On the new data set from the Homestake experiment

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Abstract. The data set of 108 runs performed with the chlorine detector (Homestake Gold Mine at Lead, South Dakota, USA), between the 1970 and 1994, are analysed to confirm or reject previous evidence of the existence of temporal and spatial modulation of the solar neutrino flux in connection with the solar activity (Massetti and Storini, 1996).

Key words: solar neutrino - neutrino flux - north-south asymmetry - solar activity cycle

1. Introduction

The consolidated ideas we have of how the Sun works are incorporated in the so--called "standard solar model" (Bahcall et al., 1997; Guenther et al., 1992). In particular, the inner nuclear reactions that power up our star, are believed to transform hydrogen into helium by proton-to-proton chains, thus generating the energy required to prevent the gravitational collapse of the solar mass and to make the Sun shine. The toll for this large amount of energy produced is also the generation of a relatively large flux of electronic neutrinos, being the low interacting leptons intimately connected with beta process, and with electron capture. Unlike photons, the neutrinos stream almost freely through the solar plasma into space (due to their very small cross-section), carrying direct and precious information about solar core reactions. The expected neutrino flux can be calculated on the theoretical basis of the solar standard model, and the characteristics of the model itself imply that the neutrino flux is constant and also isotropic. In spite of this, a general lack of solar neutrinos is observed independently and at various energies, by all the operating detectors: Homestake, Kamiokande, Sage and Gallex. This phenomenon constitutes the well-known "solar neutrino puzzle" which we are still unable to solve (see Bahcall, 1989; 1996) due to the large experimental errors that characterize neutrino flux measurements.

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Besides the neutrino deficit, another problem arises from the apparent time variability of the neutrino flux, which has been observed for more than twenty years by the Homestake detector. In fact, correlation analyses between the Homestake data and several solar activity parameters (e.g., Massetti, Storini and Iucci, 1995; 1997) have shown that long-term neutrino modulation anticorrelating with the solar activity cycle cannot be rejected, as opposed to theoretical expectation. The physical mechanism responsible for this linkage could probably be due to the unexpected strong interaction of the neutrinos with the inner solar magnetic fields, either via a large neutrino magnetic moment (Cisneros, 1971; Voloshin and Vysotskii, 1986) or via a non-zero neutrino electric charge (Ignatiev and Joshi, 1994). Since the strength of the inner solar magnetic fields is a function not only of the activity cycle period, but also of heliographic latitude (module and sign), both a temporal and a spatial neutrino modulation is expected. In this paper we analyse the new data set from the Homestake experiment (Davis, 1996) to look for evidence of a solar neutrino flux modulation, using the temporal and latitudinal distribution of the intensity of the 530.3 nm green coronal line as a proxy parameter for the inner heliomagnetic field strength. We remind the reader that the brightness of the green coronal line is the solar parameter best correlated, similarly to the solar flares, with the solar neutrino data of the Homestake detector (Massetti and Storini, 1993; Massetti, Storini and Iucci, 1995; 1997).

2. Data used

The following data have been used for the period 1970 to 1994:

– the new data set of the Homestake neutrino flux (Q) from run No.18 to No.133, a total of 108 values (Fig. 1, upper panel). As Davis (1996) underlined, *"...the new set of data has the cosmic ray muon and the fast neutron backgrounds subtracted. Therefore these neutrino capture rates are the rates above all the known backgrounds and can be ascribed to solar neutrinos".*

– the intensity (in absolute coronal units – a.c.u.) of the green coronal line 530.3 nm (GCL) on a monthly basis, estimated in steps of 5° in the heliolatitudinal range from +90° to -90°, for a total of 37 heliographic latitudes. The lower panel of Fig. 1 shows the derived density plot.

We have used the annual Earth's heliographic latitude variation ($-7.4° < \Theta_E < +7.4°$) to subdivide the original neutrino data (Q) into two subsets containing the neutrino fluxes observed when the Earth was at northern (Q_N, $\Theta_E > 0$) and at southern (Q_S, $\Theta_E < 0$) heliographic latitudes (above and below the solar equatorial plane). As the Homestake measurements are very scattered and we are interested in the long-term variation, the three data sets (Q, Q_N and Q_S) have been smoothed via a 3-point running average ($Q3$, Q_N3 and Q_S3). To allow comparison, the monthly data of the green coronal line GCL for the 37 heliographic latitudes have been reduced, i.e. averaged, to the same time base

