# Колебания Солнца и звезд и температурные волны в фотосфере

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ИЗМИРАН

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September 5, 2008


**Intrinsic stellar oscillation amplitude and granulation power density measured in photometry**

**Solar reference values and CoRoT response functions**

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# Appendix A: Visibility coefficients

The visibility factor associated with a mode observed in intensity by an observed pointing in the direction of the star rotation axis is given by the following relation (see Dziembowski 1977):

$$S_\ell(\lambda) = \frac{\int_0^1 d\mu\ \mu\, I_\lambda(\mu)\, Y_\ell^0(\mu)}{\int_0^1 d\mu\, \mu\, I_\lambda(\mu)} \qquad \text{(A.1)}$$

where $\mu \equiv cos(\theta)$, $\theta$ is the angle with respect to the $z$ axis, $I_\lambda(\mu)$ is the monochromatic specific intensity used to take into account the limb-darkening, $\lambda$ is the wavelength and $Y_\ell^m$ is the spherical harmonic associated with a mode with a degree $\ell$ and azimutal order $m$. The spherical system of coordinates $(r, \theta, \phi)$ is chosen

Astron. Astrophys. 305, L33–L36 (1996)

ASTRONOMY AND ASTROPHYSICS

*Letter to the Editor*

**Spectral darkening functions of solar *p*-modes – an effective tool for helioseismology**

Y.D. Zhugzhda[1], J. Staude[2], and G. Bartling[2]

Solar Phys
DOI 10.1007/s11207-008-9132-9

HELIOSEISMOLOGY, ASTEROSEISMOLOGY, AND MHD CONNECTIONS

**Calculation of Spectral Darkening and Visibility Functions for Solar Oscillations**

C. Nutto · M. Roth · Y. Zhugzhda · J. Bruls · O. von der Lühe

$$I_\nu(\nu,\mu) = I_{0\nu}(\nu,\mu) + \delta I_\nu(\nu,\mu) = \int_0^\infty e^{-\tau_\nu/\mu} B_\nu(\tau_\nu)\frac{\mathrm{d}\tau_\nu}{\mu} +$$

$$\boxed{\int_0^\infty e^{-\tau_\nu/\mu}\left[\frac{\mathrm{d}B_\nu(\tau_\nu)}{\mathrm{d}\ln T_0}\frac{\delta T}{T_0} + \frac{\delta\kappa_\nu}{\kappa_{0\nu}}(B_\nu(\tau_\nu) - I_\nu(\tau_\nu,\mu))\right]\frac{\mathrm{d}\tau_\nu}{\mu},}$$

**Функция потемнения**

$$I_\nu(\tau_\nu,\mu) = \int_0^{\tau_\nu} e^{(\tau_\nu/-\tau'_\nu)/\mu} B_\nu(\tau'_\nu)\frac{\mathrm{d}\tau'_\nu}{\mu},$$

Флуктуации прозрачности

Адиабатическое приближение

$$\frac{\delta\kappa_\nu}{\kappa_{0\nu}} = \left(\frac{\partial\ln\kappa_{0\nu}}{\partial\ln T}\right)_\rho \frac{\delta T}{T_0} + \left(\frac{\partial\ln\kappa_{0\nu}}{\partial\ln\rho}\right)_T \frac{\delta\rho}{\rho_0}$$

