Seismic activity of the sun and 2-yr cycle in the solar-neutrino flux

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The possible excitation of gravitational oscillations of the solar core is analyzed. Such oscillations might be responsible for a 2-yr cycle in the flux of solar neutrinos.

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According to Sakurai,[1,2] chlorine-argon measurements over the years 1970–1978 indicate variations in the flux of solar neutrinos with a period $\Pi_\nu \sim 2$ yr, which are correlated with the 26-month variations in the sunspot number. The statistical base for these arguments is so limited that we should apparently approach the asser-

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tion of neutrino fluctuations with some caution, but simply the determination that a modulation of the neutrino flux is possible in principle is very important for planning future experiments.

In this letter we will show that a natural mechanism for this modulation might be the excitation of a low-lying gravitational mode (g mode) of the solar core, under the assumption that the core is near an adiabatic equilibrium.[3,4]

We will describe the solar core by a two-zone polytrope. We assume that the radius of the first zone is $R_1 \sim 0.1$ of the solar radius $R_\odot$, and the index of the polytrope here is $n_1 = N + \nu_1$; the outer radius of the second zone is $R_2 \sim 0.2 R_\odot$, and the corresponding index is $n_2 = N + \nu_2$, where $N = 1/(\gamma - 1)$, and $\gamma = 5/3$ is the adiabatic index. We choose ν_1 and ν_2, which are measures of the deviation from the adiabatic equilibrium, in such a manner that the period Π_1 of the low-lying dipole g mode, for which the first node lies at the boundary of the inner core, R_1, is $2\Pi_\nu$, while the period Π_2 of the low-lying quadrupole g mode, for which the first node is at $R = R_2$, is[1)] 160 min. If the parameter ν_3 for the mantle satisfies the inequality $\nu_3 \gg \nu_2$, then the amplitude of the radial displacements for the 160-min mode in the core will be higher than in the mantle, according to Ref. 4. Similarly, in the case $\nu_2 \gg \nu_1$ the amplitude of the 52-month cycle in the inner core will be higher than that in the outer core.

If the nontrivial oscillations are described by linear equations,[7,8] the period can be expressed in terms of ν_1 as follows[3]:

$$\Pi_1 \approx \frac{3\pi(k+1)}{x_1} \sqrt{\frac{\pi(N+1)}{G \rho_c l(l+1)\nu_1}}, \tag{1}$$

where $x_1 = R_1/R_0$, $r_0 = (n_1 + 1)P_c/4\pi G\rho_c^2$, G is the gravitational constant, ρ_c and P_c are the density and pressure at the center of the sun, and l and k are the spherical wave number and the index of the g mode of the inner core. For example, for the core in the model of Ref. 4 ($\rho_c = 124$ g/cm^3, $P_c = 2.135 \times 10^{17}$ dyn/cm^2, $R_1 = 0.14 R_\odot$), a period $\Pi_1 = 52$ months corresponds to

$$\nu_1 \approx 4 \times 10^{-9}. \tag{2}$$

We can show that the result in (2) can be considered an extreme value, corresponding to the extreme value found for the period Π_1 from the condition stating that the quality factor of the solar resonator,

$$Q = \frac{2\pi}{\Pi_1} \frac{W}{P} \tag{3}$$

(W is the total oscillation energy, and P is the power dissipation), must be greater than unity. Let us find the order of magnitude of W and P.

We write the total oscillation energy of the sun as

$$W = \kappa W_1, \tag{4}$$

where W_1 is the oscillation energy of a core with a mass $M_1 \sim 0.1 M_\odot$, and

$$\kappa \sim \frac{M_\odot}{M_1}\left(\frac{R_\odot}{R_1}\right)^2 . \tag{5}$$

With $R_1 \sim 0.1 R_\odot$, we find $\kappa \sim 10^3$. To estimate W_1, we write the energy of the core as

$$E_1 = -\frac{3n_1 - 1}{5n_1 - 1}\,\frac{GM_1^2}{R_1} = E_{10} + \epsilon , \tag{6}$$

