MHD Solar Fluctuations and Solar Neutrinos

N. Reggiani[1], M.M. Guzzo[2], and P.C. de Holanda[3]

[1] *Faculdade de Matemática, Centro de Ciências Exatas Ambientais e de Tecnologias Pontifícia Universidade Católica de Campinas, 13086-900 Campinas-SP, Brazil*

[2] *Instituto de Física 'Gleb Wataghin', Universidade Estadual de Campinas, UNICAMP, 13083-970 Campinas, SP, Brazil*

[3] *The Abdus Salam International Centre for Theoretical Physics, I-34100 Trieste, Italy*

Received on 16 June, 2002. Revised version received on 2 July, 2002.

We analyze how solar neutrino experiments could detect time fluctuations of the solar neutrino flux due to magnetohydrodynamic (MHD) perturbations of the solar plasma. We state that if such time fluctuations are detected, this would provide a unique signature of the Resonant Spin-Flavor Precession (RSFP) mechanism as a solution to the Solar Neutrino Problem.

I Introduction

Assuming a non-vanishing magnetic moment of neutrinos, active electron neutrinos that are created in the Sun can interact with the solar magnetic field and be spin-flavor converted into sterile nonelectron neutrinos or into active nonelectron antineutrinos. This phenomenon is called Resonant Spin-Flavor Precession (RSFP). Particles resulting from RSFP interact with solar neutrino detectors significantly less than the original active electron neutrinos in such a way that this phenomenon can induce a depletion in the detectable solar neutrino flux [1].

If this interaction of the neutrinos with the solar magnetic field is the mechanism that explains the neutrino deficit on Earth [2]-[6], or, in other words, if the RSFP is the mechanism that solve the solar neutrino problem, solar magnetohydrodynamics (MHD) perturbations can lead to time fluctuations of the solar neutrino flux detected on Earth. This can be easily understood. The solar active electron neutrino survival probability based on the RSFP mechanism crucially depends on the values of four independent quantities. Two of then are related to the neutrino properties: its magnetic moment μ_ν and the squared mass difference of the physical eigenstates involved in the conversion mechanism divided by their energy $\Delta/4E$. The other two quantities are related to the physical environment in which neutrinos are inserted: the magnetic field profile $B(r)$ and the electron (and neutron, for Majorana neutrinos) number density distribution $N(r)$ along the neutrino trajectory. MHD affects both the magnetic field profile as well as the matter density and therefore its effects will strongly influence the RSFP neutrino survival probability. Indeed we believe that such consequences can be thought as a test to this solution to the solar neutrino problem based on the RSFP mechanism [7-10].

II MHD perturbations

The MHD perturbations were calculated deriving the MHD equations near the solar equator, the region relevant for solar neutrinos. Using cylindrical coordinates, considering also the effects of gravity, we obtained the Hain-Lüst equation with gravity [11, 12, 7]:

$$\frac{\partial}{\partial r}\left(f(r)\frac{\partial}{\partial r}(r\xi_r)\right)+h(r)\xi_r=0 \tag{1}$$

where

$$f(r)=\frac{\gamma p+B_o^2}{r}\frac{(w^2-w_A^2)(w^2-w_S^2)}{(w^2-w_1^2)(w^2-w_2^2)}\ , \tag{2}$$

$$\begin{aligned} h(r) &= \rho_0 w^2-k^2B_0^2+g\frac{\partial\rho_0}{\partial r} \\ &\quad -\frac{1}{D}g\rho_0^2(w^2\rho_0-k^2B_0^2)\left[gH+\frac{w^2}{r}\right] \\ &\quad -\frac{\partial}{\partial r}\left[\frac{1}{D}w^2\rho_0^2 g(w^2\rho_0-k^2B_0^2)\right] \end{aligned} \tag{3}$$

and

$$w_A^2=\frac{k^2B_0^2}{\rho_0}\ ,\ w_S^2=\frac{\gamma p}{\gamma p+B_0^2}\frac{k^2B_0^2}{\rho_0}\ , \tag{4}$$

$$w_{1,2}^2=\frac{H(\gamma p+B_0^2)}{2\rho_0}\left\{1\pm\left[1-4\frac{\gamma p k^2B_0^2}{(\gamma p+B_0^2)^2H}\right]^{1/2}\right\}\ , \tag{5}$$

$$D=\rho_0^2w^4-H[\rho_0w^2(\gamma p+B_0^2)-\gamma pk^2B_0^2]\,, \tag{6}$$

$$H=\frac{m^2}{r^2}+k^2 \tag{7}$$

where ξ_r is the radial component of the plasma displacement $\vec{\xi}$, g is the acceleration due to gravity, p is the pressure, $\gamma = C_p/C_v$ is the ratio of the specific heats, ρ_0 is the equilibrium matter density profile and B_0 is the magnetic equilibrium profile in the Sun. In this derivation we considered the equilibrium magnetic profile B_0 in the azimuthal direction.