$$\frac{\delta T}{T_0} = (\gamma-1)\frac{\delta\rho}{\rho_0},$$

$\mu = \cos\theta,\ \theta$ -

Полярный угол

$$\frac{\delta T}{T_0} = \mathrm{const.}$$

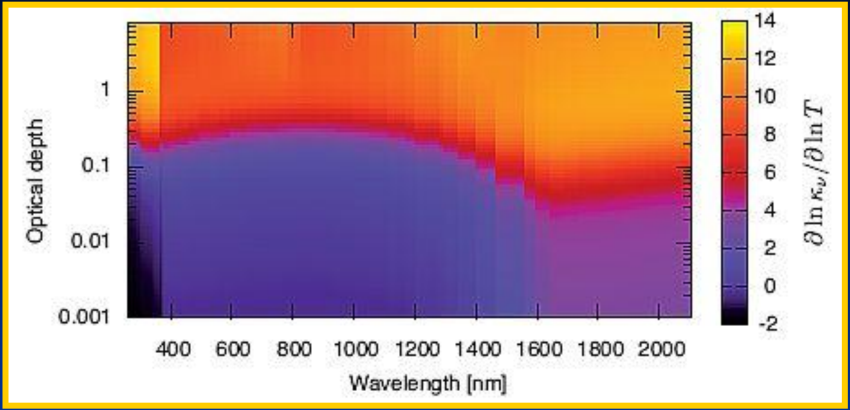
Локальное приближение

После интегрирования по диску находим относительную функцию видимости

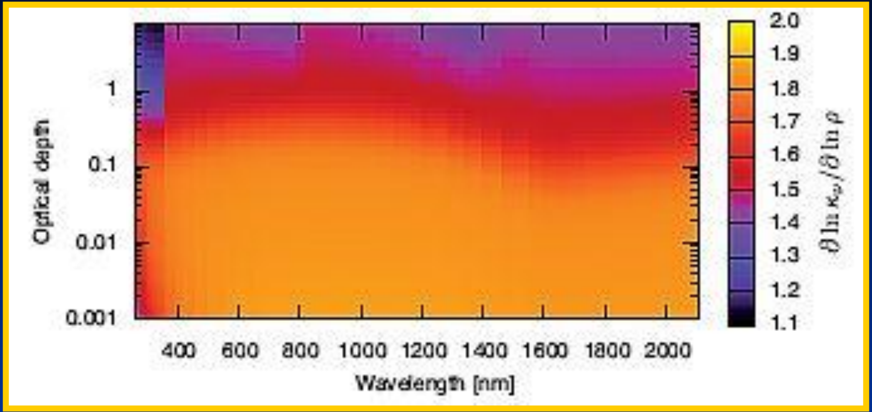
$$\frac{\delta F_\nu / F_{0\nu}}{\delta T / T_0} = \left\{ \int_0^\infty \left[ \frac{\mathrm{d}B_\nu(\tau_\nu)}{\mathrm{d}\ln T} E_2(\tau_\nu) - \left( \frac{\partial \ln \kappa_\nu}{\partial \ln T} \right)_\rho \int_{\tau_\nu}^\infty \frac{\mathrm{d}B_\nu(\tau'_\nu)}{\mathrm{d}\tau'_\nu} E_2(\tau'_\nu)\mathrm{d}\tau'_\nu - \right.\right.$$
$$\left.\left. - \frac{1}{\Gamma_3(\tau_\nu) - 1} \left( \frac{\partial \ln \kappa_\nu}{\partial \ln \rho} \right)_T \int_{\tau_\nu}^\infty \frac{\mathrm{d}B_\nu(\tau'_\nu)}{\mathrm{d}\tau'_\nu} E_2(\tau'_\nu)\mathrm{d}\tau'_\nu \right] \mathrm{d}\tau_\nu \right\} \left[ \int_0^\infty B_\nu(\tau_\nu) E_2(\tau_\nu) \mathrm{d}\tau_\nu \right]^{-1}$$

Функция видимости в локальном приближении может быть вычислена, так как она зависит только от параметров невозмущенной атмосферы

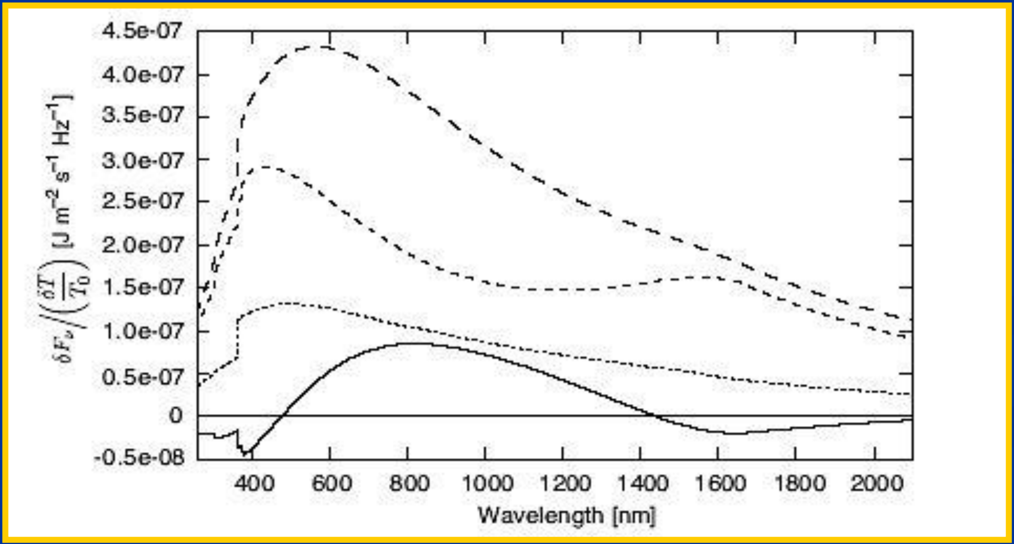
Производная от прозрачности по температуре




