The stability of solar gravity-mode oscillations and the structure of the sun

A. G. Kosovichev and A. B. Severnyi

Crimean Astrophysical Observatory, USSR Academy of Sciences, Nauchnyi

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The g-mode oscillation stability of solar-interior models with a low core heavy-element abundance $Z$ and of turbulent-diffusion models is investigated in a quasi-adiabatic approximation. The low-$Z$ models are the most unstable, and only they can fit the observed solar gravity-mode oscillations and neutrino deficiency.

1. INTRODUCTION

The task of interpreting the long-period (120–200 min) oscillations of the sun and the closely related problem of determining what mechanism excitates them are among the most urgent issues facing field of helioseismology. As often remarked, in physically admissible models of the sun's internal structure it is most natural to regard these oscillations as nonradial normal gravity-mode oscillations. They might then be excited through nonlinear resonant coupling with unstable modes.

Some recent findings support this view. Analysis of a 9-yr run of observations has disclosed 32 different solar oscillation periods between 120 and 200 min. When these are compared against theoretical calculations of free-oscillation spectra for various models, one obtains the best agreement for a model sun (model C of Christensen-Dalsgaard et al.,) having a lower heavy-element abundance in the core than the standard model. Ten of the oscillation frequencies can then be identified with g-modes of degree $l = 4$ and order $n = 10–20$; the remainder would represent combination frequencies for g-modes of differing degree and order.

An important product of this analysis has been the discovery of numerous resonance relations between the g-mode oscillation eigenfrequencies and the combination frequencies. These may be significant if the oscillations are nonlinear. In particular, for the 160-min oscillation the 2g$_{2}$ (160,80) mode is in resonance with the combination oscillations g$_{4}$ - g$_{2}$ (160,53), 2g$_{2}$ - g$_{4}$ (160,24), 3g$_{4}$ - 4g$_{14}$ (160,21). Accordingly nonlinear resonant coupling might indeed play a major role exciting the long-period oscillations. Since the presence of unstable modes is a necessary condition for this mechanism to work, it is essential to determine whether the normal-mode oscillations are stable.

For the standard model sun the stability of the free oscillations has been studied by many authors (in light of Dufay and Gough's proposed mechanism for mixing in the solar core); the subject is reviewed by Gabriel. It has been shown that the lowest gravity modes (g$_{1}$, g$_{2}$) of dipole oscillation ($l = 1$) would have been unstable in the past while the sun was evolving along the main sequence during the age interval from about $2 \times 10^{4}$ to $3 \times 10^{8}$ yr, but that for the standard model of the present-day sun all the g-modes are stable. The strong temperature dependence of the $^{3}$He (He$_{2}$, 2p) $^{4}$He reaction, which in unstable models contributes about half of all the energy in the pp cycle, will act as a destabilizing mechanism. We have performed analogous calculations for model C and have found that in this case the g-modes will remain unstable even when the sun reaches its present age.

Model C initially has low abundances of heavy elements and helium: $Z_{0} = 0.001$, $Y_{0} = 0.16$. As the sun evolves, the convection zone is assumed to become enriched with heavy elements due to accretion of interstellar matter, until the present value $Z = 0.02$ is achieved. Compared with the standard model, model C implies a lower production of energetic neutrinos, in accord with Davis's experiment.

A turbulent-diffusion model lately has also been proposed to resolve the dilemma of deficient solar neutrinos; rotational instability induced in the convective zone would produce turbulence, which would even out the gradients in chemical composition and thereby raise the hydrogen density in the core.

Our aim in this letter is to ascertain how the stability of the g-mode oscillations will be affected by changes of the chemical composition in interstellar-accretion and turbulent-diffusion models, and to compare those models against the observational evidence.