The Hain-Lüst equation shows singularities when $f(r)$ given in equation (2) is equal to zero, that is, when $w^2 = w_A^2$ or $w^2 = w_S^2$, which regions in the w^2 space are called Alfvén and slow continua, respectively. In the interval $0 \leq r \leq 1$ the functions w_A^2 and w_S^2 take continuous values that define the ranges of the values of w^2 that correspond to improper eigenvalues, associated with localized modes. Eigenvalues of the Hain-Lüst equation must be searched, therefore, outside the regions where $w^2 = w_A^2$ or $w^2 = w_S^2$, and they define the global modes which are associated with magnetic and density waves along the whole radius of the Sun.

For the equations above we considered for the solar matter density distribution, ρ_0, the standard solar model prediction, that is, approximately monotonically decreasing exponential functions in the radial direction from the center to the surface of the Sun [13]. The density profile was used to calculate the acceleration of gravity. The pressure p is related with the density by the adiabatic equation of state $p \sim 5 \times 10^{14}\rho^{\gamma}$, which is obtained from the values of density and temperature of the solar standard model.

The global modes were obtained solving numerically the Hain-Lüst equation with gravity, imposing appropriate boundary conditions to $\vec{b}_1$ and ρ_1, the magnetic and density perturbations respectively, given by [12]

$$\vec{b}_1 = \vec{\nabla} \times (\vec{\xi} \times \vec{B}_0) \tag{8}$$

and

$$\rho_1 = \vec{\nabla} \cdot (\rho\vec{\xi}). \tag{9}$$

The matter density fluctuations were very constrained by helioseismology observations. The largest density fluctuations ρ_1 inside the Sun are induced by temperature fluctuations δT due to convection of matter between layers with different local temperatures. According to an estimate of such an effect [7], we assume density fluctuations ρ_1/ρ_0 smaller than 10%. The size of the amplitude b_1 is not very constrained by the solar hydrostatic equilibrium, since the magnetic pressure $B_0^2/8\pi$ is negligibly small when compared with the dominant gas pressure for the equilibrium profiles considered. Despite this fact, it cannot be arbitrarily large when we are solving the Hain-Lüst equation. This equation is obtained after linearization of the magnetohydrodynamics equations, which requires that the solution $\vec{\xi}$ must be very small, $|\vec{\xi}| << 1$, so that the non-linear terms can be neglected. Moreover, we must have a clear distinction between the maximum and minimum magnetic field. In order to satisfy these criteria and have a significant effect, we choose the maximum value of the perturbation such that $|b_1|/|B_0| \sim 0.5$.

The localized modes are obtained solving the Hain-Lüst equation in the singularities of the function $f(r)$. Methods to analytically overcome this singularity suggest the inclusion of an arbitrary imaginary constant ia to contour the singularity in such a way that $w^2 \rightarrow w^2 + ia$. Therefore, the magnitude of a, which is directly related with the width of the localized magnetic fluctuation, is an arbitrary value which cannot be eliminated from any exact solution of the Hain-Lüst equation involving the continuum spectrum. Consequently, we adopted the following phenomenological assumption in our calculations: continuum modes introduce Gaussian-shaped magnetic fluctuations centered in r_s, with width δr, and amplitude given by a fraction of the equilibrium magnetic field in the position of the singularity, in such a way that the magnitude of the transverse component of the magnetic field, which is the relevant magnetic component for neutrino RSFP, will fluctuate in the following way:

$$|\vec{B}_\perp(r)| = |\vec{B}_0(r)| + b_0|\vec{B}_0(r_s)| \exp\left[-\left(\frac{r - r_s}{\delta r}\right)^2\right] \sin\left[w(r_s)t\right]. \tag{10}$$

where b_0 is the amplitude factor, a positive numerical value smaller than 1. We impose that $w(r_s) = w_A$ or $w(r_s) = w_S$ and, consequently, generate accordingly a time modulation of the detectable number of neutrinos coming from the Sun. Note that the shape of the perturbations being exactly Gaussian is not crucial for neutrino RSFP, once solar neutrinos are sensitive to the averaged magnetic field around r_s.

III Solar neutrino evolution

If we consider a non-vanishing neutrino magnetic moment, the interaction of such neutrinos with this magnetic field will generate neutrino spin-flavor conversion which is given by the evolution equations [1]

$$i\frac{d}{dr}\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = \begin{pmatrix} \frac{\sqrt{2}}{2}G_F N_{eff}(r) - \frac{\Delta}{4E} & \mu_\nu|B_\perp(r)| \\ \mu_\nu|B_\perp(r)| & +\frac{\sqrt{2}}{2}G_F N_{eff}(r) + \frac{\Delta}{4E} \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}, \tag{11}$$

