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# Formation of quasi-periodic oscillations in the solar corona

S. Derteev, M. Sapraliev, N. Shividov, and B. Mikhalyaev

Kalmyk State University named after B.B. Gorodovikov, Elista, 358000 Russia

**Abstract.** The dispersion of acoustic waves in the rarefied high-temperature plasma of the solar corona and its role in the propagation of disturbances occurring in the corona are analyzed. We believe that the quasi-periodic oscillations (QPOs) that are recorded when observing propagating disturbances in coronal holes and loops are formed as a result of the combined effect of dispersion and damping of compressive waves. Observations and wavelet analysis show that their spectra are continuous, where the periods are distinguished by corresponding maxima. The shape of spectrum is characteristic of localized disturbances. The study is based on the simple model of non-adiabatic waves in high-temperature plasma, taking into account the properties of thermal conductivity, radiative cooling and constant heating.

**Keywords:** Sun: corona, helioseismology, oscillations

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## 1 Introduction

The propagating disturbances (PDs) observed in the circumsolar corona, coronal loops and holes are considered. PDs are recorded in variations of radiation intensity and are also called compression waves.

An example of PD analysis is shown in Fig. 1. PDs are identified as slow waves. It is a time signal showing the change in intensity over time at a certain selected observation point. It contains a number of maxima, so the idea arises to consider it as a periodic or quasi-periodic process; its wavelet spectrum and the global wavelet spectrum, which highlights the maxima by periods throughout the entire observation time are shown.

As you can see, there are two clear maxima in the spectrum, that is, we can talk about two periods. The authors claim QPOs with two periods. We draw attention to the fact that these periods do not actually operate over the entire interval of observation time. The periods change, that is, they are irregular. What kind of two-period oscillations can we talk about here?

Further, the time signal bears little resemblance to a superposition of two harmonic oscillations. Rather, it consists of several signals that have the form of sharp maxima. We say that there are triangular maxima here.

The next remark is that disturbances are considered as waves, but their propagation speed is significantly different from the speed of sound and the speed of a slow wave.

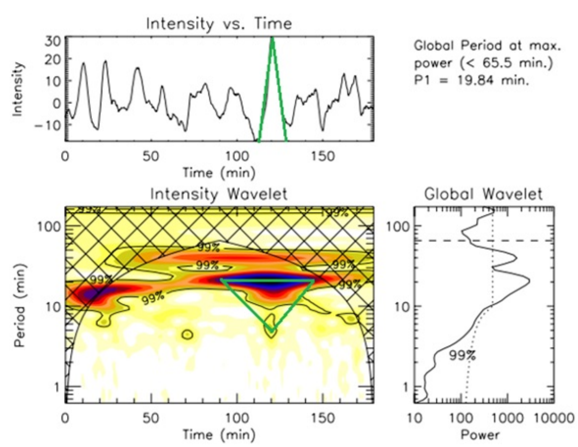


**Fig. 1.** The time signal (top panel), wavelet spectra and global wavelet (bottom panel) (Banerjee et al. 2011).

Similar observations are found in other papers on this issue, for example, Krishna Prasad et al. (2012); Gupta (2014). The maxima are triangular, the periods are irregular, and the speed of propagation of disturbances is significantly less than the speed of sound. These properties suggest that we are not dealing with waves.

## 2 Dispersion relation

To interpret PDs in the solar corona, we used a theoretical model of non-adiabatic acoustic waves in a high-temperature plasma with classical Spitzer thermal conductivity, CHIANTI[1] radiative-loss function and constant heating function. We consider equations of the gas dynamics (Derteev et al. 2023; Mikhalyaev et al. 2023; Derteev et al. 2024). We set the dimensions: $m(\rho) = 1.037 \cdot 10^{-12}\,\mathrm{kg\,m^{-3}}$, $m(\omega) = 0.1\,\mathrm{s^{-1}}$, $m(k) = 10^{-6}\,\mathrm{m^{-1}}$, $m(C_\mathrm{s}) = 10^5\,\mathrm{m\,s^{-1}}$, $m(x) = 10^6\,\mathrm{m}$, $m(t) = 10\,\mathrm{s}$.

Let us consider wave distributions in the form of functions $\exp(i\tilde{k}\tilde{x} - i\tilde{\omega}\tilde{t})$ and write the dispersion relation in the form

$$\frac{\tilde{\omega}^3}{\tilde{n}_0^3} + i\frac{\tilde{\omega}^2}{\tilde{n}_0^2}\left(B_1\frac{\tilde{k}^2}{\tilde{n}_0^2} + B_2\right) - \frac{\tilde{\omega}}{\tilde{n}_0}\tilde{C}_s^2\frac{\tilde{k}^2}{\tilde{n}_0^2} + i\frac{1}{\gamma}\left(-B_1\frac{\tilde{k}^2}{\tilde{n}_0^2} - B_2 + B_3\right)\tilde{C}_s^2\frac{\tilde{k}^2}{\tilde{n}_0^2} = 0, \quad (1)$$

where

$$B_1 = \frac{(\gamma-1)Mm(k)^2}{Rm(\rho)m(\omega)}\varkappa(T_0), B_2 = \frac{(\gamma-1)M}{Rm(\omega)}m(\rho)\Lambda'(T_0), B_3 = \frac{(\gamma-1)M}{RT_0m(\omega)}m(\rho)\Lambda(T_0). \quad (2)$$

