APPARENT LATITUDINAL MODULATION OF THE SOLAR NEUTRINO FLUX

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ABSTRACT

We examine the solar neutrino flux, as measured by the Homestake neutrino detector, to search for evidence of a dependence upon the solar latitude of the Earth-Sun line that varies from $7°.25$ south in mid-March to $7°.25$ north in mid-September. Although the flux does not obviously show any dependence on latitude, we do find evidence for a dependence of the variance of the flux upon latitude. When data from 108 runs of the Homestake experiment are divided into four quartiles, sorted according to latitude, we find that the northernmost quartile exhibits a larger variance than the other three. By applying the shuffle test, we estimate the probability that this could have occurred by chance to be in the range 1%–2%.

For more detailed information, we examine a "reconstructed flux" formed from our recent maximum likelihood spectrum analysis. This procedure indicates that the variance is largest at about $6°.5$ north. We also find that the spectrum of the variance of the reconstructed flux has a notable peak at 1 cycle y^{-1} tending to confirm a latitude dependence of the variance. We also examine the 12.88 cycle yr periodicity described in our recent paper and find that the amplitude of the periodicity is greater for the northernmost quartile than for the other quartiles. We suggest that these effects may be attributed to resonant spin-flavor precession of left-hand–helicity electron neutrinos in the magnetic field of the solar radiative zone.

Subject headings: Sun: interior — Sun: magnetic fields — Sun: particle emission

1. INTRODUCTION

In a recent paper (Sturrock, Walther, & Wheatland 1997, hereafter SWW1), we have presented evidence that the solar neutrino flux, as recorded by the Homestake neutrino experiment (see, for instance, Davis & Cox 1991), varies with a periodicity of 12.88 cycles yr^{-1}, corresponding to a synodic rotation period of 28.36 days or sidereal period of 26.32 days. This sidereal rotation rate may also be referred to as 440 nHz, a notation more familiar in helioseismology. For simplicity, we henceforward refer to this periodicity as the "SWW periodicity."

This sidereal rotation rate may be compared with the range 430–450 nHz for the outer region of the solar radiative zone, as recently determined by the MDI helioseismology experiment (Schou et al. 1997). Hence, the periodicity that emerges from our recent study is consistent with modulation of the solar flux, which originates in the solar core, by some region in the radiative zone. This region must, of course, depart from rotational symmetry. The most plausible interpretation seems to be that neutrinos have non-zero magnetic moment and that the neutrino flux is modulated by an inhomogeneity of the Sun's internal magnetic field. Possible mechanisms for this magnetic modulation will be discussed in § 6.

In this interpretation, the SWW periodicity is a reflection of a longitudinal structure of the magnetic field, when longitude is referred to a coordinate system rotating at the inferred frequency of 13.85 cycles yr^{-1}. If the magnetic field influences the neutrino flux through its longitudinal structure, it is reasonable to inquire into the possibility that it may also influence the neutrino flux through a latitudinal structure.

However, there is a big difference between the longitudinal effect and a possible latitudinal effect. The Sun-Earth line scans the entire range of 360° in longitude in the course of one synodic rotation period. Hence modulation by the magnetic field must, if it is not cylindrically symmetric, lead to some modulation of the neutrino flux, whatever the effective diameter of the neutrino-emitting region. On the other hand, the Sun-Earth line scans only the range $7°.25$ south to $7°.25$ north in the 6-month interval mid-March to mid-September, retracing the scan from mid-September to mid-March. Hence we can expect to detect the latitudinal effect only if the effective radius of the neutrino-emitting region is of order $7°.25$ or less, corresponding to a real radius of $0°.13$ $R_{\odot}$ or less, where $R_{\odot}$ is the solar radius. We see from Figure 6.1 of Bahcall (1989) that the effective radius of the source of pp neutrinos is about 0.1 $R_{\odot}$, and that of hep neutrinos is nearer 0.15 $R_{\odot}$. On the other hand, the effective radius of the source of ^{8}B neutrinos, which represent 77% of the expected flux detected by the ^{37}Cl detector, is only 0.05 $R_{\odot}$. We therefore consider it not unreasonable to search for evidence of a variation of the Homestake measurements which may be associated with a latitudinal modulation.