where ν_L (ν_R) is the left- (right-) handed component of the neutrino field, Δ is the squared mass difference of the corresponding physical fields, E is the neutrino energy, G_F is the Fermi constant, μ_ν is the neutrino magnetic moment and $|B_\perp(r)|$ is the transverse component of the perturbed magnetic field. Finally, we have $N_{eff} = N_e(r) - N_n(r)$ for Majorana neutrinos, where $N_e(r)$ ($N_n(r)$) is the electron (neutron) number density distribution, in which case the final right-handed states ν_R are active non-electron antineutrinos. For Dirac neutrinos, $N_{eff} = N_e(r) - 1/2N_n(r)$; in this case the right-handed final states are sterile non-electron neutrinos [5]. In this paper we will assume Majorana neutrinos. Note, however, that since $N_n \sim (1/6)N_e$ inside the Sun, the difference of taking Dirac or Majorana neutrinos is a multiplicative factor of $\sim 10/11$, and does not lead to sensible alterations in our conclusions, which are, in this way, valid for Majorana or Dirac neutrinos.

We are considering the standard solar electron number distribution which implies that 10^{-16} eV $\leq (\sqrt{2}/2)G_F N_e(r) \leq 10^{-12}$ eV. In order to find appreciable spin-flavor neutrino conversion governed by the equations of motion (11), we have to allow the other two relevant quantities in these equations, namely $\Delta/4E$ and $\mu_\nu|\vec{B}_\perp(r)|$, to be approximately of the same order of $(\sqrt{2}/2)G_F N_e(r)$. Assuming the magnetic fields given by equations (12), (13), if we take $\mu_\nu \approx 10^{-11}\mu_B$ (μ_B is the Bohr magneton), the quantity $\mu_\nu|\vec{B}_\perp(r)|$ varies from approximately 10^{-14} eV in the central parts of the Sun, to 10^{-15} eV in the beginning of the convective zone and smaller values than 10^{-16} eV in the solar surface, giving the order of magnitude needed for appreciable conversion. For the magnetic field given by (13) and (14) we used $\mu_\nu = 2 \times 10^{-12}\mu_B$, which gives $\mu_\nu|\vec{B}_\perp(r)|$ to be of the same order of $(\sqrt{2}/2)G_F N_e(r)$ in the convective zone.

MHD magnetic and density fluctuations, b_1 and ρ_1, induced by global or localized modes, can alter the neutrino evolution since they can induce time variation of the transverse component of the magnetic field $|B_\perp(r)|$ as well as the matter density $N_e(r)$ appearing in the evolution equation above. Therefore, the MHD fluctuations can induce a time variation on the survival probability of the neutrinos, that can be detected in the experiments on Earth.

IV Localized modes

The effect of the localized modes [7, 8] were estimated calculating the survival probability of an active solar neutrino to reach the solar surface after having interacted with the solar magnetic field perturbed by a localized MHD wave. In this estimation, we considered for the equilibrium magnetic fields the following profiles:

$$B_0(r) = \begin{cases} 1 \times 10^6 \left(\frac{0.2}{r+0.2}\right)^2 \text{G} & \text{for} \quad 0 < r \leq r_{convec} \\ B_C(r) & \text{for} \quad r > r_{convec} \, , \end{cases} \tag{12}$$

where B_C is the magnetic field in the convective zone given by the following profiles:

$$B_C^I(r) = 4.88 \times 10^4 \left[1 - \left(\frac{r-0.7}{0.3}\right)^n\right] \text{G} \quad \text{for} \quad r > r_{convec} \tag{13}$$

or

$$B_C^I(r) = 4.88 \times 10^4 \left[1 + exp\left(\frac{r-0.95}{0.01}\right)^{-1}\right] \text{G} \quad \text{for} \quad r > r_{convec} \tag{14}$$

with $n = 2, 6$ and 8 and $r_{convec} = 0.7$. This profile was used by Akhmedov, Lanza and Petcov [14] to show the consistency of the solar neutrino data with the RSFP phenomenon.

Note that $B_0^2 < \gamma p$, which is related to the fact that the magnetic pressure is negligibly small when compared to the gas pressure. Therefore, from Eqs. 4, $w_A^2 \sim w_S^2$ and for the equilibrium profiles considered above, the period of the fluctuation centered at the point of singularity varies from 1 to 10 days.

In order to appreciate the relevance of the position of the magnetic fluctuation inside the Sun, its width and amplitude on the solar neutrino survival probability, we present in Fig. 1 this probability as a function of the position r_s, where the singularity of the Hain-Lüst occurs, for several values of the width δr and the amplitude factor b_0 of the localized waves. We used the magnetic profile given by equations (12) and (13), with $n = 2$, and $\Delta/4E = 5 \times 10^{-15} eV$. Six lines are shown in each of the nine graphs appearing in Fig. 1. These lines correspond to six time deformations of the magnetic fluctuation from the situation where the fluctuation is maximal, contributing to pushing up the averaged value of the whole magnetic field (continuous line) until the opposite case where the fluctuation diminishes the averaged magnetic field.