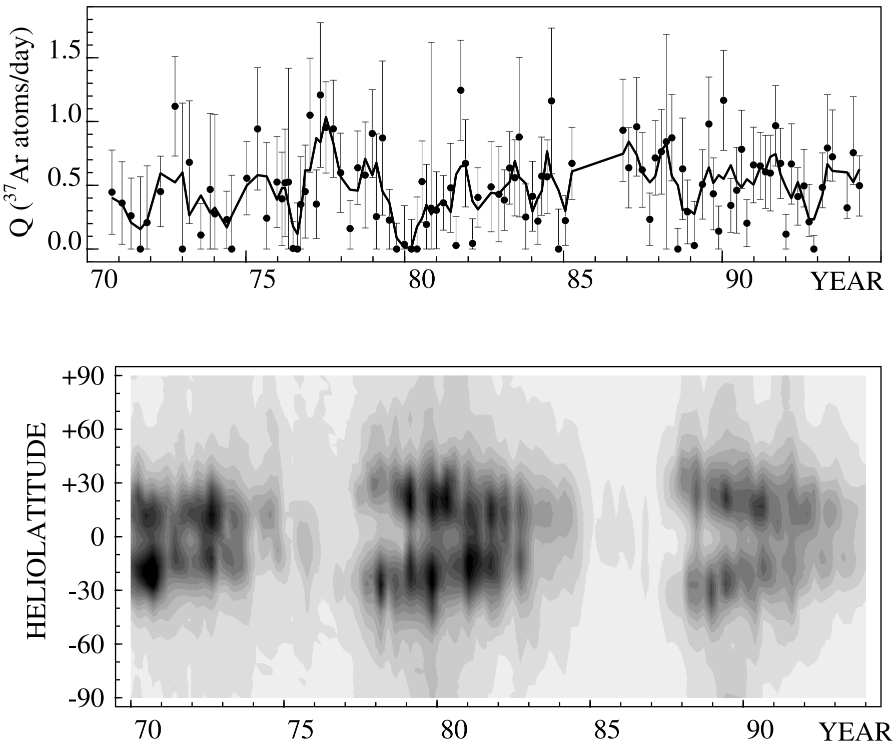


Figure 1. Upper panel: Homestake solar neutrino data (Q, filled circles) with error bars and 3-point running averaged values ($Q3$, solid line). Lower panel: density plot of the intensity of the green corona line (GCL) by step of 10 a.c.u. in a grey scale (data range: 0–180 a.c.u. from white to black).

as the Q-values (the base consisting of intervals of different length), and then subdivided into "northern" and "southern" in the same way as the Q_N3 and Q_S3 subsets.

3. North-south asymmetry

We have found that the northern component of the Homestake data exhibits broad variations of short period (approximately 5 years) whereas the southern one shows a remarkable periodicity of about 12 years, almost in antiphase with the solar activity cycle. Assuming these variations to be real, we have tried to compute a rough evaluation of the north-south asymmetry in the solar neutrino flux: since both components are not available at the same time, we have interpolated the Q_N3 set to evaluate the northern values at the dates of the Q_S3 values, and vice versa (see Fig. 2, upper panels). The $Q_N3 - Q_S3$ difference is shown in the lower panel of Fig. 2, together with the sinusoidal fit obtained with the least-squares method: it shows a periodicity of about 12 years, with a maximum in 1981 and two minima in 1976 and 1987, almost in phase with the solar activity cycle. The obtained north-south asymmetry must be considered cautiously because represents only a rough evaluation. Nevertheless, the presence of such a periodicity cannot be expected a priori and may be viewed as an independent hint, supporting the existence of some kind of linkage between the solar neutrino flux and the solar activity cycle.

4. Temporal and spatial (heliolatitudinal) dependence of the neutrino flux

We have analysed the temporal evolution of the linear correlation between the *Q3*, Q_N3 and Q_S3 neutrino sets and the corresponding three *GCL* sets. The correlation coefficient *(r)* has been calculated repeatedly beginning with the first two pairs of data and then adding one more pair of data for each time, so that the n-th value (r_n) is the correlation coefficient of the first n pairs of data:

$$r_n = linear\ correlation\ of\ [Q3(1), ..., Q3(n); GCL(1), ..., GCL(n)]$$

with $n = 2, ..., 108$ (or 53 in the case of the subsets). The obtained r_n values were then plotted as a function of the date of the last pair of data considered. The calculation was carried out both from 1970 to 1994 (forwards) and from 1994 to 1970 (backwards), to obtain almost the same statistical significance, depending on the number of the data, at the beginning and end of the period analysed. We have performed all the above calculations for each heliographic latitude of the GCL data, in order to obtain both temporal and spatial (latitudinal) dependence of the correlation coefficient. The results are shown in Figs 3–8, both as 3D and density graphs (upper and lower part of each figure, respectively). Odd figures refer to the forward temporal trend, from 1970 to 1994, and even figures to the backwards, from 1994 to 1970. Note that the correlation coefficients in the two trends at the same date (e.g., 1985) are, of course, different as they refer to the correlation calculated over two independent periods: from 1970 forwards (e.g., to 1985) in the first case and from 1994 backwards (e.g., to 1985) in the second one. To appreciate better the difference between the northern and the southern behaviour, the correlation coefficient is shown in Fig. 9 as a function of the heliographic latitude only, the computations referring to the full period (from 1970 to 1994). The results of our analyses can be summarized as follows:
– the (anti)correlation between the Homestake data and the intensity of the green coronal line increases (in module) at low solar latitudes (within about $\pm 15°$; Fig. 3) and this is particularly evident in considering the southern subsets

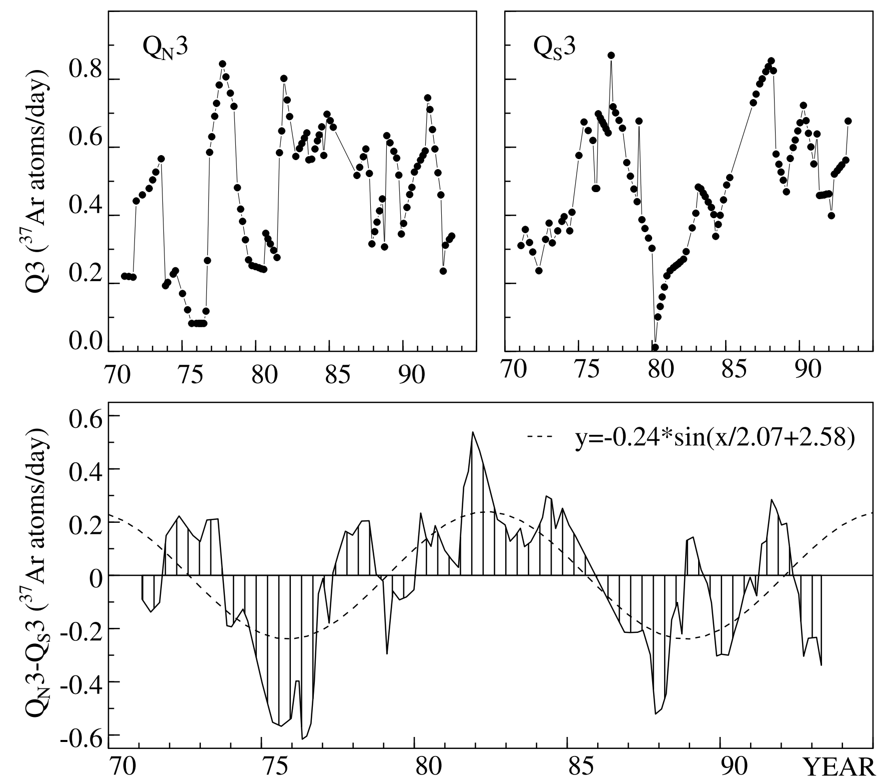
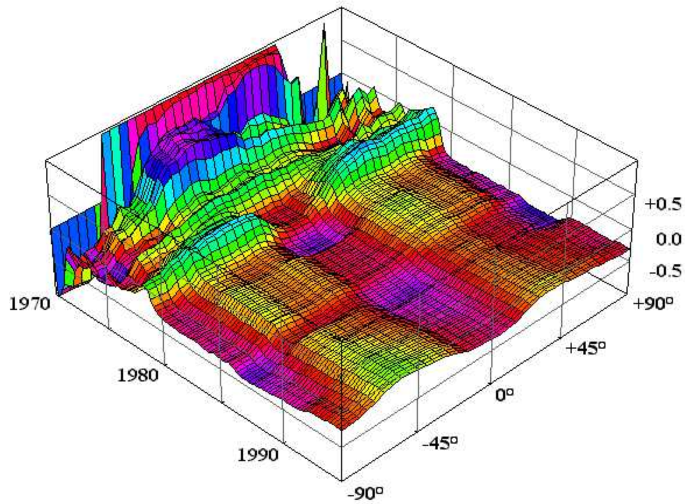


Figure 2. Interpolated northern (left) and southern (right) components (3-point smoothed values) of the neutrino flux (upper panels) together with their difference ($Q_N 3 - Q_S 3$, envelope of the filled area) and the sinusoidal fit: $T \approx 12$ years (lower panel).

