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Behavior of low-frequency waves in coronal magnetic traps

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The possible contribution to type IV radio emission of all low-frequency waves generated by energetic electrons and protons in a magnetic trap on the sun is estimated. Particular attention is paid to whistlers, since they make the main contribution to the radio emission in combining with plasma waves, $l + w \rightarrow t$. Allowance for the scattering of whistlers by ions and electrons and the conversion of ion–acoustic (s) waves into whistlers enables us to identify the following manifestations of whistlers. The whistler spectrum formed in decay processes involving s waves can yield msec pulses of radio emission and spikes in the decimeter and meter ranges. It is proposed to distinguish the mechanism of pulsing in whistlers from the magnetohydrodynamic model of pulsing in fast magnetosonic waves and the plasma model using the dependence of the depth of modulation of the pulses on their period. The excitation of whistlers based on the normal Doppler effect and their channeled propagation along the trap result in filamentary bursts with intermediate frequency drift. Periodic packets of whistlers excited by means of the anomalous Doppler effect in a quasilinear regime yield zebra-stripe patterns. The unusual broad-band, slowly drifting filamentary bursts are associated with the propagation in a trap of Alfvén solitons, which may trap whistlers.

1. INTRODUCTION

Velocity distributions of energetic electrons and protons with a loss cone are formed in magnetic traps in the solar corona, which are the sources of type IV radio bursts. It is well known that energetic protons in a trap can be a source of fast magnetosonic waves in bounce resonance and of small-scale Alfvén waves in cyclotron resonance. In addition to cyclotron and Langmuir waves, electrons excite whistlers in cyclotron resonance.

The passage of a shock wave, which comes from practically every flare and is associated with a type II burst or a transient, leaves a trail of nonisothermal plasma in a trap due to electron heating in the shock wave front, and ion–acoustic waves with a wide frequency spectrum are excited as a consequence ($T_e \gg T_i$).

Thus, in a magnetic trap in a relatively dense plasma a whole set of low-frequency (LF) waves are excited, which cannot themselves escape from the source but can interact with Langmuir waves and produce electromagnetic radiation which freely escapes from the corona. In this paper we discuss the question of which manifestations of each of the LF modes can be expected when observing type IV radio emission.

A multitude of papers have been published in which individual LF modes and their interaction with high-frequency (HF) waves are used to interpret various radio bursts. There is an unabated stream of papers which employ ion–acoustic turbulence, as applied, for example, to radio wave scattering,[1] interpreting the splitting of bursts,[2,3] explaining type I bursts,[4] etc.

Whistlers combining with plasma waves ($\ell = w \rightarrow t$) have come to be used to interpret pulses,[5] type III bursts,[6] and the fine structure of type IV radio emission: filaments of bursts with intermediate frequency drift and the zebra pattern (alternating light and dark stripes in emission and absorption, respectively, against the continuum background over a wide frequency range).[7,8] In Ref. 9 conservation laws for the $\ell = w \rightarrow t$ process were tested and equations for the intensities of the interacting waves were solved. Now comes a new wave of papers on strong turbulence of whistlers to explain the same filaments.[10] A theory of cyclotron harmonics at twice the plasma resonance has been developed as applied to the zebra structure.[11]

Without dwelling here on details of these papers, we merely point out that some one mechanism, incorporating one LF mode in isolation from the others, is usually used in them. Possible interactions between individual LF modes and their scattering by thermal ions and electrons have been ignored. These very processes determine the spectra of LF waves.[12] In the present paper we mainly devote attention to allowing for all possible scattering and decay processes in the whistler spectrum, so as to show the specific conditions under which they can produce filaments, the zebra pattern, or the briefest pulses of radio emission.

2. EXCITATION OF WHISTLERS

Starting with Ref. 13, kinetic instability with a small velocity spread for longitudinal whistlers on the sun has been considered several times for various conical distributions of energetic electrons.[7,14] In connection with the development of the theory of the maser cyclotron mechanism,[15,16] the excitation of whistlers by distributions of the DGH type and the hollow-beam type has been calculated.[17] In this case, the increments for whistlers are larger than (or of the same order as) the increments for ordinary and extraordinary waves. In Ref. 18 the critical angle of the loss cone (detected with allowance for protons) for activation of the instability of whistlers was found to be 3°.58.

Conical distributions with a large velocity spread must be more realistic, however, for electrons in magnetic traps on the sun. Calculations of kinetic instability[19] have shown, on the one hand, that there is practically no energy threshold for the excitation of whistlers. Electron beams with an energy $\sim$0.3 keV and a relative density $n^h/n^c \approx 10^{-7}$ provide positive kinetic increments for whist-

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lers. On the other hand, the kinetic increments for whistlers are of the same order as the increments for plasma waves and electron cyclotron harmonics (Bernstein modes), $\gamma^w \gtrsim \omega_H(n^h/n_c)$, whereas the hydrodynamic increments are considerably lower than this.[7]

From Ref. 19 it follows that to calculate the total growth rate of whistlers which are propagating at an arbitrary angle to the magnetic field (not merely along the field, as in all the cited calculations), one must allow for three principal resonances: cyclotron resonances based on the normal and anomalous Doppler effects and Čerenkov resonance. The contribution of anomalous resonance to the emission becomes dominant at the top of the magnetic trap, and the role of Čerenkov resonance increases with decreasing frequency when the samping of whistlers by the cool background plasma is taken into account.