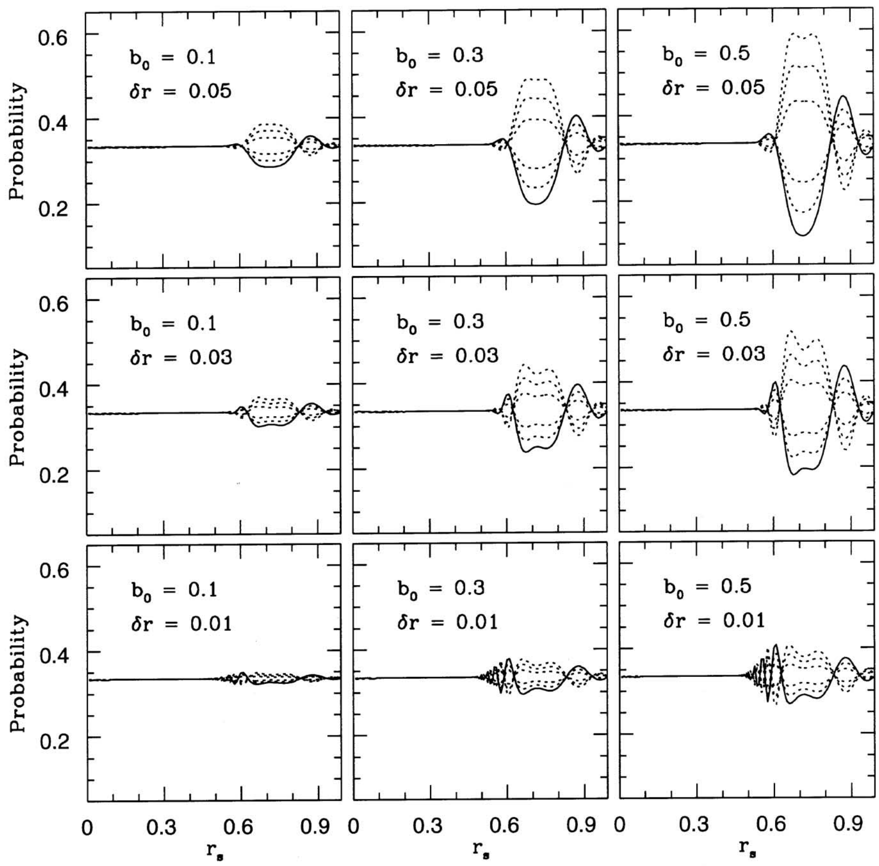

Figure 1. The survival probability $P(\nu_L \to \nu_L)$ of active neutrinos after having interacted with the perturbed magnetic field as a function of the position r_s (normalized by the solar radius) of the Hain-Lüst equation singularity for the shown values of the width δr and the amplitude factor b_0. In this figure we assume $\Delta/4E = 5 \times 10^{-16}$ eV and $n = 2$ in Eq. (13).

In Fig. 2 it is shown the survival probability as a function of $\Delta/4E$ for the indicated values of r_s. The magnetic profile used in this figure is given by Eq. (13), with n= 6, and we assume $b_0 = 0.5$ and $\delta r = 0.05$. Here the thick continuous line indicates the instant when the magnetic fluctuation is maximal and other lines are successive time deformations of this fluctuation, with the same assumptions for $w(r_s)t$ used in Fig. 1. In these figures, vertical lines indicate the value of $\Delta/4E$ corresponding to a resonance coinciding with the position of the indicated singularity r_s. We note that the presence of localized magnetic fluctuations will modify the solar neutrino survival spectrum. In general, low energy neutrinos are less affected by spin-flavor precession than high energy ones. Furthermore, fluctuations of the survival probability are maximal when r_s is close to a resonance region and are well localized in $\Delta/4E$-space for $r_s \leq 0.7$. For $r_s = 0.9$ the position of the probability fluctuations in $\Delta/4E$-space is less determined. Nevertheless localized magnetic waves near the solar surface lead to a picture for the survival probability $P(\nu_L \to \nu_L)$ which can be easily distinguishable from those ones generated by inner localized waves.

V Global modes

The global modes [9,10] obtained with the magnetic fields given by equations (12), (13) and (14), used in the analysis of the effect of localized modes, are very similar to each other. So, we present the effect of these modes on the neutrino RSFP phenomenon for just one of these magnetic fields, that we consider a good representative of the others:

$$B_0 = B_0(r) = \begin{cases} 1 \times 10^6 \left(\frac{0.2}{r+0.2}\right)^2 \mathrm{G} & \text{for} \quad 0 < r \leq r_{convec} \\ B_C(r) & \text{for} \quad r > r_{convec} \; , \end{cases} \tag{15}$$

where B_C is the magnetic field in the convective zone given by the following profiles:

$$B_C^I(r) = 4.88 \times 10^4 \left[1 - \left(\frac{r-0.7}{0.3}\right)^n\right] \mathrm{G} \quad \text{for} \quad r > r_{convec} \tag{16}$$

with $n = 6$ and $r_{convec} = 0.7$.