(Figs 5, 6, 9);
– the northern subset, extracted from the Homestake data, seems to have no latitudinal dependence (Figs 7, 8);
– the (anti)correlation between the Homestake data and the intensity of the green coronal line generally decreases (in module) during the even-numbered solar cycles (No.20 and No.22), in particular during the descending phase of solar cycle No. 20, i.e. from 1970 to 1976.



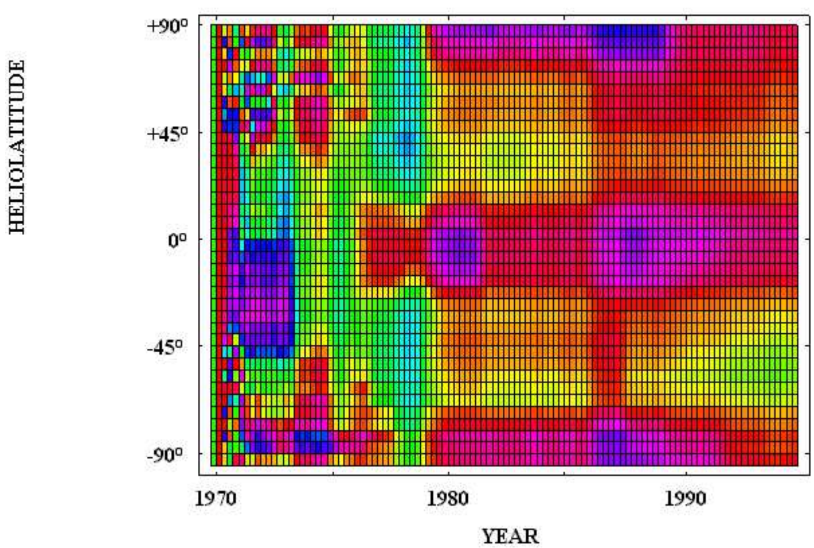
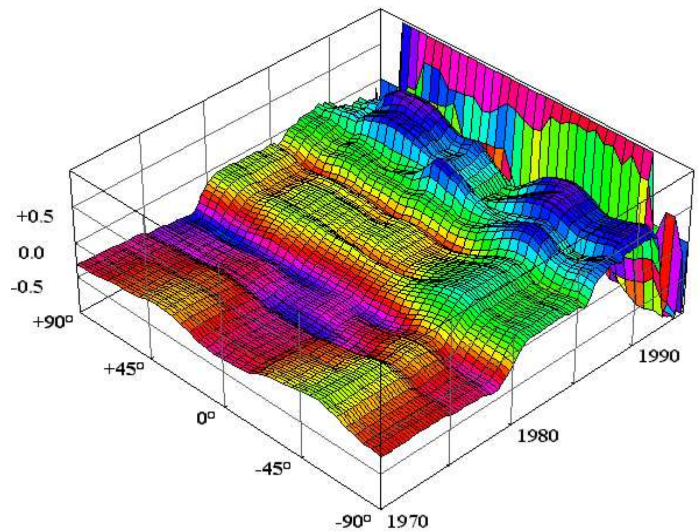


Figure 3. Upper panel: the linear correlation coefficient (z-axis) between the $Q3$ neutrino flux (3-point smoothed) and the green coronal line intensity, as a function of time (forwards: from 1970 to 1994) and heliographic latitude. Lower panel: the same of the upper panel but represented as a density plot.



