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Новый взгляд на волны сжатия в солнечной короне

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Аннотация. ***Введение.*** До настоящего времени не выяснена природа волн сжатия, наблюдаемых в солнечной короне в крайнем ультрафиолетовом диапазоне. Устоявшийся подход, связанный с проблемой нагрева корональной плазмы, основан на представлении о магнитоакустических волнах, генерируемых в нижних слоях атмосферы. Однако многочисленные наблюдения и анализ спектров волн сжатия показывают признаки, существенно отличающиеся от свойств обычных волн. ***Результаты и обсуждения.*** Нами предложена новая модель, в которой вместо регулярной волны рассматривается последовательность отдельных локализованных возмущений. ***Заключение*** Практическая значимость статьи, основанной на свойствах акустических волн, на динамику которых значительное влияние оказывают теплопроводность и излучение плазмы, что позволило показать, что наблюдаемые признаки можно объяснить на совершенно иной основе. Мы полагаем, что в действительности наблюдаются цепочки локализованных возмущений, генерируемых в нижней атмосфере.

Ключевые слова: Компьютерное моделирование, физика плазмы, функция излучения, магнитная гидродинамика, Солнце, колебания и волны.

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Research article

A new sight at compressive waves in the solar corona

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Abstract. ***Introduction.*** To date, the nature of the compression waves observed in the solar corona in the extreme ultraviolet range has not been clarified. The established approach to the problem of heating the coronal plasma is based on the concept of magnetoacoustic waves generated in the lower layers of the atmosphere. However, numerous observations and analyses of the spectra of compression waves show features that differ significantly from those of conventional waves. ***Results and discussions***. We have proposed a new model that considers a sequence of individual localized disturbances instead of a regular wave. ***Conclusion*** The practical significance of the article is based on the properties of acoustic waves, the dynamics of which are significantly influenced by the thermal conductivity and radiation of the plasma, which has shown that the observed features can be explained on a completely different basis. We believe that what is actually observed are chains of localized disturbances generated in the lower atmosphere.

Key words: Computer modeling, plasma physics, radiation function, magnetic hydrodynamics, Sun, oscillations, and waves.

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Introduction

For several decades, propagating variations in the intensity of extreme ultraviolet radiation have been observed in the solar corona, which are interpreted as compression waves. Along with the intensity change, a Doppler shift is sometimes observed, indicating plasma motion. Disturbances propagate along coronal structures, coronal loops [1,2] and coronal holes [3-6]. The spectra of time signals are usually broad, and dominant maxima, declared to be periods, are sought in the wavelet spectra (Fig. 1). Most often, two maxima are observed; they are called short and long periods. The short one lies on average in the interval of up to 10 min, the long one - in the interval of 10-30 min. Disturbances quickly attenuate, demonstrating a frequency dependence [3,4], disturbances with periods of 3-5 min are observed up to distances of 3-23 Mm, with periods of 20-30 min - up to 70-90 Mm.

An example of a wavelet spectrum is shown in Figure 1. Two maxima are prominent in the global spectrum. Analysis of multiple events allowed us to make the following observations. It is difficult to determine from the appearance of the time signal whether it is harmonic or a superposition of harmonic components. It contains sharp spikes with a broad spectrum. The main maximum of 20 minutes has a limited duration in the local spectrum, which also contains other maxima. The period registration is irregular, and the disturbances typically have a low propagation velocity, almost always significantly lower than the speed of sound. These characteristic features of compression waves require some explanation.