Производная от прозрачности по плотности

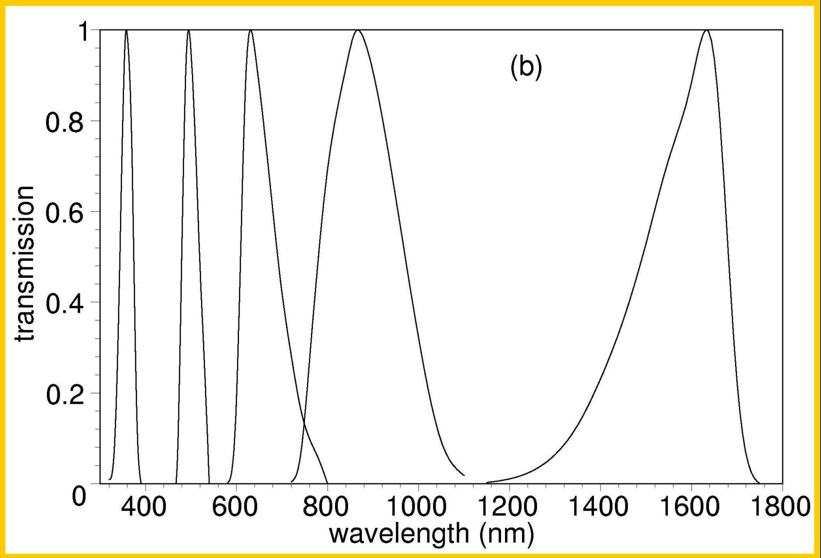


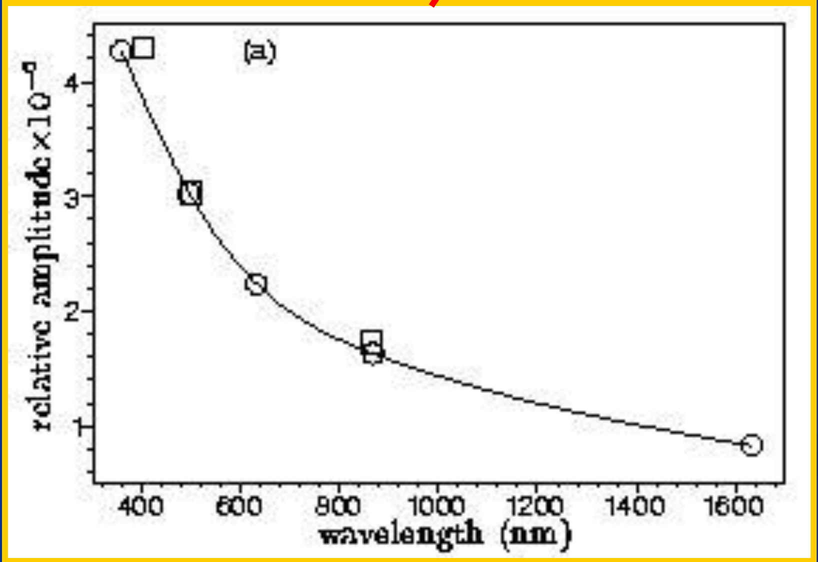

Сплошная линия – функция видимости, длинные штрихи – вклад от функции Планка, короткие штрихи и пунктир – вклады от флуктуаций прозрачности из-за флуктуаций температуры и плотности