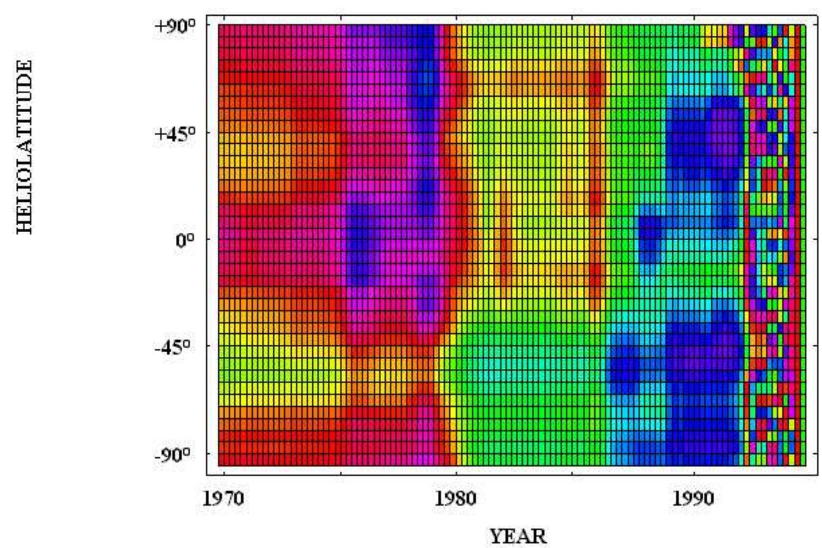
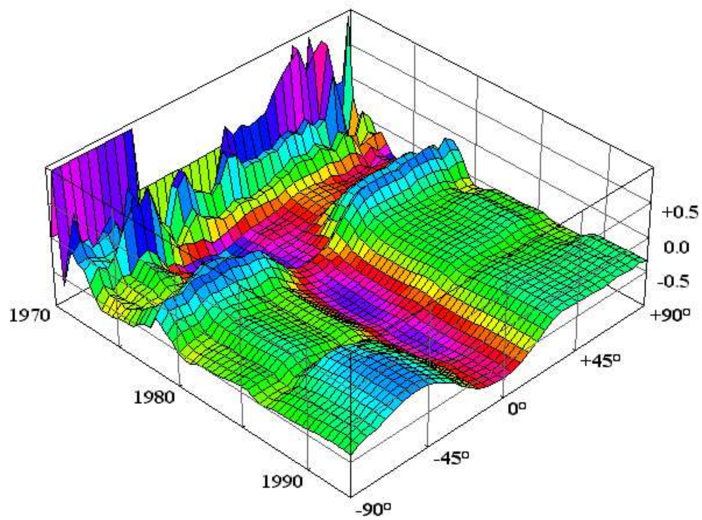


Figure 4. Upper panel: the linear correlation coefficient (z-axis) between the $Q3$ neutrino flux (3-point smoothed) and the green coronal line intensity, as a function of time (backwards: from 1994 to 1970) and heliographic latitude. Lower panel: the same of the upper panel but represented as a density plot.



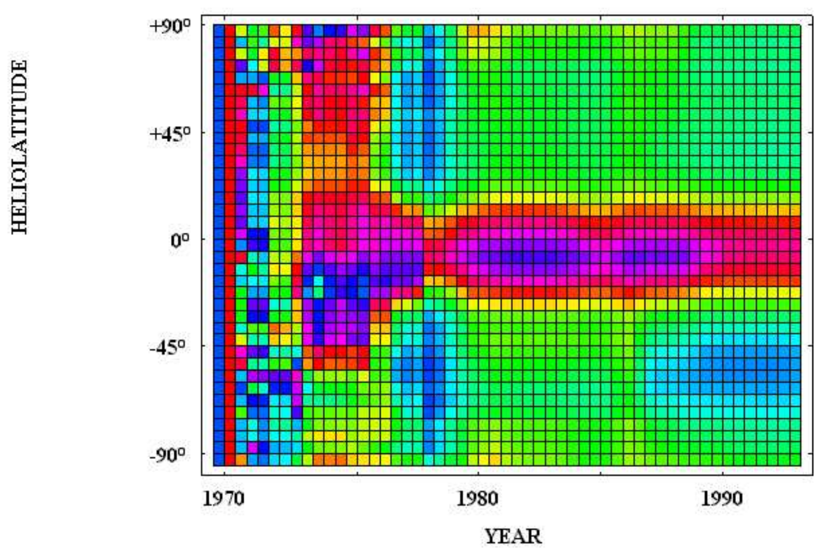
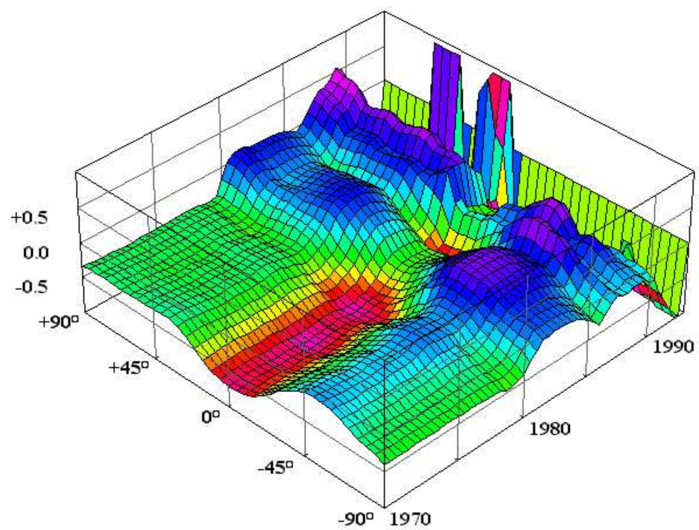


