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Experimental tests of the Mikheyev-Smirnov-Wolfenstein effect

John M. LoSecco
Physics Department, University of Notre Dame, Notre Dame, Indiana 46656
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The fundamental nature of the hypothesis of a nonzero neutrino mass and mixing makes it imperative that confirmation be sought for this as a solution to the solar neutrino problem. While observable effects for the most probable values of the parameters Δm^2 and $\sin^2(2\theta)$ can be large, in general they are not. Regeneration of the solar neutrino signal itself in the Earth is the most promising possibility. Specific orientations of the Sun and Earth give maximum effects. 20% to 30% modulation of the signal is typical for some portion of the solar neutrino flux itself. In some cases the effect can be much greater. In general, for most night observing times, the regeneration effect can be damped. Specific selection of peak sensitivity depends on the parameters Δm^2 and $\sin^2(2\theta)$, the location of the detector, and the time of night.

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INTRODUCTION

Recent reports [1] on the observation of a solar neutrino signal with ^{71}Ga still leave us with a solar neutrino problem [2]. If all of the experimental results are taken as reliable, one is still left with a deficit [3] of electron neutrinos coming from ^{7}Be and ^{8}B.

At present, the most popular candidate [4] to solve this problem is that of matter-enhanced neutrino oscillations, the Mikheyev-Smirnov-Wolfenstein (MSW) effect. The constraints imposed by three solar neutrino experiments greatly restrict the range of parameters (masses and mixing angles) still allowed. Since the mixing angle and neutrino masses are fundamental constants of nature, it is imperative that independent observations confirm the values inferred from the solar neutrino experiments. Additional measurements will also help to refine and limit the allowed range of parameters.

This paper discusses possible other manifestations of the MSW effect with parameters suggested by the solar neutrino results.

OBSERVABLES

It has been known for some time that the Earth itself can be an effective regenerator of neutrinos [5–9]. Early results using atmospheric neutrinos were able to rule out some of the range of parameters at "large" masses and mixing angles [10].

Additional work, such as the absence of a day-night effect for solar neutrinos [11,12], has also set some useful limits.

Until the recent ^{71}Ga result, the MSW effect circumscribed a set of contours in the Δm^2-$\sin^2(2\theta)$ plane. The ^{71}Ga result is only compatible with a small portion of the previously allowed range. Assuming that the correct ^{71}Ga result lies in the range of 60–100 solar neutrino units (SNU), the permitted values of Δm^2 are in a range of 3–10 $\times 10^{-6}$ eV^2 and $\sin^2(2\theta)$ in the range 0.4–1.5 $\times 10^{-2}$. A region at values of Δm^2 from 4 to 20 $\times 10^{-6}$ eV^2 is permitted for large $\sin^2(2\theta)$ in the range 0.4–0.7.

We would like to identify other physical effects that would manifest these parameters. It is impractical to contemplate a vacuum oscillation experiment to see effects of the small mixing angle since they will be very small and require high statistics. Even the large mixing angle solutions cannot be studied with terrestial vacuum oscillation experiments. The small values of Δm^2 would require very low energies and large base lines. Maximum amplitude is achieved at from 6 to 20 $\times 10^6$ m at 100 MeV. Such long base lines cannot be achieved on Earth