# Обратная задача

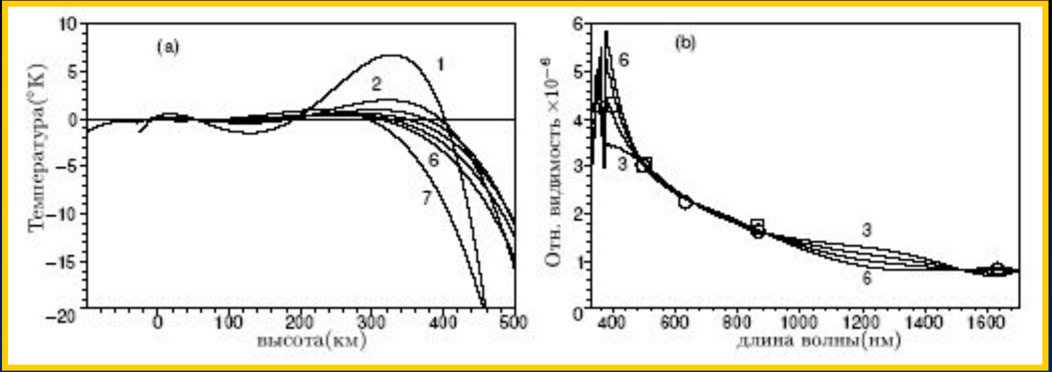
$$\left\{\int_{\nu_{n1}}^{\nu_{n2}} f_n(\nu)\int_0^\infty \frac{\delta T}{T_0}\left[\frac{\mathrm{d}B_\nu(\tau_\nu)}{\mathrm{d}\ln T}E_2(\tau_\nu) - \left[\left(\frac{\partial\ln\kappa_\nu}{\partial\ln T}\right)_\rho + \frac{1}{\Gamma_3(\tau_\nu)-1}\left(\frac{\partial \ln\kappa_\nu}{\partial\ln\rho}\right)_T\right] - \int_{\tau_\nu}^\infty \frac{\mathrm{d}B_\nu(\tau'_\nu)}{\mathrm{d}\tau'_\nu}E_2(\tau'_\nu)\mathrm{d}\tau'_\nu\right]\mathrm{d}\tau_\nu d\nu\right\}\left[\int_{\nu_{n1}}^{\nu_{n2}} f_n(\nu)\int_0^\infty B_\nu(\tau_\nu)E_2(\tau_\nu)\mathrm{d}\tau_\nu d\nu\right]^{-1} = F_n^{(obs)},$$




Многоканальный фотометр ДИФОС

Кружки –DIFOS, квадраты –SPM(SOHO)

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LAGRANGIAN AND EULERIAN STRATIFICATIONS OF ACOUSTIC OSCILLATIONS THROUGH THE SOLAR PHOTOSPHERE

INÉS RODRÍGUEZ HIDALGO, BASILIO RUIZ COBO, MANUEL COLLADOS, AND LUIS R. BELLOT RUBIO

APPLICATION OF INVERSE METHODS FOR INVESTIGATION OF SOLAR BRIGHTNESS OSCILLATIONS

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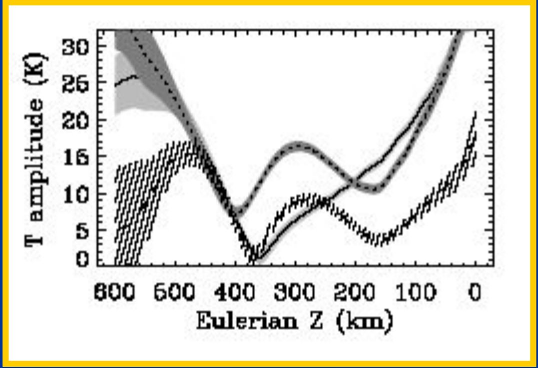


