THE ROLE OF NUCLEAR REACTIONS IN THE EXCITATION OF STELLAR OSCILLATIONS

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ABSTRACT. The contribution of each element participating in p-p chain and each region of star to oscillation excitation by nuclear energy is investigated. The gravity modes the most easily excited by this way are indicated.

The spectrum and eigen functions of each star are determined by its structure. The specific features of stellar model manifested themselves in the oscillations. The observation of the oscillations and the comparison them and calculated frequences could help to verify the correctness of stellar model. The acoustic modes have large amplitude near the surface which rapidly decreases with decreasing radius. The modes of low degree l penetrate deeper and contain the information about the internal structure of the star. The gravity modes are concentrated in stellar core.

Possible only part of eigen oscillations have been observed. These are excitated modes. The modes whose eigen functions have relatively large amplitude in nuclear burning zone can be driven by energy released from nuclear reactions.

$$\sigma_\varepsilon = \int_0^\tau dt \int_0^M dm \, \frac{\delta T}{T} \varepsilon'$$

is the part of oscillation increment depending on nuclear burning. In solar like stars the proton-proton chain is dominant.

It is usually assumed for the simplicity of calculations that lifetime of deuterium is very short but lifetimes of other elements of p-p chain are very long in comparison with periods of oscillations. Figure 1 shows the

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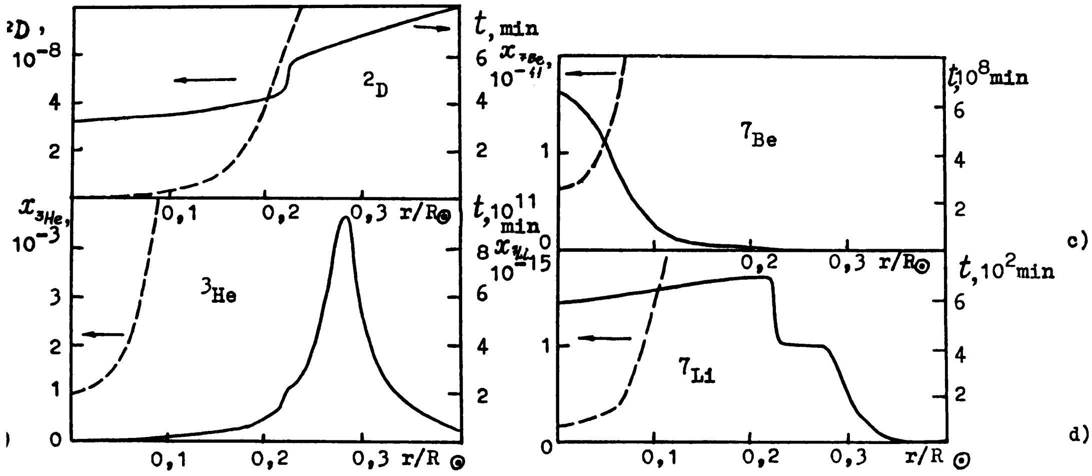

Figure 1. The radial dependences of the lifetimes (dashed lines) and abundances (continuous lines) of a) ^{2}D, b) ^{3}He, c) ^{7}Be, d) ^{7}Li in solar model with mixed core 0,4 $M_\odot$.

lifetimes (dashed lines) and the concentrations (continuous lines) of a) ^{2}D, b) ^{3}He, c) ^{7}Be and d) ^{7}Li in central part of some model of present Sun with mixed core 0,4 $M_\odot$. One can see that the lifetime of deuterium reaches a few minutes at the boundary of nuclear burning core. The corresponding value for ^{7}Li is in the range of hours. The lifetimes of other elements are much longer. But they are changing in the process of evolution and can be shorter for stars with different masses. If the lifetime is comparable to the oscillation period it must be taken into account in the calculations of variation of nuclear energy generation rate.

The change of nuclear energy generation depends on the perturbation of temperature, density and abundances of interacting elements. The positive contribution to the excitation of the oscillations by nuclear burning is conditioned by variations of abundances of elements participating in nuclear reactions ^{3}He(^{3}He, 2p) ^{4}He (about 101%), ^{3}He(4He, γ)^{7}Be (about 1%), ^{7}Li(p, 4He)4He (about 0,3%). The other p-p chain reactions take off energy of oscillations. These results can be understood on examination of the distributions of phase φ and modulus of relative Eulerian variations of chemichal abundances x'_i / x_i in star (Figure 2). It is assumed that the perturbation of the abundance depends on time in form

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$$x'_i / x_i = | x'_i / x_i | \cos (\omega_0 t + \varphi_i (r)).$$