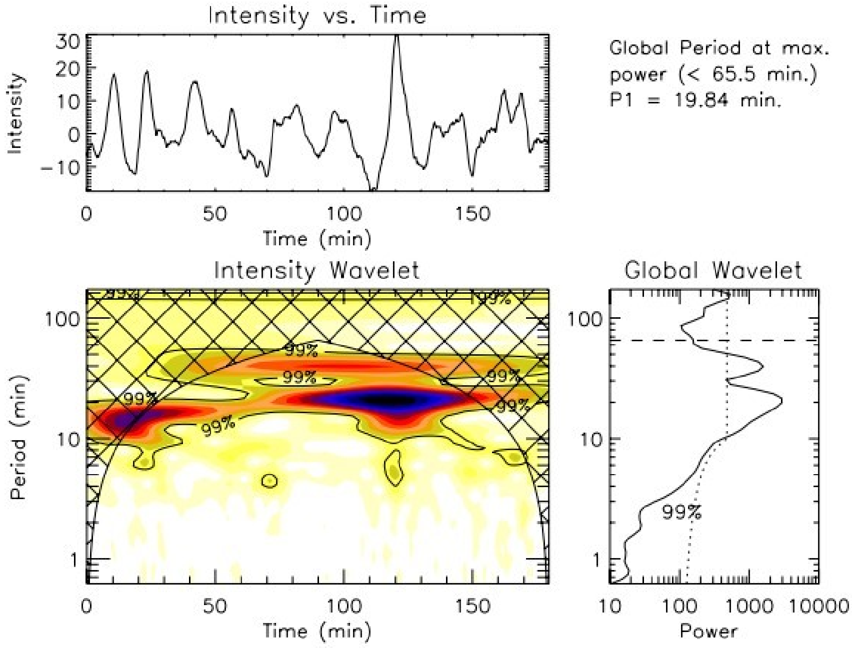

Figure 1- A typical observation of a compression wave and its wavelet spectrum. The grid highlights the region of the spectrum beyond the cone of influence, where the data is considered unreliable. The global spectrum shows two maxima, one of which has a period of approximately 20 minutes.

Nonadiabatic acoustic waves

To study compression waves, we employ the apparatus of nonadiabatic acoustic waves, whose behavior is influenced by thermal conductivity, heating, and radiation from the coronal plasma. Calculations are performed in the one-dimensional hydrodynamics approximation, and the dispersion equation has the form [7, 8]

$$\tilde{\omega}^3 + iA\tilde{\omega}^2 - \tilde{\omega}\tilde{C}_s^2\tilde{k}^2 + iB = 0, \quad (1)$$

$$A = A_1\tilde{k}^2 + A_2, B = \frac{1}{\gamma}\left(-A_1\tilde{k}^2 - A_2 + A_3\right)\tilde{C}_s^2\tilde{k}^2, \quad (2)$$

its coefficients are determined through the thermal conductivity coefficient $\varkappa(T_0)$and the radiation function$\Lambda(T_0)$

$$A_1 = \frac{(\gamma-1)Mm(k)^2}{R\rho_0 m(\omega)}\varkappa(T_0),$$
$$A_2 = \frac{(\gamma-1)M}{Rm(\omega)}\rho_0\Lambda'(T_0), \quad (3)$$
$$A_3 = \frac{(\gamma-1)M}{RT_0 m(\omega)}\rho_0\Lambda(T_0).$$

The tilde here denotes dimensionless quantities; the following scales were chosen for the solar corona conditions

$$m(T) = 10^6\ K, m(C_s) = 10^5\ \text{м с}^{-1}, m(\omega) = 0.1\ \text{с}^{-1}, m(k) = 10^{-6}\ \text{м}^{-1}, \quad (4)$$
$$m(x) = 10^6\ \text{м}, m(t) = 10\ \text{с}.\ m(\Lambda) = 10^{26}\ \text{эрг г}^{-2}\ \text{см}^3\ \text{с}^{-1}.$$

The plasma is described by the equation of state of an ideal gas, where $\gamma = 5/3$, is the molar mass $M = 0.62 \times 10^{-3}\ kg\ mol^{-1}$.. The radiation function is determined by cubic splines over a series of values found numerically [7]. For a fully ionized plasma, the thermal conductivity coefficient is determined by the expression

$$\varkappa(T_0) = 2.28 \times 10^{-11}\ T_0^{5/2}\ (\text{Вт м}^{-1}\ \text{К}^{-1}). \quad (5)$$