Proton beams can also make some contribution to the emission of whistlers. According to Ref. 20 (Sec. 6.2), ion cyclotron resonance at the first three ion harmonics for ion beams with energies from 51 to 63 keV near the frequency $\omega^w \approx \omega_{LHR}$ of the lower hybrid resonance have a maximum increment $\gamma_{max\ i} \approx (n^h/n^c)\omega_{LHR}$, i.e., lower than that for electrons by only a factor $\sim$43.

From Ref. 19 it also follows that anisotropic, energetic electron beams will, depending on the degree of conical and temperature anisotropy, excite whistlers which propagate in the direction opposite to the beam in normal cyclotron resonance if $V_\perp > V_\parallel$ and $s = 1$ in the relation

$$\omega - k_\parallel V_\parallel - s\omega_H = 0. \qquad (1)$$

But if $V_\perp < V_\parallel$ and $s = -1$ in (1), whistlers propagating in the direction of the beam are excited in anomalous resonance. If the energetic electrons are injected in pulses, quasilinear effects thereby do not operate in normal resonance, and in anomalous resonance their role increases with increasing duration of injection (or when new particles overtake the wave).

In the generation of whistlers by cyclotron resonances, $s = \pm 1$ as a result of the interaction of waves with fast resonant particles; the latter move along diffusive elliptical curves (in the $V_\perp$, $V_\parallel$ plane) so as to decrease the distribution function.[21] Particles with small pitch angles impart energy to the waves and approach the loss cone, and particles with large pitch angles, conversely, increase their energy ($V_\perp$) at the expense of the waves.[22,23] Only the particles immediately adjacent to the loss cone (with the smallest pitch angles) precipitate rapidly into it, however, and the loss cone remains empty for a long time. Estimates of the lifetime of fast electrons undergoing scattering by whistlers in regimes of moderate and strong diffusion[24] yield times of ~10-20 sec (Ref. 25). But with prolonged injection of fast particles, the regime of whistler generation should be periodic, since the instability is greatly weakened with the precipitation of electrons into the loss cone,and with the departure of particles (and of whistlers from a region of excitation with a characteristic size 10^8 cm), the conical instability recovers in about 0.2-0.3 sec (Refs. 7 and 24).

The ocnical instability will be periodic not only in time but also in space (along the trap). It must be borne in mind that particles can be scattered not only by whistlers but also by electrostatic waves,[26,27] with the diffusion occurring first from electrostatic waves in the direction of increasing $V_\parallel$ (in the $V_\perp$, $V_\parallel$ plane). Then diffusion by whistlers along the diffusive curves is turned on.

According to Ref. 26, the relaxation length for a beam which excites whistlers is

$$l^w = \Lambda \frac{c}{\omega_p} \frac{\omega_H}{\omega_p} \frac{n^c}{n^h},$$

where $\Lambda \approx 25$ in the corona. For $\omega_p \approx 2\pi\cdot 3\cdot 10^6$ $\omega_p/\omega_H = 30$, and $n^c/n^h \approx 10^6$ we obtain $\ell^w \approx 1.35\cdot 10^7$ cm. The relaxation length for a beam which excites Langmuir waves is[26]

$$l^l = \frac{1}{20} \frac{c}{\omega_p} \frac{n^c}{n^h} \frac{m_e}{m_i} \left(\frac{m_e c^2}{T_e}\right)^2 \left(\frac{V}{c}\right)^3.$$

Over a distance ℓ^ℓ the angular spread of the beam reaches $\Delta\theta \approx 1$ and most of its energy is lost. For the above parameters and $V \approx c/3$ we have $\ell^\ell \approx 2.3\cdot 10^9$ cm. Thus, relaxation via whistlers is considerably more rapid and the condition $\Delta\theta_0 > (\ell^w/\ell^\ell)^{1/3}$ on the initial angular spread of the beam, under which relaxation via Langmuir waves is unimportant,[26] is easily satisfied. Even if angular spreading is associated with whistlers, however, the energy relaxation of the beam may be associated with Langmuir oscillations.

