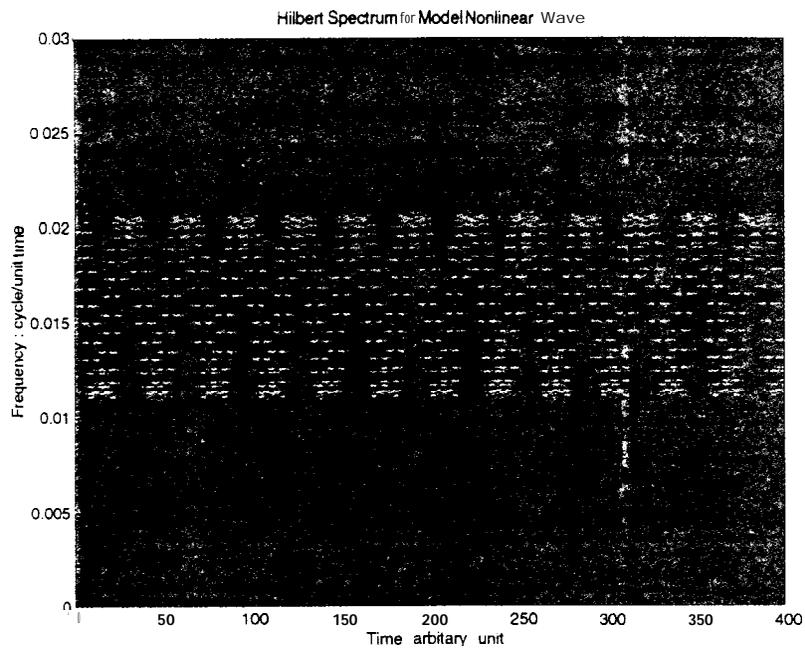


FIG. 2. The Hilbert spectrum of  $X(t)$  given by Equ. (7).  $X(t)$  has a frequency limited in a narrow band centered around the fundamental frequency  $w$ .

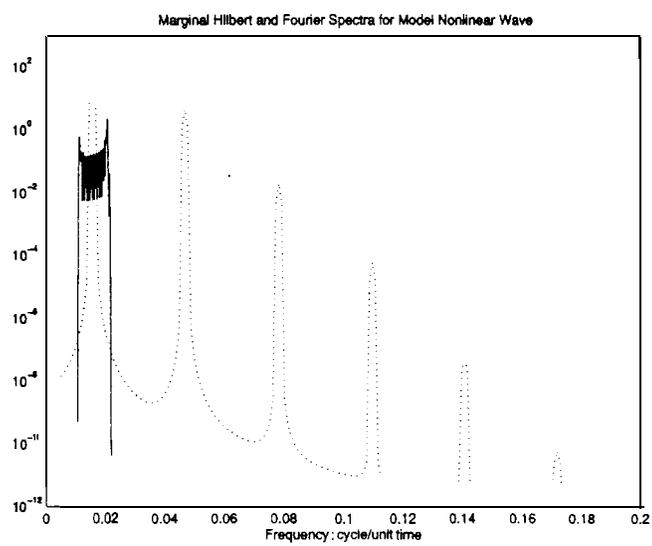


FIG. 3. The solid curve shows the marginal Hilbert spectra of the  $C_1(t)$  of Equ. (7). Fundamental and higher harmonics of the same wave under Fourier analysis are shown by the dashed curves. See text for discussions.

$$\frac{d^2x}{dt^2} + x + \epsilon x^3 = \gamma \cos \omega t \quad (8)$$

where  $\epsilon x^3$  provides a small perturbation to the driving force  $\gamma \cos \omega t$  on a simple harmonic oscillator of unit nature frequency. Traditionally, Duffing's equation has been solved by the perturbation method [10] with a solution of the form:

$$x(t) = \cos \omega t + \epsilon \cos 3 \omega t + \epsilon^3 \cos 6 \omega t + \dots$$

Applying EMD to the Duffing equation, we find:

$$x(t) = \sum_{j=1}^3 C_j(t) + r_3(t)$$

where  $C_1(t)$  = the profile of the wave, a cosine wave distorted by the small perturbation,

$C_2(t)$  = the driving force,

$C_3(t)$  = the low intensity perturbation.