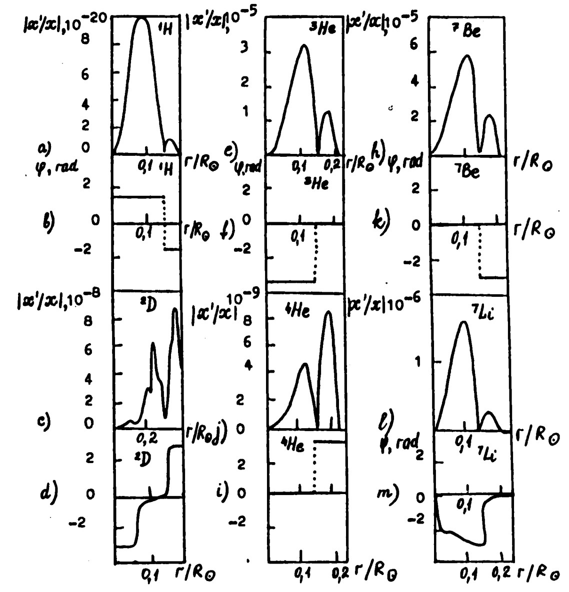

Figure 2. The radial dependences of the phase φ and modulus of relative Eulerian variation of chemical abundance $|x'_i/x_i|$ of a,b) ^{1}H; c,d) ^{2}D; e,f) ^{3}He; j,i) ^{4}He; h,k) ^{7}Be; l,m) ^{7}Li for g5-mode, l = 2.

As one can see on Figure 2a,b the variation of hydrogen abundance is extremely small and practically sinusoidal. This is caused by constant hydrogen abundance in the depth of this solar model with mixed core and very slow rate of the reaction p(p,e ν)^{2}D.

The gradient of deuterium is not large but positive in nuclear active core (Figure 1a). The dependence of the phase on radius is intricate (Figure 2d). Therefore the contribution of deuterium to the excitation of oscillations can be positive as well as negative.

The ^{3}He abundance variation plays the main role in the excitation. The lifetime is much longer then the periods of oscillations some hours long (Figure 1b). The gradient of ^{3}He abundance is not small. The energy released from ^{3}He(^{3}He, 2p)^{4}He reaction is relatively large. $x'_{3He} \simeq - \delta r \, dx_{3He}/dr$, $dx_{3He}/dr > 0$ and x'_{3He} is in anty-phase with the displacement (Figure 2e,f) and in phase with Lagrangian variation of the temperature. That is why the contribution of this reaction and ^{3}He in the work integral characterising the oscillation excitation is the largest and positive.

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The Figure 2 j,i shows the change of ^4He abundance in phase with displacement and in anty-phase with Lagrangian temperature variation. It causes the oscillation damping.

The situation is the same for ^7Be. Although $x'_{^7Be} > x'_{^3He}$ (Figure 2 h,k) but $dx_{^7Be}/dr < 0$ (Figure 1c) and the energy generation is small in the reaction with the participation of ^7Be. Consequently the decrease of oscillation energy due to the ^7Be influence is slight.

The behavior of the modulus and the phase of ^7Li abundance variation $x'_{^7Li}$ is interesting. The ^7Li lifetime is comparable with oscillation periods. This causes the existence of the sinusoidal component of $x'_{^7Li}$ and complex dependence of the phase (Figure 2l,m). The contribution of this element to oscillation excitation is positive but not large because $x'_{^7Li} < x'_{^3He}$ and the generation of energy in $^7Li(p, {}^4He){}^4He$ reaction decreases fast with the distance from the centre of the Sun.

The contributions of different elements of p-p chain to the oscillation increament σ_ε depending on nuclear reactions are represented in Table as an example.

TABLE

THE CONTRIBUTIONS OF DIFFERENT ELEMENTS OF P-P CHAIN TO INCREMENT σ_ε FOR TWO QUADRUPOLE GRAVITY MODES g_5 AND g_6 IN ONE OF SOLAR MODELS WITH THE MIXED CORE 0,4 $M_\odot$.

	P	^2D	^3He	^4He	^7Be	^7Li
g_5	$7{,}74\cdot10^{-4}$	$-4{,}19\cdot10^{-5}$	1,031	$-1{,}59\cdot10^{-6}$	$-5{,}45\cdot10^{-4}$	$4{,}74\cdot10^{-3}$
g_6	$1{,}8\cdot10^{-3}$	$7{,}26\cdot10^{-4}$	1,03	$-2{,}43\cdot10^{-6}$	$-6{,}12\cdot10^{-4}$	$4{,}94\cdot10^{-3}$

