Microstructure in continuous emission of type IV meter bursts. Modulation of continuous emission by wave packets of whistlers

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The dynamic spectra of the microstructure in emission and absorption in the event of July 3, 1974 and a possible model of the emission source were discussed in the first part of the report {G. P. Chernov, Astron. Zh. **53**, 798 (1976) [Sov. Astron. **20**, 499 (1976)]}. In the second part the emission of this microstructure is interpreted as the nonlinear interaction of Langmuir oscillations with wave packets of whistlers. The possibility of the generation of packets of whistlers and their reflection at the lower hybrid frequency during propagation in a source of the magnetic trap type is discussed. A band of enhanced emission is formed in the confluence at sum frequencies, while the emission is suppressed at frequencies encompassed by the whistlers. In this case the radiation must be strongly polarized and of the ordinary type. Frequency profiles of the bands in emission and absorption are calculated which agree with the observed profiles.

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I. INTRODUCTION

In ref. 1 the complex microstructure with absorption in the event of July 3, 1974 was examined and it was compared with structures of the "zebra" type observed in other events. It was also noted that the known mechanisms of generation cannot explain the unsteady nature of the bands in emission and absorption (irregular variations in time and in frequency). A model was proposed for the steady type IV source: a magnetic field tube filled with wave packets of whistlers, which can give rise to the diverse modulation of the continuous emission.

The possibility of such modulation with allowance for the conditions of escape of the radio radiation from the corona in the process of interaction of whistlers with Langmuir waves is demonstrated in the present article.

The characteristics of the propagation of whistlers in the sources of type IV bursts are discussed in Sec. II and the interaction of whistlers with Langmuir waves (conditions of resonance, formation of frequency profiles of bands in emission and absorption, polarization, and the role of other effects) in Sec. III. The effect of the conditions of escape of radio radiation on the formation of the frequency profiles of bands in emission and absorption has not been examined at all before. Moreover, it does not contradict the results of ref. 2, in which filaments with intermediate frequency drift (fiber bursts) are interpreted as the confluence of whistlers with longitudinal waves.[1)]

II. PROPAGATION OF WAVE PACKET OF WHISTLERS IN THE CORONA

1. Index of refraction. It is known that whistlers (howls, spiral waves, or helicons) are almost transverse waves which carry their energy predominantly along the magnetic field in both directions. The rotation of the electric vector of a whistler corresponds to the extraordinary wave (e) (some renaming of the waves is allowed for oblique propagation[3]). In contrast to other low-frequency waves, whistlers are purely electron oscillations and can propagate in a plasma with a high enough density, i.e., when the whistler frequency $\omega = 2\pi f \ll \omega_{Pe}$ – the electron plasma frequency. The expression for the index of refraction in the quasilongitudinal approximation of the propagation of whistlers, following the formalism of refs. 4 and 5, will be

$$\mu^2=\frac{k^2c^2}{\omega^2}=\frac{\omega_{Pe}^2}{\omega^2}\frac{\omega}{\omega_{He}}\frac{1}{\cos\theta-(\delta\omega/\omega_{He})(1+\omega_{He}^2/\omega_{Pe}^2)} \quad (1)$$

where $\delta = 1-\omega_{LHR}^2/\omega^2$, θ is the angle between the wave normal and the direction of the magnetic field, ω_{LHR} is the frequency of the lower hybrid resonance

$$\omega_{LHR}^2=\frac{\omega_{He}}{M}\frac{\omega_{He}^2/M+\omega_{Pe}^2}{\omega_{He}^2+\omega_{Pe}^2}, \quad (2)$$

M is the ratio of the proton (i) and electron (e) masses, ω_{He} is the electron gyrofrequency, k is the wave number, and c is the velocity of light.

Under the conditions of the middle corona, as for the earth's magnetosphere, $\omega_{Pe}^2 \gg \omega_{He}^2 \gg \omega_{He}^2/M$ and (2) is simplified: $\omega_{LHR} \approx \omega_{He}/\sqrt{M} \approx \omega_{He}/43$. The variation in the frequency $f_{LHR} = \omega_{LHR}/2\pi$ with height in the corona is shown in Fig. 10 in ref. 1.

The frequency ω_{LHR} is the resonance frequency in the case of $\delta \approx 0$; when θ approaches $\pi/2$ then $\omega \approx \omega_{LHR}$ and $\mu \to \infty$.

For quasilongitudinal propagation at frequencies $\omega \gg \omega_{LHR}$ we have $\delta \approx 1$ and the dispersion relation is simplified[5]:

$$\omega=\omega_{He}k^2c^2\cos\theta/(\omega_{Pe}^2+k^2c^2). \quad (3)$$

The location of the whistler branch (w) among all the dispersion curves[6,7] is shown in Fig. 1. The coordinates along the axes of frequency and wave number are set up for the frequency $\omega_{Pe} = 2\pi \cdot 200$ MHz and the typical parameters of the coronal plasma: electron thermal velocity $V_{Te} = 5\cdot10^8$ cm/sec ($T_e = 10^6$ °K) and $\omega_{Pe}/\omega_{He} \approx 20$, i.e., $\omega_{He} \approx 2\omega_{Pi}$.