If there were to be a simple variation of the neutrino flux with latitude, it would show up as an annual variation of the flux if the magnetic inhomogeneity has a north-south asymmetry, or as a 6 month variation if the inhomogeneity varies with latitude but has north-south symmetry, as in the Babcock (1963) model of the solar cycle. Such a variation would show up as a peak in the time-series spectrum at a frequency of 1 or 2 cycles yr^{-1}, respectively. We have examined the spectrum presented in SWW1 and find no evidence of a significant peak at either frequency. This examination therefore seems to indicate that there is no latitudinal modulation of the neutrino flux.

On the other hand, we found in SWW1 that the time-series spectrum of the Homestake data displays peaks not only at $\nu_{SWW} - 1$, but also at frequencies close to $\nu_{SWW} - 3$,

$v_{SWW} - 2$, v_{SWW}, and $v_{SWW} + 1$. It appears from these results that the basic rotational modulation (reduced as usual by 1 cycle yr^{-1}) due to Earth's rotation around the Sun) is being modulated by a process related to the annual cycle. The fact that we see sidebands displaced from $v_{SWW} - 1$ by both 1 and 2 cycles yr^{-1} is suggestive of modulation by a latitudinal structure that is neither strictly symmetric nor strictly antisymmetric about the solar equator. This suggests that the rotational modulation of the neutrino flux varies with latitude.

If the rotational modulation varies with latitude, this effect may show up as a dependence of the neutrino flux variance with latitude. In § 2 of this article, we search for such an effect by comparing the variances of the flux measurements for four latitude quartiles, formed by ordering runs according to their mean-time latitude. We find that the northernmost quartile has the largest variance and that this departure from average appears to be significant at the 2% significance level.

In § 3, we examine the variance of the flux as a function of latitude. We find that the latitude profiles obtained from the March-to-September scan and from the September-to-March scan are quite similar. Both indicate that the biggest contribution to the variance comes from a latitude band nearest to the northernmost limit.

In § 4, we examine the spectrum of the variance to look for evidence of a peak at either 1 or 2 cycles yr^{-1}. We may take advantage of the maximum likelihood spectrum analysis of SWW1 by extracting from that analysis the amplitude and phase of each frequency component. We then regard this procedure as providing an estimate of the Fourier transform of the flux and invert that function to obtain a "reconstructed flux." We may then examine the spectrum of the variance of the reconstructed flux. We find that, apart from a peak at zero frequency, the largest peak in the range 0–20 cycles yr^{-1} is that of 1 cycle yr^{-1}. We estimate the probability of obtaining this result by chance to be less than 1%.

In § 5, we examine the reconstructed flux as a function of phase with respect to the SWW periodicity for each of four latitude bins. We find that the four waveforms are similar, but the waveform of the northernmost bin has the biggest amplitude and accounts for about one half of the total waveform. Physical processes that might lead to the results of this analysis are discussed briefly in § 6.

2. NORTH-SOUTH VARIANCE ANALYSIS

Cleveland of the Homestake team has developed a code that can be used both to simulate the Homestake experiment and to analyze either data acquired by the actual experiment or data generated by simulations (B. Cleveland 1996, private communication). He has generously provided us with a copy of this code. In addition, Lande has generously provided us with the results of their complete renalysis of the Homestake data (K. Lande 1996, private communication): these results comprise the production rate g_i and also f_i and h_i, the lower and upper 68% confidence limits, respectively, all measured in ^{37}Ar atoms per day.