Figure 2 shows the dependence of the group velocity on the period and the attenuation length. The group velocity has two minima $P_1$and P_2, at a temperature of 1 MK they are equal to

5.04 and 68.4 min. The first of these is due to thermal conductivity, the second to heating and radiation. The first is important for us, as it divides the periods into short ($P < P_1$) and long ($P > P_1$). Short-period waves have weak dispersion and strong attenuation, while long-period waves, on the contrary, have strong dispersion and weak attenuation. We have thus obtained a relationship between the minimum group velocity and the properties of dispersion and attenuation. To confirm this, we present the asymptotic values of the wave number

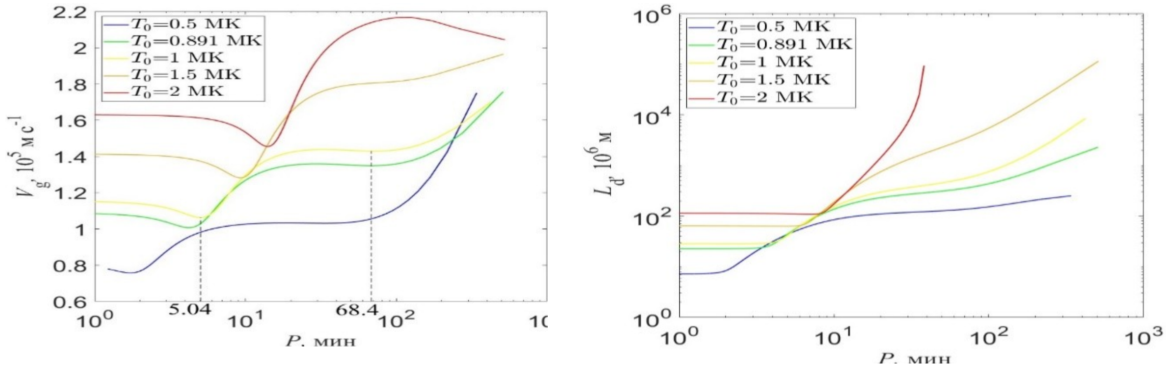

Figure 2 - Properties of dispersion and attenuation of an acoustic wave. On the left, the dependence on the group velocity period; on the right, the dependence on the attenuation coefficient length.

$$\tilde{k} \approx \frac{\sqrt{\gamma}\tilde{\omega}}{\tilde{C}_s}\left(1+\frac{S_1}{\tilde{\omega}^2}+O(\tilde{\omega}^{-4})\right)+\frac{i(\gamma-1)\tilde{C}_s}{2\sqrt{\gamma}B_1}\left(1+\frac{S_2}{\tilde{\omega}^2}+O(\tilde{\omega}^{-4})\right), \tilde{\omega}\to\infty, \quad (6)$$

$$S_1 = \frac{\widetilde{n_0^2 C_s^2}}{\gamma}\left(\frac{(\gamma-1)(5-\gamma)\tilde{C}_s^2}{8\gamma B_1^2}-\frac{B_3}{2B_1}\right),\ S_2 = \frac{\tilde{n}_0^2\tilde{C}_s^2(B_3-B_2)}{2(\gamma-1)B_1}, \quad (7)$$

fair provided

$$\tilde{P} \ll \tilde{P}_c = \frac{\pi\gamma\sqrt{\gamma}B_1}{2\tilde{n}_0\tilde{C}_s^2}. \quad (8)$$

It turns out that , $P_c \approx P_1$, so the asymptotics allow us to determine the applicability limits of the short- and long-period approximations. According to Figure 2, the attenuation length $L_\mathrm{d} = 1/\mathrm{Im}k$for short periods takes on a practically constant value.