Figure 5. Upper panel: the linear correlation coefficient (z-axis) between the Q_S3 southern neutrino flux (3-point smoothed) and the green coronal line intensity as a function of time (forwards: from 1970 to 1994) and heliographic latitude. Lower panel: the same of the upper panel but represented as a density plot.



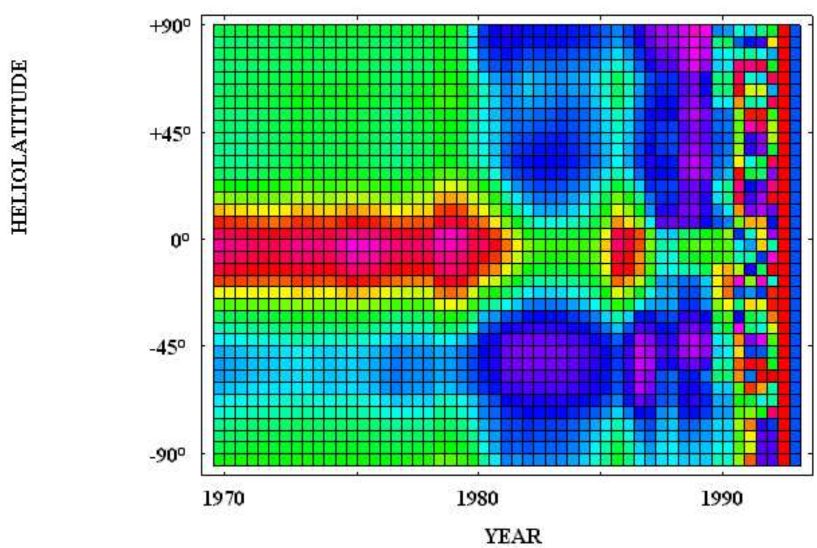
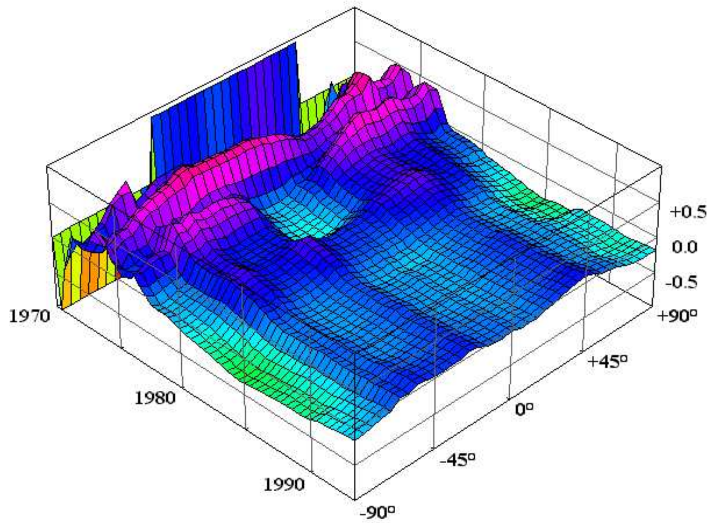


Figure 6. Upper panel: the linear correlation coefficient (z-axis) between the Q_S3 southern neutrino flux (3-point smoothed) and the green coronal line intensity, as a function of time (backwards: from 1994 to 1970) and heliographic latitude. Lower panel: the same of the upper panel but represented as a density plot.