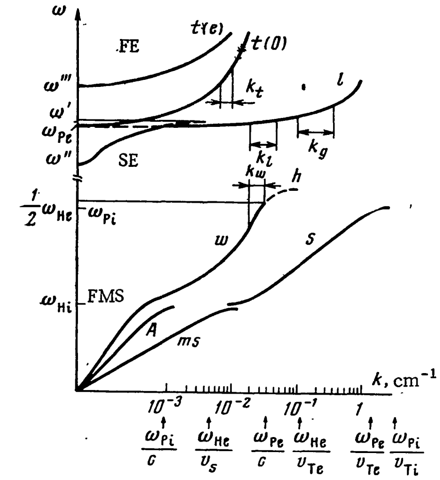

Fig. 1. Qualitative behavior of dispersion curves of waves in coronal plasma: $\omega_{Pe}/\omega_{He} \approx 20$, $\omega_{He} \approx 2\omega_{Pi}$, $V_{Te} \approx 5 \cdot 10^8$ cm/sec; t(e): fast extraordinary wave (FE); t(0): ordinary wave; SE: slow ordinary wave; l: longitudinal plasmons; h: gyrofrequency plasmons; w: whistlers; FMS: fast magnetosonic waves; A: Alfvén waves; s: ion-sonic waves; ms: slow magnetosonic waves; $\omega' = \omega_{Pe} + \frac{1}{2}\frac{\omega_{He}^2}{\omega_{Pe}}\sin^2\theta$; $\omega'' = \omega_{Pe} - \frac{1}{2}\omega_{He}$; $\omega''' = \omega_{Pe} + \frac{1}{2}\omega_{He}$ (refs. 6 and 7).

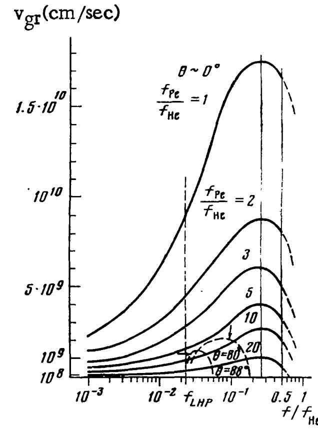

Fig. 2. Group velocity of whistlers in quasilongitudinal propagation for values of ratio ω_{Pe}/ω_{He} = 1-20 as a function of the relative frequency f/f_{He} of the whistlers. The qualitative decrease in v_{gr} for angles $\theta \approx \pi/2$ (ref. 5, Fig. B1) is shown by a dashed line.

The index of refraction assumes high values ($\mu \gg 1$) along the entire branch of the whistling wave, which is the high-frequency extension of the fast magnetosonic wave.[7] The analysis of just the high-frequency whistlers ($\omega_{He} > \omega \gg \omega_{Hi}$) excites the greatest interest, since the Cerenkov damping of whistlers is exponentially small at these frequencies (ref. 7, Sec. 5.4) and they can propagate in a dense plasma without appreciable absorption. Collisional damping is also small since the whistler frequency $\omega \gg \nu_{ef}$ – the effective frequency of collisions in the fully ionized coronal plasma. The whistler branch is not altered in the transition from a cold plasma to a plasma with hot electrons, with no other branches existing at these frequencies except whistlers and rapidly damped ion-sonic oscillations (ref. 7, Sec. 5.5).

2. Group velocity and reflection of whistlers. It is known that in the quasilongitudinal case the effect of the protons is not important, and a simplified equation is obtained for the group velocity of whistlers[5]:

$$v_{gr} = 2c\sqrt{f(f_{He} - f)^3}/f_{Pe}f_{He}. \quad (4)$$

The values of v_{gr} calculated from Eq. (4) for the values of the parameter $f_{Pe}/f_{He} \approx$ 1-20 realized in the solar corona are plotted in Fig. 2.

The maximum of the group velocity varies from $\sim 10^9$ cm/sec at middle heights in the corona to $1.6 \cdot 10^{10}$ cm/sec in deep layers of the corona. The qualitative decrease in v_{gr} for large angles θ is shown by a dashed line. The frequency $f_{LHR} \approx f_{He}/43$ of the lower hybrid resonance is marked by a vertical dashed line. If conditions for the propagation of a wide-band packet of whistlers were realized in the corona then the dispersion of v_{gr} would lead to its spreading out into almost the entire magnetic trap. However, the isolated position of magnetospheric whistlers at frequencies $f \approx (0.3\text{-}0.5)f_{He}$ allows one to consider the wave packet as more monochromatic, with a confinement to frequencies at which the group velocity is maximal.

The trajectories of the magnetospheric whistling waves are determined by the configuration of the magnetic field lines.[8] The monotonic variation in the characteristics of the magnetospheric plasma leads to an increase in the angle θ. In the quasi-transverse case the effect of the protons comes down to the fact that the index of refraction does not go to infinity, thanks to which at a frequency $f \approx f_{LHR}$ in a very narrow height range the group velocity reverses direction with insignificant damping of the wave packet.[5] This is a linear refraction effect described by Snell's law. But other processes can interfere with the reflection of whistlers: self-focusing of the waves, nonlinear confluence of whistlers with one another, and interactions producing low-frequency plasma turbulence and plasma heating.[9]

Probably, analogous behavior of whistlers should also be characteristic of magnetic traps in the solar corona. Since a time of ~15-20 sec is needed for a wave packet excited at the top of the magnetic trap with a maximum v_{gr} of $\sim 10^9$ cm/sec to reach the level where the whistler frequency f is $\sim f_{LHR}$, the reflection of such a packet becomes unlikely. In a much shorter time, owing to decay processes and the resonance interaction with plasma particles, the wave packet either is "eroded" entirely (in a stable plasma), or, conversely, is spread out and modulated in amplitude (in an unstable plasma).[10] The latter fact is very important for an analysis of the interaction of whistlers with longitudinal waves in the sources of type IV bursts.