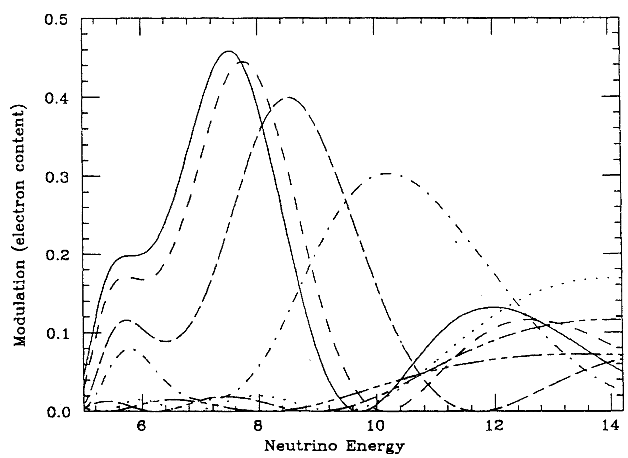

FIG. 1. Modulation of a pure muon neutrino beam as a function of zenith angle and energy for $\Delta m^2 = 6 \times 10^{-6}$ eV^2 and $\sin^2(2\theta) = 0.007$. Solid curve is 180°. Dashed curve is 170°. Double dashed curve is 160°. Dot dashed curve is 150°. Dotted curve is 140°. Short short medium long dashed curve is 130°. Short short long dashed curve is 120°. The general trend is that curves move to higher energies and lower amplitudes further from 180°.

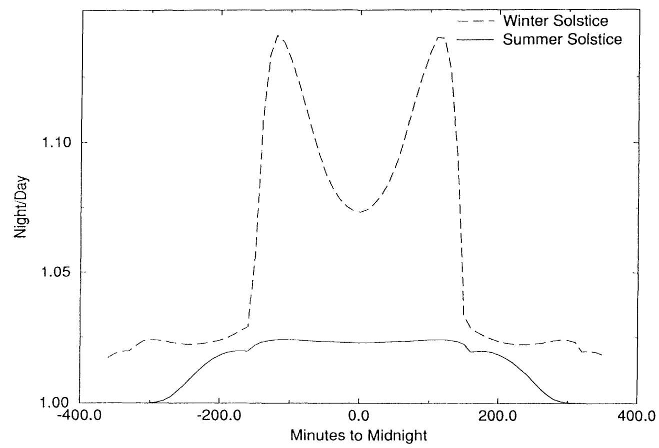

FIG. 2. Modulation of the solar neutrino event rate as a function of minutes to midnight on the winter and summer solstices for a detector located 35° of the equator. The curves are made for $\Delta m^2 = 6 \times 10^{-6}$ eV^2 and $\sin^2(2\theta) = 0.007$, a preferred solution.

except by traversing matter.

Except at very low energies, matter effects tend to dampen the oscillation amplitude. Figure 1 indicates the modulation to be observed for a muon neutrino beam traversing the Earth at a variety of zenith angles. The figure indicates that in excess of 30% of a muon neutrino beam would convert to electron neutrinos at zenith angles above 150° and energies in the range 6–12 MeV, for $\Delta m^2 = 6 \times 10^{-6}$ eV^2 and $\sin^2(2\theta) = 0.007$, a preferred solution to the solar neutrino problem.

Most significant oscillation effects are restricted to neutrino energies below about 15 MeV. There are few practical intense sources of muon neutrinos at such low energies. The most reasonable intense source is the Sun itself. So this argument leads us back to looking for Earth-induced modulations of the solar neutrino flux itself.

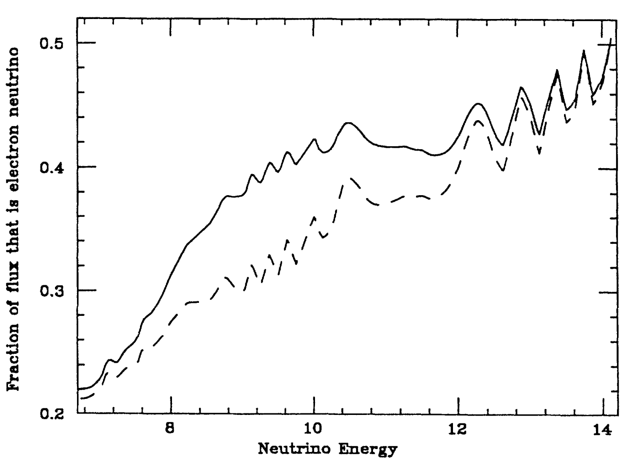

FIG. 3. Modulation of the solar neutrino flux as a function of day or night. The upper curve is the modulation of a beam for a 4-h period around midnight, as the Sun passes behind the Earth. The lower curve is the daylight flux modulation. The curves are made for 23° north, $\Delta m^2 = 6\times10^{-6}$ eV^2, and $\sin^2(2\theta) = 0.007$.