By rewriting Equ. (8) into:

$$\frac{d^2x}{dt^2} + (1 + \epsilon x^2)x = \gamma \cos \omega t. \quad (9)$$

We see a simple harmonic oscillator with a time varying spring constant. Equ. (9) describes a simple pendulum with pendulum length varying in time. The underlying physics presented by EMD analysis is clear. See reference [9] for more examples and details.

### 111-3. Homestake <sup>37</sup>Cl data

The Homestake data taken in 1970–1994 [5] is shown in Figure 4. To apply EMD and Hilbert Spectral Analyses to the data, central values of the data points are connected via cubic spline fitting. The smoothed time series,  $X(t)$ , is decomposed into five IMF's. The bases,  $C_j(t)$  for  $j=1, 2, \dots, 5$ , of the IMF's as shown in Figure 5, admit well behaved Hilbert transforms. In other words, we have decomposed the Homestake data,  $X(t)$ , into:

$$X(t) = \sum_{j=1}^5 C_j(t) + r_5(t)$$

where  $r_5(t)$  is not an IMF, instead, it is a monotonic increasing function of time, indicating that the annual average event rate of Homestake increases smoothly from 2.2 SNU in 1970 to 3.4 SNU in 1994. This can be compared with their 25 year average of  $2.54 \pm 0.14$  (Stat.)  $\pm 0.14$  (syst.) SNU. The Hilbert spectra yielded by Hilbert transforms on the IMF's give sharp identifications of the embedded structures. As shown in Figure 6,  $C_1(t)$  with a constant frequency of  $0.1 \text{ y}^{-1}$  and constant strength of 10.8 SNU is clearly a prominent feature of the data. The marginal Hilbert spectrum of  $X(t)$  is shown in Figure 7. The 11 year periodicity is clearly identified by the statistically significant peak found at a frequency of approximately  $0.1 \text{ y}^{-1}$ . The marginal spectrum of  $X(t)$  obtained from a Fourier analysis

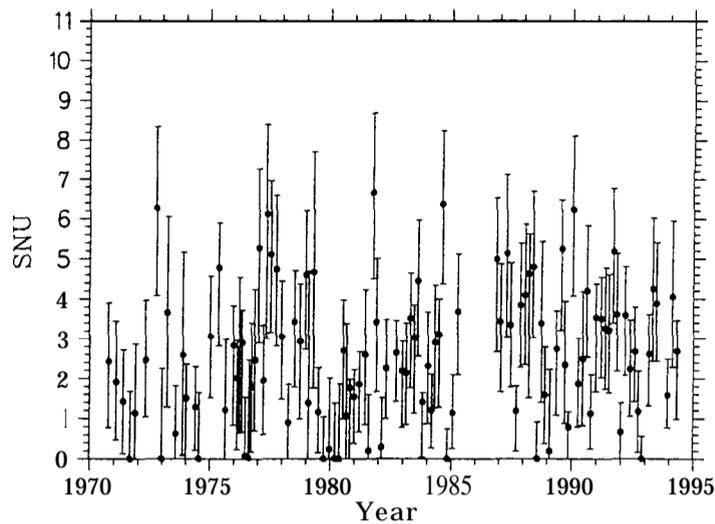


FIG. 4. Results of the 108 observations of the CHLORINE detector (Courtesy of the Homestake Collaboration).

of the same data is shown in Figure 7 by the dashed curves, where no prominent features of the data can be identified.