In order to illustrate the effect of the parametric resonance, we used other magnetic fields that have been used by different authors to solve the solar neutrino problem through the RSFP mechanism [15]:

$$B_C^{II}(r) = \begin{cases} B_{initial} + [\frac{B_{max}-B_{initial}}{r_{max}-r_{convec}}](r - r_{convec}) & \text{for } r_{convec} < r < r_{max} \\ B_{max} + [\frac{B_{max}-B_{final}}{r_{max}-1.0}](r - r_{max}) & \text{for } r > r_{max} \end{cases} \tag{17}$$

where $B_{initial} = 2.75 \times 10^5\ G$, $B_{max} = 1.18 \times 10^6\ G$, $B_{final} = 100\ G$, $r_{convec} = 0.65$ and $r_{max} = 0.8$. Although the magnetic field in this configuration seems to be too strong to be present in the convective layer of the Sun, we extend our analysis for this configuration because it is very useful to illustrate the parametric resonance effect for different values of the perturbation oscillation length. It is also important to notice that the important quantity for the neutrino evolution is not the magnetic field itself, but the product $\mu_\nu|\vec{B}_\perp(r)|$, which we impose to be of the same magnitude in the Sun convective layer for all magnetic field configuration chose here.

We considered also a third field, constant all over r, given by [16]:

$$B_0 = 253 \text{ kG} \quad \text{for} \quad 0 < r < 1.0 \tag{18}$$

For the solar matter density distribution, ρ_0, and for the pressure p, we considered the standard solar model prediction, i.e., approximately monotonically decreasing exponential functions in the radial direction from the center to the surface of the Sun [13]. The density profile was used to calculate the gravity acceleration.

As the density profile found in [13] is given just until $r = 0.95$ we have performed our calculations just until this value of r. The conditions that we imposed on $\vec{\xi}$ is over all the calculated values of r: $0 < r < 0.95$.

In this work we were interested in calculating the eigenfunctions of the Hain-Lüst equation out of the continua determined by the functions $w^2 = w_A^2$ and $w^2 = w_S^2$. As w_A and w_S depend linearly on B, the magnetic profiles used were such that there is no value of r for which B is zero, because, if $w_A = 0$ or $w_S = 0$, this means that the continua extend until $w = 0$ and in this way all the oscillatory modes below the continua would be killed. Otherwise, it is very reasonable that the magnetic field is non-zero inside the Sun if we choose magnetic profiles which value in the convective zone is $\sim 10^5 G$.

For the magnetic profiles given by (15) and (16) we have possible solutions for $w > 4.40 \times 10^{-5} s^{-1}$ or $w < 5.98 \times 10^{-6} s^{-1}$, which gives a period of $\tau < 1.65$ days or $\tau > 12.14$ days, respectively. For the magnetic profile given by (15) and (17) we have $w > 4.95 \times 10^{-4} s^{-1}$ or $w < 5.32 \times 10^{-6} s^{-1}$, which gives a period of $\tau < 0.15$ days or $\tau > 13.7$ days, respectively. For the magnetic profile given by (18) we have $w > 6.28 \times 10^{-4} s^{-1}$ or $w < 2.56 \times 10^{-6} s^{-1}$, which gives a period $\tau < 0.11$ days or $\tau > 28.5$ days, respectively.