## 3 QPOs in the acoustic waves

We have studied the properties of dispersion and damping of acoustic waves, which play a major role in the occurrence of QPOs. Figure 2 shows the dependence of the group velocity on the period. There are two minima. We number them from right to left. We call the right minimum the first and denote it as $P_1$; it is caused by heating and radiative cooling. The left minimum of $P_2$ is caused rather by the action of thermal conductivity; it can be called a thermal minimum. Comparison of the figures shows that radiation affects oscillations only at large periods. The thermal minimum $P_2$ divides periods into short and long.

Using the found dispersion, we consider the wave packet in the form of the Fourier integral

$$\rho = \varepsilon\rho_0\int_0^{k_\mathrm{max}} F(k)\mathrm{e}^{-\delta(k)t}\cos(kx - \omega(k)t)dk, \quad (3)$$

[1] https://chiantidatabase.org/

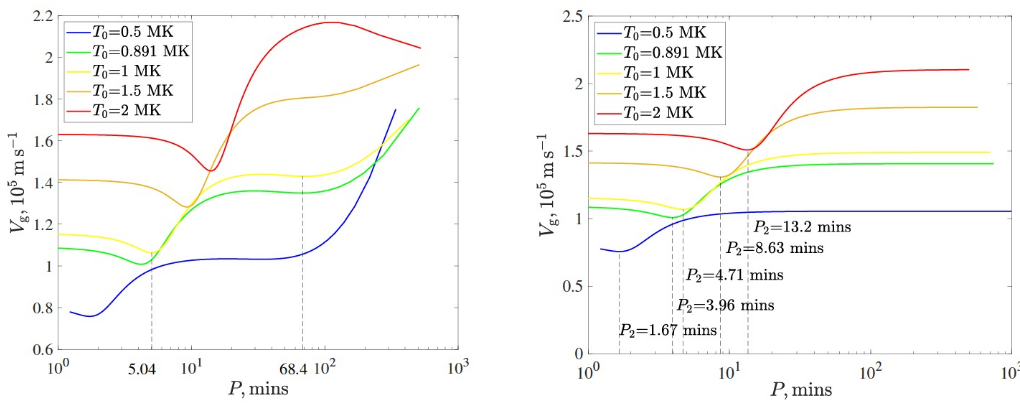


**Fig. 2.** Group velocity $V_{\rm g}(P)$ for $n_0 = 10^{15}$ m$^{-3}$ when taking into account the thermal conductivity and heating and cooling (left), and the thermal conductivity only (right). Shown in dashed lines for $T_0 = 1$ MK (left) (Derteev et al. 2024).

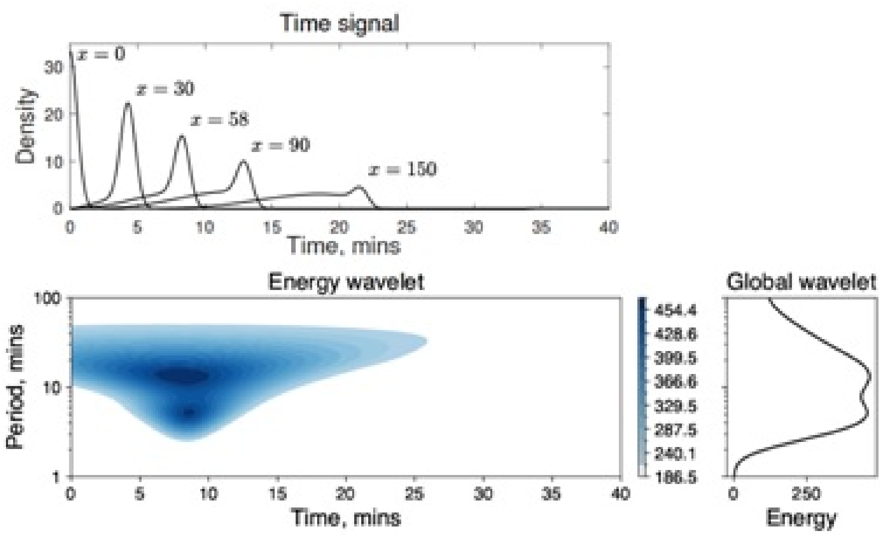


**Fig. 3.** Original time signals (top plot) and wavelet spectrum at the distance $x = 58$ Mm from the source of pulse generation (bottom plot). The initial pulse length $d = 5.3$ Mm. Plasma parameters: $T_0$= 1 MK, $n_0 = 0.45 \cdot 10^{15}$m$^{-3}$ (Derteev et al. 2024).