#### IV. Homestake vs sunspots

To compare the IMF's of Homestake solar neutrino data vs those of the Wolf Index on sunspot numbers (available from 1770 to 1995), the sunspot data are also decomposed into IMF's with the EMD method. A total of seven IMF's are needed to describe the 225 year sunspot data, where the second IMF,  $C_2(t)$  with an 11 year periodicity, is the most prominent feature. In Figure 8-a the IMF,  $C_2(t)$ , of the sunspot data is superimposed onto that of  $C_5(t)$  of Homestake solar neutrino data taken in the same time period. The sunspot IMF has been normalized to the same amplitude of the neutrino data, but kept its own phase. A correlation among the two data can be achieved if a phase shift is allowed. As shown in Figure 8-b, the two sets of data points fall upon each other in perfect agreement for the whole 25 year time period when a 3.5 year phase difference correction is applied to the sunspot time spectrum. We suspect that the sunspot cycles may have delayed by 3.5 years with respect to that of the solar neutrinos.

The IO's resulting from the EMD analysis on the Homestake and sunspot data are 0.0017 and 0.0048 respectively. For the Homestake  $^{37}\text{Cl}$  data, we find the covariances among relevant IMF's are:

$$IO_{4,5} = -0.073,$$

and

$$IO_{5,6} = -0.020.$$

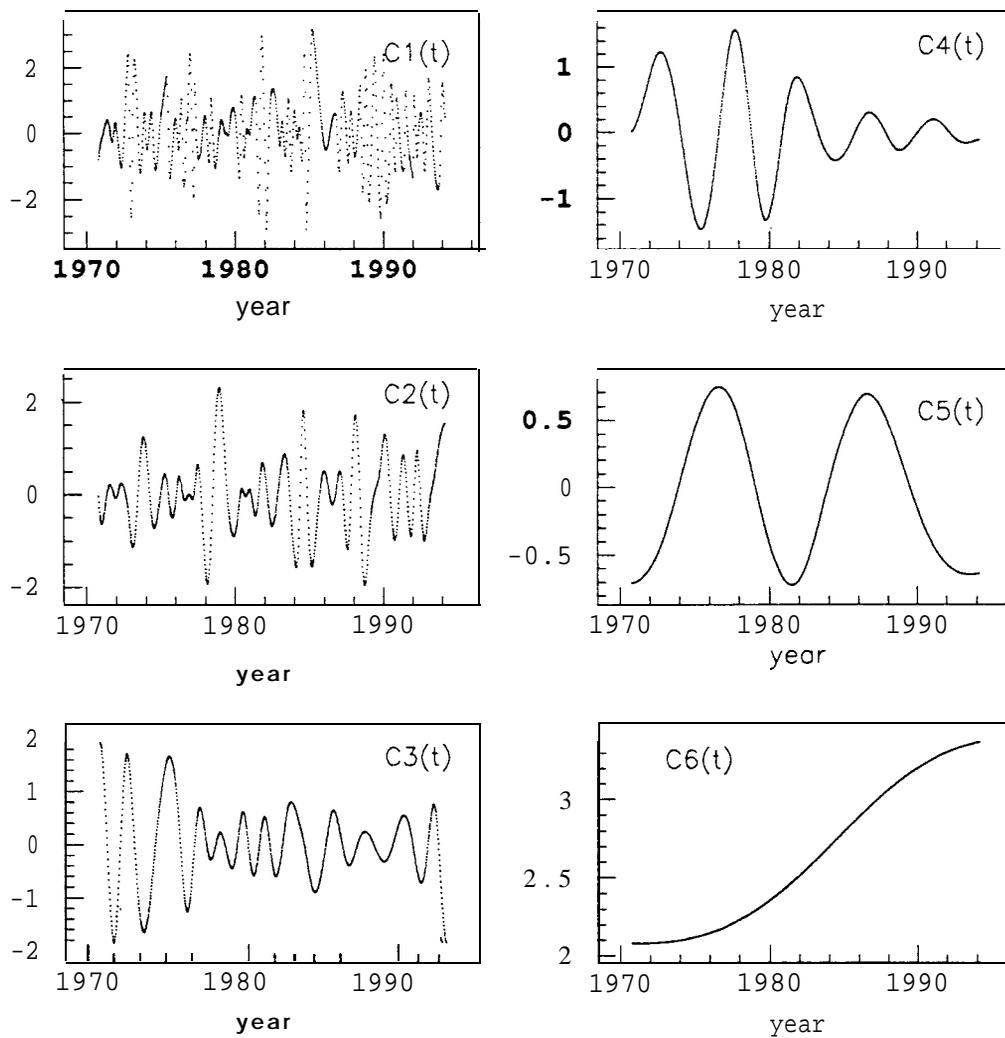


FIG. 5. The IMF's of the Homestake solar neutrino time spectrum.  $C_5(t)$  is clearly linear and stationary in strength and frequency. The component  $r_5(t)$  is a monotonic increasing function of time, indicating that the annual average event rate of Homestake increases smoothly from 2 SNU in 1970 to 3.2 SNU in 1994.

For the sunspot data, they are:

$$IO_{1,2} = -0.004,$$

and

$$IO_{2,3} = -0.010.$$

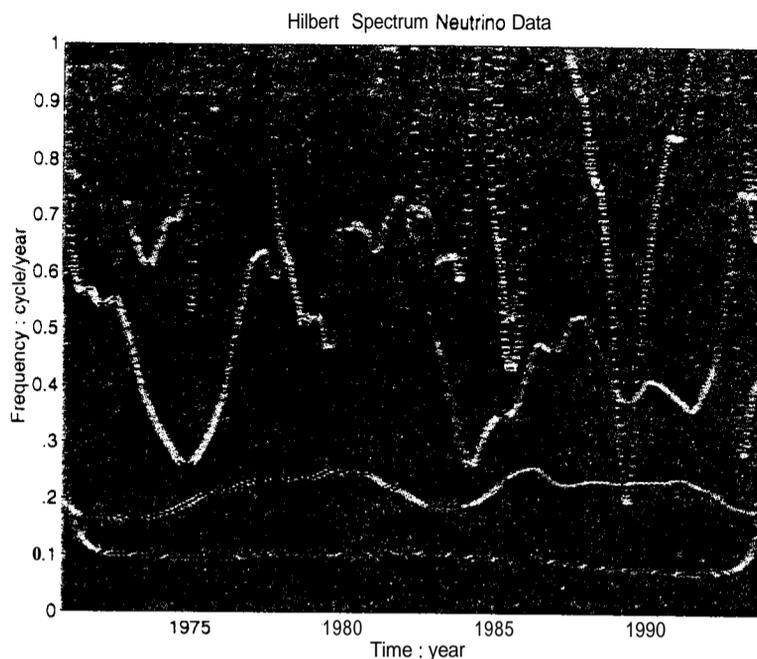


FIG. 6. The Hilbert spectra of the IMF's of the Homestake data.

To summarize, we find that:

- a prominent feature of the Homestake data is a statistically significant peak found at a frequency of approximately  $0.1 \text{ y}^{-1}$ ,
- positive correlation can be achieved if the sunspot cycles are delayed by 3.5 (or by  $n \times 22 - 3.5$ , for  $n=0,1,2,\dots$ ) years with respect to the solar neutrino cycles,
- neither the sunspot cycles nor the solar neutrino time series are described by sinusoidal waves, and their amplitudes and frequencies have not been assumed to be constants. The correlation found should, therefore, not be taken for granted.