During the time in which the precipitating electrons escape from the loss cone,[24] $T_c \approx \ell/2V \approx 0.25$ sec (for a trap length $\ell \approx 5\cdot 10^9$ cm), whistlers at the frequency $\omega^w \approx 0.1\,\omega_H$ travel an interval $\Delta\ell = T_c\cdot V^w_{gr} \approx 1.25\cdot 10^8$ cm at the group velocity $V^w_{gr} \approx 5\cdot 10^8$ cm/sec. Thus, as a result of quasilinear relaxation of a beam via whistlers, the entire trap will be divided into zones of maximum amplification of whistlers, with a thickness ℓ^w, separated by intervals $\Delta\ell$. The oscillations in radio emission intensity along one filament with a period 0.3–0.4 sec, presented in Ref. 10, can be explained entirely by the quasilinear relaxation of a beam via whistlers.

3. SCATTERING, MERGING, AND DECAY OF WHISTLERS

In addition to interacting with fast particles, whistlers can be scattered by thermal ions and electrons,

$$w + i \to w' + i', \quad w + e \to w' + e'.$$

This is induced scattering by the background plasma within an eigenmode. Below we shall show that scattering by electrons plays a major role.

The most efficient merging and decay takes place upon interaction with Langmuir waves,

$l + w \to t$ at the sum frequency $\omega^t = \omega^l + \omega^w$,

$l \to t + w$ at the difference frequency $\omega^t = \omega^l - \omega^w$,

since they produce radio emission that escapes rapidly from the source.

Under the conditions of a nonisothermal plasma, $T_e \gg T_i$, the conservation laws are satisfied for the interaction with low-frequency ion–acoustic waves (ω^s close to ω_H), $w + s \to w'$, within an eigenmode N as the angle between $\bar{k}^w$ and the magnetic field increases to 70-80° (Refs. 28 and 29), and with high-frequency ion–acoustic waves in scattering by ions, $w + i \rightleftarrows s + i'$, although only the reverse process of generation of whistlers by ion-borne sound is efficient.[12]

Under the conditions $T_e \gg T_i$ the main process consists in the interconversion of ion-borne sound into whistlers and back,[12] $s + s' \rightleftarrows w$. Here there is a strong constraint, however, on the angle between k^W and the magnetic field, $\vartheta^W \gtrsim 70°$.

According to Ref. 30, predominant scattering of whistlers by ions occurs only in strong magnetic fields,

$$V_A > V_{T_e}(m_e/m_i)^{1/4} \approx 0{,}15 V_{T_e}. \quad (2)$$

Here V_A and V_{T_e} are the Alfvén and thermal velocities. For the corona it is more convenient to convert this inequality into a condition on the ratio ω_p/ω_H. Since $V_A \approx (c/43)(\omega_H/\omega_p)$, (2) implies that $\omega_p/\omega_H < 12$ for $T_e \approx 10^6$ K, which is reached in deep layers of the corona. There is no limit on scattering by ions over the entire range of existence of whistlers, $\omega_{H_i} \ll \omega^W < \omega_H \cos\vartheta^W$.

Predominant scattering by electrons occurs for the inequality opposite to (2) and with a lower limit on the frequency,

$$\omega^w > \omega_{H_i}\left(\frac{V_{T_e}}{V_A}\right)^2. \quad (3)$$

The right-hand side of (3) will be $\sim 0.155\omega_H$ for $\omega_p/\omega_H \approx 30$ and it will be $\sim 0.068\omega_H$ for $\omega_p/\omega_H \approx 20$ and $T_e \approx 10^6$ H.

Both types of scattering yield a whistler energy spectrum

$$W^w \sim \frac{1}{\sqrt{\omega^w}}.$$

Whereas whistlers become aligned along the field during scattering by ions, however, in scattering by electrons the spectrum is unstable: continuous transfer to larger angles ϑ^W occurs. In the range where $\omega_p/\omega_H > 12$, scattering by ions is possible only at low frequencies, for the relation opposite to inequality (3).

It is important to note that the time of scattering by ions can be short (~ 1 sec) only for high-energy whistlers, $H^W/H_0 \approx 10^{-3}$. Then one instance of scattering with relative frequency change $\Delta\omega^W/\omega^W \ll 1$,

$$\frac{\Delta\omega^w}{\omega^w} \sim \sqrt{\frac{\omega_{H_i}}{\omega^w}}\frac{V_{T_i}}{V_A} = \frac{1}{43}\frac{V_{T_e}}{c}\frac{\omega_p}{\omega_H}\sqrt{\frac{\omega_H}{\omega^w}} \approx 6\cdot 10^{-3}, \quad (4)$$

occurs in a time approximately inverse to the increment,[12]

$$\gamma_{w+i}^{-1} \approx \frac{\Delta\omega^w}{\omega^w}\frac{1}{\omega_{H_i}}\frac{n_e m_i V_A^2}{W^w} = \frac{\Delta\omega^w}{\omega^w}\frac{2}{\omega_{H_i}}\left(\frac{H_0}{H^w}\right)^2 \approx 0{,}02 \text{ sec}. \quad (5)$$

Scattering by electrons occurs faster by a factor $(\omega_H/\omega_{H_i})(V_s/V_A)$ (by a factor ~ 43 for $\omega_p/\omega_H = 30$).