2. INFLUENCE OF ABUNDANCES ON g-MODE STABILITY

We have calculated the stability in the quasadiabatic approximation. Table I gives the parameters of each model considered, with the sun now taken to be $4.5 \times 10^{5}$ yr

![FIG. 1. Histogram for the distribution with respect to solar mass zone of the relative contribution to the parameters $F_{\nu}$, $\nu_{i}$ and to the parameter $F_{\gamma}$.](image-url)
TABLE I. Model Parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>Z0</th>
<th>X0</th>
<th>XH</th>
<th>( \rho_0 \text{ g/cm}^3 )</th>
<th>( T_0 \text{ K} )</th>
<th>( D \cdot R_\odot )</th>
<th>( F_\nu \text{ SNU} )</th>
<th>( P_\nu \text{ min} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.02</td>
<td>0.739</td>
<td>0.369</td>
<td>153.4</td>
<td>1.51</td>
<td>0.272</td>
<td>7.9</td>
<td>36.8</td>
</tr>
<tr>
<td>B</td>
<td>0.004</td>
<td>0.832</td>
<td>0.482</td>
<td>129.0</td>
<td>1.41</td>
<td>0.303</td>
<td>2.3</td>
<td>37.9</td>
</tr>
<tr>
<td>C</td>
<td>0.001</td>
<td>0.881</td>
<td>0.519</td>
<td>153.7</td>
<td>1.39</td>
<td>0.335</td>
<td>1.7</td>
<td>37.6</td>
</tr>
<tr>
<td>D</td>
<td>0.02</td>
<td>0.703</td>
<td>0.572</td>
<td>108.0</td>
<td>1.46</td>
<td>0.260</td>
<td>2.7</td>
<td>56.4</td>
</tr>
<tr>
<td>E</td>
<td>0.02</td>
<td>0.718</td>
<td>0.619</td>
<td>99.6</td>
<td>1.43</td>
<td>0.242</td>
<td>1.8</td>
<td>61.5</td>
</tr>
</tbody>
</table>

TABLE II. Calculated Oscillation Period and Damping Time

<table>
<thead>
<tr>
<th>Model</th>
<th>( l=1, \xi_0 )</th>
<th>( l=2, \xi_0 )</th>
<th>( l=3, \xi_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( P \text{ min} )</td>
<td>( \tau_d \text{ 10^4 yr} )</td>
<td>( P \text{ min} )</td>
</tr>
<tr>
<td>A</td>
<td>63.13</td>
<td>0.0062</td>
<td>85.46</td>
</tr>
<tr>
<td>B</td>
<td>78.81</td>
<td>-1.86</td>
<td>90.05</td>
</tr>
<tr>
<td>C</td>
<td>72.87</td>
<td>-0.712</td>
<td>102.25</td>
</tr>
<tr>
<td>D</td>
<td>86.61</td>
<td>-1.86</td>
<td>122.59</td>
</tr>
<tr>
<td>E</td>
<td>95.97</td>
<td>-2.94</td>
<td>133.92</td>
</tr>
</tbody>
</table>

old. Model A is the standard model; B, C are models in which heavy elements are being accreted; 1, 2 are turbulent-diffusion models with values \( Re = 10^2, 200 \), respectively, for the turbulent Reynolds number. Here \( Z_0 \), \( X_0 \), denote the initial heavy-element and hydrogen abundances; \( X_H \), is the hydrogen abundance at the center; \( \rho_0 \), \( T_0 \), are the central density and temperature; \( D \) is the convection-zone depth in units of the solar radius; \( F_\nu \) is the neutrino flux in solar neutrino units; and \( P_\nu \) is the parameter in the asymptotic expression\(^{13}\) for the periods of g-modes having low degree \( l \) and high order \( n \):

\[
P \approx P_0 (n + l/2 - \nu_0)/\sqrt{l (l + 1)}, \quad P_0 = 2\pi^2 \left( \int_0^R N/ r \, dr \right)^{-3/2},
\]

with \( N \) the Brunt–Väisälä frequency and \( R_\odot \) the radius at the base of the convection zone.\(^2\)

The outcome of these stability calculations is shown in Table II; \( P \) denotes the free-oscillation period in minutes and \( \tau_d \) is the time scale for damping of the oscillations. A minus sign denotes instability. We see that the instability is enhanced both as the core heavy-element abundance diminishes (model C) and as turbulent diffusion increases the hydrogen density. In the latter case, however, a further rise in \( X_H \) (making \( X_H/X_0 > 0.9 \)) will suppress the instability.