TEMPORAL DEPENDENCE

Calculating matter-enhanced oscillation effects for the solar neutrino signal itself is complicated. The flux from the Sun at the Earth is not an eigenstate of neutrino flavor. It is a mixture of the two vacuum mass eigenstates m_1 and m_2. A calculation must first propagate the signal through the Sun, taking into account the noncentral distribution of the source and the variation of electron concentration with depth and local composition. Once the signal emerges it can be projected onto the vacuum eigenstates which are determined by Δm^2 and $\sin^2(2\theta)$ since the coherence will be lost en route to the Earth. At the Earth the two different states must be propagated through the ground and the electron fraction projected out as the beam emerges. The remaining, nonelectron, fraction can still participate in neutral current reactions.

While it has been known for some time that seasonal and day-night modulation of the solar neutrino signal will occur if the MSW effect is indeed responsible for the deficiency, the point of this paper is that, for the currently permitted range of parameters, modulation will occur in shorter periods. By effectively exploiting these temporal dependencies, modulation effects of 20–30 % may be observed. A major reason for the more complicated temporal dependency is that the Earth is not a homogeneous mass and that neutrino oscillations, for some range of the permitted parameters, are damped by the presence of matter.

Figure 2 illustrates the effect. The ratio of nighttime to daytime event rate is plotted as a function of minutes past midnight of the winter or summer solstice for a detector located at 35° north of the equator. While the figure manifests a true day-night effect, and a seasonal effect, a more careful analysis of the data would be far more sensitive to enhancements. The figure was calculated including the effect of a 7.5 MeV recoil electron trigger threshold on the event rate, since the y distribution implies that, on average, only about half of the neutrino energy is transferred to the electron. Contributions of the μ or τ neutrino to the event rate have been included.

Exploiting this temporal modulation is more effective than just a simple day-night or seasonal check since, as can be seen from Fig. 2, the enhancements can be large during a small portion of these larger intervals. The modulations are a consequence of Earth-induced changes to the solar neutrino spectrum and content. Figure 3 illustrates the modification to the electron neutrino spectrum for a typical period of 4 h around midnight.

The correlation of event rate with time is much easier to carry out than direct measurements of the solar neutrino spectrum itself. The incident solar spectrum is also sensitive to the MSW parameters but will undergo substantial Earth-induced modulation which can introduce some ambiguity into the solution and will certainly require attention to the effects considered here for a clear interpretation.

The Earth-induced effects are a function of the location of the detector and the time of year, as well as the time of night. We have investigated a number of locations including the equator, 23° north, 35° north, and 45° north. A range of dates has been studied.

Figure 4 shows the maximum night-day rate to be observed for 12 possible locations and times. All effects, including y distribution and μ or τ neutrino contributions, have been included. The enhancement rate is plotted as a function of $\sin^2(2\theta)$. The value of Δm^2 is taken as $\Delta m^2 \approx 4.6 \times 10^{-8}$ eV$^2/\sin^2(2\theta)$. Many locations give in excess of 25% enhancements at least some time of the year. The dates displayed in Fig. 4 are the winter and summer solstice and the equinox. To achieve maximum sensitivity to oscillation effects, one would like the largest amplitude oscillations for the largest period of time. Clearly, a detector at the equator has advantages for both of these factors. All other locations suffer significant degradation in possible signal in the period around the summer solstice. Most nonequatorial detectors would have a hard time detecting values of $\sin^2(2\theta) < 0.0075$ for a period of half a year or more. Still, detectors as far north as 45° are sensitive to most ranges of parameters for at least several months of the year. Processes, other than νe scattering, or a different threshold could modify these results, but the qualitative results would be the same. Processes that are insensitive to the non-electron-neutrino component would manifest a larger enhancement since the daytime signal would be lower.