Therefore, at altitudes in the corona where $\omega_p/\omega_H > 12$, whistlers can be tranasferred rapidly to frequencies $\omega^W \approx 0.1\omega_H$ (and simultaneously transferred in angle) in the course of scattering by electrons, after which only scattering by ions can operate. But since the latter is slow, whistlers can propagate far at the groups velocity

$V_{gr}^w \approx 43 V_A$.

Slow scattering by ions is confirmed indirectly by observations of filaments (fiber bursts) in the decimeter wavelength range, since we do not see a decrease in ω^W for ~ 10 sec in the course of a filament. At least this scattering can be completely compensated by an increase in the ratio ω^W/ω^H as the whistlers propagate upward in the corona. In accordance with (4) and (5), in the time $\gamma_{W+i}^{-1} \approx 0.02$ sec it takes to produce a shift of $\Delta\omega^W/\omega^W \approx 6\cdot 10^{-3}$ for $H^W/H_0 \approx 1.8\cdot 10^{-3}$, $f_p/f_H = 10$, and $f_p = 600$ MHz, whistlers are able to travel in altitude by $\sim 0.4\cdot 10^8$ cm at the group velocity $v_{gr}^W = 2\cdot 10^9$ cm/sec (for the frequency $f^W/f_H = 1/4$, at which the increment of conical instability is highest[7]), which corresponds to a chnage in f_H of ~ 0.4 MHz (for grad $f_H \approx 1$ MHz/10^8 cm in the decimeter range[8]), i.e., $\Delta f_H/f_H \approx \Delta\omega^W/\omega^W \approx 6\cdot 10^{-3}$. The decrease in f^W with time in the decimeter range is thereby actually compensated for in each differential scattering event, and the ratio f^W/f_H remains almost constant, ~ 0.25.

The angular dispersal of whistlers via electron scattering helps to satisfy the condition for merging and decay with ion-acoustic waves, $\vartheta^W \gtrsim 70°$. Interaction with LF s waves also results in angular scattering of whistlers (see Fig. 1 in Ref. 28), but the maximum increment of Čerenkov instability for s waves falls at frequencies close to the ion plasma frequency ω_{pi}.

The maximum increments for merging and decay of whistlers and s waves (for ω^S close to ω_{pi}) occur only when their frequencies coincide, which means that ω_H and ω_{pi} approximately coincide (more precisely, $(0.2\text{–}0.25)\,\omega_H \approx \omega_{pi}$). Just such a relation is satisfied in the solar corona. The approximate behavior of the main plasma frequencies in the corona is shown in Fig. 1. It is seen that the $0.25f_H$ curve intersects the $f_{pi} = \omega_{pi}/2\pi$ curve in the vicinity of $f_p \approx 300$ MHz, so this level is the middle of the range where rapid conversion of whistlers into ion-acoustic waves and back can occur ($s + s' \rightleftarrows w$). This region is hatched in Fig. 1.

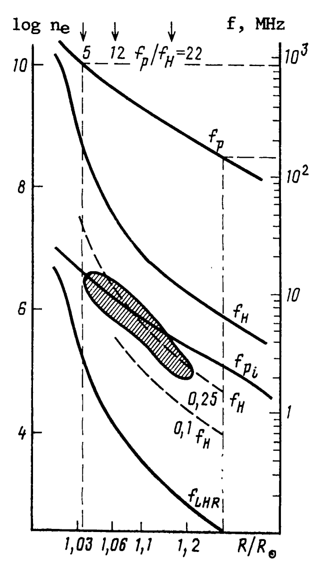

FIG. 1. Variation of characteristic frequencies with distance R in the corona (from the center of the sun in solar radii $R_\odot$): electron (plasma f_p and cyclotron f_H) frequencies and the corresponding ion frequencies (f_{p_i} and f_{H_i}) and the frequency f_{LHR} of lower hybrid resonance. The mechanism of one-second pulses from whistlers is most efficient in the hatched region (around the intersection of the f_{p_i} and $\sim 0.25f_H$ curves).

The interaction $s + s' \rightleftarrows w$ has been discussed theoretically and observed experimentally.[12,31,32] In Ref. 31 it was shown that this interaction should proceed with fixed phases, since the frequencies of the s waves and whistlers are commensurable. Moreover, the spectrum of s waves is assumed not to decay (processes $s \to s' + s''$ are absent), so the main role in forming the ion-acoustic spectra is played by induced differential scattering by ions, which is predominantly angular scattering ($\Delta k^2/k^S \ll 1$).[33] The scattering of whistlers by ions also has the differential nature of slow frequency transfer, but only angular transfer occurs in scattering by electrons. All these facts justify the assumption that the interaction occurs with fixed phases. The actual angular distribution of energy density of s waves oscillates in the Čerenkov cone from $\vartheta^S \approx 0$ to $\vartheta^S \approx \cos^{-1}\frac{v_s}{v_d}$ (Ref. 34). Then for an electron drift velocity $v_d \approx 5v_s$ we have $\vartheta^S \lesssim 80°$. Thus, the ocnditions are created for a completely reversible pulsed process.

