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# SOLAR MAGNETIC FIELD MODULATION OF THE NEUTRINO FLUX

Soon after the first neutrino observations had been published it became clear that the solar neutrino flux was not only much smaller than expected from the solar standard model (the first neutrino problem). It also proved to be variable in time (the second neutrino problem), which implied that the Sun was a variable neutrino star. (For more detail see Bahcall (1993), Rivin (1993) and references therein).

Time fluctuations of the solar neutrino are not quite understood. Some authors believe them associated with solar activity whose growth results in a decreased neutrino flux $\nu$ ($^{37}Ar$ measurements at South Dakota), i.e. a negative correlation with the solar activity indices is supposed (Voloshin *et al.*, 1986, Rivin, 1993) According to this hypothesis, the neutrino flux passing through a strong magnetic field is modulated, as part of the left–hand neutrino are transformed into the right–hand neutrino. The modulation mainly depends on two factors: the magnetic moment of the neutrino and the absolute value of the transverse magnetic field component. This modulation is difficult to obtain in laboratory. However there is evidence indicating that it occurs in the Sun, as the high–energy neutrino flux from the core passes through the magnetic field in the solar convection zone.

To verify this hypothesis, it is essential to choose an index that would characterize most adequately the magnetic field in the solar interior along the neutrino propagation line. Such indices used in early work are the Wolf number or the mean photospheric field. However both of them are dissatisfactory, as they are global indices. We have used magnetic field measured every day from the Zeeman effect at intersection of the "solar center – Earth" line with the photosphere. The data were obtained at the John Wilcox Observatory of the Stanford University (WSO). These observations started in May 1976 (Carrington rotation 1641) and the data are available up to 1992 inclusive (Hoeksema and Scherrer, 1986; Hoeksema, 1991). The earlier period since 1970 is covered by the data obtained at the Mount Wilson Observatory (MWO) by Robert Howard's group and kindly placed at our disposal by J. Stenflo. Both data series are used in our analysis in spite of some nonuniformity.

These measurements based on potential approximation can be used to calculate the daily and, then, the annual mean values of the three magnetic field components ($B_r$, $B_\theta$, and $B_\varphi$ — the radial, meridional and azimuthal components, respectively). The error is shown to be no more than $\sim 10\%$. Since the neutrino flux propagates radially from the solar interior to the Earth, the absolute values of the two latter components must play a decisive role in its modulation.

The high–energy boron neutrino flux ($E \simeq 0.1$ MeV) from the solar core has been measured at South Dakota (USA) since 1970. The data of several observation runs with their errors are given in (Bahcall, 1993). As the runs are different in length, the scale of data is nonuniform. We have applied linear interpolation to obtain a uniform scale as a series of monthly mean values covering the whole observation interval. These have been used in turn to yield the annual mean values, as well as the mean square root error.

The data from individual runs have been analyzed to give an average signal–to–noise ratio equal to $\simeq 0.5$. This ratio however grows to $\simeq 2 - 2.5$ when the annual mean values are considered.

These facts allow us to compare the neutrino flux variations and the absolute values of the magnetic field components along the flux propagation line over a time interval of 22 years. The correlation coefficient between the neutrino flux and $<\mid B_\theta \mid>$, $<\mid B_\varphi \mid>$, and $<\mid R_r \mid>$ was found to be $-0.66$, $-059$, and $-0.62$, respectively. Note that correlation coefficient with the Wolf number is as small as $-0.37$. On the other hand, the correlation coefficient reaches $-0.84$ if only the uniform data series from Stanford is used.

The high correlation coefficient indicates a possible relationship between both phenomena. As should be expected, it is most pronounced when direct physical parameters of magnetic fields are considered. Relationship between the neutrino flux and the average field components ($< B_\theta >$, $< B_\varphi >$, $< B_r >$) is practically absent (correlation coefficient from $-0.35$ to $-0.15$).

Besides South Dakota, neutrino measurements (though much shorter series) were also obtained with the Japanese neutrino detector Kamiokande–II. The annual mean values of the neutrino flux from both detectors show a good agreement over the time interval of 1988–1991. It should be noted that neutrino flux variations over this interval are relatively small compared to the Wolf numbers, so that dependence on the solar cycle may not exist. This inconsistency can be avoided by using direct physical parameters. In fact, the heights of the solar maxima in Wolf numbers in 1979 and 1989 are practically equal, whereas the amplitude of magnetic field components in 1989 are much lower than in 1979.

Besides the 11–year cycle, the $^{37}Ar$ curve displays a significant quasi–biennial fluctuation (Sakurai, 1979; Rivin, 1993). In time variations of the absolute magnetic field values, this fluctuation is absent. Therefore it should be suppressed to obtain adequate correlation coefficients.

Suppression has been realized by smoothing the original data series over 3–year intervals. For the smoothed data, the correlation coefficients of the neutrino flux with $<\mid B_\theta \mid>$, $<\mid B_\varphi \mid>$, and $<\mid B_r \mid>$ increases to make $-0.79$, $-0.79$, and $-0.85$, respectively. The correlation coefficient with the Wolf number also increases ($-0.60$), but it still remains lower than correlation between $^{37}Ar$ and the field components. And finally, comparison of the smoothed neutrino data with a uniform series of magnetic field data from WSO yields a correlation coefficient as high as $-0.90$.

Our conclusions are as follows:

1. The fact that linear correlation between the neutrino flux and the solar magnetic field increases significantly when absolute values of the magnetic field components along the "solar center — Earth" line are considered, as well as high correlation coefficients themselves suggest that solar magnetic fields are responsible for variations of the high–energy neutrino flux from the solar interior detected at South Dakota.

2. As the absolute values of the magnetic field components display mainly an 11–year variation, the neutrino flux is modulated by the fields in the convection (or maybe even radiative) zones in the Sun. These are the fields that determine the basic solar activity cycle with a period of $\simeq 22$ years.

3. The fact that magnetic field curves do not display significant quasi–biennial fluctuation that is present in the curve of the neutrino flux shows that generation of quasi–biennial fluctuations has nothing to do with the fields of the basic solar cycle, but is rather due to the thermal processes in the solar core, as suggested by Sakurai (1979).

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