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# UNSTEADY WAVE-PACKETS IN THE RANDOM ENSEMBLES OF MAGNETIC FLUX TUBES: ACOUSTIC HALOS

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ABSTRACT The propagation of unsteady acoustic wave-packets in a randomly magnetized solar atmosphere is accompanied by specific morphological effects which include the spreading of the energy absorption region over scales much larger than the size of the initial energy source. One of the manifestations of these effects can be acoustic halos. The regions of an efficient energy input and their localization crucially depend on the distribution of magnetic structures in space and over their physical parameters which makes the present study useful for diagnostic goals.

The randomness of magnetic structures in the solar atmosphere provides the existence of simple physical effects which, in principle, can be observed, and which play an important role in its dynamics, and, particularly in energy transfer from lower to upper layers.

Magnetic regions in the solar atmosphere can be roughly divided into two different types. One type corresponds to regions with a small magnetic filling factor where the ensembles of widely spaced magnetic flux bundles are embedded in almost nonmagnetized plasma.

The second type of region can be characterized as a dense conglomerate of closely packed magnetic flux tubes. This model relates, for example, to sunspots, prominences, and to any other region which can be described as a mosaic of random domains where all the parameters (magnetic field, density, etc.) change from one domain to other by the order of unity.

The dynamics of these two different kinds of regions, particularly in their response to the propagation of acoustic waves, are completely different.

Here we consider the case of widely spaced magnetic flux tubes randomly distributed in space and over their parameters (first studied by Ryutov and Ryutova, 1976, below as RR'76).

A key element in the theory is the distribution function of flux tubes $f(\Xi)$ which we define as follows:

$$d\alpha = f(\Xi)d\Xi \qquad (1)$$

$\Xi$ is a set of flux tube parameters: radius $R$, magnetic field $B$, the ratio of plasma densities inside and outside flux tube, $\eta = \rho_i/\rho_e$, and inclination of the flux tube axis $n$; $d\alpha$ is the fraction of the volume occupied by flux tubes with parameter values in the interval $d\Xi$. Thus

$$\alpha = \int_0^\infty \int_0^\infty f(\Xi) d\Xi$$

is the total fraction of the volume occupied by flux tubes, which simply corresponds to a magnetic filling factor of the medium. In a case of widely spaced magnetic flux tubes

$$\alpha \propto R^2/d^2 \ll 1. \tag{2}$$

The broad distribution function $f(\Xi)$ with the width, $\Delta\Xi$, which is much larger than the magnetic filling factor, $\Delta\Xi \gg \alpha$, allows us to obtain the averaged set of equations describing the complex dynamics of randomly magnetized medium.

As it was shown in RR'76 the system of random flux tubes with the broad distribution function reveals a crucial physical feature: the interaction of an acoustic wave with an ensemble of flux tubes results in the excitation of oscillations propagating along those particular flux tubes for which the following resonance condition is satisfied:

$$\omega = (kn)v_{ph} \tag{3}$$

$\omega$ and $k$ are frequency and wave vector of an acoustic wave, $v_{ph}$ is the phase velocity of flux tube oscillation, and $n$ is a unit vector along the tube axis. $v_{ph}$ corresponds either to kink mode (with azimuthal wave number $m = \pm 1$), or to sausage mode (with $m = 0$) and, carrying the required information on flux tube parameters, $v_{ph}$ completely determines its individuality. The phase speeds for a kink (RR'76) and sausage modes (Defouw, 1976) are, respectively

$$v_{ph}{}^{m=\pm 1} = c_A\sqrt{\eta/(1+\eta)}$$

$$v_{ph}{}^{m=0} = c_i c_A/\sqrt{c_i^2 + c_A^2}$$

$c_i$ and $c_A$ being sound and Alfven speeds inside flux tube.

Thus, under the condition (3) the energy of acoustic waves is transferred to oscillation energy of flux tubes; the mechanism of the absorption is similar to Landau damping in a rarefied plasma, and condition (3) is the analogue of the Cherenkov condition in Landau resonance.

The damping rate $\nu_L$ corresponding to this process is proportional to a magnetic filling factor of the medium:

$$\nu_L \propto \alpha k c_{se} \tag{4}$$

(The exact expressions for Landau damping rates due to the excitation of kink modes can be found in RR'76, and due to the excitation of sausage modes are in Ryutova and Priest I, 1992)

As was shown in RR'76 the oscillating flux tube can be a source of a secondary acoustic (or MHD waves). The radiative damping rates $\nu_{rad}$ are proportional to $(kR)^2$ (the exact expressions are: in RR'76 for kink mode, and in Ryutova, 1981 for sausage mode):

$$\nu_{rad} \propto \omega(kR)^2 \tag{5}$$

The interaction of a sound wave with magnetic flux tubes can now be easily described: under the Cherenkov condition (3) the resonant flux tubes absorb the energy of the sound wave in a time

$$\tau_L = \nu_L{}^{-1} \tag{6}$$

Excited oscillations propagate along flux tubes and, in a time

$$\tau_{rad} = \nu_{rad}{}^{-1} \propto \omega^{-1}(kR)^{-2} \tag{7}$$

the absorbed energy is reradiated as a secondary acoustic wave.