3. Excitation of whistlers in the corona. It is knwon that during complex radio bursts of types II–IV a nonisothermal plasma with a considerable excess of the electron temperature above the ion temperature ($T_e/T_i \approx$ 4-6) always forms in a steady type IV source,[11] which leads to the generation of ion-sonic waves. There are also many other mechanisms for the excitation of ion-sonic turbulence: excitation by strong electric currents or magnetic field gradients, through processes of decay

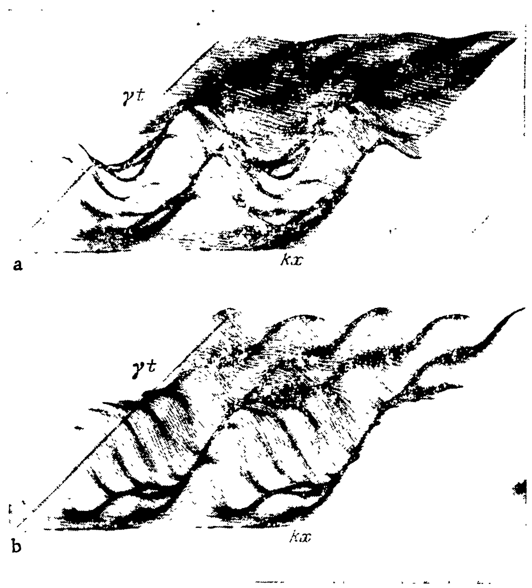

Fig. 3. Amplitude of field of whistlers under conditions of driving of a hose or mirror-machine instability within the limits of the coordinates of $\gamma t \approx 0$-11.1 and $kx \approx 0$-4π; γ: linear increment; k: wave number.[13]

into Langmuir turbulence.[6] The frequencies of ion-sonic waves and whistlers coincide (Fig. 1) and therefore when ion-sonic waves are scattered on thermal ions and electrons their energy is transferred to whistlers.

Whistlers are also generated directly in the presence of electrons escaping along a magnetic field.[12] The condition of instability requires the presence of fast electrons with velocities $V_{\|}$ parallel to the magnetic field determined by the weak inequality $V_{\|}/c > \omega_{He}/\omega_{Pe}$. The lowest instability threshold is realized at the top of the magnetic arc, where $\omega_{He}/\omega_{Pe} \approx 1/20$. The increment of this instability becomes negative only for strict longitudinal propagation.[2)]

The generation of whistlers by anisotropic instabilities has been analyzed theoretically in ref. 13 for a collisionless electron plasma in a magnetic field. The numerical solution of the Vlasov–Maxwell equations for weak perturbations of the wave field for hose and mirror-machine instabilities reveals the absolute instability of whistlers in both cases for a large enough temperature anisotropy. The amplitude of the wave field with oblique propagation of whistlers in the plane [γt; kx] within the limits of the coordinates ~ [0; 4π] under the conditions of driving (γ is the linear increment) is shown in Fig. 3 (Fig. 2 in ref. 13). With driving the wave field has the form of sporadic irregular oscillations. The wave amplitude dies out instantaneously with the transfer of energy from waves with small k to waves with larger wave vectors. Analogous oscillations of the magnetic energy of whistlers with time are obtained in ref. 14 by numerical modeling of the behavior of whistlers in an unstable plasma.

High-frequency whistlers should be excited most efficiently, since the growth increments of the waves increase with an increase in frequency (ref. 7, Sec. 6.2). According to observations of magnetospheric whistlers,[8] their upper limiting frequency, connected with the conditions of generation, is ($f \approx (0.4$–$0.5)f_{He\,min}$, where $f_{He\,min}$ is the minimum gyrofrequency along the trajectory. Trigger emissions are excited by whistlers and the maximum interaction of the waves with each other and with plasma particles occurs at the same frequency. The lower limiting frequency must be determined by the local frequency of the lower hybrid resonance.[5,15]

III. INTERACTION OF WHISTLERS WITH LANGMUIR WAVES

1. Conditions of resonance and increment. First of all we note that Langmuir oscillations can be efficiently transformed into electromagnetic radiation in the process of induced scattering on ions, with which we will henceforth connect the generation of the continuous radio radiation.[2] In this case the Langmuir wave vectors are aligned along the external magnetic field (ref. 6, Sec. 8). It is also known that the wave numbers of the Langmuir waves k_l and the whistlers k_w are quantities of the same order of magnitude and are both $\gg k_t$ – the wave numbers of the electromagnetic waves (Fig. 1). One can therefore assume that with the wave vectors $\bar{k}_l$ and $\bar{k}_w$ directed along the magnetic field the conditions of resonance for confluence (l + w → t) and decay (l → t + w) are satisfied for these three waves. In order to find the limits on the magnitudes of the interacting wave vectors, we substitute into the first resonance equation $\bar{k}_l \pm \bar{k}_w = \bar{k}_t$ their values from the respective dispersion equations for whistlers, Langmuir waves, and high-frequency transverse waves:

$$k_w = \frac{\omega_{Pe}}{c}\left(\frac{\omega_{He}}{\omega_w} - 1\right)^{-1/2}; \tag{5a}$$

$$k_l = \left[\frac{2}{3}\frac{\omega_{Pe}}{V_{Te}^2}(\omega_l - \omega_{Pe})\right]^{1/2}; \tag{5b}$$

$$k_t = \left[\frac{2\omega_{Pe}}{c^2}(\omega_t - \omega_{Pe})\right]^{1/2}. \tag{5c}$$

After uncomplicated simplifications we find the ratio ω_l/ω_{Pe} of the frequency of the longitudinal plasmons to the local plasma frequency for the conditions typical in the middle corona: $V_{Te} = 5 \cdot 10^8$ cm/sec and $\omega_{Pe}/\omega_{He} = 20$ for $\omega_{Pe} = 4\pi \cdot 10^8$ Hz, taking the whistler frequency $\omega_w = 0.4\omega_{He}$ corresponding to the wave number $k_w = 3.4 \cdot 10^{-2}$ cm^{-1}. We obtain the value $\omega_l/\omega_{Pe} = 1 + 4.5 \cdot 10^{-4}$, the second term of which represents the thermal correction to the plasma frequency, equal to $(3/2)(V_{Te}^2 k_l^2/\omega_{Pe}^2)$. From this we obtain the required value of the wave number $k_l \approx 4.3 \cdot 10^{-2}$ cm^{-1} for longitudinal waves, which corresponds to a phase velocity $V_{ph} = \omega_{Pe}/k_l = 4\pi \cdot 10^8/(4.3 \cdot 10^{-2}) \approx 2.9 \cdot 10^{10}$ cm/sec for the wave. Even higher phase velocities of the longitudinal waves are required with a decrease in the frequency of the whistlers. Thus, for $\omega_w = 0.3\omega_{He}$, i.e., $k_w = 2.8 \cdot 10^{-2}$ cm^{-1} with $k_l < k_w$, we find $k_l \approx 1.8 \cdot 10^{-2}$ cm^{-1}, which corresponds to $V_{ph} \approx 6.9 \cdot 10^{10}$ cm/sec. The values of the wave numbers found are marked by arrows on the corresponding dispersion curves in Fig. 1. The branch of plasma oscillations in the region of wave numbers $k_l \approx 1.8 \cdot 10^{-2}$ cm^{-1} approaches the branch of slow extraordinary waves.