where

$$E_{10} = -\frac{3N - 1}{5N - 1}\,\frac{GM_1^2}{R_1} \tag{7}$$

is the total energy of the core at adiabatic equilibrium, and

$$\epsilon \approx -\frac{2\nu_1}{(5N - 1)^2}\,\frac{GM_1^2}{R_1} \tag{8}$$

is a small increment which determines the deviation from the adiabatic equilibrium and which is a measure of the energy which can be contained in the elastic degrees of freedom of the core. Energy is pumped into the g_1 mode of the core through perturbations of the rate at which ^{3}He is consumed,[8,9] which are caused by a circulation of material in a strong gradient in the ^{3}He concentration. We must require that the circulation amplitude be $\sim R_1$ in view of the pronounced modulation of the count rate of solar neutrinos[2] (~1 SNU at the minimum and 3–4 SNU at the maximum) which arises in our model, because the chain of reactions $^3\mathrm{He}(\alpha, \gamma)\,^7\mathrm{Be}(p, \gamma)\,^8\mathrm{B}(e^+\nu)\,^8\mathrm{Be}^*$ is accelerated by the drift of the excess ^{3}He toward the center of the sun. The oscillation energy, $W_1 \sim (2\pi/\Pi_1)^2 R_1^2 M_1$, is therefore close to its limiting value, $W_1 \sim \epsilon$. Under the assumption that the dissipation P is equal to the fusion energy which is converted into vibrational energy, we find the following equation from (3)–(5) and (8):

$$Q \sim \frac{4\pi}{(5N - 1)^2}\left(\frac{M_1}{M_\odot}\right)^2 \frac{L_\odot}{P}\,\frac{R_\odot}{R_1}\,\frac{t_k}{\Pi}\,\nu_1 \kappa , \tag{9}$$

where $t_K = GM_\odot^2/R_\odot L_\odot = 3 \times 10^7$ yr. Using (1) and (2), and setting $P \sim 0.5 L_1 \sim 0.1 L_\odot$, we find the following expression with $M_1 = 0.1 M_\odot$ and $R_1 = 0.1 R_\odot$:

$$Q \sim 10^{-2}\kappa\left(\frac{\Pi_1}{\Pi}\right)^3 . \tag{10}$$

With $\kappa \sim 10^3$ and $\Pi = \Pi_1$ we find $Q \sim 10$; in other words, Π_1 is a limiting value, since a further increase in the period ($\Pi > \Pi_1$) leads to an unacceptable reduction of the quality factor. It follows from (10) that the condition $\kappa \gg 1$ is a necessary condition for the excitation of oscillations. The physical meaning of this inequality is that the great preponderance of the energy generated in the circulation of material should be expended not so much on maintaining the circulation itself as on stimulating thermal fluctuations of the core. The energy of these fluctuations must be converted into the energy of gravitational oscillations of the solar mantle, perhaps through a parametric resonance. A seismic wave should propagate away from the core toward the surface, and this wave may also modulate the spot-forming activity of the sun.

In 1963, Zatsepin[10] raised the hypothesis of an 11-yr variation in the flux of solar neutrinos. In our model, this is a real possibility if, in addition to g_1, the g_4 dipole mode of the inner core is excited; its period is ~22 yr. The excitation of the g_4 mode in particular might be a consequence of its resonance with a magnetohydrodynamic pole reversal of the solar magnetic field. In this case the 11-yr activity is synchronized with oscillations of the core, and the core would be that hidden chronometer whose existence was suggested by Dicke.[11] The index of the 11-yr modulation must be lower than that of the 2-yr modulation. Experimentally, the 11-yr variations in the flux are far more difficult to distinguish than the 2-yr variations.

Rotation complicates the model, but it will not change the situation fundamentally if the angular momentum per unit mass remains constant along the radius. Such a distribution might be established as the result of a slow mixing caused by an angular inhomogeneity in the buildup of ^{4}He, which is unavoidable in the case of nonradial vibrations of the core. The same mixing could apparently be primarily responsible for keeping the inner core nearly at an adiabatic equilibrium.

The 2- and 11-yr fluctuations of the core may lead to a frequency and amplitude modulation of the 160-min oscillations. The frequency modulation could be sought in a periodic phase shift of these oscillations.

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[1)] Oscillations of the solar surface with Π_2 = 160 min were first observed at the Crimean Astrophysical Observatory.[5,6] The possibility of explaining these oscillations on the basis of oscillations of the solar core was discussed in Refs. 3 and 4.

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