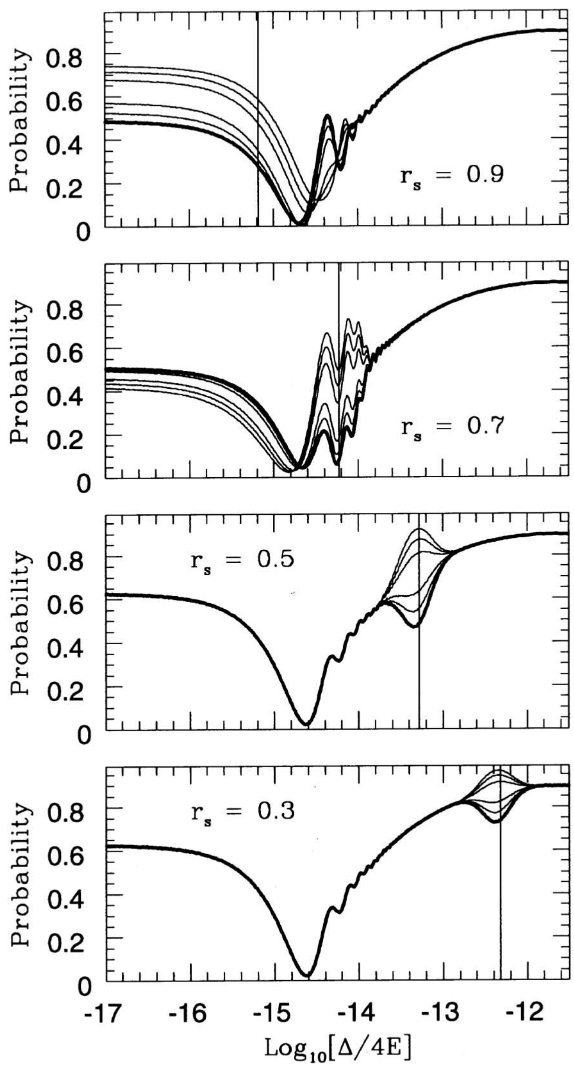

Figure 2. The survival probability $P(\nu_L \to \nu_L)$ as a function of $\log_{10}(\Delta/4E)$ ($\Delta/4E$ in units of eV) for the shown position r_s of the magnetic wave. Vertical lines indicate the value of $\Delta/4E$ corresponding to a resonance coinciding with the indicated position of the singularity r_s. We considered for the equilibrium magnetic profile $n = 6$ in Eq. (13).

In the first row of Fig. 3 we present the profile of the radial displacement ξ_r, calculated by solving the Hain-Lüst equation (1), when the magnetic profiles given in equations (15), (16), (17) and (18), respectively, are

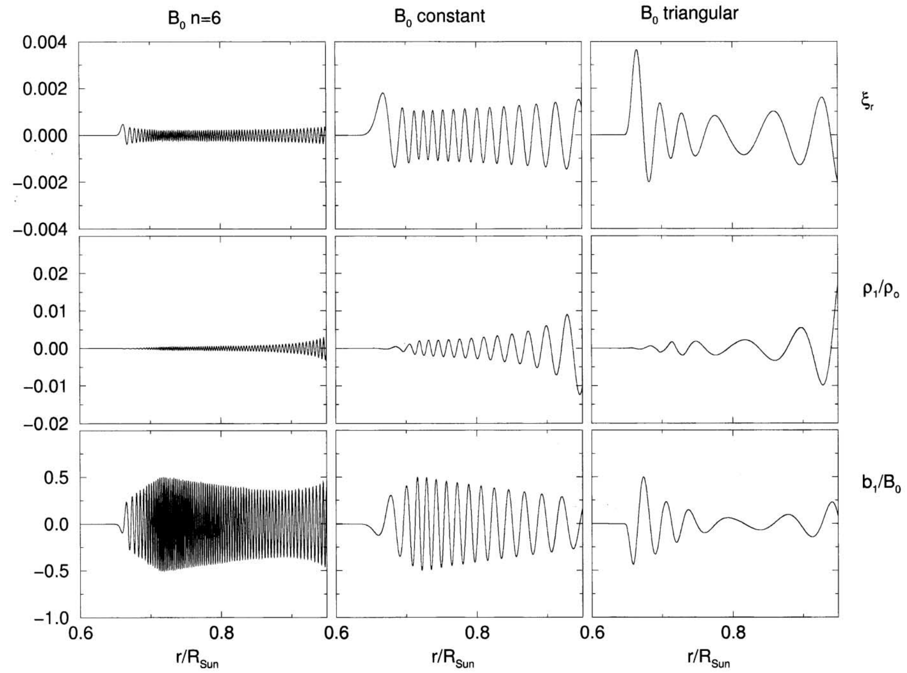

Figure 3. Profile of a) ξ_r, after normalization, and b) ρ_1/ρ_0 and c) b_1/B_0 that are caused by the magnetohydrodynamic effect, for the magnetic profiles given by equations [15] and [16] (B_0 with n=6), equation [18] (B_0 constant) and equations [15] and [17] (B_0 triangular).

assumed. It is important to notice that clearly different ξ_r wavelengths appear for each one of the magnetic fields employed. This will be reflected also in the MHD fluctuations of the matter density ρ_1/ρ_0 and the magnetic field b_1/B_0, which are directly calculated from ξ_r and are shown in the second and third rows of Fig. 3, respectively.

The Hain-Lüst solutions shown in Fig. 3 are found in the region of the MHD spectrum in which frequencies are smaller than the continuum frequencies: $w^2 < w_A^2 \approx w_S^2$. The period of the solutions found above the continua are smaller than $O(1 \text{ sec})$, very tiny, therefore, to be detected by present experiments.

In Fig. 4 we present the effects on the solar neutrino survival probability when the perturbations ρ_1 and b_1 are included in the evolution equations (11). In this figure we plot the difference of the survival probability calculated in two different situations: when the effect of the MHD perturbations maximally increases the survival probability and the opposite case when the perturbations destructively contribute to this probability, decreasing it.

We see that the range of the values of $\Delta/4E$ for which this difference is significant varies for each of the magnetic field profile considered. This is a direct consequence of the appearance of a parametric resonance [17] in the evolution of the neutrino due to the MHD perturbations along its trajectory. To understand this effect we have to consider the neutrino oscillation length. When we have a neutrino oscillation length similar to the wavelength of the magnetohydrodynamic perturbations, a significant enhancement of the neutrino chirality conversion occurs. This is the parametric resonance which is clearly observed in the neutrino survival probability. In other words, when the neutrino is evolving, an intense chirality conversion from left to right-handed neutrinos occurs when the magnetic field is increased by the perturbation. On the contrary, when the neutrino oscillation would lead to the opposite chirality conversion from right to left neutrino, this coincides with a period of lower magnetic field, and this conversion is suppressed. If the perturbation wavelength is very different from the neutrino oscillation length than this effect will not be relevant and we can understand the behavior of Fig. 4 far from the peaks.