A crude measurement of the live time for the enhancement is shown in Fig. 5. The figure represents the full width at half maximum for the situations of Fig. 4. Ideally one would like to have a large full width at half maximum (FWHM) and large amplitude at the same time. The FWHM is only a rough measure of the duration of the enhancement since as seen from Fig. 2 the maximum rarely occurs when the Sun is at the antipode. From the

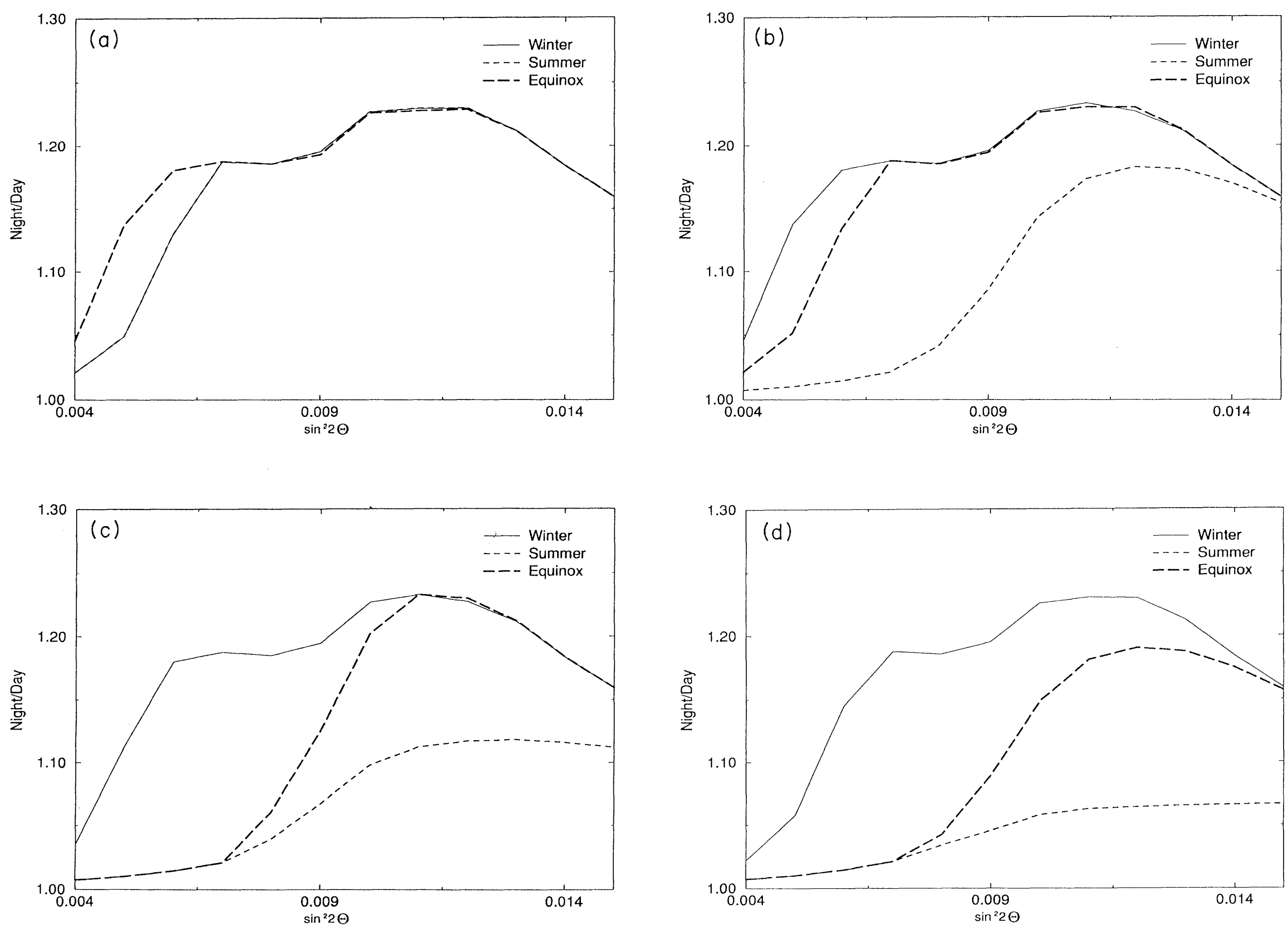

FIG. 4. Maximum ratio of night to day event rate to be observed at a number of different detector locations and seasons, as a function of $\sin^2(2\theta)$. The value of Δm^2 is taken as $\Delta m^2 \approx 4.6 \times 10^{-8}$ eV$^2/\sin^2(2\theta)$. The locations are (a) equator, (b) 23° north, (c) 35° north, and (d) 45° north.