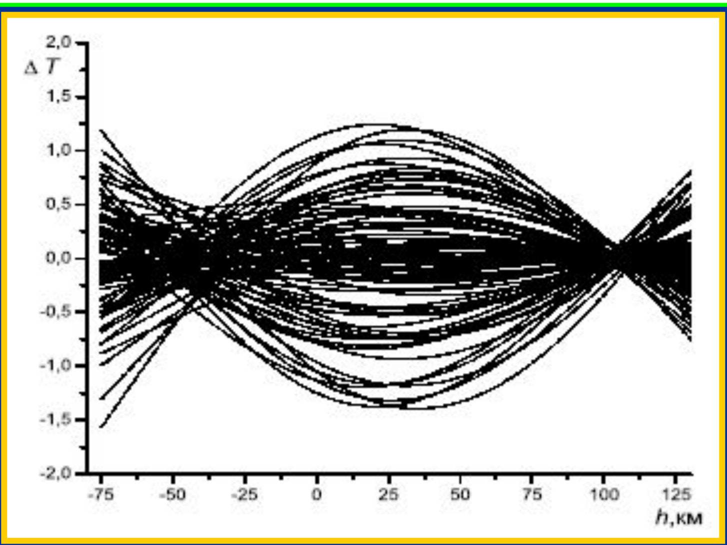


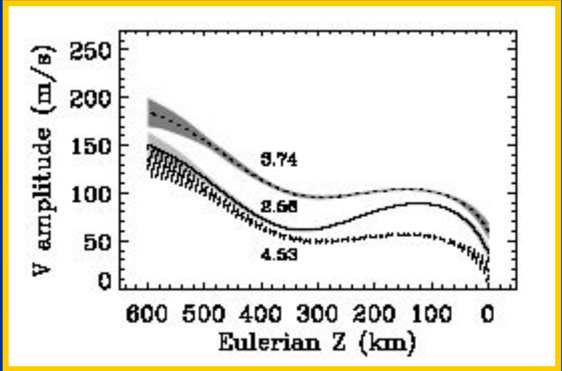

# Функции потемнения

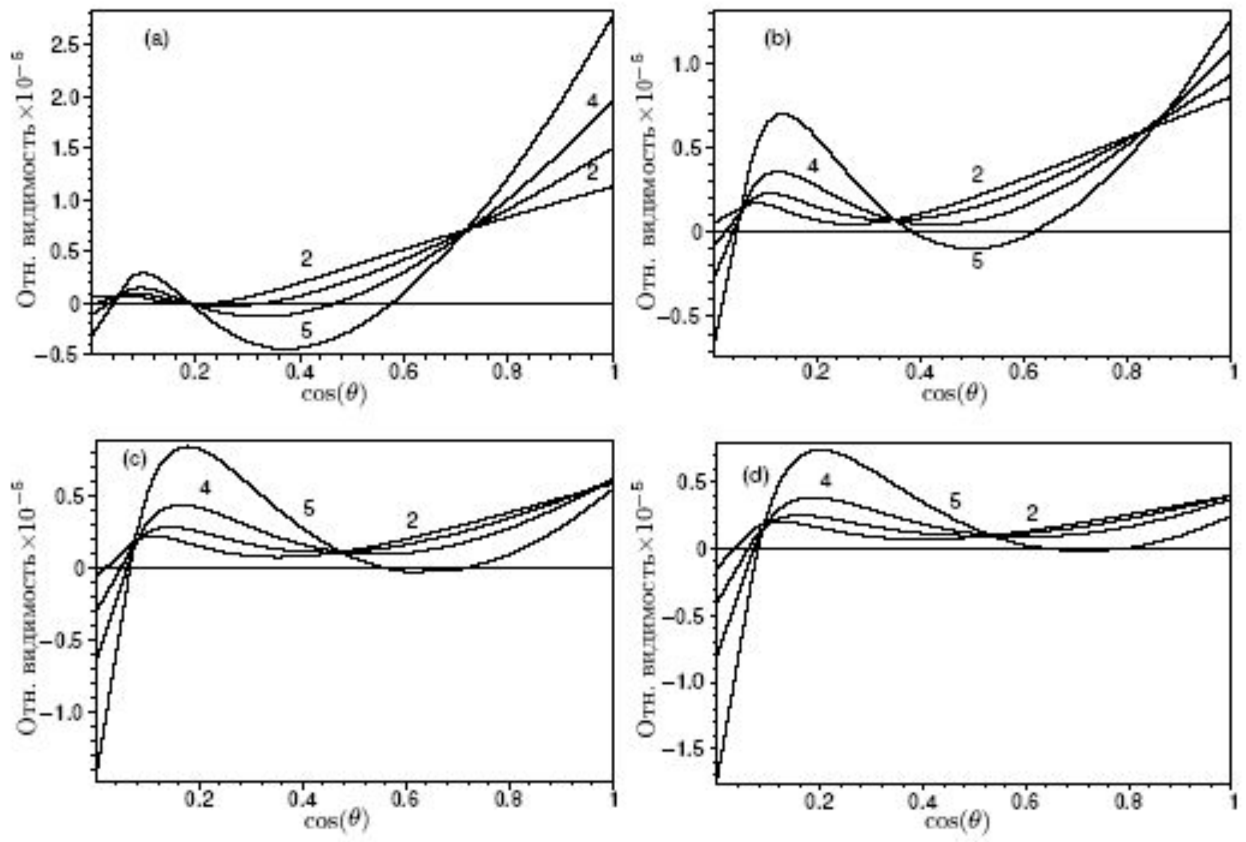


Рис. 6: Функции потемнения для p-мод с $l = 0$ для четырех каналов фотометра ДИФОС с длинами волн $\lambda = 357.6(a), 494.5(b), 630.7(c), 866.3(d)$нм. Номера кривых на графиках соответствуют номерам моделей с фиксированной оптической толщиной на графиках рис.5.