We have used this code to generate 1000 simulations of the actual sequence of 108 runs, based on an assumed constant Ar production rate of 0.475 atoms per day, the value obtained by the Homesake team by their maximum likelihood analysis of the actual sequence of 108 runs. This code begins by simulating (for a given flux of neutrinos) the

Poisson process that governs the creation of radioactive Ar atoms due to the conversion of Cl atoms. The code then simulates the known background radiation and also the Poisson process of the decay of the Ar atoms, so producing a series of times at which detection events would be registered in the counter following the Ar extraction operation. The simulations generated by this code mimic the real experiment as accurately as possible: the exposure time, the experimental efficiencies of extracting and counting, the length of counting, the counter resolution, and the background radiation in the counter, have all been chosen to be identical to those of each real run.

For each run of each simulation, the series of beta-decay detection times was then analyzed with exactly the same maximum likelihood program that had been used to determine the production rate and the confidence limits for each run in the Homestake experiment. Each simulation ($\alpha = 1$, ..., 1000) therefore yields 108 estimates $g_{i,s\alpha}$ ($i = 1, \ldots, 108$) of the production rate g_i, and also of f_i and h_i, the lower and upper 68% confidence limits, all measured in ^{37}Ar atoms per day. We found that, for each run, the 1000 estimates of the production rate may be fitted approximately (but only approximately) to a Gaussian distribution. Hence, for each run, we could determine from the simulations a standard deviation $\sigma_{i,s}$. The departure from a Gaussian form is not crucial for the analysis in this section.

In SWW1, we formed the χ^2 statistic from the experimental data

$$\Gamma_e = \sum_i \left(\frac{g_i - \bar{g}}{\sigma_{i,s}} \right)^2 , \qquad (2.1)$$

where $\bar{g}$ is chosen to minimize this statistic. We then compared the resulting value with the corresponding values obtained from the simulations. We considered three choices of the quantity σ_i: one taken from the simulations, and two taken from combinations of f_i and h_i, following earlier suggestions by Bahcall, Field, & Press (1987) and by Bieber et al. (1990). There is little correspondence between these three estimates, and it is certainly not clear why any one should be preferred to the other two. For this reason, we will here and subsequently consider the variance:

$$v = \langle (g_i - \bar{g})^2 \rangle , \qquad (2.2)$$

where $\bar{g}$ is chosen to minimize the statistic.

The heliographic latitude b of the Earth-Sun line is given by

$$b = b_{max} \cos \left[2\pi(\varphi_y - 0.688) \right] , \qquad (2.3)$$

where σ_y is the phase of the year (0 to 1) and $b_{max} = 7°15'$. We have divided the runs into four "latitudinal quartiles" by ordering the runs according to the latitude b_m of the Earth-Sun line at the "mean time" of the run, and then dividing that set into four groups (1, 2, 3, 4) of 27 runs each, such that quartile 1 is the southernmost and quartile 4 is the northernmost. We denote the resulting values of v by v_1 to v_4, for which we obtain the values of 0.073, 0.102, 0.082, and 0.161, respectively.

We assess the significance of this result, that one quartile has a much larger variance than the others, by using the "shuffle test" that was used by Bahcall & Press (1991) in their analysis of the Homestake data, and that we used also in SWW1. The procedure is to form many "pseudosequences" by permuting the order of the runs (retaining for each run the duration, the "dead time" if any up to the
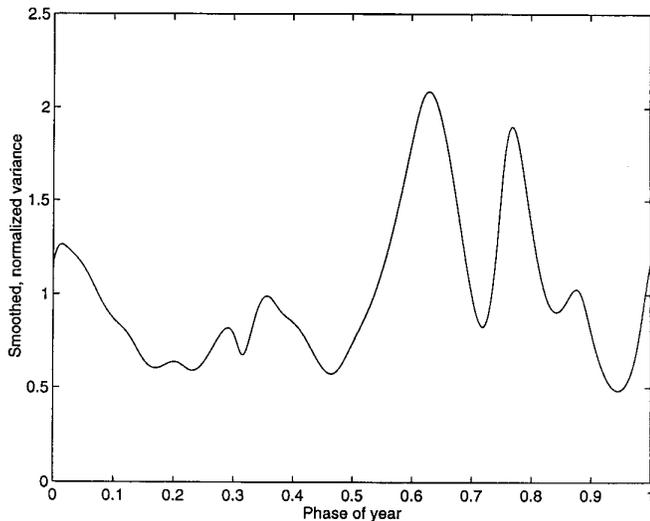
FIG. 1.—Variance of the neutrino flux as a function of phase of the year. This estimate, which has been smoothed as described in the text and normalized to average value unity, has been formed from the "reconstructed flux."