Thus, longitudinal waves having wave numbers equal to the wave numbers of generation k_g (i.e., with $V_{ph} = V$ – the velocities of fast particles) still cannot enter into interaction with whistlers. But an interaction becomes possible in the

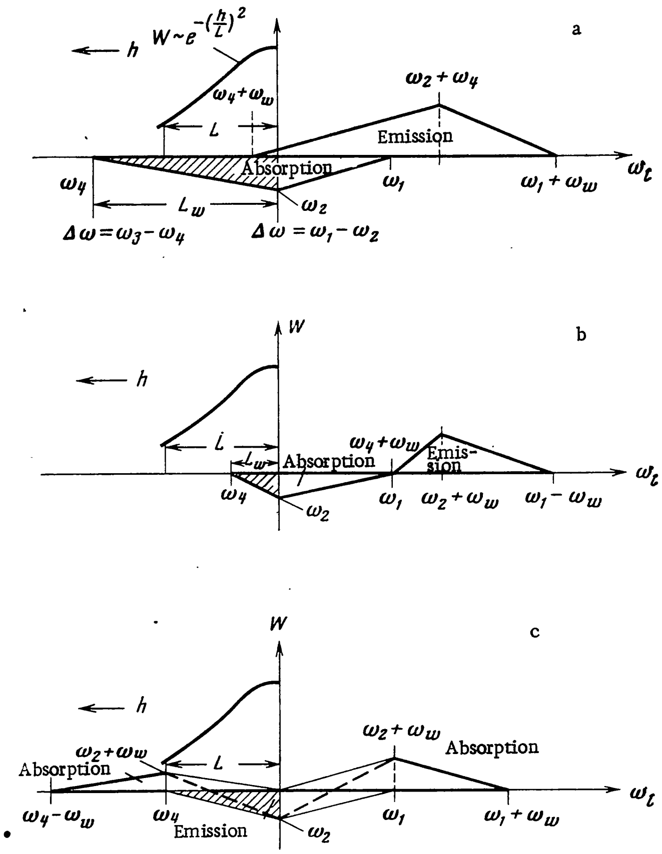

Fig. 4. Qualitative diagram of formation of bands in emission with LF-absorption for different dimensions L_W of wave packets of whistlers. ω_l and h: Langmuir frequency and height in corona. a) $L_W > L$, $\omega_W > \Delta\omega$, regions in emission and absorption overlap in frequency; b) $L_W \approx L$, $\omega_W \gtrsim \Delta\omega$, these regions are separated; c) $L_W \approx L$, $\omega_W \lessapprox \Delta\omega$, regions produce a form of the "tadpole" type on the spectrum owing to the yield of radiation at the difference frequency. In all cases the frequency separation between neighboring maxima in emission and absorption equals the whistler frequency ω_W.

process of differential scattering of l-plasmons on thermal ions, as a result of which their power is transferred along the spectrum into the region of the main scale of wave numbers $k_l = k_0 \ll k_g$, i.e., into the region of phase velocities $V_{ph} > c$ – the velocity of light[3)] (ref. 6, Sec. 4). The frequency of the interacting l-wave must be close to ω_{Pe} because of the fact that in the process of nonlinear transfer along the spectrum the frequency decreases both with a decrease in the wave numbers (when the thermal correction, as shown above, decreases to a negligibly small quantity) and with a decrease in the angle θ between the wave vector and the magnetic field, with the alignment of the wave vectors of the l-plasmons along the magnetic field (ref. 6, Sec. 8). And in this case the magnitude of the correction to the Langmuir frequency in the magnetic field, equal to $(\omega_{He}^2/2\omega_{Pe})$, also becomes negligibly small. Therefore, in the process of confluence l + w → t the frequency of the electromagnetic wave $\omega_t \approx \omega_{Pe} + \omega_W$, and thereby is close to ω_{Pe}, since $\omega_W \ll \omega_{Pe}$. Its wave vector must be directed toward the larger wave vector of the interacting waves.[4)]

As is known from laboratory experiments, the process of interaction of low- and high-frequency radiation proceeds equally efficiently both at the sum and at the difference frequencies.[17] In the given case the interaction at the difference frequency, according to conservation laws, consists in the decay l → t + w. However, because of the position of the steady emission source at the corresponding plasma level[1] the radiation at the difference frequency cannot escape from the corona, since the corresponding plasma level lies higher.

It is known that the processes of confluences and decays of waves are primary with respect to other nonlinear processes. And the process having the maximum increment and minimum threshold amplitude proves to be the most efficient. Out of all the processes of interaction of high- and low-frequency radiation the process l + w → t satisfies these conditions.[6] For example, the efficiency of the inverse process t → l + w will be reduced as a result of the fact that the electromagnetic radiation rapidly leaves the region of interaction.

The process of confluence l + w → t proceeds with an increment

$$\gamma^t = \beta^{lw} W_k^l / k_l^2, \tag{6}$$

where the coefficient of confluence is

$$\beta^{lw} = \sqrt{2}\, \omega_{Pe}^{9/2} / \omega_{He}^{3/2} N_e m_e c^4; \tag{7}$$

W_k^l is the spectral power of the Langmuir plasmons (ref. 6, Appendix). The substitution into (6) and (7) of the characteristic values $\omega_{Pe} = 4\pi \cdot 10^8$ Hz, $\omega_{He} = 2\pi \cdot 8 \cdot 10^6$ Hz, and $W_k^l \approx 10^{-5}\ N_e T_e$ (four orders of magnitude over the thermal level) gives the value $\gamma^t \approx 10^3$. The spectral density of the transverse plasmons can be estimated from the equation[6]

$$\frac{\partial W_k^t}{\partial t} = \beta^{lw} \frac{W_k^l W_k^w}{k_l}, \tag{8}$$

which shows that even for small values of the spectral power W_k^W of the whistlers one obtains large values of the spectral density of transverse plasmons, which freely escape the solar corona.

