A Search for Periodicity in the Super-Kamiokande Solar Neutrino Flux Data

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Abstract
The publicly available Super–Kamiokande 10 day plot data have been searched for a periodic modulation in the range between 10 and 500 days, with the periodogram method. A peak is observed for $T = 13.75$ days, significant at 98.9 % C.L. I discuss possible ways to check this result and, if confirmed, to investigate its origin.

1 Introduction
In recent years, we have witnessed a dramatic improvement in our assessment of the solar neutrino problem. The very high statistics of solar neutrino interactions in ordinary water, obtained in the Super-Kamiokande experiment [1, 2], together with results from the chlorine [3], gallium [4, 5, 6] and heavy water [7, 8] detectors, have demonstrated that neutrinos undergo flavor conversion between the solar core and the earthly experiments. In parallel and at about the same time, the enormous progress in helioseismology and in solar models led to a firmer and refined estimate of the emitted solar neutrino flux [2], that agrees perfectly with the measurements. A few domains were singled out in...
the $\Delta m^2$ vs. $\tan \theta$ parameter plane (see e.g. [10]), with the so-called Large Mixing Angle solution being the favored one. The very recent observation of reactor neutrino oscillations by the KamLAND group [11] has further pinned down this solution, although the allowed domain in parameter space is now comprised of two disjoint sub-domains (see e.g. [12]).

In the present standard view, no large periodic modulation is expected in the solar neutrino signal. Two small effects might be observed, with periods of one year and one day. The obvious yearly modulation is due to the Earth’s orbit excentricity, $e = 0.0167$, which induces a flux variation $4e/(1-e)^2 \approx 7\%$ between aphelion and perihelion. There is now some evidence for this flux modulation, at a modest significance level [1]. The possible daily periodicity stems from neutrino oscillations inside the Earth [13]. The amplitude of this so-called day/night effect depends strongly on the neutrino masses and mixings. The day/night comparisons by the Super-Kamiokande [1, 2] and SNO [8] collaborations helped to reject some solutions to the solar neutrino problem, and to narrow down the allowed parameter space domain.

Searches for other periodicities have also been performed, such as correlations with the 11-year solar cycle (e.g. [14]), or the solar synodic period (see e.g. [15] [16] and references therein); it seems fair to say that no consensus exists on the presence of such periodic modulations.

Very recently, in December 2002, the Super-Kamiokande collaboration has released its solar neutrino flux data in 10 and 45 day bins over the period May 1996 to July 2001, corresponding to 22,400 solar neutrino interactions (see \url {http://www-sk.icrr.u-tokyo.ac.jp/sk/lowe/index.html}). This makes it possible to perform a systematic search for any periodicity in this data set, not restricted to the four periods listed above. The present paper reports the results of such a search in the period range from 10 to 500 days, as well as evidence for a periodic modulation, at $T = 13.755 \pm 0.011$ days. I am not
aware of any previous systematic periodicity search on solar neutrino fluxes in a wide period range, and especially below 18 days.

2 The data sample and the search for periodicity

I have used the Super-Kamiokande solar neutrino flux in 10 day bins only, in order to probe the shorter periods. There are \( N = 184 \) such data points, for each of which are provided the date and time of the beginning and end of the 10-day bin (in Japan Standard Time JST), the value of \( d^2 \), the average squared Sun-Earth distance in this bin, and the boron-8 solar neutrino flux, together with errors, uncorrected for this distance variation. The relative flux errors are typically between 10 and 20%.

The total time span of the data is 1,864 days (184 bins of 10.1 days in average), corresponding to an actual live time of 1,496 days. The bin size is rather constant, as only 13 bins are shorter than 8 or longer than 12 days, and the standard deviation of the bin size distribution is 1.27 day. The actual distribution of dead time is not provided, so that I have chosen to assign the neutrino flux value to the center of each bin. I have then corrected this flux value for the Sun-Earth distance, using in effect a flux rescaled at 1 AU. (I have used the \( d^2 \) factor provided in the data table, and have checked that it agrees with that computed using the JPL DE406 Solar System ephemerides available at [http://ssd.jpl.nasa.gov/]().) Finally, I subtract in each bin the average flux value given in the same table.