beginning of the next run, the estimated count rate, and the error estimates). We obtain a value of v as large as 0.161 in only 20 out of 1000 shuffles, indicating a significance level of 2%.

It appears, from this result, that the variance of the flux estimates is a function of latitude, and is greatest for the northernmost range of latitudes.

We have repeated this analysis, incorporating the estimate of the standard deviation taken from the simulations,

$$w = \left\langle \left(\frac{g_i - \bar{g}}{\sigma_{i,s}} \right)^2 \right\rangle , \qquad (2.4)$$

and we obtain the values 0.78, 1.13, 1.02, and 2.05 for the four latitude quartiles. We find, from the shuffle test, that we obtain a value as large as 2.05 in only 10 out of 1000 shuffles, indicating a significance level of 1%.
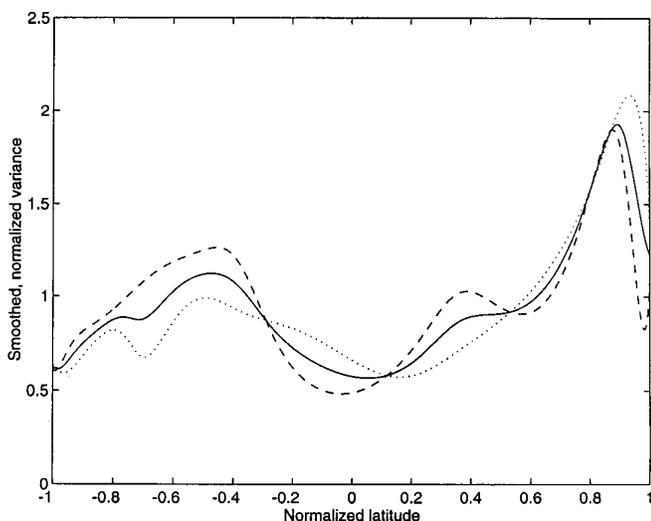

FIG. 2.—Variance, calculated as for Fig. 1, now displayed as a function of latitude. Dotted line, south to north passage; broken line, north to south passage; solid line, average of both passages.

3. LATITUDINAL VARIATION

We have just seen that there appears to be evidence that the variance of the neutrino flux, as measured by the Homestake experiment, depends upon latitude. Since the Earth-Sun line scans the south-north latitude range twice a year, it is interesting to see if both scans yield similar curves for the dependence of variance on latitude.

We have referred flux estimates to the phase of year ϕ, running from 0 to 1, as determined by the mean time of each run. We order runs according to ϕ, and then smooth both phase and variance estimates by Gaussian smoothing according to

$$\bar{v}_i = \frac{\sum v_{i+k} \exp \left[-(k/\kappa)^2 \right]}{\sum \exp \left[-(k/\kappa)^2 \right]} , \qquad (3.1)$$

with a corresponding formula for $\bar{\phi}_i$. The summation is over all k, and we have adopted $\kappa = 4$.

For display purposes, it is convenient to interpolate the data with cubic splines. In this way, we obtain Figure 1 as a display of the variance as a function of phase of year. There are two prominent peaks that are on either side of $\phi = 0.688$, the phase of year that corresponds to the maximum northerly excursion of the Earth-Sun line.

The data shown in Figure 1 are repeated in Figure 2 that shows the smoothed variance (defined by eq. [3.1] as a function of latitude. We display as distinct lines the average variance obtained in the south-to-north part of the year (March to September) and the north-to-south part of the year (September to March). We see that the curves are quite similar and, in particular, that both curves peak near $f = 0.9$, corresponding to latitude $6°5$ north.