For regions with the small magnetic filling factor,

$$\tau_{rad} \gg \tau_L. \tag{8}$$

Thus, the energy of the incident acoustic waves remains for a long time in the form of oscillating flux tubes. It is important that different flux tubes radiate secondary acoustic waves at different heights and over different times. Thicker tubes, for example, radiate sooner than thinner ones (cf. (7)). And, of course, radiated waves have random phases:

$$\Delta\omega \approx \nu_L \tag{9}$$

These features, being typical for the interaction of monochromatic acoustic waves with the random ensemble of flux tubes, produce an additional phenomena in the propagation of unsteady wave packets through such tubes. These phenomena manifest themselves in a clear "morphological" effects; for example, the energy release spreads over the region that is much larger than the the size of the initial wave-packet. The amount of the energy input and its location are determined by the distribution of magnetic fluxes in the medium.

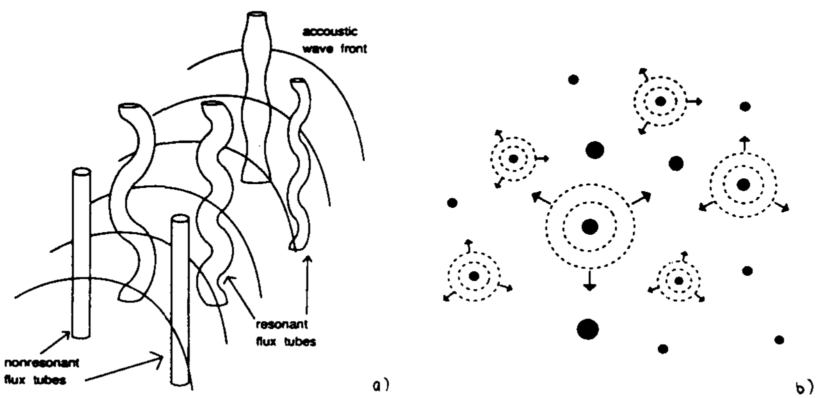


Fig.1. a) Along the acoustic wave path some flux tubes are nonresonant, while others are resonant with respect to kink or sausage modes; b) radiation of secondary acoustic waves by resonant oscillating flux tubes.

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To visualize some "morphological" effects we give here the qualitative picture of two limiting cases (the quantitative theory can be found in Ryutova and Priest (RPII), 1992): the case of a "large" wave-packet, and the case of a "short" wave packet. We compare the size of wave packet, $D$, with the Landau damping length:

$$L_L = c_{se}/\nu_L, \tag{10}$$

which actually carries the information on the statistical properties of the medium.

In a case of a "large" wave packet, when

$$D \gg L_L, \tag{11}$$

the time during which the wave-packet passes any particular flux tube, $T_{pass} \propto D/c_{se}$, is much larger than the Landau time:

$$T_{pass} \gg \tau_L \tag{12}$$

This means that the "large" wave packet interacting with the ensemble of flux tubes is damped away without a considerable displacement: all the resonant flux tubes are excited in the initial area of the wave-packet.

A scheme for the interaction of a large wave-packet with a flux tube ensemble is thus simply understood. At the initial moment of time $t = 0$ flux tubes are not excited.

At a time which is larger than the Landau damping time and less than the time of radiation of secondary acoustic waves

$$\nu_L^{-1} \ll t \ll \nu_{rad}^{-1} \tag{13}$$

the wave-packet is already damped away, but excited flux tubes have not yet radiated secondary waves. Thus, the wave-packet energy remains in a form of natural oscillations of resonant flux tubes imitating the initial area of the wave-packet.

After a time

$$t = \tau_{rad} \approx \nu_{rad}^{-1} \tag{14}$$

secondary acoustic waves are radiated.

Since different flux tubes radiate at different times and at different heights the energy input region spreads significantly with respect to the initial size of the wave packet. The location of the energy input, or in other words, the location of "reappearance" of the wave packet image, differs completely from the expected position of the wave-packet: it is determined by the radiated secondary waves, while in the absence of flux tubes the wave packet continues to travel along its initial direction. It is also clear that noncollinearity of flux tubes enhances the effect of the spreading of the energy input region, and may produce an acoustic halo above the corresponding region.

The "short" wave-packet with

$$D \ll L_L \tag{15}$$

is in some sense "fast" compared with the "large"-"slow" wave packet; it traverses any particular flux tube within a time which is much less than Landau time: $T_{pass} \ll \tau_L$.

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Thus, the short wave-packet excites resonant flux tubes in some area and propagates further, leaving a trace of excited flux tubes, which in turn radiate secondary acoustic waves at definite heights and within definite times. Unlike the case of a "large" wave-packet, now the first excited flux tubes can already radiate their energy before the wave packet finally is damped away. And, secondary acoustic waves coexist with the initial wave packet.

The particular scenario of wave-packet dynamics and the final region of the energy input depend on the specific distibution of flux tubes, determining the "memory" of the system.

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