Other decays and confluences of waves also occur simultaneously with the process under consideration. The whistlers participate in confluences and decays with each other as well as with ion-sonic waves, which leads only to a change in the spectrum of the low-frequency waves. The Langmuir plasmons, besides scattering on one another, also interact with ion-sonic waves. But confluence into other Langmuir plasmons proceeds with the maximum increment in this case (ref. 6, Sec. 3). Therefore the confluence and decays

$$l + w \to t; \qquad l \to t + w \tag{9}$$

are the natural efficient processes of interaction of low- and high-frequency radiation with the yield of transverse plasmons.

2. Formation of bands in absorption and in emission. Let us examine in more detail the yield of radio radiation in this process. First of all we consider that in the propagation of a stream of fast particles

in the nonuniform solar corona radiation at a fixed frequency can be generated in an extended region. This extent can be connected with the finite width of the spectrum of longitudinal plasma oscillations in the stream–plasma system. We designate the dimension of the emitting region in the direction parallel to grad N_e as L, assuming that the intensity of the radiation of a given frequency declines exponentially in this region with height, reckoned from the level of $v = \omega_{pe}^2/\omega^2 = 1$.

A wave packet of whistlers occupying the height interval $h = L_w > L$ in the corona is shown schematically in Fig. 4a (shading). In accordance with the model of the source of ref. 1, we assume that in the transverse direction the wave packet occupies the entire width of the magnetic field tube. The curve $W \sim \exp[-(h/L)^2]$ qualitatively shows the exponential decline in the intensity of radiation of frequency ω_l in the height interval L. Langmuir plasmons in the height interval L_w interact efficiently with whistlers, and therefore the radio radiation of frequency $\omega_t \approx \omega_l$ will be attenuated, since the Langmuir plasmons of frequency ω_l are efficiently pumped on transverse plasmons at frequencies $\omega_l \pm \omega_w$.

Assuming that a spectrum of frequencies $\Delta\omega$ is emitted from each level in the corona, we can find the necessary conditions for the formation of lines in absorption. If $\Delta\omega = \omega_1 - \omega_2$ at the level of the lower boundary of the wave packet while $\Delta\omega = \omega_3 - \omega_4$ at the upper boundary, then as a result of confluence (9) the radiation at frequencies from $\omega_1 + \omega_w$ to $\omega_4 + \omega_w$ will be strengthened, freely escaping from the source. The radiation at the difference frequency will not emerge from the corona if $\omega_w > \Delta\omega$, or, which is the same, $\omega_1 - \omega_w < \omega_2$. Absorption should be observed in the entire spectrum of frequencies encompassed by the interval L_w, i.e., from ω_1 to ω_4 with a maximum at the frequency ω_2. Depending on the dimension L_w, the emission and absorption can overlap in frequency, as is schematically shown in Fig. 4a, when $L_w > L$. This causes a rapid decline in intensity from emission to absorption, decreasing the frequency range encompassed by absorption. Figure 4b is drawn for $L_w < L$. In this case the band widths in emission and absorption are the same: $\Delta\omega_{emis} = \Delta\omega_{abs} = \Delta\omega + L_\omega \text{grad}\,\omega_l$. For the accomplishment of absorption the whistler frequency here can even be slightly $< \Delta\omega$. To be more exact, the radiation at the difference frequency does not escape from the region and the lines in emission and absorption will not overlap if the minimum sum frequency $\omega_4 + \omega_w$ is greater than the maximum difference frequency $\omega_1 - \omega_w$. In this case the dimension L_w of the wave packet must be such that the inequality $\omega_w > (1/2)(\Delta\omega + L_w \text{grad}\,\omega_l)$ is satisfied. Thus, the unique position in the spectrum of absorption on the low-frequency edge of an emission line is explained. Taking the possible values of $\sim 2 \cdot 10^8$ cm for L and ~ 2 MHz for ω_w, the possibility of the formation of very narrow bands with a width of $\leqslant$ 1-2 MHz becomes understandable. A smaller value of L ($L \ll 10^8$ cm, i.e., $\Delta\omega \ll 1$ MHz) gives rise to a trapezoidal form of the frequency profile of the emission and absorption lines, which is not observed.[1] We consider the natural width of the whistler spectrum to be negligibly small (this is characteristic of magnetospheric whistlers), although in the general case it can lead to some broadening of an emission line. In the case shown in Fig. 4b, the frequency separation between maxima in the emission and absorption lines is exactly equal to the whistler frequency: $\Delta\omega_t = \omega_w$. Allowance for the increase in ω_w in depth in the corona (together with ω_{LHR}) (see Fig. 10 in ref. 1), expressed in the shift in the maximum of V_{gr} to higher frequencies, allows one to explain the observed increase in $\Delta\omega_t$ with frequency.[1]

The duration of the radiation of the bands will be determined both by the lifetime of the wave packet as a whole (several seconds) and by the time of existence of its parts which are modulated in amplitude. The latter time is determined by the nonlinear interactions of the whistlers with each other and can be very small ($\leqslant$0.1 sec) (see Fig. 3). It thereby becomes possible to explain both a pair of bands and several pairs intermittent in time, with an overall duration of several seconds in the pulsations of microstructure (see Fig. 4, b, c, d in ref. 1).

The rate of frequency drift of the bands, which varies both in magnitude and in sign, is determined by the movement of wave packets of whistlers having group velocities in different directions (see Fig. 2).