I have then performed a search for periodicity on these “flux excursions”,

\footnote{Half a day after this preprint was first posted, I became aware of a similar search by P.A. Sturrock and D.O. Caldwell, through an AAS meeting abstract, posted at [http://www.aas.org/publications/baas/v34n4/aas201/647.htm](http://www.aas.org/publications/baas/v34n4/aas201/647.htm). I very much thank T. Lasserre for pointing this out to me. The periodicity found in the present paper agrees perfectly with that given in this conference abstract.}
using a slight variant of the periodogram method \[17, 18\]. All flux values were used with equal weights, \textit{i.e.} ignoring their errors. The frequency range from 0.002 to 0.100 d\(^{-1}\) was searched, with a frequency step of 0.0001 d\(^{-1}\); this corresponds to a period range between 500 and 10 days. (The most significant peaks were then scanned again, with a 10 times smaller step, 0.00001 d\(^{-1}\).) The resulting power spectrum is shown in Fig. 1, where the plotted variable is

\[
z(\nu) = \frac{\left| \sum_i (\Phi_i - \Phi_{av}) e^{2\pi i \nu t_i} \right|^2}{\sum_i (\Phi_i - \Phi_{av})^2},
\]

where \(\Phi_i\) is the flux measured at time \(t_i\), \(\Phi_{av}\) the average flux and \(\nu\) is the probed frequency; the sums run over the \(N\) data points.

Only one prominent peak is found, at a frequency \(\nu = 0.07270\) d\(^{-1}\) \(\simeq 842\) nHz, corresponding to \(T = 13.75 \pm 0.05\) days. (This error is only an estimate, from the width of the periodogram peak.) The height of the peak is \(z_0 = 10.4\), corresponding to a probability \(p = e^{-z_0} \simeq 3 \cdot 10^{-5}\). The \(z\) distribution is shown in Fig. 2. In order to estimate the probability that such a peak be compatible with a statistical fluctuation, one has to know the number of independent frequencies tested by the periodogram analysis. For the frequency range tested here, essentially between 0 and twice the Nyquist frequency, this number is close to \(2N\), \textit{i.e.} twice the number of data points (see \textit{e.g.} \[19\], section 13.8, and references therein). The probability to obtain a peak height greater than \(z_0\) from \(2N\) tested frequencies is \(1-(1-p)^{2N} \simeq 2Np \simeq 1.1\%\). Thus the observed peak corresponds, at 98.9\% C.L., to a periodicity in the Super-Kamiokande 10 day plot data (as of December 2002). The second highest peak of the periodogram, with \(z_1 = 6.4\), is perfectly compatible with statistical noise at 47\% C.L.

Note that the sampling, though quite regular, is sufficiently variable that no aliasing is observed in the periodogram.

The folded flux values are plotted versus their phase in Fig. 3. The phase
here is defined as the fraction of a period $T$ counted from an arbitrary origin (Modified Julian Day 0, or JD 2,450,000 ≡ 1995, Oct 9.50 UTC); it is a number between 0 and 1. The modulation is clearly visible on Fig. 3.

In order to better estimate the parameters and their errors, I have fitted the 184 data points $(\Phi_i, \sigma_{\Phi_i})$ with a sinusoidal flux modulation,

$$\Phi_0 \left[ 1 + A \sin(2\pi \frac{t_i - 1200}{T} + \phi_{1200}) \right],$$

where $\Phi_0$ is the time-averaged $^{8}$B neutrino flux, $A$ the relative signal modulation, $T$ the period and $\phi_{1200}$ the phase at a reference date, MJD 1200.0, chosen close to the median time of the SK data. In this fit, the points were weighted using the inverse squared errors quoted by the Super-Kamiokande collaboration. The resulting $\chi^2$ is 165.8 for (184 − 4) degrees of freedom. The fitted parameters values are: $\Phi_0 = 2.329 \pm 0.024 \times 10^6$ $^{8}$B−$\nu$ cm$^{-2}$ s$^{-1}$, $A = 0.067 \pm 0.014$, $T = 13.755 \pm 0.011$ days and $\phi_{1200} = 0.55 \pm 0.22$ rad. (In comparison, the $\chi^2$ of a constant fit is 187.7 for 183 d.o.f.)