The larger the oscillation amplitude in the nuclear active core, the more effective is the excitation of such mode by nuclear energy. The Figure 3 displays the radial distributions of radial displacement amplitude δr, the ratio of Lagrangian temperature perturbation to the equilibrium temperature $\delta T/T$, standardized nuclear $\sigma_\varepsilon/|\sigma_s|$ and total $\sigma/|\sigma_s|$ increments, oscillation energy $E(r)/E$ for two gravity modes in the same solar model. The curve $L(r)/L_\odot$ represented in Figure 3d characterises the contribution of different zones of star to its luminosity. One can see that the small central zone from $0{,}05R_\odot$ to $0{,}15R_\odot$ provides the main part of luminosity

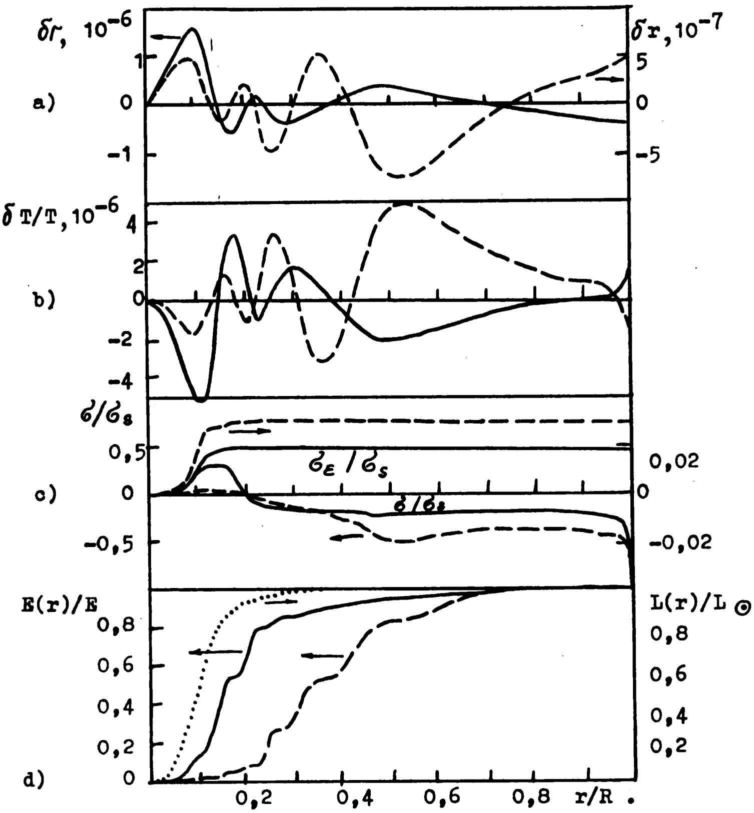

Figure 3. Radial distributions of a) radial displacement amplituble δr , b) the temperature perturbation $\delta T/T$, c) nuclear $\sigma_\varepsilon/\sigma_s$ and total σ/σ_s increments, d) oscillation energy $E(r)/E$ and luminosity $L(r)/L_\odot$ for g5(l=2) (continious lines) and g6(l=2) (dashed lines).

The oscillation amplitude of g5 mode is much larger inside the solar core than outside. As it has been shown earlier the oscillation amplitude has such distribution for example in the model with mixed interior if the node of the radial displacement is on the boundary of the mixed core. The similar modes have the advantages in the nuclear energy excitation. The energy of such modes amounts almost entirely in stellar core.

The dependences of σ_ε , σ and E on radius are stepped. The steps of σ_ε , σ and E are caused by low contribution to the work integral of regions near nodes of Lagrangian temperature perturbation and displacement. A zone passive to oscillation excitation exists near centre because displacement and $\delta T/T$ are small in this region although the nuclear reactions are the most intensive here.