## V. Speculations

Magnetic activity is a fundamental feature of the sun. It induces, among many other observable cosmic phenomena, the 11 year periodicity of sunspot numbers. It is believed that the solar magnetic activity is the manifestation of a hydromagnetic dynamo mechanism operating in the solar convection zone. The differential rotation,  $w$ , and the cyclonic convection, the  $\alpha$ -effect, of the electrically conducting plasma in the solar convection zone provides the regenerative dynamo. Magnetic field lines are carried and twisted by the convective flows. As the field strengths grow in the course of the dynamo process, the magnetic

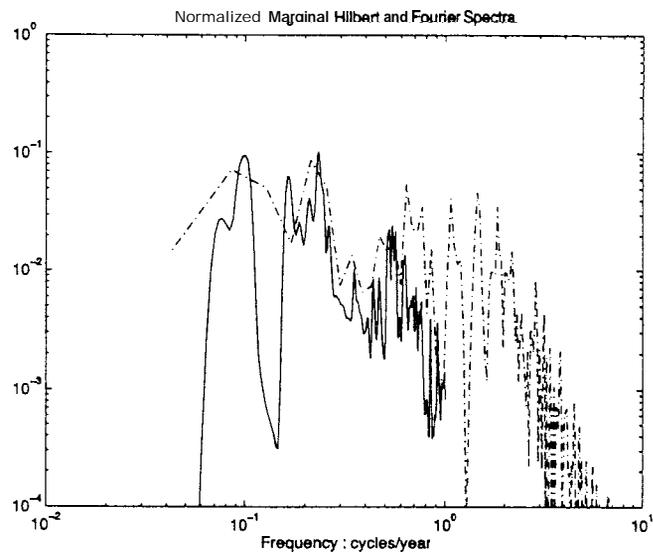


FIG. 7. Solid curve shows the marginal Hilbert spectrum of the Homestake data. Superimposed, the dashed curve, is the result obtained from a Fourier analysis of the same data

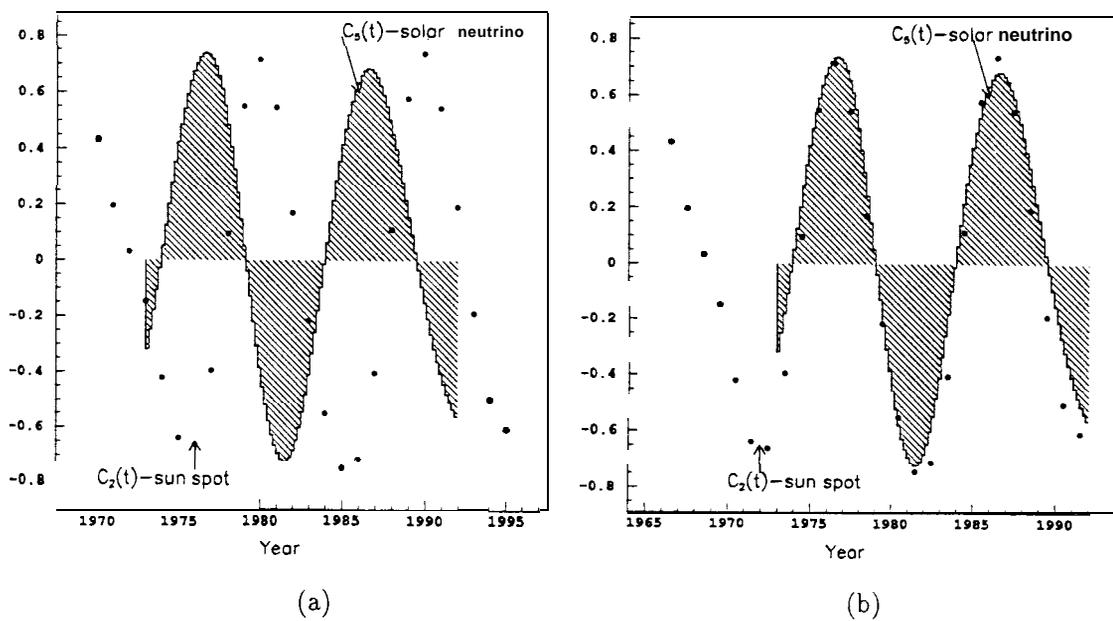


FIG. 8. (a)  $C_2(t)$  of the sunspot data vs  $C_5(t)$  of Homestake solar neutrino data taken in the same time period from 1970 to 1994. (b) The correlation between the IMF's of the sunspot numbers and that of the Homestake solar neutrinos. The Sunspot IMF is delayed by 3.5 years relative to the solar neutrino IMF.