plot it is clear that to be most sensitive to regeneration effects using a simple measure of the night-day rate one should use care in defining the nighttime interval. These periods run from 7 to 2 h even at the same location. For example, at 35° north the duration varies from 3 h at the winter solstice to 10 h at the equinox, for small values of the mixing. The enhancement averaged over the entire period of Fig. 5 is about 45–60% of the maximum values indicated in Fig. 4. In general, this gives a measurable, if not strong signal.

Figure 6 plots the time to (or from) midnight of the maximum enhancement as a function of $\sin^2(2\theta)$. The value of Δm^2 is taken as in Fig. 4. As can be seen from the figure, the time of maximum is location and seasonally dependent and may be a useful tool in confirming the MSW effect. It is noteworthy that midnight is rarely the time at which maximum is achieved. In general, the temporal distributions are flattened or have a dip, similar to the one seen in Fig. 2.

To achieve sufficient statistics the enhancement must be large and occur frequently. Some locations may have a large enhancement for only a portion of the year. Figure 7 illustrates the seasonal dependence at a location 35° north. The figure shows the night-day ratio as a function of day of the year. As expected, the enhancement is lower in the summer months. More significant is the depth of the decrease and its duration. For $\sin^2(2\theta)$=0.005 and $\Delta m^2 = 9.2 \times 10^{-6}$ eV^2, the gap is about 8 months long. During this period a 12% enhancement drops to about 1%. On the other hand, for $\sin^2(2\theta)$=0.012 and $\Delta m^2 = 3.8 \times 10^{-6}$ eV^2, the gap is only 3 months long and the drop relatively weak from 22% to 11%.

The large mixing solutions are still viable [2]. Figure 8 illustrates the night-day modulation to be expected from such solutions. For a detector at 35° during the equinox, the maximum enhancement is a factor from 2 to 4 depending, primarily, on the mixing angle. This result is typical. The FWHM for all observing locations up to 45°