It is in model C that the g-modes are most unstable, bearing out the suggestion\(^2\) that the long-period oscillations might be resonantly excited in this model. To measure the efficiency of the excitation mechanism, a special analysis is required, based on the general theory developed by Dziembowski.\(^{15}\)

3. COMPARISON OF INTERNAL-STRUCTURE MODELS AGAINST OBSERVATIONS OF SUN

To a first approximation the following four parameters may be used for comparison purposes: 1) the depth \( D \) of the convection zone; 2) the neutrino flux \( F_\nu \); 3) the parameter \( \nu_0 = 2 \int_0^R (d l/c) \) in the asymptotic distribution of p-mode oscillation frequencies (the global 5-min oscillations); 4) the parameter \( P_0 \) [see Eq. (1)] in the asymptotic distribution of g-mode oscillation periods, a quantity recently measured by several groups.\(^{3,4,14,16}\)

The data presently available are inadequate to pin down the depth of the convection zone, A deep zone (\( D \approx 0.3 R_\odot \)) would help explain the lithium deficiency and interpret the \( (l, \omega) \) diagram for nonradial oscillations of high degree \( l \); but other evidence (sunspots, granulation, and so on) suggests a shallow convection zone, hardly any deeper today than \( 5 \times 10^4 \text{ km} = 0.07 R_\odot \).

Now let us consider the relative contribution of different interior layers to the three integral parameters \( F_\nu, \nu_0, P_0 \). We shall use the histogram that Bahcall et al.\(^{25}\) have prepared for the relative contributions to \( F_\nu, \nu_0 \), supplementing it by the parameter \( P_0 \) (Fig. 1). Notice that the value of \( F_\nu \) conveys information only on the centermost zone of the sun (the central 5% of the mass contributes 95% of this quantity). In \( \nu_0 \), on the contrary, the greatest contribution comes from the surface layers, so this parameter is of little value in gauging the internal structure of the sun.\(^21\) For \( P_0 \), the contribution is rather evenly distributed through nearly the whole sun, apart from the central zone, where 5% of the total mass contributes 40% of \( P_0 \). By Eq. (1) there is no contribution to \( P_0 \) from the convective envelope.

![Diagram](image-url)
Short-period pulsations in solar hard x-ray bursts recorded by Venera 13, 14


Moscow Engineering Physics Institute

V. Sh. Dolidze and V. M. Zenchenko

Institute for Space Research, USSR Academy of Sciences, Moscow

G. Vedrenne, M. Niel, C. Barat, G. Chambon, and R. Talon

Centre d’Etude Spatiale des Rayonnements, Toulouse
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Power-spectrum analysis of the time profiles of several solar hard x-ray events recorded by Venera 13 and Venera 14 discloses two cases of recurrent bursts from the same active region, with quasiperiodic (1–0.7 ) intensity pulsation.

Time-profile analysis indicates that in many solar flares the hard x-ray intensity varies quasiperiodically. Although such effects have been reported by a number of authors, the x-ray experiments of the 1960s and 1970s had a temporal resolution too low to permit the study of short-period processes. But if one examines type IV solar radio bursts, which result from the synchrotron radiation of fast electrons, one finds evidence of quasiperiodic processes having time scales of around 1 sec or even shorter (Refs. 5–8). It therefore is of great interest to look for short-period pulsations in the hard x-ray emission as well. Data of this kind might set constraints both on the physical parameters of the fast-particle beam interaction zone and on the acceleration mechanism.

Carrying SPEX 2 MS (SNe 2 MZ) instrument packages, the Venera 13 and Venera 14 space probes were launched 1981. October 30 and November 4, respectively. We have analyzed the solar-flare information acquired by these spacecraft through 1982 May 30, comprising 140 records of solar events, each 16 sec long with (1/64)-sec resolution, or 64 sec long with (1/2)-sec resolution.

The data processing was done in two steps. First the 140 burst events were Fourier-analyzed by the pro-