The Astrophysical Journal, 523:L177–L180, 1999 October 1

ROTATIONAL SIGNATURE AND POSSIBLE *r*-MODE SIGNATURE IN THE GALLEX SOLAR NEUTRINO DATA

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Received 1999 May 24; accepted 1999 August 4; published 1999 August 24

ABSTRACT

Recent analysis of the Homestake data has yielded evidence that the solar neutrino flux varies in time—more specifically, that it exhibits a periodic variation that may be attributed to rotational modulation occurring deep in the solar interior, either in the tachocline or in the radiative zone. Here we present a spectral analysis of the GALLEX data that yields supporting evidence for this rotational modulation. The most prominent peak in the power spectrum occurs at the synodic frequency of 13.08 yr^{-1} (cycles per year) and is estimated to be significant at the 0.1% level. It appears that the most likely interpretation of this modulation is that the electron neutrinos have nonzero magnetic moment, so that they oscillate between left-hand (detectable) and right-hand (nondetectable) chiralities as they traverse the Sun's internal magnetic field. This oscillation could account for the neutrino deficit. The second strongest peak in the GALLEX spectrum has a period of 52 days, and this period occurs in other solar data as well. We suggest that this periodicity and also the Rieger 154 day periodicity, which shows up in many solar parameters and in the Homestake data, are due to *r*-mode oscillations.

Subject headings: elementary particles — methods: statistical — Sun: interior — Sun: particle emission

1. INTRODUCTION

Since the measured neutrino flux is only a fraction of that expected on the basis of the standard solar model, there has long been a suspicion that electron neutrinos produced in the solar core are transmuted, in flavor or chirality (or both), on their way to Earth (Bahcall et al. 1996). In attempting to explain this deficit, theorists have proposed three mechanisms for the modulation of the solar neutrino flux. The first to be suggested is the MSW effect (Mikheyev & Smirnov 1986a, 1986b; Wolfenstein 1978, 1979), whereby electron neutrinos may be converted into either μ or τ neutrinos as they propagate through matter in the solar interior. The second to be proposed is the VVO effect (Voloshin, Vysotskii, & Okun 1986a, 1986b), whereby left-handed neutrinos, as they propagate through a magnetic field, are converted into right-handed neutrinos that are "sterile" as far as nuclear processes are concerned and so would not be detected by the Homestake experiment (Davis & Cox 1991; Lande et al. 1992; Cleveland et al. 1995) or the GALLium EXperiment (GALLEX; Anselmann et al. 1993, 1995; Hampel et al. 1996). The third possibility is the resonant spin-flavor precession (RSFP) process, by which neutrinos propagating through a medium permeated by a magnetic field may be converted into neutrinos of different flavor and opposite chirality (Akhmedov 1988a, 1988b; Lim & Marciano 1988).

If it can be determined that the neutrino flux is dependent on the timescale of the neutrino experiments, this would indicate that transmutation is occurring, and it may help us decide which of the three candidate processes is dominant. In the past, measurements of the neutrino flux have had a high noise level, making it difficult to answer this question by direct examination of the data, but SuperKamiokande (Fukuda et al. 1988) and the Sudbury Neutrino Observatory (McDonald 1995) may change this situation. The technique of choice has been to search for a correlation between the solar neutrino flux and an index of solar variability, usually the Wolf sunspot number (Bahcall, Field, & Press 1987; Bahcall & Press 1991; Bieber et al. 1990; Dorman & Wolfendale 1991), although the surface magnetic field strength (Massetti & Storini 1993; Oakley et al. 1994), the intensity of the green-line corona (Massetti & Storini 1996), and the solar wind flux (McNutt 1995) have also been considered. Walther (1997) has recently examined and criticized the statistical procedures that have been used to support the claim that the neutrino flux is anticorrelated with the sunspot number, and he concluded that there is no evidence for such a relationship.