$$L_\mathrm{d} \approx L_\mathrm{d0} = 2.87 \cdot 10^4 \frac{T_0^2}{n_0}\ (\text{Мм}), P < P_1. \quad (9)$$

Modeling of wave packets

Let's consider the behavior of an initial pulsed acoustic disturbance. We assume that it originates in the lower atmosphere and propagates upward into the corona. The disturbance is represented by a Fourier integral.

$$\rho = \varepsilon\rho_0 \int_0^{k_\mathrm{max}} F(k)e^{-\delta(k)t}\cos(kx-\omega(k)t)dk, \quad (10)$$

where k $_{\mathrm{max}}$ is the maximum wave number that determines the width of the spectrum. The function$\omega(k)$ is found by numerically solving equation (1)-(3). For the spectral density, we choose a Gaussian form . $F(k) = e^{-d^2k^2/4}$The parameter d is the length of the initial pulse, its duration $d/\bar{V}_\mathrm{ph}$is V $_{\mathrm{ph}}$ is the average phase velocity in the interval $0 < k < k_\mathrm{max}$. The wave packet disperses and decays, and the expression under the integral $F(k)e^{-\delta(k)t}$can be considered as a local spectral function at the current moment in time. The presence of a minimum in the group velocity leads to the formation of quasi-periodic oscillations [9]. Depending on the dispersion properties, wavelet spectra shaped like a tadpole or boomerang can form [10,11]. In our case, this is impossible due to the rapid attenuation of the waves.

In our case, the wavelet spectrum has the shape of two separated maxima, which give rise to short and long periods. The formation of the periods is shown in Figure 3 based on the dispersion and attenuation properties of acoustic waves. The solid and dashed blue lines show the initial perturbation spectrum for two different values of length d (left figure). The solid and dashed yellow lines show the same spectra at a certain moment. t_0.At the minimum of the group velocity P_1 the spectral function experiences a dip due to uneven attenuation. Two groups of waves with different periods P_s are formed on either side of the minimum and P_l , but the same speed (right figure). The long period is close to P m, this is the boundary of the periods when such pairs are possible.

Thus, instead of a single initial Gaussian packet, two separate wave packets are obtained, one formed by short-period waves, the other by long-period ones. To confirm this, we conducted a wavelet analysis of time signals recorded at specified distances from the source (Fig. 4). The appearance of the signals themselves shows that the initial Gaussian signal has split into two signals, narrow and wide. Figure 5 shows their wavelet spectra, constructed using the Morlet wavelet using the Torrance-Compeau algorithm [12]. Indeed, in addition to one maximum characteristic of a quasi-Gaussian signal, we see a second maximum located in the region of long periods. Over time, this maximum becomes the dominant one, and the initial short-period signal disappears due to the rapid attenuation of the short-period components.