It may seem strange to be able to detect a period that is only 35 % longer than the average time bin size. The neutrino flux in each bin is integrated over the bin width, so that any periodic signal will be washed out when integrated over $\simeq 3/4$ of a period. In the case of a purely sinusoidal modulation, with amplitude $A$ relative to the average flux, the measured amplitude after signal averaging over a random 3/4 fraction of a period is $A' = (2^{3/2}/3\pi)A \simeq 0.30A$. I will discuss this further in the next section.

Note that, for such an integrated signal, the periodogram search has a much reduced sensitivity to periods close to the time sampling, 10.1 days, and twice the time sampling, 20.2 days. Thus the number of independent frequencies, $2N$, that was used above is probably a bit overestimated, and the signal significance under-estimated. A full Monte-Carlo simulation would be necessary to quantify this.
In order to search for a possible bias, either on the 13.75 day period or on its significance level, I have performed a Monte-Carlo simulation generating 10,000 experiments with exactly the same 10 day time bins as Super-Kamiokande, and flux values taken at random from a normal law with the same average $(2.35 \cdot 10^6 \nu \text{cm}^{-2} \text{s}^{-1})$ and the same dispersion $(0.33 \cdot 10^6)$ as the 184 time bins. The observed $z$ distribution is in perfect agreement with an exponential law, and no significant bias is observed near 13.75 days, or anywhere else in the periodogram. Out of the 10,000 simulated data sets, 123 have a maximum $z$ value larger than $z_0 = 10.4$. This agrees with our confidence level estimate of 98.9%.

I have also performed a periodogram search on the combined results of the GALLEX [4] and GNO [5] collaborations over the period 1991-2001. No significant peak was found. This gives no information on a possible 13.75 day periodicity however: out of the 100 GALLEX and GNO runs, 65 correspond to an exposure time very close to 27.5 days, i.e. twice 13.75 days, so that a much reduced sensitivity is expected. I have not analysed the chlorine data, as the time between extractions is even longer for this experiment.

3 Discussion and Future Work

Provided the signal presented in the previous section is not simply due to a statistical fluctuation, there exist many tests that could be performed to verify its existence. An identical analysis using the same Super-Kamiokande data, but binned in 3-4 days bins would already prove very useful. The statistics in each bin would decrease by a factor 3, and the statistical errors would increase typically by $\sqrt{3}$. The distribution of measured fluxes would hence be wider. But a 13.75 day periodic signal would then, in these bins, be integrated over 1/4 of a period instead of 3/4. The amplitude of the signal would increase
by a factor 3, to about 20\%, thus more than compensating the increase in the width of the distribution; the significance of any real modulation could be clearly established.

It would then be interesting to check what the actual period is, as 13.75 days could very well be the (dominant) second harmonic of a 27.5 day period. (The periodogram method is not well suited in such a case; the AoV method \cite{20} could be used instead.) One should also check for aliases with periods shorter than 10 days.

A search for periodicity is always more efficient starting from unbinned data. The ultimate verification would be to search for periodicity using information on each “candidate solar neutrino”, i.e. the time of detection, the angle with respect to the Sun \((\cos\theta_\odot)\) and the energy. For the Super-Kamiokande data, one can only speak of “candidate solar neutrinos” as the boron-8 solar neutrino flux is measured as an excess over the roughly constant background in the \(\cos\theta_\odot\) distribution (see for example figure 1 of \cite{21}). One could use a modified version of a periodogram analysis, where each “candidate” would receive a \(\cos\theta_\odot\)-dependent weight, equal to the fraction of solar neutrinos at its measured \(\cos\theta_\odot\). (The closer \(\theta_\odot\) to zero, the larger the weight.)