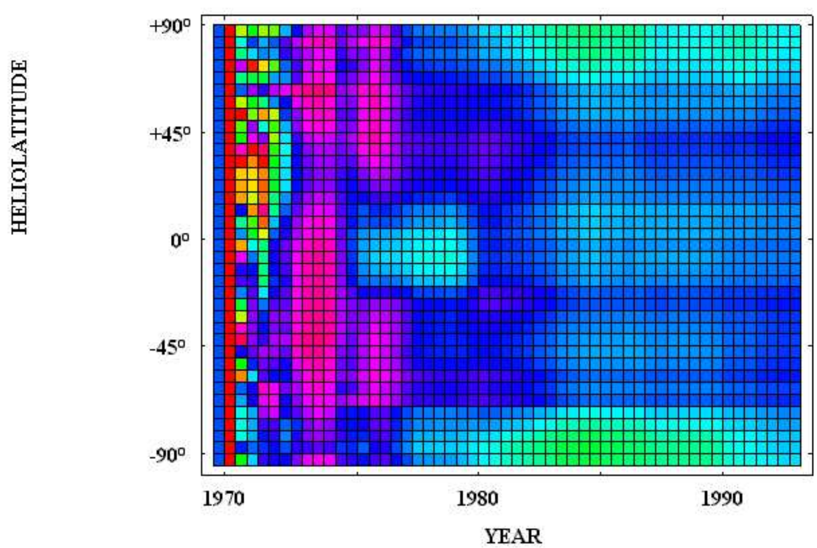
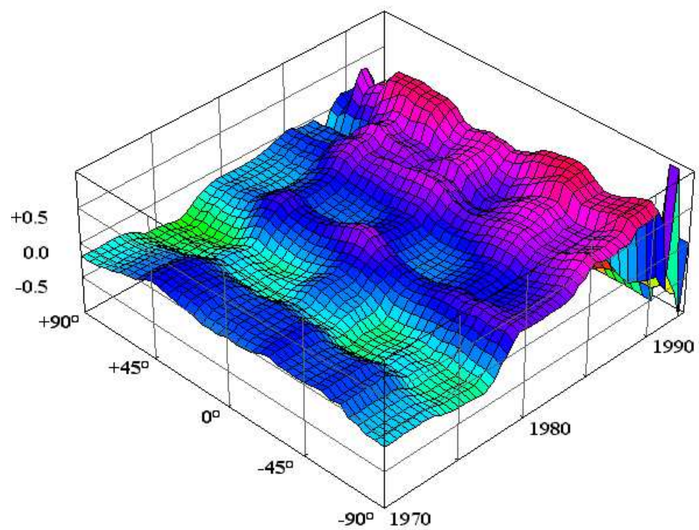


Figure 7. Upper panel: the linear correlation coefficient (z-axis) between the Q_N3 northern neutrino flux (3-point smoothed) and the green coronal line intensity, as a function of time (forwards: from 1970 to 1994) and heliographic latitude. Lower panel: the same of the upper panel but represented as a density plot.



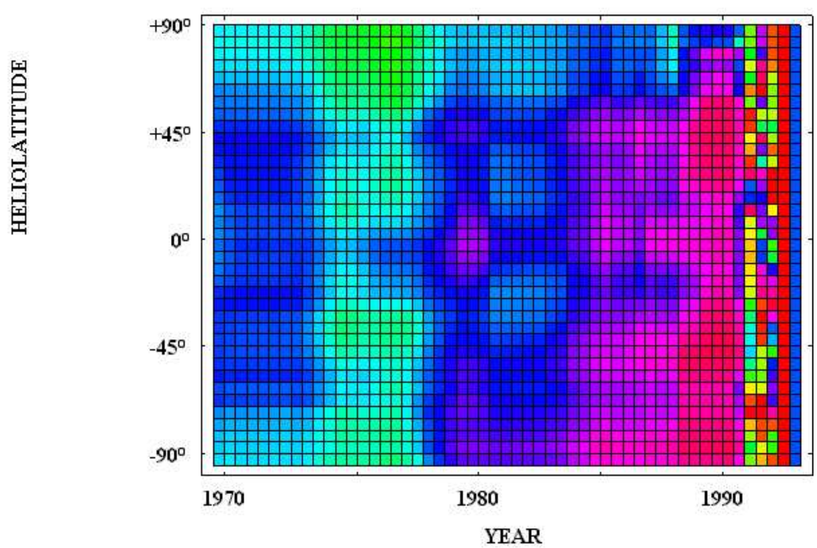


Figure 8. Upper panel: the linear correlation coefficient (z-axis) between the Q_N3 northern neutrino flux (3-point smoothed) and the green coronal line intensity, as a function of time (backwards: from 1994 to 1970) and heliographic latitude. Lower panel: the same of the upper panel but represented as a density plot.