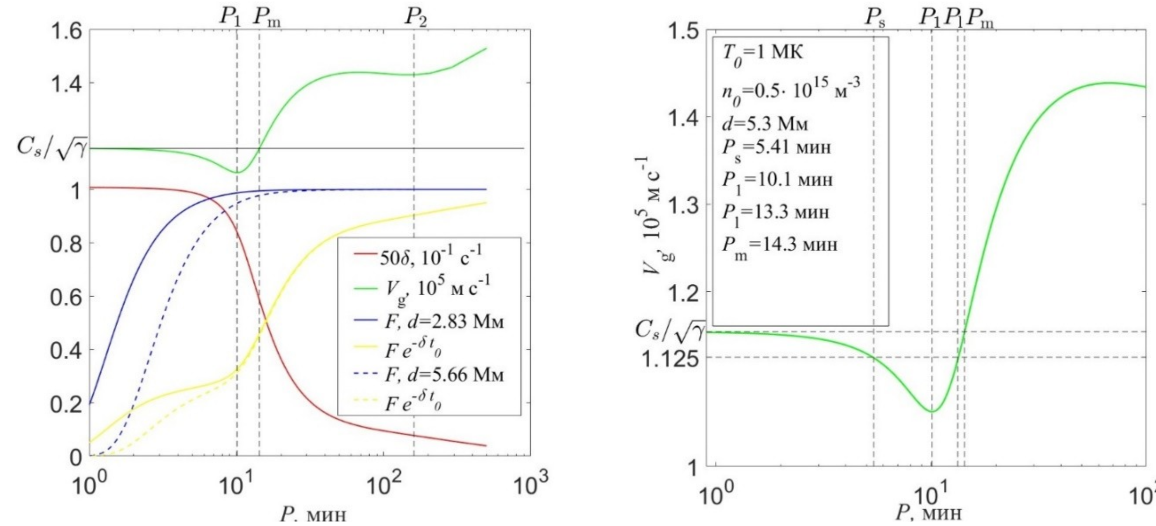

Figure 3 - Formation of two maxima in the spectrum. The green line shows the group velocity, and its minimum is marked P_1. The red line shows the attenuation coefficient, and the blue and yellow lines show the spectral densities at the initial and current moments of time .

At a distance of 58 Mm, the maxima have values of 5.11 and 13.3 min at $T_0 = 1\text{MK}$, $n_0 = 0.45 \cdot 10^{15}\text{m}^{-3}$, they are well within the range of observed values.

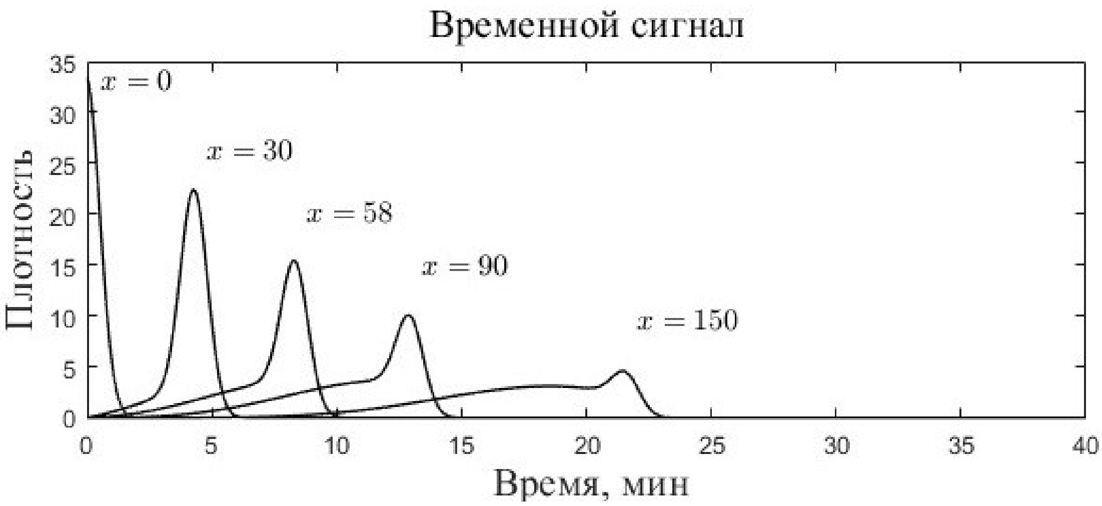

Figure 4 - xThe time signal generated by a wave packet at a given distance x from the source .