Keeping in mind the possibility of the amplitude modulation of wave packets of whistlers,[10] one can expect the simultaneous formation of several bands. The condition of frequency separation of bands in emission in this case means that the maximum sum frequency formed through confluence in the first (moving upward) packet (soliton) must be less than the minimum sum frequency in the next maximum. From this it is easy to show that the distance between neighboring solitons must be greater than L, the characteristic interval from which the given frequency is emitted. When the distance between maxima is still greater the bands in emission will be separated by bands in absorption if the condition for their formation is satisfied ($\omega_w > \Delta\omega = L\,\text{grad}\,\omega_l$). Since almost 100% amplitude modulation with a period of $\sim$0.1-0.2 sec is observed in the magnetospheric propagation of VLF radiation,[15] one can assume that the mechanism under consideration for the formation of several bands in the solar corona can be very efficient.

The possibility of the yield of radiation at the difference frequency, when the inequality $\omega_1 - \omega_w > \omega_2$ is satisfied, is shown in Fig. 4c. Here the width of absorption narrows while that of emission increases. The frequency profile of the intensity shown schematically in this case resembles the "tadpole" form. The emission level in the tail will be lower than the emission level at the high-frequency edge since the former emission overlaps with the absorption region while the latter is superimposed on the continuum. The diagram of Fig. 4c is applicable to the miniature "tadpoles" of type No. 9 in Fig. 4 of ref. 1. Wide-band tadpoles[18] can be the result of an interaction with large-scale modulated packets.

3. Polarization. Since howls propagate as slow ordinary (O) waves, one can assume that the resultant transverse wave, propagating in the direction of the vector $\bar{k}_w$, must also be ordinary.[5)] In ref. 19 it is shown that the transverse wave directed oppositely to $\bar{k}_w$ is the (O) type, and in this case waves of opposite polarizations are emitted at angles of $\pm\rho/2$.[6)] One can show, however, that even for a small magnetic field strength in the source (of a new Oersteds) only the ordinary wave can emerge

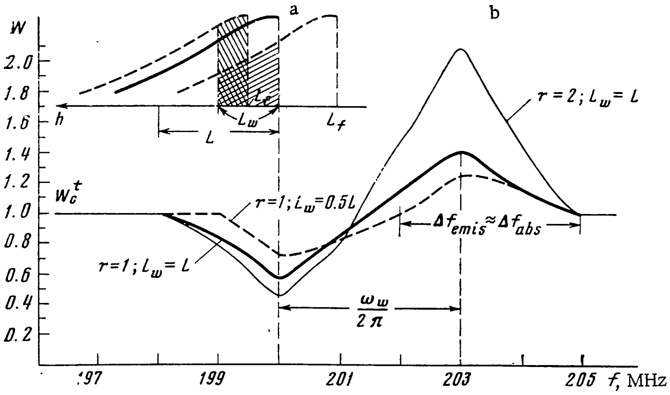

Fig. 5. Calculated frequency profile of bands in emission and absorption in units of the continuous emission power W_c^t.

from the source in the mechanism of confluence $l + w \rightarrow t$ under consideration.

Let us consider the conditions of the yield of radio radiation of the frequency $\omega_t = \omega_l + \omega_w$ from a source with dimensions equal to L_w, at the lower level of which the Langmuir frequency is $\omega_l \approx \omega_{Pe2}$. It is known that only the (O) wave will emerge from the emission region if its frequency satisfies the inequality $v \geqslant 1 - \sqrt{u} = 1 - \omega_{He}/\omega_t$ (ref. 20, Sec. 23). Since the frequency ω_t is also emitted from the upper level of the source (when $L \geqslant L_w$), where the plasma frequency is $\omega_{Pe1} = \omega_{Pe2} - L_w \operatorname{grad} \omega_{Pe}$, the inequality $v \geqslant 1 - \sqrt{u}$ must be written in the form

$$\frac{(\omega_{Pe2} - L_w \operatorname{grad} \omega_{Pe})^2}{(\omega_{Pe2} + \omega_w)^2} \geqslant 1 - \frac{\omega_{He}}{\omega_{Pe2} + \omega_w}. \tag{10}$$

By simplifying the inequality we arrive at the limitation on ω_w, neglecting the quantities ω_{He}/ω_{Pe} and $(L_w \operatorname{grad} \omega_{Pe})^2/\omega_{Pe}^2$ in comparison with unity in the final expression: $\omega_w \leqslant (\omega_{He}/2) - L_w \operatorname{grad} \omega_{Pe}$. With allowance for the limitation $\omega_w > \Delta\omega = L \operatorname{grad} \omega_{Pe}$, which is necessary so that absorption is formed and the pattern is not washed out, we obtain the required limitation on the gyrofrequency: $\omega_{He} \geqslant 2(L + L_w) \operatorname{grad} \omega_{Pe}$. Taking the value $L \approx L_w = 2 \cdot 10^8$ cm and the value $\operatorname{grad} \omega_{Pe} \approx 2\pi \cdot 1$ MHz/10^8 cm, typical of the middle corona in Newkirk's model, we obtain the field strength at which the radiation will be fully polarized of the (O) type: $H \geqslant 2.9$ Oe. This value agrees with model representations of the field strength at the level corresponding to $\omega_{Pe} \approx 2\pi \cdot 200$ MHz.

4. Calculation of frequency profile of bands in emission and absorption. Processes of confluence will proceed efficiently enough only in an optically thick source of radiation. This condition is clearly satisfied for extended packets of whistlers ($L_w \approx 10^8$ cm) if one assumes that the increment (6) is large enough ($\gamma^t \approx 10^3$).

Let us consider the conditions for the generation of radiation for a fixed time, assuming that the radiation power of the longitudinal plasmons from a unit volume at a given frequency declines by a Gaussian curve $W^l \approx \exp[-(h/L)^2]$ in the finite height interval L, reflecting the decrease with height in the electron concentration and the number of fast particles generating longitudinal oscillations of the given frequency in the height interval L.