The similarity of the two curves shown in Figure 2 tends to support the view that the variance is being modulated by an effect that depends upon heliographic latitude. If the modulation were due to some other annual effect (such as an annual change in experimental, for instance), one would not expect the south-to-north curve and the north-to-south curve to be similar.

4. SPECTRUM OF VARIANCE OF RECONSTRUCTED FLUX

If the variance really is modulated by an effect that depends upon heliographic latitude, this should lead to an annual periodicity in the variance. Rather than analyze the original data, we have chosen to form a "reconstructed flux" from the amplitude and phase information derived from the maximum likelihood spectrum analysis of SWW1, and then to examine the spectrum of the variance of the reconstructed flux. This procedure has certain advantages over attempting a similar analysis in terms of the raw data. (1) By using this procedure, we are implicitly taking into consideration the experimentally determined errors of flux measurements as well as the flux estimates themselves since that information was used in the maximum likelihood analysis. (2) Since we can form the reconstructed flux for any sequence of time steps, we can adopt a uniform time resolution (typically 0.01 yr) that facilitates spectrum analysis.

The maximum likelihood spectrum of the flux estimates was obtained by adopting the following model for the time series,

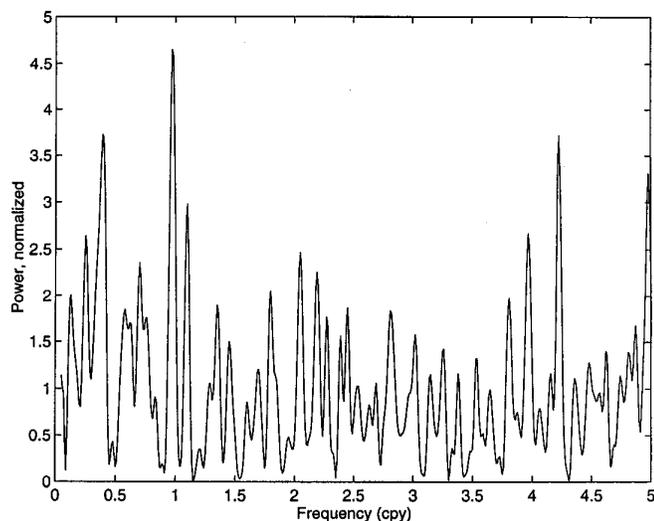$$\gamma_{m,v}(t) = C_v + A_v \cos (2\pi vt) + B_v \sin (2\pi vt) . \qquad (4.1)$$

FIG. 3.—Spectrum of the variance of the reconstructed flux in the frequency range 0.1–5 cycles yr^{-1}.

For each frequency v of a discrete range of frequencies, we determined the values of A_v, B_v, and C_v that maximize the likelihood of obtaining the measured fluxes. To do so, we used estimates of the standard deviation derived from the experimental data analysis (Cleveland 1996, private communication).

We form a "reconstructed" time series by summing the frequency components estimated in this way:

$$\tilde{g}(t) = \sum_v [A_v \cos (2\pi vt) + B_v \sin (2\pi vt)] , \qquad (4.2)$$

ignoring the constant term C_v, since we are interested only in the variance of the reconstructed time series. Hence each time step provides the following contribution to the variance:

$$v(t) = [\tilde{g}(t)]^2 . \qquad (4.3)$$

We have evaluated $v(t)$ at intervals of 0.01 y for the time period 1970.00 to 1995.00, and this makes it possible to make a simple estimate of the power spectrum $S(v)$ of $v(t)$. Figure 3 shows the spectrum, normalized to mean values unity, over the frequency range 0–5. There is a notable peak with power $S = 4.7$ at $v = 0.97$, with half-height half-width 0.03. This is the strongest peak over the entire range $v = 0$–50 that we have examined, apart from a peak at zero frequency which has no significance and therefore is not shown in the figure.