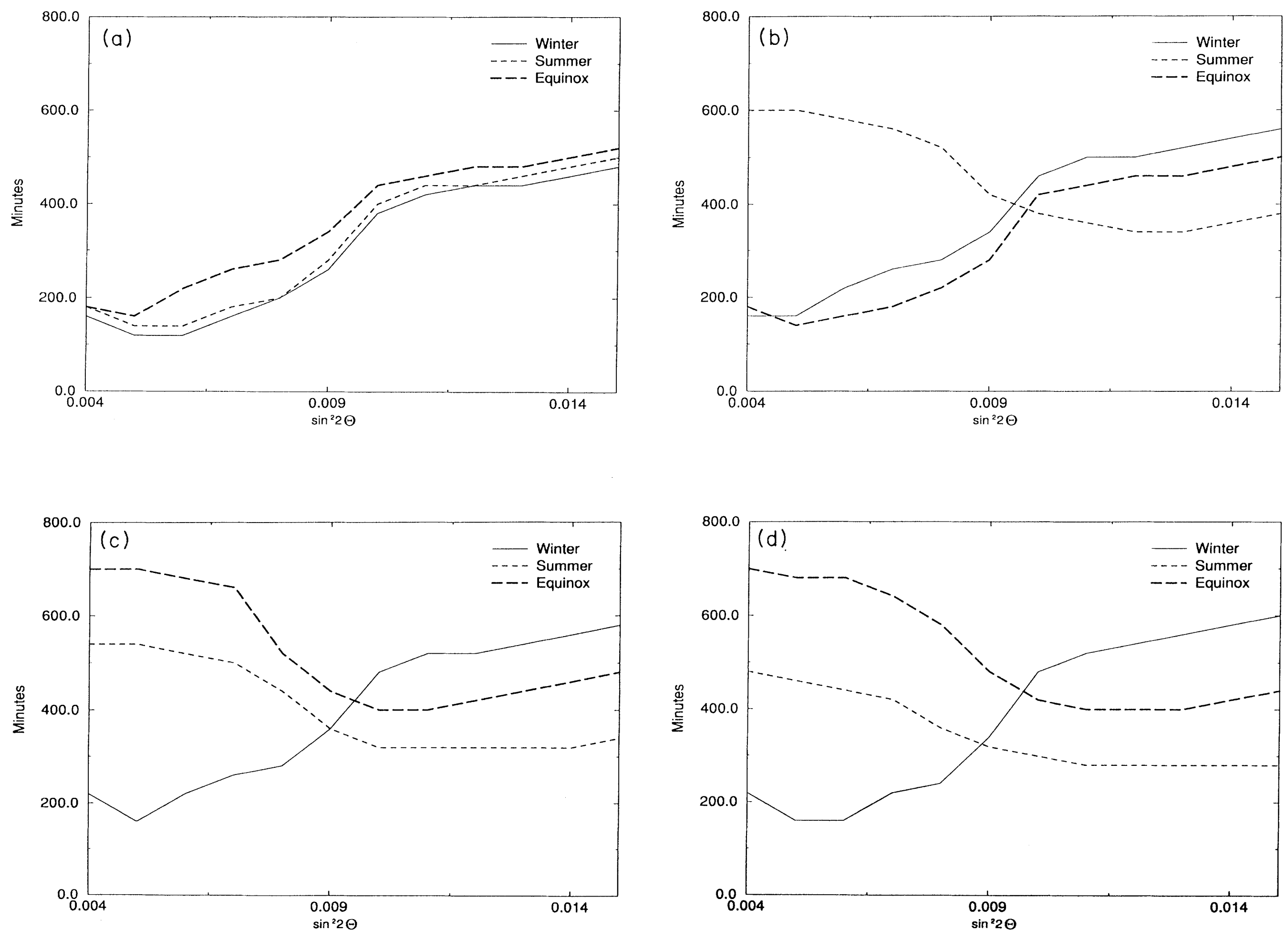

FIG. 5. Full width at half maximum for the enhancement to be observed at a number of different detector locations and seasons, as a function of $\sin^2(2\theta)$. The value of Δm^2 is taken as $\Delta m^2 \approx 4.6 \times 10^{-8}$ eV$^2/\sin^2(2\theta)$. The locations are (a) equator, (b) 23° north, (c) 35° north, and (d) 45° north.

and at all seasons is in excess of 500 min and the amplitudes are comparable to those shown in Fig. 8. During these nighttime periods the enhancement ranges, on average, from 45% to 60% of the maximum value.

TESTS

The modulation is not periodic except on time scales of a year. There is unlikely to be sufficient data to permit a Fourier analysis to extract such a long period. But the expected event rate is a predictable function of the MSW parameters. In fact, the relative modulation is insensitive to the overall intensity of the source but depends only on the shape of the ^{8}B decay. To that extent it gives a prediction that is insensitive to most details of neutrino production in the Sun.

The Smirnov–Cramer–von Mises test [13] can be used to compare the observed temporal distribution of events with that expected from a specific MSW hypothesis. The test is insensitive to normalization and combines the square of the deviations of the two functions, and so it may be more sensitive in cases such as these where the data rate will vary slowly about the average value.

There may be tests which are even more sensitive to the temporal distribution of the data. In principle, one would like to fit the MSW parameters from the event times. But it is difficult to construct an analytic expression for the distribution as a function of these parameters.