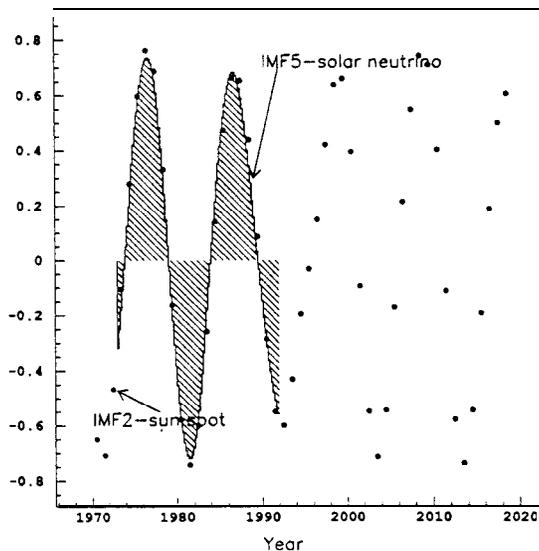


FIG. 9. The correlation among the IMF's of the two data sets remains excellent when the solar neutrino data are compared with the sunspot data 22 years back with the same phase shift.

flux of active regions may erupt into a sunspot, an effect which seems to have nothing to do with the core of the sun where the  ${}^8B$  solar neutrinos are produced.

There is evidence that the solar magnetic activity modulates the ratio of  ${}^{14}C/{}^{12}C$  found in tree rings, and also the  ${}^{10}Be$  isotopes found in the ice cores of the earth. These effects can be traced back to the modulation of galactic cosmic rays by solar magnetic activities. Likewise, modulation by solar magnetic activity on the atmospheric radioactive isotopes, which decay into neutrinos with an energy in  $1 \rightarrow 10 MeV$  region, is anticipated. The question is whether these neutrinos can modulate the Homestake solar neutrino capture rate? The answer is no, because these neutrinos can only contribute at most on the order of  $10^{-9}$  SNU of the Homestake measured neutrino fluxes.

The deficit of solar neutrinos occurs in the  ${}^7Be$  and  ${}^8B$  solar neutrino sectors. In SSM, the production rate and the flux of the  ${}^8B$  neutrinos is expected to be: (i) four orders of magnitude weaker than that of the most fundamental pp solar neutrinos which has no problem; (ii) heavily depend on the production, diffusion and consumption of  ${}^3He$  in the core of the sun, and (iii) very sensitive to the core temperature,  $\phi({}^8B) \sim S_{17} T^{24}$  [11]. We speculate that a correlation found between the solar magnetic activity and the measured flux of  ${}^8B$  solar neutrinos may suggest an alternate solution to the solar neutrino problem. Because such a correlation suggests either a common source for the generation of the magnetic tubes and the  ${}^8B$  neutrinos, or the penetration of the magnetic flux tubes into the core of the sun.

A common source for these two effects is believed to be beyond the traditional comprehension based on the SSM. However, if such a source were proven to exist, we would have the opportunity to restore the traditional simplicity in neutrino physics. It would be possible to shift the onus off the solar neutrino problems on the imperfections of the solar

physics instead of casting doubts on the fundamental properties of the neutrinos. With the neutrino behaving like a structureless spin 1/2 massless Dirac particle, without magnetic moment, flavor mixing, neutrino oscillations, it provides us a powerful tool for the probing of the universe beyond the existing experimental horizon.