2. ROTATIONAL MODULATION

The density structure of the Sun is close to spherical symmetry and even closer to cylindrical (rotational) symmetry; therefore, one would not expect the MSW effect to produce a modulation of the neutrino flux at the solar rotation frequency. On the other hand, the Sun's photospheric magnetic field is far from being cylindrically symmetric with respect to the rotation axis, and there is no obvious reason why the axes of the dipole and multipole components of the Sun's internal magnetic field should all be aligned with the solar rotation axis. It follows that if neutrinos have a nonzero magnetic moment, either the VVO effect or the RSFP effect can lead to the rotational modulation of the solar neutrino flux. In principle, the conversion may occur in the radiative zone, the tachocline, the convection zone, or some combination thereof. However, an observable modulation is most likely to be produced in the radiative zone since that is the largest in extent, and it can accommodate the strongest magnetic field because of its high gas pressure. Even if the neutrino magnetic moment is less than $10^{-12}\mu_B$, where μ_B is the Bohr magneton (the most stringent upper limit on the

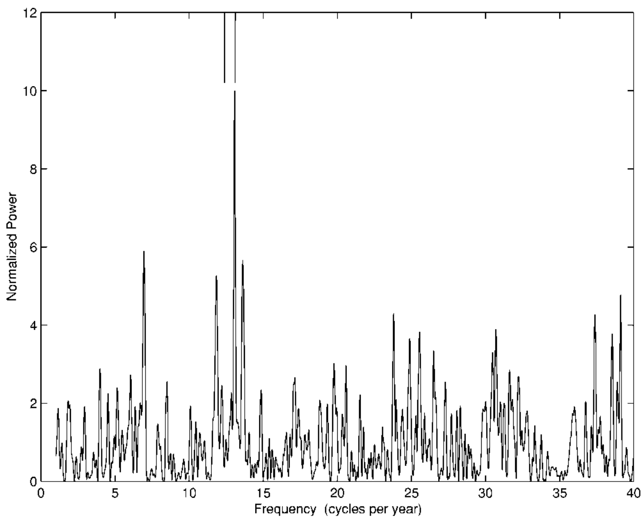

FIG. 1.—Power spectrum of the GALLEX neutrino data over the frequency band of 1–40 yr^{-1}. The biggest peak lies in the search band of 12.4–13.1 yr^{-1} specified in Sturrock et al. (1997).

neutrino magnetic moment cited by Bahcall 1989), it appears that the RSFP effect can lead to the modulation of the solar neutrino flux since the Sun's internal pressure is so large that a magnetic field of 10^6 G or more represents only a very weak perturbation of the solar structure.

These considerations led us (Sturrock, Walther, & Wheatland 1997) to reexamine the Homestake data, seeking to determine whether or not the solar neutrino flux varies in time. We tested for time variability by comparing a χ^2 measure of the variability of the flux measurements with the values of the same statistic computed for 1000 Monte Carlo simulations of the Homestake experiment. Three versions of that comparison led to the result that one may reject the hypothesis that the solar neutrino flux is constant, with confidence estimates in the range of 5.8%–0.1%.

Following this assessment that the solar neutrino flux is time variable, and in line with the above theoretical considerations, we then carried out a spectral analysis of the Homestake data to search specifically for evidence of the effect of solar rotation. The helioseismology data then available (Kosovichev et al. 1997) yielded 13.4–14.1 yr^{-1} as the absolute (sidereal) rotation rate of the radiative zone. We therefore adopted the corresponding synodic range of 12.4–13.1 yr^{-1} as the "search band" for a possible rotational modulation frequency of the solar neutrino flux as it would be measured on Earth. A maximum likelihood spectral analysis of the Homestake neutrino data gave a prominent peak at 12.88 yr^{-1}, within the search band. To assess the significance of this peak, we performed 1000 Monte Carlo simulations of the experiment with an assumed constant neutrino flux and found 30 trials with a peak in the search band as large as or larger than the actual peak, thus arriving at a significance level of 3%.

We also found four peaks at frequencies close to 10.88, 11.88, 13.88, and 14.88 yr^{-1} that may be interpreted as annual and semiannual sidebands of the peak at 12.88 yr^{-1}. Monte Carlo tests show that this set of five related peaks is significant at the 0.2% significance level. The detection of sidebands related to a 1 yr periodicity suggests that the internal structure responsible for the modulation of the neutrino flux varies in latitude as well as in longitude. More recently, we have examined this conjecture (Sturrock, Walther, & Wheatland 1998) and find evidence that the modulation is indeed latitude-dependent. For the Homestake data, the strongest modulation occurs when the Sun-Earth line is at about 6°.5 north.