VI Observing MHD fluctuations in solar neutrino detectors

According to these results and equilibrium profiles used, we conclude that neutrinos with energy of the order 1 MeV will be very sensitive to MHD fluctuations if RSFP phenomenon is the solution of the solar neutrino anomaly. Some operating solar neutrino detectors that are sensitive to such energy range, like Homestake [2], Gallex/GNO [18, 3] and Sage [4] can not detect these fluctuations because they do not operate in a real time basis, and such small fluctuations will be averaged out over the detection time. The Super-Kamiokande [5] and SNO [6] detectors operate in real-time basis but have a too high threshold in the neutrino energy to be

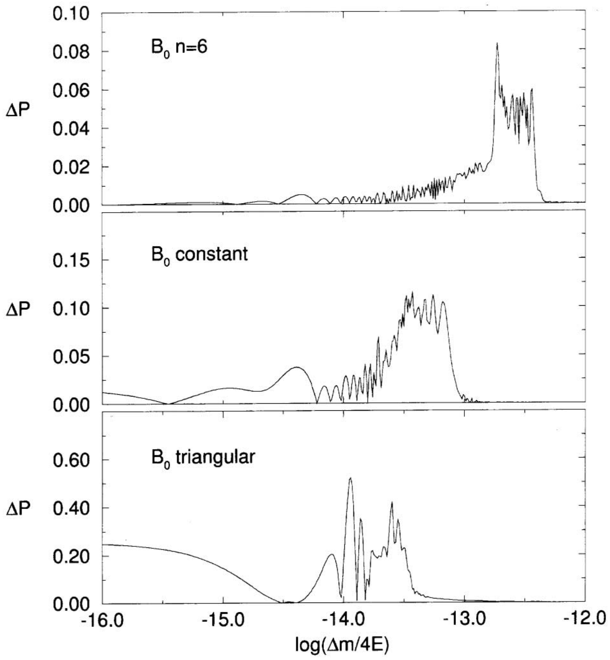

Figure 4. Amplitude ΔP of the survival probability in function of $\Delta m/4E$ for the magnetic profiles given by equations [15] and [16] (B_0 with n=6), equation [18] (B_0 constant) and equations [15] and [17] (B_0 triangular).

sensitive to such fluctuations. So, it is necessary to consider [10] the detectors that operate in a real time basis and that have a low threshold in the neutrino energy, like Borexino [19], Hellaz [20] and Heron [21].

The Borexino experiment [19]: this experiment will be able to measure the Berilium line neutrinos, in a real time basis. Since the Berilium neutrinos have a fixed energy ($E = 0.863$ MeV), it is quite easy to predict the time dependence of the neutrino signal in Borexino for a given Δ. Fixing the neutrino energy and taking the magnetic field normalization $f_{B_0} = 5$, within 99% C.L. no reasonable time fluctuation will be felt by this experiment.

This behavior happens for the three magnetic fields given by (15), (16), (17) and (18), and this can be understood analysing the properties of theses solutions to the solar neutrino problem. In this scenario, we need a strong suppression of the ^7Be neutrinos (similar to the small mixing angle solution in MSW scenario) in order to accommodate both results from Homestake and Gallium experiments (Sage, Gallex, GNO). So, for the ^7Be neutrino line we must have a completely adiabatic transition, which makes this line very stable in front of perturbations on the magnetic field profile.

But although we can not use MHD perturbations to test the RSFP solution in Borexino, it has been recently discussed [22] how the low value of the expected rate of the Berilium line neutrinos on this experiment would be a clear indication of the RSFP mechanism.

The experiments Hellaz [20] and Heron [21]: these experiments will utilize the elastic reaction, $\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$, for real-time detection in the energy region dominated by the *pp* and ^7Be neutrinos. They will both measure the energy of the recoil electron and the overall rate. These low energy neutrinos are the most abundant solar neutrinos, and the prediction of their flux is the one which carries less uncertainty, because of the correlation of these neutrinos with the solar luminosity. Since the MHD fluctuations we found in [9] appear to be affecting neutrinos with an energy range of the order of the pp-neutrinos energy, maybe Hellaz and/or Heron would be able to feel the time fluctuations on the neutrino signal generated by the MHD fluctuations.

Since we expect something around ∼ 7 pp-events/day on experiments like Hellaz or Heron we can see that, for one year (365 days, or ∼ 2500 events) of data taking, in principle it is possible to distinguish such fluctuations in Hellaz experimental results.

Acknowledgments

The authors would like to thank Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for financial support.