4. MANIFESTATIONS OF LF WAVES IN RADIO EMISSION. ONE-SECOND PULSES

In the pulsed regime of energy transfer between whistlers and s waves the combining mechanism $\ell + w \to t$, which yields pulses of radio emission in a wide frequency range, is turned on at times of maxima of W^W. As a result of decay processes, a flat spectrum $W^W \approx$ const (with respect to frequency and angle) is established for whistlers, so the absorption bands typical of filaments and the zebra pattern will be washed out, and we should observe brief wideband pulses with a period that depends on W^W (~0.01-1 sec).

The source of the pulses may consist of a region of reconnection of high coronal loops containing a neutral point of the X type. Even in an initially isothermal plasma in the reconnection region, ion-acoustic waves with a large increment,[33,35]

$$\gamma^s \approx \omega^s \sqrt{\frac{\pi}{8}\frac{m_e}{m_i}}\left(\frac{v_d}{v_s}\cos\vartheta^s - 1\right),$$

are excited by the Čerenkov mechanism between the fronts of fast shock waves (moving upward and downward) due to electron drift v_d relative to ions in the electric field of the current sheet. Ion-acoustic instability changes smoothly into Buneman instability for $v_d > v_{T_e}$, maintaining nonisothermicity $T_e \gg T_i$ in the reconnection region.[31,35] The heating occurs simultaneously over a wide altitude range between shock wave fronts. The conservation laws for the processes $s + s' \rightleftarrows w$ and $1 + w \to t$ can be satisfied simultaneously over the entire reconnection region, generally speaking, only after the spectra of s waves and whistlers become isotropic due to scattering, since $\bar{k}^S \perp \bar{H}_0$ for the wave vectors of generation of s waves (along the electric field), while $\bar{k}^W \parallel \bar{H}_0$ for the whistlers. The process $s + s' \to w$ can proceed at both the sum and the difference frequencies, $\omega^S \pm \omega^{S'} = \omega^W$ (i.e., at frequencies $\sim 2\omega_{p_i}$ and $< \omega_{p_i}$), as confirmed experimentally.[32] For merging, $\omega^S + \omega^{S'} = \omega^W$, the wave vectors k^S and $k^{S'}$ must be opposed (by analogy with the process $\ell + \ell' \to t$), and for the frequency $\omega^S - \omega^{S'} = \omega^W$ they must be in the same direction at a small angle to one another, since $k^W \ll k^S$.

We found earlier that high in the corona whistlers should be scattered by electrons and s waves should be scattered predominantly by ions,[12,33] the process $s + i \to s'$ being very fast,

$$\gamma_{s+i} \simeq \omega^s \frac{W^s}{n_e T_e}\frac{k^s}{\Delta k^s}\frac{T_i}{T_e} \approx \omega^s.$$

Therefore, vectors k^S are instantly flipped over to $-k^S$, and the combining process $s + s' \to w$ at the sum frequency $\omega^S - \omega^{S'} = \omega^W \approx (0.1\text{-}0.5)\omega_{pi} \approx$ (0.02- in parallel with th eprocess at the difference frequency. But high in the corona $\omega_{p_i} \approx \omega_H/4$ and these whistlers should have a frequency $\omega^W \approx 0.5\omega_H$ and undergo strong cyclotron damping.[7] At the altitudes of the m range, therefore, the whistler spectrum due to ion-acoustic turbulence will be associated with the process at the difference frequency $\omega^S - \omega^{S'} = \omega^W \approx (0.1\text{-}0.5)\omega_{p_i} \approx (0.02\text{-}0.12)\omega_H$.

This process is also very fast. In the laboratory experiment of Ref. 32 whistlers at the frequencies ω_{p_i} and $2\omega_{pi}$ appears $\sim$0.2 μsec after the excitation of s waves by a direct discharge current. The slowest process will be overall scattering of whistlers by electrons, in the course of which the whistler spectrum becomes isotropic. Since scattering by electrons is slower than scattering by ions by a factor $(\omega_H/\omega_{H_i})(v_s/V_A)^4$, for a whistler power $W^W/nT \approx 2.5 \cdot 10^{-6}$ and $f_p/f_H \approx 30$ we obtain $\gamma_{w+e}^{-1} \approx 0.4$ sec from (5) for the time of scattering by electrons.