3. ANALYSIS OF GALLEX DATA

This Letter presents the results of a search for evidence of rotational modulation in an independent data set. We have spectrum-analyzed the GALLEX solar neutrino data (Anselmann et al. 1993, 1995; Hampel et al. 1996), including the recent data generously provided by Professor W. Hampel on behalf of the GALLEX consortium. The measurements comprise 64 runs over the time interval from 1991 May 14 to 1997 January 22. Since these measurements were not made at regular time intervals, it is necessary to use a procedure that is appropriate for irregularly sampled data such as the Lomb-Scargle method (Lomb 1976; Scargle 1982). However, that method rests on the assumption that, in testing for a sinusoidal component, one may assume that the constant offset is given by the mean value of the data. This assumption is valid if the data set is sufficiently long or if the sampling is sufficiently irregular, but these assumptions prove not to be appropriate for the GALLEX data. It was therefore advisable to use a procedure (Knight, Schatten, & Sturrock 1979) that avoids this assumption but is otherwise similar to the Lomb-Scargle method.

For each frequency ω of a chosen range of frequencies, we form the statistic

$$V = \sum \frac{1}{\sigma_\alpha^2} (g_\alpha - A \cos \omega t_\alpha - B \sin \omega t_\alpha - C)^2, \qquad (1)$$

where the t_α are the end times, g_α the experimental estimates of the flux, and σ_α the experimental error estimates. (The experimental estimates are of course made on the assumption that the flux is constant during each run.) If one were concerned about the phase of the modulation, it would not be satisfactory to assign the experimental estimates to the end times, but if the phase is not important, this simplification permits a reasonably accurate determination of the spectrum. For each frequency, we adjust A, B, and C in order to minimize the quantity V. The "power" S at each frequency may then be estimated from

$$S = A^2 + B^2. \qquad (2)$$

This procedure breaks down at zero frequency where the relevant matrix is ill-conditioned, so we ignore very low frequencies. In order to examine the properties of the output from this method of analysis, we have used the shuffle procedure (Bahcall & Press 1991) in order to simulate a large number of sequences that have no real time variation but otherwise have statistical properties identical to those of the actual time series. The distribution of power is found to be very close to that which is expected for Gaussian noise; i.e., the probability of finding a power larger than S is e^{-S}, if the power is normalized so that the mean value of S is unity. For this reason, we have thus normalized the power calculated from equation (2).

Figure 1 shows the normalized power over the frequency band $\nu = 1$–$40\ yr^{-1}$, where $\omega = 2\pi\nu$. This figure also shows the original search band (Sturrock et al. 1997): 12.4–13.1 yr^{-1}. We find the highest peak at $\nu = 13.08$, which is within the search band. The normalized power is 9.83, so there is a probability of only 0.00005 of finding a peak that big or bigger at a specified frequency. The length of the GALLEX data sequence is about 6 yr, so that the Nyquist frequency is 0.08 yr^{-1}, from which we infer that there are nine independent frequencies in the search band. Hence, to judge from the height of the peak, the probability of finding a peak that large or larger in the search band is 0.0005. It appears, therefore, that the peak is significant at the 0.05% confidence level. To obtain a more robust significance estimate, we have formed the power given by equation (2) for 10,000 sequences in which the g_α-σ_α pairs were shuffled with respect to the end times t_α. In only eight of those 10,000 cases was the power of the strongest peak in the search band larger than that found for the actual data. This yields a confidence estimate of 0.08%.

4. DISCUSSION

On calculating the Nyquist frequency for each data set, we find that an analysis of the Homestake data yields a periodicity with a frequency of 12.88 $\pm$ 0.03 yr^{-1}, and an analysis of the GALLEX data yields a periodicity with a frequency of 13.08 $\pm$ 0.08 yr^{-1}. The difference is small and is not obviously statistically significant, suggesting that the two analyses point to a periodicity with a synodic frequency of 13.0 $\pm$ 0.15 yr^{-1} or a sidereal frequency of 14.0 $\pm$ 0.15 yr^{-1} that converts to 444 $\pm$ 5 nHz. Recent analyses of helioseismology data indicate that the radiative zone and the lower part of the tachocline both have rotation rates in this band (Schou et al. 1998).