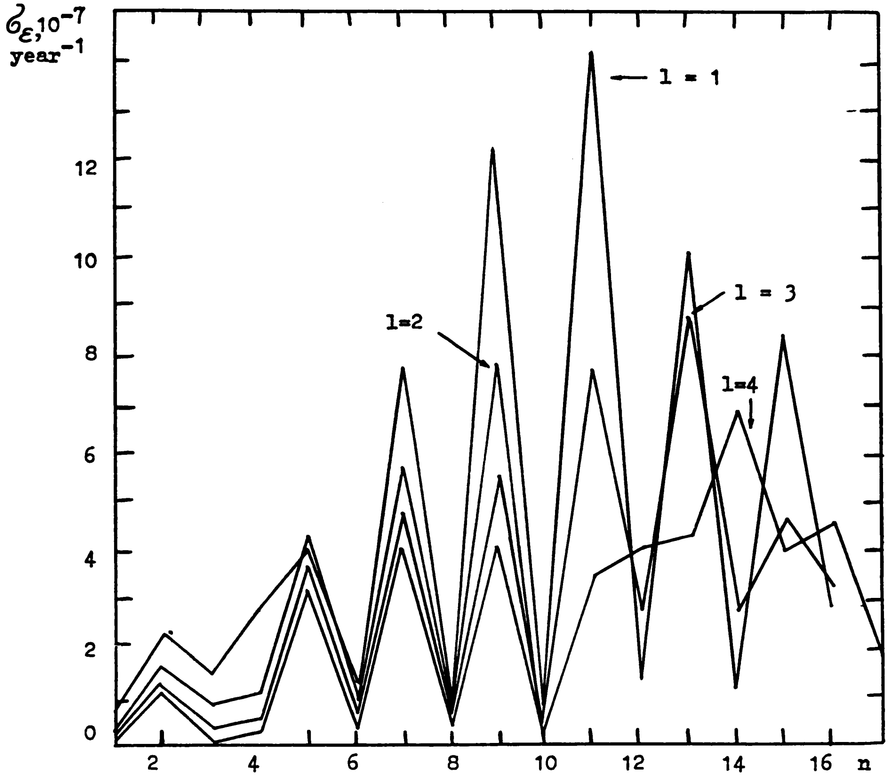

Figure 4. The dependence of nuclear oscillation increment on radial order n at l = 1,2,3,4.

This passive zone is wider than the corresponding passive zone for L(r) since the Eulerian perturbation of energy generation rate is proportional to displacement ($\varepsilon' \propto -\delta r$), but σ_ε is proportional to δr square

$$\sigma_\varepsilon \propto \int_0^\tau dt \int_0^{M_r} dm\, \delta T/T\, \varepsilon' \propto \delta T\, \delta r \propto (\delta r)^2.$$

The main contribution of nuclear reaction to the increment σ_ε is provided by next zone connected with first maximum of displacement amplitude arranging on the layer with high energy generation rate. Next zone becomes passive again, forth is active and so on. The further is active zone from the centre, the smaller is its contribution to σ_ε. The first maximum of displacement amplitude increases with the increase of n. But first zone of excitation becomes narrower, the most part of intensive energy generation zone becomes passive to oscillations.

The same phenomenon takes place at the growth of l . The competition of these two processes leads to the existense of broad maximum of the dependence on radial order n at n = = 4–16. It makes certain selective property of excitation by nuclear reactions. σ_ε rapidly decreases at smaller and greater n. Correspondingly the smaller l the greater is nuclear reaction contribution to oscillation excitation (Figure 4). The excitation by nuclear energy should be expected for low degree oscillations with n about n = 5 – – 15, instead of low radial order modes. The observation of such gravity modes could give the important information on stellar structure.

The numerical investigation of properties of such long periodical modes executed on models of present Sun with different part of mixed mass has shown that the existence in the star more ore less sharp boundary leads to irregularity in spacing of g-mode periods (Figure 5). Such behavior allows to confirm or reject the supposition on the existance of mixed core in the Sun (because standard solar model predicts almoust equidestant spacing of g-mode periods). Unfortunately now there are not sufficiantly reliable experimental data in this region of periods.

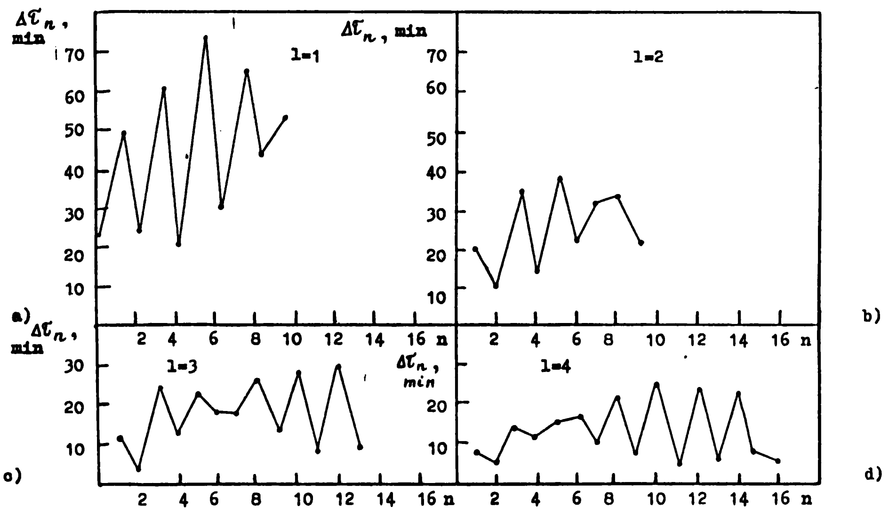

Figure 5. Spacing of g-modes periods $\Delta\tau_n = \tau_{n+1} - \tau_n$ in solar model with mixed core 0,4 $M_\odot$ for l = 1,2,3,4.