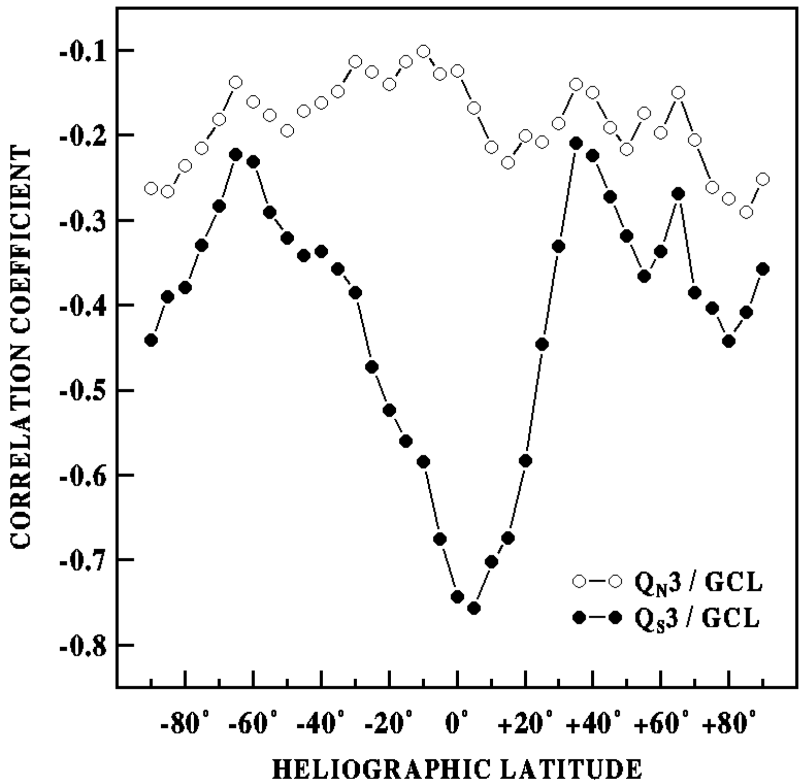


Figure 9. Latitudinal dependence of the linear correlation of the northern Q_N3 and the southern Q_S3 set, 3-point smoothed, with the corresponding values of the green coronal line intensity (GCL).

5. Summary and conclusion

The study of the new data set from the Homestake experiment (1970-1994) outlines the following scenario for the solar neutrino flux variability:
i) there exists a negative correlation with the 11-year solar activity cycle or, considering the possible differentiation between odd- and even-numbered solar cycles, with the 22-year heliomagnetic cycle;
ii) the time behaviour of the northern and southern neutrino flux seems to be different, with the latter correlated with the solar activity parameter better than the former;
iii) the neutrino flux is characterised by a north-south asymmetry with a roughly 12-year periodicity which is practically in phase with the solar activity cycle;
iv) the anticorrelation of the total neutrino flux with the GCL in the solar equa-

torial belt (±15°) is statistically significant (correlation coefficient = −0.41), with a confidence level better than 99%.

We conclude that our new results are in agreement with the Oakley et al. (1994) and Massetti and Storini (1996) findings, supporting a good connection between solar features in the equatorial belt and neutrino flux modulation. Moreover, the present study indicates that this correlation is enhanced (correlation coefficient = -0.73, confidence level > 99.9%) if only the southern neutrino flux is considered. In other words, the results suggest that the neutrino flux is linked to the solar activity cycle by some kind of interaction (Voloshin et al., 1986; Ignatiev and Joshi, 1994) connected with the heliomagnetic fields in the equatorial belt. However, it remains to be understood why the behaviour in the solar activity-neutrino relationship for the northern and southern neutrino flux differs. To explain the observed north-south asymmetry in the neutrino flux, we may hypothesize that the cyclical evolution of the toroidal magnetic fields does not occur symmetrically with respect to the solar equatorial plane. The known north-south asymmetries that appear, for example, in the sunspot number (Swinson et al., 1986), solar flares (Garcia, 1990) and solar corona (Sýkora, 1994), together with the evidence of a difference between odd and even solar cycles in several solar activity parameters (see, for instance, Storini, 1995; Storini and Pase, 1995; Storini and Sýkora 1995; 1997) could support this scenario. We believe that a careful study of the hemispheric heliomagnetic flux would be appropriate not only to clarify the subject, but also to understand solar-terrestrial relationships better.

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