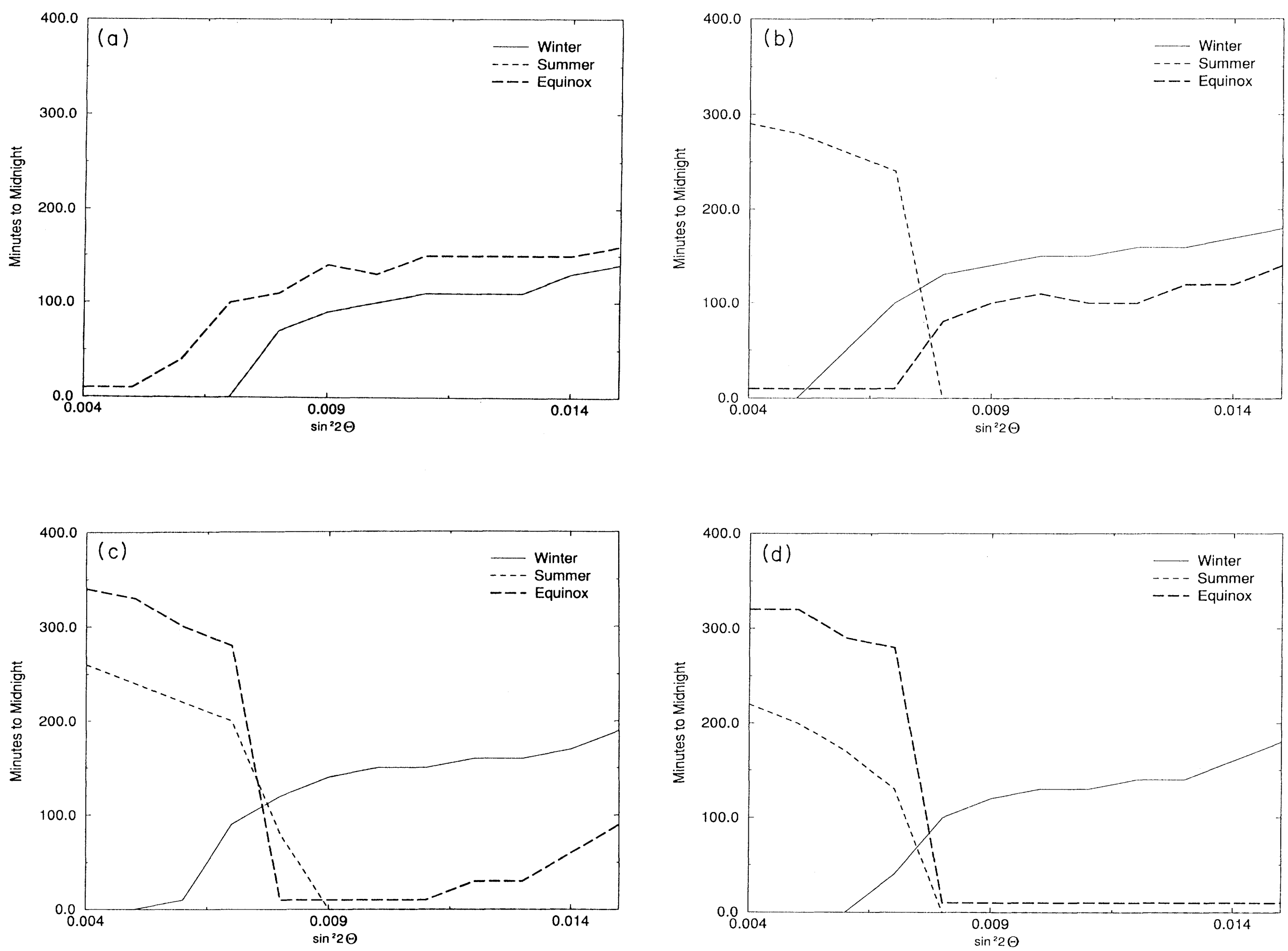

FIG. 6. Time of night in minutes to midnight at which the maximum enhancement is observed at a number of different detector locations and seasons, as a function of $\sin^2(2\theta)$. The value of Δm^2 is taken as $\Delta m^2 \approx 4.6 \times 10^{-8}$ eV$^2/\sin^2(2\theta)$. The locations are (a) equator, (b) 23° north, (c) 35° north, and (d) 45° north. Note that in general the maxima are not at midnight. Here the term "midnight" refers to the time the Sun is at the antipode and not the local value of midnight which depends on the location of the detector in the time zone. The resolution of the estimate is only about 10 min.