After this time, the emission of pulses $\ell + w \to$ of very short duration

$$\gamma_{l+w}^{-1} \sim \beta_{lw}\frac{W^l}{k} \approx 10^{-3}\text{—}10^{-4} \tag{6}$$

is turned on for $W^t \approx W^W$ and $W^\ell \approx 10^{-5}$ erg/cm³, where $\beta_{\ell W}$ is the combining coefficient.[35] The radio emission is subsequently damped in collisions: $\nu_{ei}^{-1} \approx 10^{-2}$ sec. Thus, the duration of a pulse will be comprised of the processes

$$\gamma_{l+w}^{-1} + \nu_{ei}^{-1}.$$

After the escape of whistlers at the group velocity and in the processes $w \to s + s'$ and $\ell + w \to t$, the spectrum of W^W recovers again after a time (period T)

$$\gamma_{s+i}^{-1} + \gamma_{s+s'}^{-1} + \gamma_{w+e}^{-1} \approx 0{,}1\text{—}0{,}4 \text{ sec},$$

depending on the power of the whistlers and the ion-acoustic waves.

All these nonlinear processes are accelerated with an increase in W^S and W^W, and if $T > \nu_{ei}^{-1}$ then the period will decrease with increasing W^W (i.e., with increasing pulse intensity and modulation depth), regardless of the level W^ℓ of the plasma waves (i.e., the continuum level W_c^t). For high levels W^W, when $T < \nu_{ei}^{-1}$, the pulse modulation depth $\Delta W/W$ will decrease sharply with decreasing period due to the coalescence of individual pulses, when intermittence disappears. Therefore, the dependence of $\Delta W/W$ on period T should typically have a maximum at $T \approx \nu_{ei}^{-1}$.

If one series of pulses is associated with one fast reconnection event, then the duration of the series should be determined by the isothermalization time[12] $\tau_{T_e \sim T_i} \sim \left(3\frac{m_e}{m_i}\nu_{ei}\right)^{-1} \approx 12$ sec, during which the power level of the whistlers will gradually decrease (i.e., the period will increase). One series may contain up to 100 pulses or more with a large modulation depth (a high Q-factor).

The rate of rise of whistler power in the process $s + s' \to w$,

$$\frac{\partial W^w}{\partial t} \sim \left(\frac{V_{T_e}}{c}\right)^3 \omega_{p_i} \left(\frac{\omega_{p_i}}{\omega_H}\right)^3 \frac{W^{s2}}{n_e m_i V_A^2} \tag{7}$$

(see 4.299 in Ref. 12), increases with ω_{p_i}/ω_H, so the efficiency of this process increases with altitude in the corona, i.e., it favors pulses in the m range (the lower part of the hatched region in Fig. 1). If electron heating ($T_e \gg T_i$) in the reconnection region occurs locally in small discrete volumes, then discrete spike bursts, spread out over the range, which often accompany one-second pulses in type IV bursts, as is well known, should appear instead of pulses.

For an accurate determination of the whistler-induced pulse modulation depth, we use a steady-state scheme of formation of stripes in emission and absorption in the $\ell + w \to t$ model with whistlers,[8] with allowance for the fact that absorption in pulses should be washed out because of the wide spectrum of the whistlers. The continuous emission W_c^t is, as usual, the result of induced scattering of ℓ waves by thermal ions, and the modulation depth $\Delta W/W_c{}^t = (W - W_c)/W_c{}^t$ will be determined by the relative efficiencies of the two processes, expressed in terms of the ratio of the coefficients of combining $\beta_{\ell w}$ and differential transfer α_{1+i} (Ref. 35) and the ratio r of rates of rise of the radio emission in these processes. The estimate of the relative intensity of the maxima in the pulses (in units of the continuum level) will have the form

$$W \approx 1 + \frac{\beta_{lw}}{\alpha_{l+i}} \frac{W^w}{W_c{}^t} \frac{r}{1+r} \int_{L_f}^{L_w} e^{-(h/L)^2} dh, \tag{8}$$

where the integral is used to sum the radiation at a fixed frequency f which escapes from a finite range of altitudes L (in which radiation falls normally from the altitude h, $W^\ell \propto \exp(-(h/L)^2)$, in the range from the lower boundary L_f to the upper boundary L_w (in units of L) of the whistler wave packet).

The ratio r of rates increases with decreasing isothermicity, since $\partial W^t/\partial W^w/\partial t \propto V_{T_e}^3 W^s$ in the process $\ell + w \to t$ and $\partial W^t/\partial t \propto V_{T_e}^{-4}$ in the process $\ell + i \to t$ (Ref. 36). Then for r = 1 and an energy density $W^w \approx 10^{-6} n_e T_e$ (attained in the experiment of Ref. 32) we obtain a period $T \approx 0.4$ sec from (5), and after calculating the intensity of radio emission (see Ref. 8) we estimate the modulation depth to be $\Delta W/W_c^t \approx 0.46$. In Fig. 2 we show the modulation depth as a function of period, calculated for several values of W^w under the conditions r = 1 and 2, $T_e \approx 10^6$ K and $3 \cdot 10^6$ K, and $f_p/f_H \approx 30$. The presence of a maximum in the dependence of $\Delta W/W_c$ on T at the value $T \propto \nu_{ei}^{-1}$ is the main indicator for the model of pulses from whistlers. The number of electron–ion collisions decreases with increasing T_e (approximately as[37] $\sim T_e^{-3/2}$), so a shift in the maximum with time provides information about the variation of T_e in the source. With a decrease in f_p/f_H to 20, the values of $W^w/n_e T_e$ increase by about a factor of five. The amplitude of the pulses increases sharply with increasing r. Then strong pulses should be observed even against a weak continuum. The sharp maximum may also be smoothed out if W^w does not exceed 10^{-6} $n_e T_e$. If a filament is superposed on the pulses, then the modulation depth should increase due to the contribution of LF absorption. All these features are well known from observations.