with spectral density $F(k) = \mathrm{e}^{-d^2k^2/4}$ of Gaussian shape, as in the original pulse. $d$ denotes the length of the initial pulse. We take it small, so that the initial disturbance has the form of a localized pulse. By setting a constant coordinate $x$, we obtain time signals at a given observation point. The source of disturbance is at the origin of coordinates. We use wavelet analysis to study time signals from Python library[2]

$$f(\tau) = \frac{1}{\sqrt{2\pi}}\mathrm{e}^{-\tau^2/2}\mathrm{e}^{i6\tau}. \quad (4)$$

Figure 3 shows the disturbance, time signals and wavelet spectrum when it has two maxima at $x = 58$ mm. According to the generally accepted point of view, we have QPOs here. Since the duration of the maximum increases with the period, the wavelet has a triangular shape, as does the time signal itself. The signal can be distinguished by a short-period part, which forms a sharp peak. It has a short duration and quickly decays. The structure of the signal shows regularities in the splitting of the spectrum into two parts, which we call short $P_\mathrm{s}$ and long $P_\mathrm{l}$ periods. The signal can be considered as a superposition of two wave packets – waves-counterparts. Thus, we show that from the initial localized pulse, under the action mainly of thermal conductivity, two separate wave packets can arise, which give two maxima in the wavelet spectrum. The QPO mechanism is described in the paper Roberts et al. (1984), and its practical application is described in the paper Derteev et al. (2024).

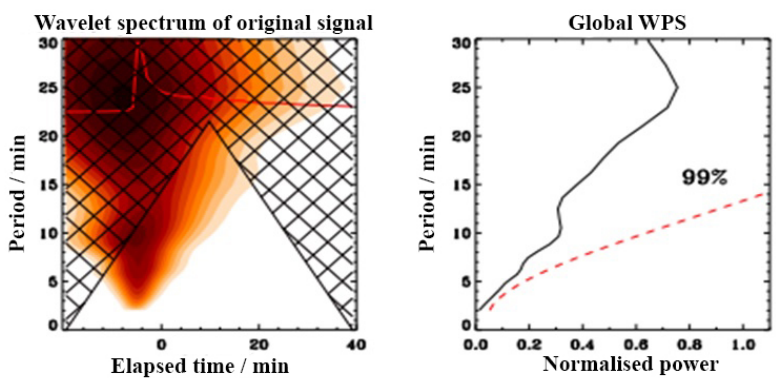


**Fig. 4.** Triangular signals and triangular wavelet spectra in observations of the paper Nakariakov et al. (2018).

The first separate triangular-shaped signal was noted in the paper Berghmans & Clette (1999), but did not attract much attention. We now assume that the so-

[2] https://github.com/PyWavelets/pywt/tree/main/pywt

called propagating disturbances or compressive waves are formed from such separate signals. A similar separate triangular signal is shown in Fig. 4. From the shape of the signal itself, it is clear that it consists of two wave packets with different periods. These periods are obtained in the wavelet spectrum. The wavelet spectrum also has a triangular shape.

## 4 Conclusions

The results of the work show that the original time signal contains individual triangular-shaped signals. In the wavelet spectrum, they correspond in time to pairs of maxima of a triangular shape (Fig. 1, the triangular signal and the corresponding triangle in the wavelet spectrum are highlighted by green lines). Propagating disturbances can be considered as a sequence of separate pulses. This explains such properties as the sharpness of maxima and irregularity of periods.

We propose to divide propagating disturbances into individual triangular-shaped perturbations instead of looking for a harmonic envelope in them. Then what can we call quasi-periodic oscillations?

In the spectrum of each individual triangular disturbance there are short and long periods, the duration of the oscillations is of the order of the period. The oscillations damp quickly, so the duration of disturbance itself is determined by a long period and in observations is 20–30 minutes. It follows that QPOs exist for only 20–30 minutes, then we observe other QPOs with a different pair of periods.

A sequence of triangular disturbances gives a sequence of QPOs, the periods of which may or may not coincide depending on the properties of the original pulses.

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## References

Banerjee D., Gupta G.R., Teriaca L., 2011, Space Science Reviews, 158, 2-4, p. 267
Berghmans D. and Clette F., 1999, Solar Physics, 186, 1-2, id. 207
Derteev S., Shividov N., Bembitov D., et al., 2023, Physics, 5, p. 215
Derteev S.B., Sapraliev M.E., Shividov N.K., et al., 2024, Solar Physics, 299, 10, id. 141
Gupta G.R., 2014, Astronomy & Astrophysics, 568, id. A96
Krishna Prasad S., Banerjee D., Singh J., 2012, Solar Physics, 281, 1, id. 67
Mikhalyaev B.B., Derteev S.B., Shividov N.K., et al., 2023, Solar Physics, 298, 9, id. 102
Nakariakov V.M, Kolotkov D.Y., Kupriyanova E.G., et al., 2018, Plasma Physics and Controlled Fusion, 61, id. 014024
Roberts B., Edwin P.M., Benz A.O., 1984, Astrophysical Journal, 279, p. 857