It appears, from this analysis, that the variance of the reconstructed flux contains a significant periodic component with period 1 yr. This offers supporting evidence for our finding, in § 2, of a north-south difference in the variance. Considering only the frequency range 0–20 for which spectrum analysis of the experimental data is a reasonable procedure, the probability of finding the strongest peak, of half-height full width 0.06, at the frequency $v = 1$ is about 0.3%.

The analysis of this section does not indicate whether this periodicity is due to a real variation of the solar neutrino flux or to some other process such as an annual change in the experimental program or an annual variation of the cosmic-ray flux. (It is too large to be attributed to the eccentricity of Earth's orbit.) However, we noted in the previous section that the similarity of the south-north and north-

south variance curves provided evidence that the modulation is association with latitude, rather than simply with an annual modulation.

5. LATITUDINAL ANALYSIS OF THE ROTATIONAL PERIODICITY

In §§ 2 and 3, we have found evidence that the variance of the neutrino flux measurements depends upon heliographic latitude. We therefore need to inquire into the possible origin of this dependence. This effect may be due in part to the rotational modulation analyzed in SWW1. If the flux is subject to rotational modulation, and if that modulation depends upon heliographic latitude, we must expect that the variance of the flux will show a latitude dependence: rotational modulation would most likely be due to an inhomogeneity with longitudinal structure, and such an inhomogeneity is likely also to have latitudinal structure.

We therefore investigate in this section the variation of the flux as a function of rotational phase for each of the four latitude quartiles. Since we now examine a periodicity with period shorter than the duration of a typical run, and shorter than the half-life of ^{37}Ar nuclei, it is not appropriate to attempt to examine the rotational periodicity by assigning the flux estimate of each run to the phase determined by either the mean time or the stop time of that run. For this reason, we once again examine the reconstructed flux defined by by equation (4.2). Since the procedure used in SWW1 does not make reliable estimates of the amplitudes and phases of harmonics of the rotational periodicity, we examine only the fundamental term. It is also convenient to introduce a rotation phase measured from 1970 "January 0":

$$\phi_R = \omega_R(t - 1970) , \qquad (5.1)$$

where ω_R is the rotation frequency (13.88 cycles yr^{-1}) inferred from the analysis of SWW1. In this way, we have formed a sinusoidal fit to the reconstructed flux

$$\tilde{g}_R(t) = A_R \cos (\phi_R) + B_R \sin (\phi_R) . \qquad (5.2)$$

Figure 4 presents a display of this quantity for each latitude quartile and for the sum over all quartiles. We see that all four contributions have similar phase, but the contribution
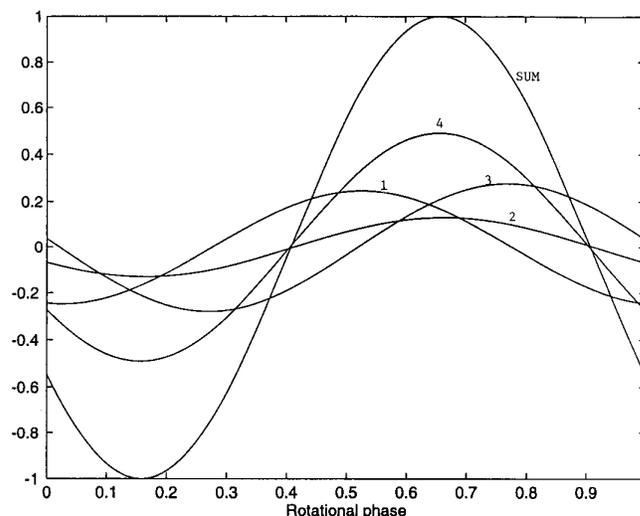

FIG. 4.—Sinusoidal fits to the 12.88 cycles yr^{-1} component of the reconstructed flux for the latitude quartiles 1–4 (southernmost to northernmost) and for the sum of all four quartiles.

from the northernmost quartile is substantially larger than that from any other quartile.