**TEMPERATURE WAVES IN THE SOLAR ATMOSPHERE**

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*Solar Physics* **124:** 205–209, 1989.



**NON-ADIABATIC OSCILLATIONS IN AN ISOTHERMAL ATMOSPHERE**

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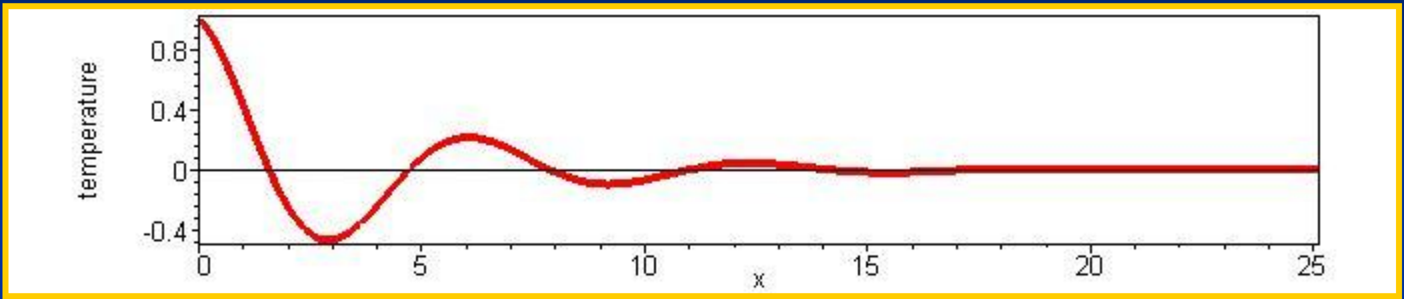
*Astrophysics and Space Science* **95** (1983) 255–275. 0004-640X/83/0952–0255$03.15.



# Температурные волны




$$k^4 - k^2\left(\frac{\omega^2}{c_T^2} + \frac{i\omega}{\chi}\right) + \frac{i\omega^3}{\chi c_s^2} = 0$$

Квази-адиабатическое приближение

$$k_a = \frac{\omega}{c_T} + i\,\frac{c_T}{2\chi c_s^2}\,(c_s^2 - c_T^2) \quad \text{(acoustic wave)}\,,$$

$$k_T = (1 + i)\sqrt{\frac{\omega}{2\gamma\chi}} \quad \text{(temperature wave)}\,,$$

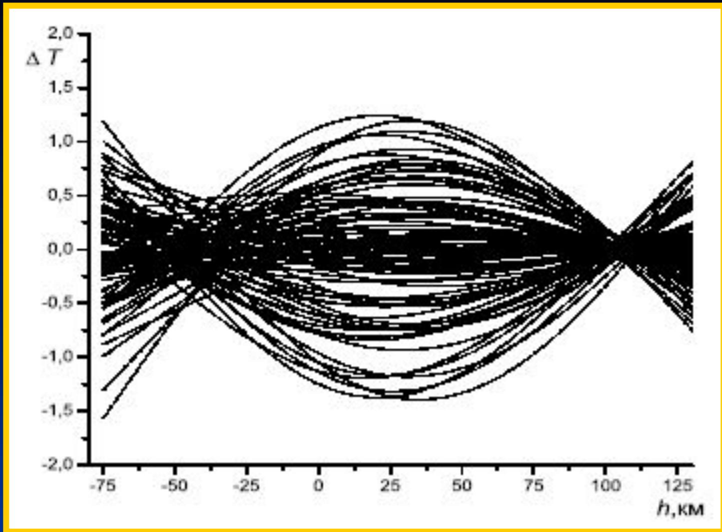
$$|k_T| << |k_a|$$

Квази-изотермическое приближение

$$k_a = \frac{\omega}{c_s} + i\,\frac{\omega^2\chi}{2c_s}\left(\frac{1}{c_T^2} - \frac{1}{c_s^2}\right) \quad \text{(acoustic wave)}\,,$$

$$k_T^2 = \frac{i\omega}{\chi} + \omega^2\left(\frac{1}{c_T^2} - \frac{1}{c_s^2}\right) \quad \text{(temperature wave)}\,,$$