There is no priori reason to preclude the penetration of the magnetic flux tubes into the core of the sun. The penetrating magnetic tubes are capable of modulating the temperature of the solar core hence the rate of production of  ${}^8\text{B}$  solar neutrinos in many ways. For instance, there is evidence that temperature, pressure and density of the plasma inside the flux tube are different from that of the surroundings outside the tube. This is at least known to be true on the surface of the sun based on measurements made on the sunspots. It may also be true deep into the core of the sun, hence the core temperature is modulated. One can also see the effect of a penetrating magnetic flux tube on the plasma temperature in the core of the sun through the energy equation [12]:

$$\frac{\partial}{\partial t} \left( \frac{B^2}{8\pi} \right) + \frac{\partial}{\partial x_i} \left( v_i \frac{B^2}{8\pi} \right) = M_{ij} \frac{\partial v_i}{\partial x_j}$$

where  $B$ ,  $v_i$  and  $M_{ij}$  are the magnetic field, plasma velocity, and the Maxwell stress tensor respectively. The energy equation states that the rate of increase of magnetic energy in the plasma in the core of the sun is precisely equal to the rate at which the fluid velocity  $v_i$  works against the magnetic forces on the fluid. This is equivalent to stating that energy is pumped into the core by the penetrating magnetic flux tubes, which then increases the core temperature. The reverse must be true when the flux tube moves outward or dies out. Hence the core temperature might be modulated by the solar magnetic activity through the penetration of the magnetic flux tubes into the solar core. In principle, knowing the chemical composition of the sun, the core temperature can be derived from the helioseismology data [13]. But to match the temperature sensitivity of the SSM  ${}^8\text{B}$  neutrino production rate of the sun remains a challenge task for the helioseismology measurements. It is also known that the cross section of the reaction  ${}^7\text{Be}(p, \gamma){}^8\text{B}$ , most crucial to the solar neutrino problem, remains one of the most poorly known quantity in the entire nucleosynthetic chains. Measuring the cross section of  ${}^7\text{Be}(p, \gamma){}^8\text{B}$  in the solar temperature region with high precision in the laboratory remains also a challenging experiment. We speculate that neutrino properties beyond the standard model itself may not be the only reason for the solar neutrino problem.

EDM analysis provides only an evidence that the solar neutrino fluxes measured by the Homestake  ${}^{37}\text{Cl}$  experiment shows a prominent periodicity at a frequency of approximately  $0.1 \text{ y}^{-1}$ . This is an undebatable truth of the data. Evidence on correlation between the measured  ${}^8\text{B}$  solar neutrino rate and the solar magnetic activity is, however, a speculation. It suggests that the solar magnetic activity may indeed affect the  ${}^8\text{B}$  solar neutrino production rate. Only future experiments such as Super-Kamiokande, SNO and the next generation Homestake, with overwhelmed statistics and high precision, can confirm or deny this pioneering observation made by Homestake. Of course a convincing evidence of neutrino oscillation found with a controlled source in laboratory may also provide an answer to the question.

Finally, we emphasize that the observed effect, if established, can only account for  $\pm 0.8\text{SNU}$  of the  $2.5\text{SNU}$  as it was measured by the Homestake experiment while  $9.3\text{SNU}$

was the SSM prediction. Also it is worth of caution that EMD method is only on its early stage of development, imperfection is anticipated.

## VI. onclusion

To conclude, using the Empirical Mode Decomposition method developed by Huang, et al, we have examined the time dependence of the solar neutrino fluxes measured by the Homestake  $^{37}\text{Cl}$  experiment. Our analysis shows that a prominent feature in the Homestake data is the statistically significant peak found at a frequency of approximately  $0.1 \text{ y}^{-1}$ . A similar analysis has been applied to the Wolf Index on sunspot numbers. Possible correlation among the Intrinsic Mode Functions of the two analysed data sets can be achieved with a 3.5 year shift in phase.

It is a pleasure to thank Professor Adil Hassam for useful discussions. We acknowledge the courtesy of Homestake collaboration for providing us the  $^{37}\text{Cl}$  data. This research is partially supported by DOE and NASA in the United States.

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