6. DISCUSSION

We argued in the introduction that the frequency spectrum of the Homestake solar-neutrino data suggests that the flux is being modulated on a one-yr and also on a six-month timescale, and that such modulation may be due to a latitude-dependence of the solar neutrino flux. As we have seen in SWW1, the flux itself does not exhibit such a periodicity. However, we have found in this article that the variance of the flux shows both a dependence upon latitude (§§ 2 and 3) and, as one would then expect, a one-year periodicity (§ 4). Furthermore, we have found in § 5 that the amplitude of the 12.88 cycles yr^{-1} periodicity is latitude-dependent, with a dependency on latitude similar to that of the variance. For both the variance and the 12.88 cycles yr^{-1} modulation we find that, when analyzed in terms of latitude quartiles, the northernmost quartile exhibits the biggest effect.

It has been recognized for some time that the key to the puzzle of solar neutrinos may be that neutrinos produced in the center of the Sun are transformed into another type of neutrino on their way to the terrestrial detector (Bahcall 1989, p. 28). Although such transformations are not possible in the "standard model" of electroweak interactions, the "nonstandard" extension of this model does allow for such transformations. (See, for instance, Raffelt 1996.)

Wolfenstein (1978, 1979), and, later, Mikheyev & Smirnov (1986a, 1986b, 1986c) proposed that the apparent deficit of solar neutrinos might be caused by a conversion of electron neutrinos to mu or tau neutrinos due to the interaction of neutrinos with matter as they travel through the solar interior. This is now known as the "MSW effect." However, discussion of solar neutrinos has been strongly influenced by the perception that there is an anticorrelation between magnetic indicators (such as sunspot number) and the neutrino detection detection rate. The MSW effect could not explain this anticorrelation. As Raffelt (1996, p. 387) remarks, "If the anticorrelation between disk-centered magnetic indicators of solar activity and the event rate at Homestake is taken seriously, the only plausible explanation put forth to date is that of magnetically induced neutrino spin or spin-flavor transitions ... ."

According to nonstandard theory, each "flavor" of neutrinos (electron, mu, or tau) can have either left-handed neutrinos so that right-handed neutrinos are "sterile" as far as nuclear processes are concerned. In particular, nuclear reactions in the solar core produce only left-handed electron neutrinos, and the Homestake experiment detects only left-handed electron neutrinos. Cisneros (1971) pointed out that the apparent anticorrelation of the solar neutrino flux and solar activity may be due to the conversion of left-handed neutrinos into right-handed neutrinos in the presence of a magnetic field. The process was analyzed in more detail by Voloshin, Vysotskii, & Okun (1986a, 1986b) and is generally referred to as the "VVO effect." The effect of a dense medium on this process originally appeared to be adverse: left-handed and right-handed neutrinos have different propagation characteristics in matter; this removes the mass degeneracy and so limits the efficacy of conversion between the left-handed and right-handed helicity states.

Voloshin et al. (1986a, 1986b) also considered the more complex behavior of neutrinos propagating in a magnetic field and in a medium, allowing for the possibility that spin and flavor both change at the same time. It appeared that this "spin-flavor precession" also would be suppressed since neutrinos of different flavors have different masses. Subsequently, however, Akhmedov (1988a, 1988b) and Lim & Marciano (1988) noted that left-handed neutrinos of one flavor and right-handed neutrinos of a different flavor experience different coherent forward scattering on the particles of the medium and that this difference can offset the effect of the mass difference. According to Akhmedov (1997), the difference in forward propagation gives rise to a "potential energy difference" that must be subtracted from the "kinetic energy difference" (i.e., the mass difference). For a given mass difference, and for given neutrino energy, the two effects just cancel for some value of the mass density. Hence if neutrinos propagate through a medium of varying density (such as the solar interior), they can exhibit strong conversion in a "resonant" region. This is known as "resonant spin-flavor precession" (RSFP). According to Raffelt (1996), pp. 387–388; see also Akhmedov 1997), "the measured signals in the detectors as well as the time variation at Homestake and the absence of such a variation at Kamiodande can all be explained by a suitable choice of neutrino parameters and magnetic-field profiles of the Sun."