The formation of absorption and amplification by the scheme discussed above must depend strongly on the ratio of efficiencies of the processes of confluence and induced scattering on ions. We designate the ratio of the rates of rise of the power of the residual radio radiation in these two process through r and the power of the residual radio radiation in the absorption region through W^t_{abs}. The power of the longitudinal plasmons interacting with whistlers at the frequency f in the height interval L_w encompassed by the packet is proportional to the area under the curve (shaded in Fig. 5a) corresponding to this frequency. Then the dependence of W^t_{abs} on the frequency is easily represented in the form

$$W^t_{abs} = W^t\left(1 - \frac{r}{1+r}\int_{L_f}^{L_w} e^{-(h/L)^2} dh\right), \tag{11}$$

where W^t is the power level of the continuum. The lower integration limit L_f is equal to the coordinate reckoned along grad f_l in fractions of L in both directions from the level of the lower boundary of the whistler packet (where the local plasma frequency in the terms of Sec. III, 2 will be f_2; Fig. 4a) to the plasma level corresponding to the given frequency f.

We can estimate the quantity r through the ratio of the right side of Eq. (7) to the analogous expression for scattering $l + i \rightarrow t + i'$ (ref. 6, p. 420):

$$\frac{\partial W^t}{\partial t} = \frac{\pi}{108}\frac{\omega_{Pe}^3}{N_e m_i V_{Te}^4}\frac{W^t}{k_l}\frac{\partial}{\partial k_l}(k_l W^l). \tag{12}$$

It is easy to show that under the conditions of the middle corona, where $\omega_{Pe}/\omega_{He} \approx 20$–25 and $V_{Te}/c \approx (5/3) \cdot 10^{-2}$, the two processes will be equally efficient (r = 1) if W^w reaches the value $W^t \ll W^l$. To be more exact, this is true for a rather flat spectrum $W^l(k_l)$, when the quantity $k_l \partial W^l/\partial k_l$ can be neglected in comparison with W^l. The latter can be considered as satisfied, since in the process of scattering on ions the spectrum remains flat down to the very lowest wave numbers (Fig. 5 in ref. 6). With the opposite relation $k_l \partial W^l/\partial k_l > W^l$, a large value $W^w \approx W^t(1 + k_l \partial W^l/\partial k_l)(W^l)^{-1}$ is required to achieve the condition r = 1. Even in this case, however, it remains $\ll W^l$. Such a low level of power of whistlers is probably reached easily in the emission source.

Expressing W^t_{abs} in units of the continuum power, we can reduce (11) to a form suitable for calculation:

$$W_{abs}^t = 1 - \frac{r}{1+r}[\Phi(L_w) - \Phi(L_f)] \tag{13}$$

(for frequencies $f < f_2$), where Φ is the probability integral. It is clear from Fig. 4a that for $L_w > L$ at frequencies $f > f_2$ and for $L_w < L$ at frequencies $f > f_2 + (L - L_w)\operatorname{grad} f_l$ we have $\Phi(L_w) = \Phi(1)$ in (13). At intermediate frequencies $f_2 < f < f_2 + (L - L_w)\operatorname{grad} f_l$ for $L_w < L$ one must take $\Phi(L_w + L_f)$ in place of $\Phi(L_w)$ in (13). The dependence of L_f on the frequency f is easily represented in the form $L_f = |f_2 - f|/(L \operatorname{grad} f_l)$. In Newkirk's model the value of $\operatorname{grad} f_l$ in the vicinity of the frequency of 200 MHz comprises ~1 MHz/10^8 cm.

The radio radiation formed in the confluence of longitudinal plasmons with whistlers at the sum frequency is superimposed on the continuous emission formed at the same frequencies through the induced scattering of l-plasmons on ions. Therefore, similarly to Eq. (11), the power in an emission line can be represented in the form

$$W^t_{emis}=W^t+\beta^{lw}\frac{W^w W^l}{k_l}\frac{r}{1+r}\int_{L_f}^{L_w} e^{-(h/L)^2}dh. \qquad (14)$$

Assuming that the rate of rise in W^t is determined by Eq. (12) and neglecting the quantity $k_l\partial W^l/\partial k_l$ in comparison with W^l, as before, we can reduce (14) to a form suitable for calculating W^t_{emis} in units of W^t:

$$W^t_{emis}=1+\frac{\beta^{lw}}{\alpha}\frac{W^w}{W^t}\frac{r}{1+r}[\Phi(L_w)-\Phi(L_f)], \qquad (15)$$

where $\alpha = (\pi/108)(\omega_{Pe}^3/N_e m_i V_{Te}^4)$ is the coefficient in Eq. (12). As noted above, the condition $r = 1$ requires that $W^w \approx W^t$, while an estimate of the ratio β^{lw}/α for the conditions of the middle corona under consideration $[V_{Te}/c \approx (5/3)\cdot 10^{-2}$, $(\omega_{Pe}/\omega_{He}) \approx 20$–$25]$ gives a value of $\beta^{lw}/\alpha \approx 1$, and therefore (15) takes the simple form $V^t_{emis} = 1 + 0.5[\Phi(L_w) - \Phi(L_f)]$. Curves in emission and absorption for $r = 1$ and two values of L_w, 0.5L and L, are presented in Fig. 5b. In this case, if the regions of emission and absorption do not overlap, their frequency bands equal $\Delta f_{emis} = \Delta f_{abs} = \Delta f + L_w \operatorname{grad} f_l$, where $\Delta f = 2$ MHz is the frequency band emitted from each plasma level. The third curve is drawn for $r = 2$, when $W^w/W^t = 2$ and $r/(1 + r) = 2/3$.

The calculated depth of modulation agrees with that observed in the event of May 3, 1973 (ref. 21). In the event of July 3, 1974 the continuum is sometimes amplified by an order of magnitude in the emission lines, which indicates a much higher efficiency for the confluence process (9) under consideration. As follows from (14), a power $W^w \approx 10W^t$ of the whistlers in the source is required for this. In ref. 22 it is shown that all longitudinal plasmons participate in confluence with whistlers. This means a high efficiency of the processes (9), i.e., the quantity r should most likely be $\gg 1$.