On the other hand, we have carried out a similar spectral analysis of the Wolf sunspot number for the period of time covered by the Homestake data, and we find that it shows significant peaks at both 12.90 and 13.09 yr^{-1}. The two neutrino experiments sample the solar interior in different ways because of the different radii at which the relevant nuclear reactions occur and also possibly because of the difference in the energy of the neutrinos that the experiments detect. The latter is an important factor to consider since the VVO effect is energy-independent, whereas the RSFP effect is energy-dependent. These points will be pursued in a later article, which will also address the implications of these results for particle physics. It is already clear that rotational modulation, which has now been detected in both the Homestake and GALLEX data, must be due to the Sun's internal magnetic field and that this effect can occur only if neutrinos have a nonzero magnetic moment.

Rotational modulation also has a bearing on the deficit problem. On determining the sinusoidally modulated neutrino flux (with a frequency of 13.08 yr^{-1}) that leads to the best fit with the experimental data, we find that the depth of the modulation must be on the order of 100%. This implies that the average measured flux is approximately one-half the flux produced in the solar core, thus resolving the deficit problem for the gallium experiment. We find a similar result for the Homestake experiment.

The second largest peak in Figure 1 occurs at $\nu = 7.00$ yr^{-1} and has a normalized power of $S = 5.8$. The probability of finding a peak this large or larger *at a specified frequency* is 0.3%. We do not find a peak at the Rieger frequency of 2.37 yr^{-1} (154 days) (Rieger et al. 1984; Bai 1994; Oliver, Ballester, & Baudin 1998), but we note that $\nu = 7.00$ yr^{-1} corresponds to a period of 52 days, which also is a well-known period in solar activity data (Bai 1994), with properties similar to the Rieger periodicity.

Bai & Sturrock (1993) have drawn attention to the fact that solar activity exhibits several similar oscillations, with periods that appear to be multiples of a "fundamental" period in the range of 25–26.3 days. We have now found that this fundamental period corresponds to the sidereal rotation period of that region of the solar interior where the modulation of the neutrino flux occurs. This result may be understood if we identify the Rieger and related periodicities with *r*-mode oscillations in a region that is in approximately rigid rotation, possibly the radiative zone. In the rotating frame of a rigidly rotating fluid sphere, these oscillations have frequencies of

$$\nu = \frac{2m\nu_R}{l(l+1)}. \qquad (3)$$

In this formula, ν_R is the rotation frequency, and l and m are the usual spherical-harmonic indices, restricted by $l \geq 2$ and $|m| \leq 1$ (Papaloizou & Pringle 1978; Provost, Berthomieu, & Rocca 1981; Saio 1982; Wolff & Blizard 1986).

If, on the basis of our analysis of the Homestake and GALLEX data, we adopt $\nu_R = 14.0 \pm 0.15$ yr^{-1}, we find that the frequency of the $l = 3$, $m = 1$ mode is 2.33 $\pm$ 0.03 yr^{-1}, corresponding to a period of 154 $\pm$ 2 days, and that of the $l = 3$, $m = 3$ mode is 7.00 $\pm$ 0.08 yr^{-1}, corresponding to a period of 52 $\pm$ 1 days. The frequency of the $l = 3$, $m = 2$ mode is 4.67 $\pm$ 0.05 yr^{-1}, corresponding to a period of 78 $\pm$ 1 days, which also is a well-known solar frequency (Bai 1992). This interpretation therefore offers an explanation of three well-known but puzzling oscillations with periods of approximately 52, 78, and 154 days. The rotational modulation of the neutrino data may be attributed to a magnetic structure that rotates within the deep solar interior. The modulation at the Rieger and related periods may be attributed to *r*-modes that move magnetic structures in latitude and thereby modulate the neutrino flux at the *r*-mode periods with respect to the rotating frame. Further details of this analysis and further discussion will be presented in future articles.

This work was supported by NASA grants NAS8-37334 and NAGW-2265 and by Air Force grant F49620-95-1-0008.

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