The nonlinear oscillatory regime of conical instability, discussed in Ref. 38 for microwave pulses, can also yield weak meter-wave pulses. The period of such plasma oscillations, $T \approx 2\pi/\nu_{ei}$, increases with increasing modulation depth and with the development of instability it also increases with intensity.

Pulses in the model of MHD oscillations of coronal traps with fast magnetosonic (FMS) waves in bounce resonance[25,39] have relatively long periods ($\gtrsim$1 sec), determined only by the size of the magnetic trap, and a small modulation depth, proportional to the magnetic field oscillations in the FMS wave, $\Delta W/W \propto \Delta B/B$ ($\Delta B \ll B$).

Pulses in radiation are often accompanied by sudden-reduction (SR) oscillations of the continuum with relatively long ($\gtrsim$1 sec) and irregular periods. Sudden reductions are caused by the cutoff of conical instability of plasma waves as a result of the injection of new particles into the loss cone. The qualitative location of th epossible values of $\Delta W/W(T)$ in the plasma (pl) and MHD models of pulsations and reductions of the SR type is also shown in Fig. 2. It may be seen that these values actually do not overlap with the values for pulses from whistlers, which makes it possible to determine the mechanism of pulses by constructing functions like those presented in Fig. 2 from observations.

5. FILAMENTS AND ZEBRA PATTERN

It is well known that filaments are observed predominantly in the decimeter range and the zebra pattern in the meter range (at <300 MHz). In the context of the $\ell + w \to t$ mechanism and on the basis of the foregoing, it is possible that filaments are associated with the propagation, channeled along

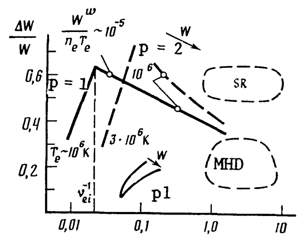

FIG. 2. Calculation of the modulation depth ($\Delta W/W$) of radio emission as a function of the pulse period T in the model based on whistlers whose level is maintained by ion-acoustic turbulence. Whistler energy densities $W^w/n_e T_e \approx 10^{-5}$-$10^{-7}$, $f_p/f_H = 30$, $T_e \approx (1\text{-}3)\cdot 10^6$ K, and ratios of rates of rise of radio emission $r = (\partial W^t/\partial t)_{\ell+\omega\to t}/(\partial W^t/\partial t)_{\ell+i\to t} = 1$ and 2 were used. The approximate domains of the pulse parameters in the models of MHD oscillations, plasma oscillations of conical instability (pl), and sudden reductions (SR) are also shown qualitatively.

the field, of whistlers that are generated by means of the normal Doppler effect at the base of a magnetic trap and propagate up to the level of cyclotron damping.[24]

A number of features of the emission of filaments were analyzed in Ref. 40. One of the most important results of this analysis is the correct determination of the magnetic field strength in the source from the frequency separation between the maxima in emission and LF absorption, $\Delta f_{ea} \approx f^W$, under the assumption that $f^W \approx 0.25 f_H$ in the decimeter range and $f^W \approx 0.1 f_H$ in the meter range. Constancy of the whistler frequency in the meter-range is provided by transfer to this frequency in scattering by electrons; whistler scattering by ions, which proceeds considerably more slowly, predominates in the decimeter range, so the frequency transfer in each scattering event can be compensated by the decrease in f_H with altitude in the corona.

The model of the zebra pattern based on whistlers[8,41] avoids the main defect of many other models, in which excitation of either parallel stripes or a continuum without stripes is provided for, whereas it is manifested as modulation of the continuum.

In the upper parts of a trap, whistlers are excited predominantly via the anomalous Doppler effect at an angle to the magnetic field in a quasi-linear regime.[19] Then discrete wave packets of whistlers will propagate unchanneled and yield a series of zebra stripes with varied frequency drift (whistlers can be reflected at the lower hybrid resonance).

In the zebra-pattern model based on Bernstein modes there is some difficulty in determining the magnetic field strength using the obvious approximate equality of the frequency separation between stripes to the electron gyrofrequency,[11] $\Delta f \approx f_H$: these values do not display the strict dependence on frequency (or altitude in the corona) characteristic of filaments (and of the model of the field in the corona in general).[42] Even when zebra stripes are equidistant, the estimates of the field are found to be too low and not consistent with the model which is determined from the aggregate of other radio data.[43]

In the mechanism of the zebra pattern based on whistlers,[8] the magnetic field is determined from the frequency separation between a stripe in emission and a stripe in absorption on the LF edge, Δf_{ea}, which is approximately equal to the whistler frequency, $\Delta f_{ea} \approx f^W$.