The frequency separation between maxima in emission and absorption is determined by the whistler frequency f_w. Taking it as $\sim 0.4f_{He}$, we find that the observed frequency separation $\Delta f_t \approx 3$ MHz corresponds to a magnetic field $H \approx 3$ Oe. This value agrees with model representations of the field at the level of $f_{Pe} \approx 200$ MHz.

5. Role of other effects. Since the emission of the transverse wave must be concentrated in a rather narrow angle along the magnetic field direction while the continuous emission is distributed more isotropically, in the case when the direction toward the earth makes a large angle with the magnetic field we may not receive amplified radiation at the frequencies $\omega_t = \omega_l \pm \omega_w$, whereas absorption will be observed as before. Observations of various forms of absorption without enhanced emission at the HF edge (Nos. 6 and 7 in ref. 1) and the appearance of tadpoles without an eye or tail (ref. 18, Fig. 7) may be connected with this circumstance.

The frequency drift may not always be determined by the magnitude and direction of the group velocity. The nonsimultaneity of the nonlinear stage of behavior of whistlers at different heights in the corona gives rise to drift of both signs in transient elements of the microstructure. The presence, for example, in tadpoles of inclination of the body in both directions with respect to the frequency axis is thereby explained. Thus a high drift rate does not necessarily mean the movement of the agent in the corona with a high velocity or a considerable variation in the magnetic field.

A large role is probably also played by other low-frequency radiation induced by powerful wave packets of whistlers (forerunners of howls, razors, hooks, etc.[15]) which are often observed simultaneously with magnetospheric howls. The sporadic nature of the microstructure can be connected precisely with the induced emission. A simultaneous change in the sign of the drift in several lines (saw form, No. 3, Fig. 3 in ref. 1) can also be assigned among such elements, for example.

Very narrow-band bursts of the "spike" type (Fig. 3 in ref. 1) are frequently observed simultaneously with other elements of the microstructure. They are distinguished by the absence of definite absorption of the LF edge and by a high rate of frequency drift. Such bursts can also be produced by the amplification of emission by short-lived wave packets of whistlers if the conditions $L_w > L$ and $\omega_w < \Delta\omega$ are satisfied. They signify that emission at the difference frequency will also be received while the frequency range occupied by the burst will considerably exceed $\Delta\omega$. In some cases miniature streams of fast electrons can also be responsible for the emission of spikes.[23] Streams of small sizes cannot give rise to the efficient absorption of the continuous emission emerging from a much more extensive source. In this case some of the fastest particles of the stream absorb only the low-frequency emission spectrum generated by the stream itself.

IV. CONCLUSION

The scheme discussed for the modulation of continuous emission by wave packets of whistlers with the formation of bands in emission and absorption satisfactorily explains the dynamic spectra and the polarization of the observed elements of the microstructure. The possibility of the formation both of one pair of bands with absorption on the LF edge of the emission and of a series of such bands, unsteady in time and in frequency, is demonstrated.

In the first stage of development of the instability the whistlers probably uniformly fill the magnetic trap. In this case the amplification of emission in a wide frequency band of the type of one-second pulsations occurs with the confluence $l + w \rightarrow t$. Subsequently in the nonlinear stage of instability the whistler wave packets are modulated in amplitude in the form of solitons, dying out in seconds or fractions of a second, which leads to modulation of the radiation in each pulsation in the form of diverse bands in emission and absorption. The event of July 3, 1974 developed by just such a scheme.

Thus, the formation of a microstructure in the continuous emission indicates a considerable level of turbulence of the whistlers in steady type IV sources. It is known that the absorption of whistlers unwinds the electrons across the magnetic field, i.e., promotes the confinement of fast particles in the magnetic trap and thereby maintains the prolonged existence of the source of continuous emission.

The modulation of radio radiation by whistlers is probably also accomplished in the radiation belts of Jupiter, since the observed irregular zebra structure in the decameter bursts of Jupiter very much resemble the solar microstructure in the meter range.[24]

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1)In ref. 2, in turn, questions are discussed which were not examined in detail in the present report, particularly the generation of the continuous emission, the excitation of whistlers by a conical instability, and the damping of whistlers on electrons.

2)The generation of whistlers by a conical instability is examined in ref. 2, where it is shown that quasilinear effects lead to the generation of discrete wave packets of whistlers with a period on the order of several inverse increments.

3)Melrose,[16] in noting the limitations on the phase velocities of the longitudinal waves ($V_{ph} > c$) and on the frequency of the whistlers ($\omega_{Hi} \ll \omega_W \leqslant \omega_{He}$) for the satisfaction of the conservation laws, assumes that the possibility of the process of confluence $l + w \rightarrow t$ in the solar corona is probably limited. However, the first condition actually is not a limitation, since it is known that in scattering on ions a certain steady spectrum of longitudinal plasmons is established in the entire range of wave numbers with a maximum near $k_l = k_0 \ll k_g$. Estimating k_0 from Eq. (4.21) in ref. 6, Sec. 4, we obtain $k_0 \approx 10^{-4}$ cm^{-1}, which corresponds to $V_{ph} \gg c$. The second condition is also not an obstacle, since precisely the high-frequency whistlers are generated the most efficiently (see Sec. II). In this case damping on electrons, as shown by Kuijpers,[2] remains low up to frequencies $\omega_W \approx 0.5\omega_{He}$.

4)Exact positions of $k_t = k_l - k_W$ on the dispersion curves have been calculated by Kuijpers in ref. 2, where it is shown that the values of k_t for angles $\theta \leqslant 10°$ lie on the branch of the ordinary wave.

5)See second footnote.

6)The type of wave does not change upon reversal of the direction of the wave vector, since the direction of rotation of its electric vector and the polarity of the external magnetic field are not changed in this case.

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