As we remarked earlier in this section, the above analyses dealing with the effect of magnetic field on neutrino propagation have been based implicitly or explicitly on the assumption that the effects would occur in the convection zone, on the basis of apparent evidence that there is an anticorrelation between the neutrino flux and solar magnetic activity. However, Bahcall (1989, p. 326 ff.) was not persuaded by the evidence, our recent spectrum analysis (SWW1) shows no evidence for a solar-cycle variation of the neutrino flux, and the recent reanalysis by Walther (1997) has led him to conclude that there is no correlation between the neutrino flux and the sunspot number. Furthermore, our evidence (SWW1) that there is a high-Q rotational periodicity (Q of order 100) argues against the convection zone being the location in which the modulation occurs. Since the convection zone has strong differential rotation, one cannot expect that it will contain a long-lasting magnetic pattern that is not of cylindrical symmetry, such as appears to be necessary to understand a high-Q rotation modulation.

The radiative zone is a much more hospitable location for the RSFP process, since: (1) the extent of the radiative zone is about four times that of the convection zone; (2) the density in the radiative zone is larger than that at the base of the convection zone by about 2 orders of magnitude; and (3) the gas pressure is larger by about 3 order of magnitude and, in consequence, the magnetic field strength can be much larger in the radiative zone than in the convection zone.

If the RSFP effect does indeed play a significant role in modulating the solar neutrino flux, the precise effects will depend sensitively on the configuration as well as the strength of the magnetic field. Further discussion of these effects is well beyond the scope of this article. Nevertheless, we may venture to hope that, if the effects found in SWW1 and in this article are corroborated, further analysis of solar neutrino data from existing and from future experiments, may yield valuable information about the solar interior (notably its internal rotation and magnetic field) and about neutrinos.

REFERENCES

Akhmedov, E. K. 1988a, Soviet J. Nucl. Phys., 48, 382
———. 1988b, Phys. Lett. B, 213, 64
———. 1997, Proc. 4th Int. Solar Neutrino Conf., Heidelberg, Germany (1997 April 8–11), in press
Babcock, H. W. 1963, ARA&A, 1, 41
Bahcall, J. N. 1989, Neutrino Astrophysics (Cambridge: Cambridge Univ. Press)
Bahcall, J. N., Field, G. B., & Press, W. H. 1987, ApJ, 320, L69
Bahcall, J. N., & Press, W. H. 1991, ApJ, 370, 730
Bieber, J. W., Seckel, D., Stanev, T., & Steigman, G. 1990, Nature, 348, 407
Cisneros, A. 1971, ApSS, 10, 87
Davis, R., Jr., & Cox, A. N. 1991, Solar Interior and Atmosphere, ed. A. N. Cox, W. C. Livingston, & M. S. Matthews (Tucson: Univ. Arizona Press), 51
Lim, C. S., & Marciano, W. J. 1988, Phys. Rev. D, 37, 1368

Mikheyev, S. P., & Smirnov, A. Y. 1986, Soviet J. Phys., 42, 913
———. 1986b, Soviet Phys.—JETP Lett., 64, 4
———. 1986c, Nuovo Cimento, 9C, 17
Raffelt, G. G. 1996, Stars as Laboratories for Fundamental Physics (Chicago: Chicago Press)
Schou, J., et al. 1997, ApJ, submitted
Sturrock, P. A., Walther, G., & Wheatland, M. S. 1997, ApJ, 491, 409 (SWW1)
Voloshin, M. B., Vysotskii, M. I., & Okun, L. B. 1986a, Soviet J. Nucl. Phys., 44, 440
———. 1986b, Soviet Phys.—JETP, 64, 446
Walther, G. 1997, Phys. Rev. Lett., 79, 4522
Wolfenstein, L. 1978, Phys. Rev. D, 17, 2369
———. 1979, Phys. Rev. D, 20, 2634