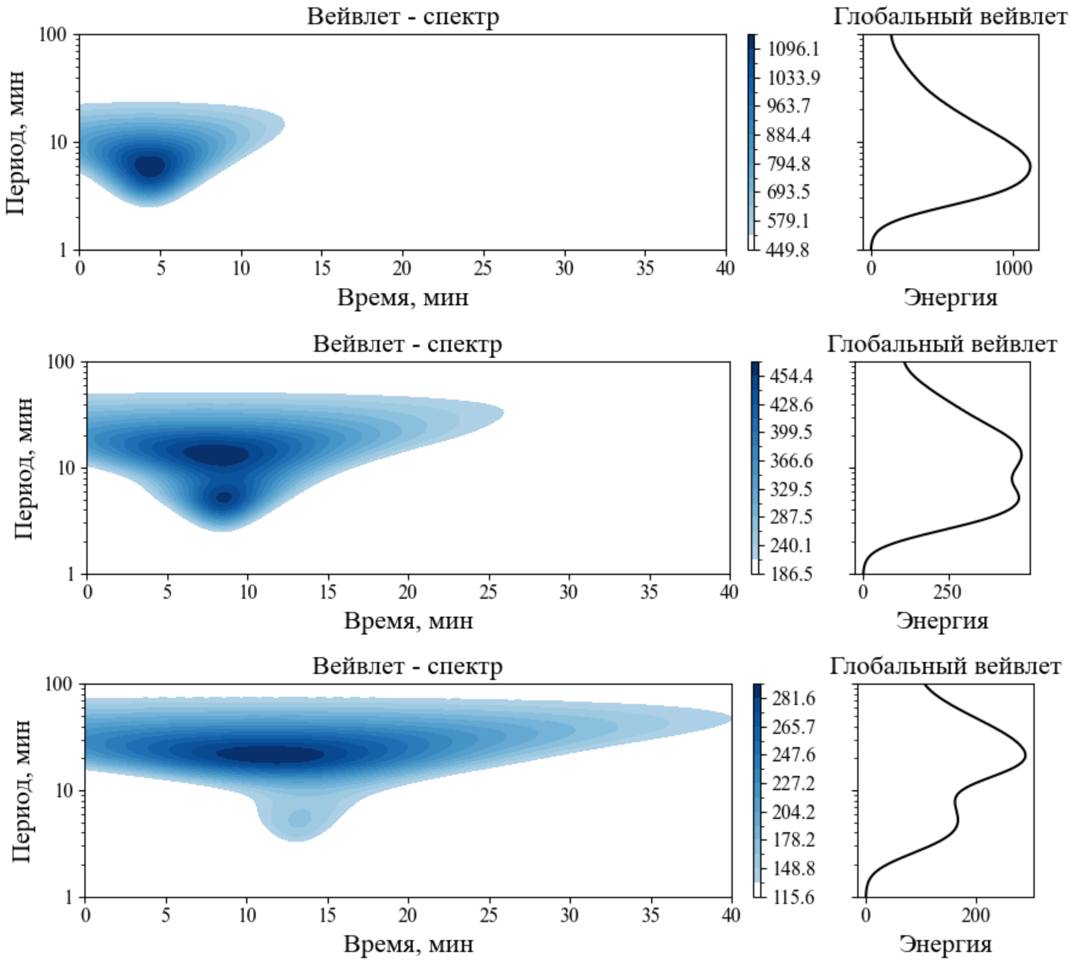

Figure 5 -Wavelet spectrum of signals generated by a wave packet at distances x=30 mm, 58 mm, 90 mm from the source. Plasma parameters: T_0=1 MK, n_0= 〖0.45·10〗^15 m-3. The initial pulse length is d = 5.3 mm.

Conclusion

Studying the dispersion and attenuation properties of acoustic waves in the solar corona's plasma allows for a new interpretation of the nature of compression waves, which are ubiquitous in the corona and are crucial for solving fundamental problems in heliophysics. Each spike in the recorded time signals of extreme ultraviolet radiation intensity can be viewed as a reflection of a localized disturbance generated in the lower atmosphere and then propagated into the corona. Under the influence of dispersion and attenuation, which have a specific nature, each localized initial disturbance is transformed into a signal with two clearly defined periods in its spectrum. The observed so-called compression waves represent a chain of such disturbances, generated independently of one another and having different periods. This approach immediately explains the first two characteristics of compression waves. The disturbances propagate with a velocity close to the group velocity, which is always less than the phase velocity. This also explains the third characteristic.

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