References

[1] A. Cisneros, Astro. & Space Sci. **10**, 87 (1971); M.B. Voloshin, M.I. Vysotskii, and L.B. Okun, Yad. Fiz. **44**, 677 (1986) [Sov. J. Nucl. Phys. **44**, 440 (1986)]; C.S. Lim and W.J. Marciano, Phys. Rev. D **37**, 1368 (1988); E.Kh. Akhmedov, Phys. Lett. B **213**, 64 (1988); A.B. Balantekin, P.J. Hatchell, and F. Loreti, Phys. Rev. D **41**, 3583 (1990); J. Pulido, Phys. Rep. **211**, 167 (1992); E.Kh. Akhmedov, A. Lanza, and S.T. Petcov, Phys. Lett. B **303**, 85 (1993); P.I. Krastev, Phys. Lett. B **303**, 75 (1993).

[2] K. Lande *et al.*, (Homestake Collaboration), Astrophys. J. **496**, 505 (1998).

[3] M. Altmann *et al.* (GNO Collaboration), Phys. Lett. B **490**, 16 (2000); C. Cattadori on behalf of GNO Collaboration, talk presented at TAUP2001, 8-12 September 2001, Laboratori Nazionali del Gran Sasso, Assergi, Italy.

[4] D. N. Abdurashitov *et al.*, (SAGE Collaboration), Nucl. Phys. (Proc. Suppl.) **91**, 36 (2001); Latest results from SAGE homepage: `http://EWIServer.npl.washington.edu/SAGE/`.

[5] S. Fukuda *et al.* (SuperKamiokande Collaboration), Phys. Rev. Lett. **86**, 5651 (2001); ibid, Phys. Rev. Lett. **86** 5656 (2001).

[6] Q. R. Ahmad *et al.* (SNO Collaboration), Phys. Rev. Lett. **87**, 071301 (2001).

[7] M.M. Guzzo, N. Reggiani, and J.H. Colonia, Phys. Rev. D **56**, 588 (1997).

[8] M.M. Guzzo, N. Reggiani, J.H. Colonia, and P.C. de Holanda, Braz. J. Phys. **30**, 594 (2000).

[9] N. Reggiani, M. M. Guzzo J. H. Colonia-Bartra, and P. C. de Holanda, Eur. Phys. J. C **12** 269 (2000).

[10] M.M. Guzzo, P.C. de Holanda, and N. Reggiani, "MHD fluctuations and Low Energy Solar Neutrinos", to appear in Eur. Phys. J. C (2002).

[11] E.R. Priest, *Solar Magnetohydrodynamics*, (D.Reidel Publishing Company, 1987).

[12] J.P. Goedbloed, Physica **53**, 412 (1971); J.P. Goedbloed and P. H. Sakanaka, Phys. Fluids **17**, 908 (1974).

[13] J. N. Bahcall and R. K. Ulrich, Rev. Mod. Phys. **60**, 297 (1988); J. N. Bahcall and M. H. Pinsonneault, Rev. Mod. Phys. **64**, 885 (1992); J. N. Bahcall, Neutrino Astrophysics (Cambridge University Press, Cambridge, England, 1989); J. N. Bahcall, S. Basu, and M.H. Pinsonneault, Astrophys. J. **555**, 990 (2001).

[14] E.Kh. Akhmedov, A. Lanza, and S.T. Petcov, Phys. Lett. B **303**, 85 (1993).

[15] M.M. Guzzo and H. Nunokawa, "Current status of the Resonant Spin-flavor Solution to the solar neutrino problem", HEP-PH/9810408.

[16] H. Minakata and H. Nunokawa, Phys. Rev. Lett. **63**, 121 (1989); A. B. Balantekin, P. J. Hatchell, and F. Loreti, Phys. Rev. D **41**, 3583 (1990); H. Nunukawa and H. Minakata, Phys. Lett. B **314**, 371 (1993).

[17] V.K. Ermilova, V.A. Tsarev, and V.A. Chechin, Kr. Soob, Fiz., Lebedev Inst. **5**, 26 (1986); E. Akhmedov, Yad. Fiz. **47**, 475 (1988); P.I. Krastev and A.Yu. Smirnov, Phys. Lett. B **226**, 341 (1989).

[18] W. Hampel *et al.* (GALLEX Collaboration), Phys. Lett. B **447**, 127 (1999).

[19] S. Malvezzi, Nucl.Phys. B (Proc. Suppl.) **66**, 346 (1998).

[20] T. Patzak, Nucl.Phys. B (Proc. Suppl.) **66**, 350 (1998).

[21] R. E. Lanou, Nucl. Phys. Proc. Suppl. 77 (1999) 55-63; Proceedings of the 8th International Workshop on Neutrino Telescopies (Venice, Italy, 1999), ed. by M. Baldo Ceolin, Vol.I, page 139.

[22] E. Kh. Akhmedov, J. Pulido, hep-ph/0201089, to be published in Phys. Lett. B.