In the atlas of Ref. 42, the value of Δf_{ea} cannot be determined even roughly because of frequency gaps between the channels. In high-resolution dynamic spectra of Ref. 8 the quantity Δf_{ea} behaves far more stably than the frequency separation between stripes in emission. With allowance for peculiarities in the determination of the magnetic field from Δf_{ea} in Ref. 40 (where $f^W \approx 0.1 f_H$ in the meter-wave range (<300 MHz) is assumed due to differential transfer of whistlers by electrons), this method yields field strengths that are close to those determined from filaments in Ref. 40.

The model of the zebra pattern based on whistlers corresponds to the well-known predominant appearance of the zebra pattern only in the meter-wave range ($f \lesssim 300$ MHz), whereas filaments are observed mainly in the decimeter range. This limit agrees approximately with th elevel in the corona where scattering of whistlers by electrons starts to predominate ($f_p/f_H > 12$). The angular transfer of whistlers by electrons facilitates the unchanneled propagation at large angles to the magnetic field with multiple reflections. In the process, the whistler frequency varies smoothly together with f_H, and this accounts for the fairly stable behavior of Δf_{ea} over the course of a zebra-pattern series. The rate of angular transfer can differ greatly at different levels, and this explains the fairly random appearance of the stripes of the zebra pattern with respect to frequency.

The group spreading of whistlers which is typical of the spectra of magnetospheric whistlers is hardly seen under solar conditions, since the bandwidth of whistler instability is very narrow (sharp maxima of increments as a function of frequency[7,40]).[1)]

Extending the comparison of this model with the mechanism based on double plasma resonance, we also note that, according to Ref. 14, Fig. 12, instability of plasma waves at the top of a magnetic loop should yield continuous emission, and at the base of a loop (i.e., in the decimeter range) it should yield stripes of the zebra pattern. This is inconsistent, however, with the predominant appearance of the zebra pattern in the meter-wave range.

6. UNUSUAL FILAMENTS

In powerful events, amid the zebra pattern and the ordinary filaments with intermediate drift, one sometimes observes unusual wide-band filaments in emission, distinguished mainly by slow random frequency drift.[42,44] The unusual drift indicates the propagation of some disturbance with a slow velocity in a trap almost along the direction grad f_p. Such a disturbance might be an Alfvén soliton in which whistlers are trapped. This model has been considered in Ref. 10, for example. As before, the emission is the result of the combining mechanism $\ell + w \rightarrow t$.

It is well known that small-scale Alfvén waves are excited in a trap by fast protons at the cyclotron resonance.[45,46] The Alfvén waves themselves cannot trap whistlers, however, since the amplitude of the magnetic field variation in them is low, $|\delta B| \ll B$, and the plasma density doe snot vary sufficiently. But they can form solitions, which propagate as solitary disturbances of field and density at an angle to the magnetic field with velocities close to V_A. The broad emission band of unusual filaments ($\gtrsim 3$ MHz) is determined by the size of the Alfvén solition: according to estimates in Ref. 10, these are inhomogeneities which extend 10^8-10^9 cm along the field and have a transverse size $(1\text{-}10)\cdot 10^5$ cm.

7. CONCLUSION

The above analysis shows that many LF waves that are generated in a magnetic trap on the sun are manifested in type IV radio emission. Whistlers play a major role in the formation of fine structure. The type of structure depends on the nature of the formation of the whistler spectrum: millisecond pulses are associated with dynamic energy transfer between s waves and whistlers; the strongest pulses will be the briefest. Filaments are associated with the excitation of whistlers in the interior of the trap based on the normal Doppler effect; the zebra pattern is associated with the excitation of whistlers in the upper part of the trap based on the anomalous Doppler effect with unchanneled propagation.

Plasma oscillations of conical instability can produce brief weak pulses ($T \approx 2\pi/\nu_{ei}$), but the strongest pulses must have longer periods. The FMS waves excited in the trap by fast protons in bounce resonance result in one-second pulses (MHD model) with a small depth of modulation. The dependence of the depth of modulation and intensity of the pulses on their period thereby enables one to distinguish pulses due to whistlers from other models.

Solitons of Alfvén waves, excited in a trap by protons in cyclotron resonance, are manifested in slowly drifting filaments in emission.

Ion cyclotron waves, which result only in angular scattering of whistlers, can also be excited in a magnetic trap.[20,47]

Whistlers can be excited by escaping electrons at the top of a trap, where the condition $V/c > \omega_{He}/\omega_{pe}$ is satisfied most easily.[48]

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1)The widening of the spectrum in the decimeter range turns out to be symmetric about v^{w}_{gr}.

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