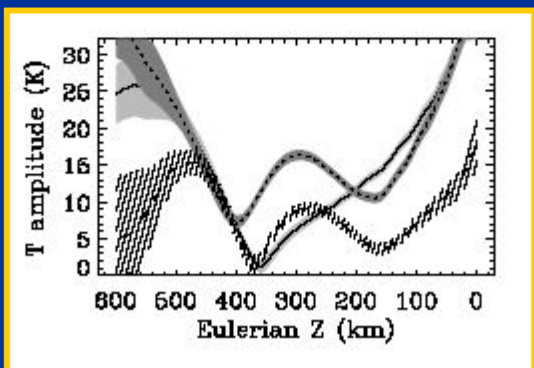
$$|k_T| >> |k_a|$$

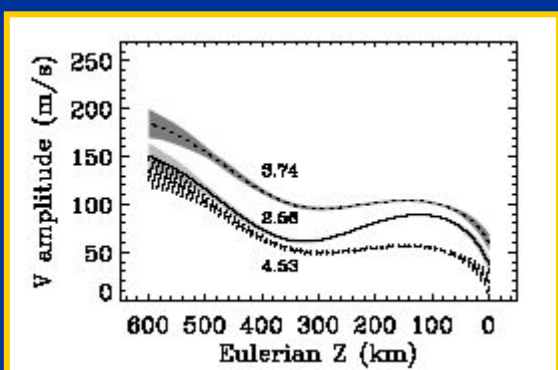



diffuse approximation is not correct in this layer. The temperature conductivity of the solar photosphere is about $10^{11}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ and the wavelength of temperature waves is around

$$\lambda(\mathrm{km}) = 10\sqrt{P} \quad (\mathrm{s})\,, \tag{10}$$

where $P$ is the period of a wave.




Five-minute oscillations in the solar photosphere must generate temperature waves due to a linear interaction. In the layer of interaction, the temperature waves are not damped over short distances because of reinforcing by acoustic waves. In the photosphere the temperature disturbances of low-frequency (Equation (8)) temperature waves are connected with the velocity amplitude by

$$\left|\frac{\delta T}{T}\right| \simeq (P\,(\mathrm{s}))^{3/2}\ \frac{V}{c_s}\ . \tag{11}$$

The temperature fluctuations of the five-minute temperature waves are greater by a factor $10^3$ than temperature fluctuations generated by pure acoustic $p$-modes of the same velocity amplitude.

# Взаимодействие р-мод и температурных волн

$$i\omega\rho' + w\frac{\rho_0}{H} + \rho_0 u = 0,$$

$$i\omega\rho_0 w + \frac{dp'}{dz} - \rho' g = 0,$$

$$i\omega T' + (\gamma - 1)T_0 u = \frac{Q'}{\rho_0 c_v},$$

$$\frac{p_0}{T_0}T' = p' - \frac{p_0}{\rho_0}\rho';$$

Оптически толстая атмосфера

$$Q' = \lambda\left(\frac{d^2T'}{dz^2} - k_\perp^2 T'\right) + \frac{d\lambda}{dz}\frac{dT'}{dz}.$$

Оптически тонкая атмосфера

$$Q' = -\rho_0 c_v q T',$$

$$\lambda = \lambda_0 \exp\left[\frac{(1-s)z}{H}\right].$$

Изотермическая атмосфера
H-шкала высот

$$\frac{d^2}{dz^2}\left(\frac{Q'}{p_0}\right) + \frac{1}{H}\frac{d}{dz}\left(\frac{Q'}{p_0}\right) + \left(\frac{\omega^2}{c_*^2} - k_\perp\right)\frac{Q'}{p_0} - \frac{i\gamma\omega}{(\gamma-1)T_0} \times$$
$$\times\left[\frac{d^2T'}{dz^2} + \frac{1}{H}\frac{dT'}{dz} + \left(\frac{\omega^2}{c_0^2} + \frac{(\gamma-1)g^2k_\perp^2}{\omega^2 c_0^2} - k_\perp^2\right)T'\right] = 0,$$

Уравнение имеет точное аналитическое решение в виде обобщенных гипергеометрических функций