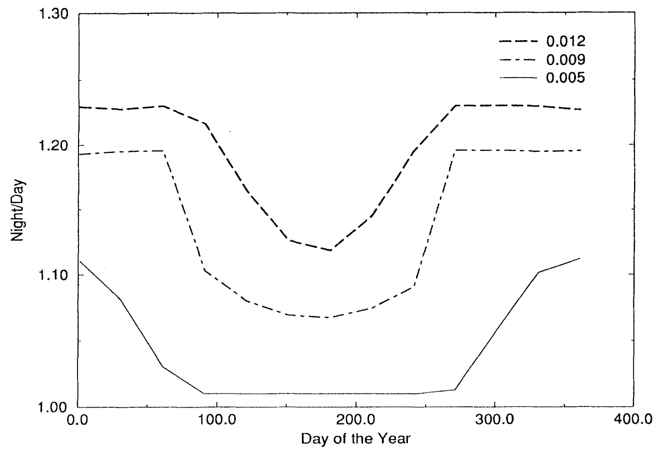

FIG. 7. Seasonal variability of the night-day enhancement for a detector located at 35° north. The maximum night-day event rate ratio is plotted as a function of day of the year for a number of values of the "non-adiabatic" solution. While there is always some seasonal variation at this location, its amplitude and duration depend on the MSW solution.

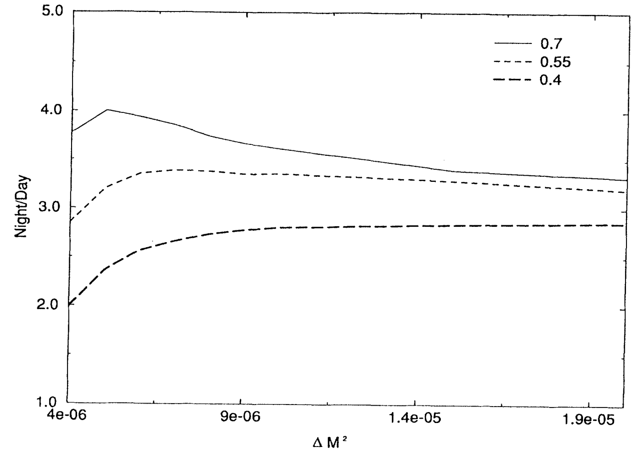

FIG. 8. Maximum ratio of night-day event rates for a detector located 35° from the equator at the time of the equinox. Three possible values of large $\sin^2(2\theta)$ are plotted: 0.4, 0.55, and 0.7. The allowed range of Δm^2 is on the horizontal axis. The figure clearly indicates that, typically, the nighttime enhancement is large for this class of solutions.

CONCLUSIONS

The values of $\sin^2(2\theta)$ and Δm^2 expected to solve the solar neutrino problem can be tested. The most directly feasible test at present would be to observe the time dependence of the solar neutrino signal itself. The enhancement in rate is about 5% at the lowest favored value of $\sin^2(2\theta)$, but it is about 25% for most detector locations for at least some period of time for much of the allowed region. Cuts designed to emphasize the most enhanced time regions, such as around but not at midnight, can increase the sensitivity.

The modulation is a predictable consequence of the MSW solution to the solar neutrino problem. It is relatively insensitive to many details of solar physics, such as the normalization. It does depend, roughly, on the electron density profile in the Sun since these densities determine the daylight spectra, which are the starting point for our calculations.

This modulation test will most likely be rate limited. The optimal location for such an experiment would be in the tropics since this optimizes both the amplitude of the effect and its duration.

If, at some future time, a terrestrial source capable of producing a neutrino flux in excess of 10^{10} neutrinos/cm^2 sec at a range of 10^7 m and an energy below 15 MeV becomes available, studies of this range of MSW parameters will be much more straightforward.

Note added in proof. In practice the effects described in this article must be observed in the presence of an experimental background. Such a background could be mistaken for the modulation. In particular, if the path of the Sun moves through local regions of rock that are sources of energetic γ rays the Compton scattering of these γ rays could be mistaken for a modulation of the solar neutrino signal itself. A careful study of such sources, which should have no temporal dependence themselves, is needed to remove them from a possible signal.

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