A simplified Monte-Carlo simulation of such a weighted periodogram analysis has been performed \cite{22}. It shows that a search for an unknown periodic modulation of the flux in the period range from a few hours to a year would allow to detect a 10 % modulation at better than 99 % C.L. (The confidence level increases very fast with the amplitude.) This means that, for a fixed confidence level, the searched frequency interval would then be about a hundred times greater than in the present paper. Equivalently, examining in such an analysis only periods greater than 10 days would lead to confidence levels 100 times better.

In case the signal is confirmed, this would not tell us whether it is due to
an instrumental effect, to an actual modulation of the boron-8 neutrino flux, or if it is induced by a modulation in the background. The latter hypothesis could be tested, for example, by a periodogram analysis of events that enter the $\cos\theta_\odot$ plot at negative values (the anti-solar hemisphere): they are almost all background events. It would also be interesting to search for the same periodicity in other Super-Kamiokande data sets, such as atmospheric neutrinos.

One cannot help noticing that 13.75 days is very close to half the solar synodic rotation period. This may turn out to be a coincidence, or not. There exist many solar observables that display a 13-14 day periodicity, although the peak in their Fourier spectrum is usually quite wide. Examples of these are properties of the chromosphere, solar wind characteristics at the Earth, and even induced geomagnetic activity (see e.g. [24] and references therein). (The latter two might influence the background level in underground experiments; a quick bibliographic search did not allow me to find a reference in the literature to a periodicity in the flux of cosmic rays.) Note however that the observed 13.5 day periodicities have not been seen to persist over a very long time span, such as the 5 years of data analysed here. Moreover, the intensity of these modulations vary during the 11-year solar cycle, and often show phase changes between consecutive periods of 13.5 day variability. For that reason, I have tried to split the Super-Kamiokande data into various time bins to search for such phase shifts, with no positive results. It is likely however that the 10-day binned data sensitivity is not large enough to detect such effects, and that the periodogram is not the proper tool here.

In case there is a connection between the observed signal and solar properties, it would certainly be interesting to search for a correlation with the position of the Earth relative to the Sun’s heliographic or heliomagnetic latitude.
Regarding other experiments, we have already mentioned that the gallium and chlorine data have a lower sensitivity, due to the long time between extractions, and to an unfortunate coincidence. If the Super-Kamiokande signal is confirmed by further analyses, the matter should of course be reconsidered, as one would then just have to study the amplitude of a modulation at a known period. In contrast, all other solar neutrino experiments with “real time detection” such as SNO, or the forthcoming Borexino [23], can use the techniques described above or similar ones to search for a signal. One would expect the SNO data to display the same kind of variation as the SK data, at the level of 20%.

4 Summary

I have presented the results of a search for a periodic modulation in the Super-Kamiokande 10 day plot data (as of December 2002). At 98.9 % C.L., a $T = 13.75 \pm 0.01$ day modulation is found. This is close to half the Sun’s synodic rotation period. I have discussed methods to soon check this result, and have sketched possible future directions, in case it is confirmed.

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Figure Captions

1. The power spectrum in the Super-Kamiokande 10 day plot data, from a periodogram analysis. The levels corresponding to a 1, 5 and 20 percent probability of a statistical fluctuation correspond here to $z = 10.5, 8.9$ and 7.4, respectively.

2. The $z$ distribution corresponding to Fig. 1. For data with no significant periodicity, this distribution should be exponential ($\propto e^{-z}$). The three $z$ values in excess of 6.5 all belong to the same periodogram peak at $\nu = 0.07270 \text{d}^{-1}$.

3. The flux values versus their phase in a period $T = 13.75 \text{d}$. The phase here is the fraction of the period $T$, counted from an arbitrary origin (MJD 0.0 $\equiv$ JD 2,450,000). It is a number between 0 and 1, but each data bin has been plotted twice, at its phase and phase + 1.
Phase
Flux ($10^6$/cm$^2$/s)