Some features of the formation of filaments in type IV radio bursts

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A number of features of filaments with intermediate frequency drift can be explained in the context of the ordinary $l + w \to t$ mechanism with a detailed analysis of the directivity of emission and the channeled propagation of whistlers. The position of the absorption on the HF side of a filament in emission is related to radio emission at the difference frequency $\omega^{t-} = \omega^l - \omega^w$. The conservation laws for the $l + w \to t$ and $l \to t + w$ processes are verified using a graphic solution of the dispersion equations. Radiation at the frequency ω^{t-} can escape from the source under the condition $\omega_p/\omega_H \gtrsim 17$ for $\omega^w = \omega_H/4$, which is satisfied at meter and decimeter wavelengths. The broadening of the bandwidth b_t with frequency is explained by broadening of the whistler spectrum with a decrease in the ratio ω_p/ω_H. It is noted that a level of strong turbulence of whistlers may be reached in powerful type IV bursts. It is shown that the relation $\Delta f_{ea} \approx f^w \approx 0.1 f_H (f_p/f_H \sim 30)$, which satisfies the condition $\beta \lesssim 1$, must be used to calculate the magnetic field strength in a source of filaments. The well-known deficit of filaments with positive frequency drift is explained by the directivity of the emission at the frequencies ω^{t+} and ω^{t-}. In the context of strong turbulence of whistlers, the formation of filaments is possible only when plasma waves at the upper hybrid frequency combine with lower-hybrid solitons.

1. INTRODUCTION

Filaments (fiber bursts) or bursts with intermediate frequency drift are one type of fine structure of continuous type IV solar radio bursts in the decimeter and meter wavelength ranges or at frequencies from ~ 1000 to ~ 100 MHz. On a dynamic spectrum they consist of narrow (~1 MHz at 150 MHz) bands in emission and absorption, which drift predominantly toward lower frequencies at the so-called intermediate rate of frequency drift (between the rates for types II and III bursts), from −2 to −10 MHz/sec. Rich observational material has recently been gathered from these events.[1-3]

The main properties of filament emission are explained satisfactorily by the interaction of Langmuir waves (ℓ), which are responsible for the continuous type IV emission, with whistlers (w), which are excited in the type IV sources by fast particles having a conical velocity distribution (Refs. 4 and 5).[1)] The recent theoretical work on strong turbulence of whistlers has stimulated the development of a new soliton model for filaments.[3,6-8]

Some simple properties of filament emission still remain unexplained, however. The strict constancy of the ratio of the instantaneous bandwidth of filament emission to the observing frequency (b_t/f) was noted in Ref. 2, for example. The magnetic field strengths in the source that are determined from filaments,[2,5] which are too low, and the extremely rare appearance of filaments with reverse drift are surprising. Detailed data on the frequency—time profiles of filaments in Ref. 3 show great variety in the emission level in filaments relative to the continuum (and in the depth of the corresponding absorption), as well as quasiperiodic variations of emission (and of the symmetric absorption) in the course of the frequency drift of an individual filament.

In this paper we present and analyze observations of filaments with unusual parameters. In particular, filaments with an unusual position of the absorption band on the high-frequency edge of the filament in emission and filaments in emission that border an absorption band on both sides have been observed. In this connection, we show that not only combining of ℓ and w waves[9] (ℓ + w → t) but also decay at the difference frequency $\omega^{t-} = \omega^\ell - \omega^w$ are possible. Here the directivity of all three waves plays an important role. Some of the problems enumerated above are also discussed briefly.

2. RADIO EMISSION AT THE DIFFERENCE FREQUENCY $\omega^{t-} = \omega^\ell - \omega^w$ AND THE ROLE OF DIRECTIVITY OF THE WAVES

First let us turn to the observations. It is well known that each filament is accompanied on the low-frequency edge by an absorption band of the continuum. In a series of periodic filaments this can be detected only for the first and last filaments, and this fact can be examined clearly in single filaments.[1-4] The unusual filament shown in Fig. 1a, which was observed on 18 May 1981 at 08:31:20 UT in a small type IV burst (duration ∿ 30 min and flux density ∿ (300-700)·10^{-22} W/(m^2·Hz), Fig. 2), is therefore of considerable interest.

As seen in the dynamic spectrum of this filament (Fig. 1a), in its high-frequency (HF) part (238-222 MHz) the absorption band is unusually placed, on the HF side of the filament in emission, while in the LF part of the spectrum (215-200 MHz) the position of the absorption band changes to the usual LF side. If both parts are assumed to be one drifting filament (television interference in the spectrum hinders a definite determination), then this change occurred in about 1 sec. But the essence of the matter is changed little if there are two different filaments here. The important thing is the change from unusual to ordinary filaments with a decrease in the rate of frequency drift.

In a careful examination of Fig. 1a at 6-7 sec before the unusual filament one can note two dark filaments (only in absorption) in the HF part of the spectrum. At ∿ 212 MHz they are superposed onto two ordinary filaments with a decreased rate of frequency drift. If we assume that these two pairs

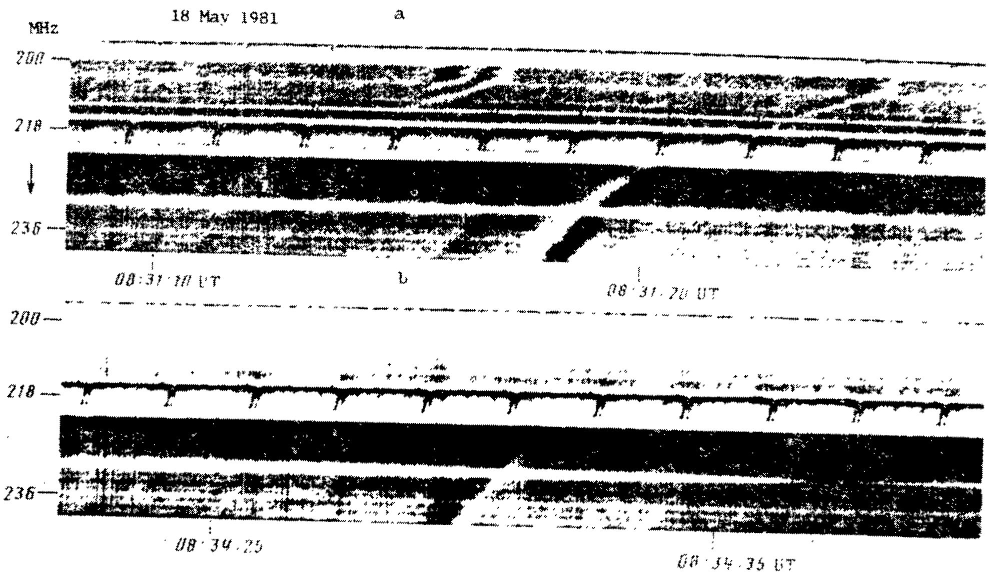

FIG. 1. Filaments with intermediate frequency drift in a small type IV burst on 18 May 1981: a) change in the position of the absorption band relative to the filament in emission; b) ordinary filament.

of filaments are somehow related, then in this part of the spectrum we observe a gradual change from dark filaments in absorption to ordinary ones.

At 2 sec before the appearance of the unusual filament at the HF edge of the spectrum one can distinguish a kind of precursor: a faint filament in emission, also accompanied by absorption on the HF edge. The main unusual filament therefore cannot be taken to be the accidental superposition of a band in absorption and a bright filament (only in emission). Both ordinary filaments and filaments only in absorption were subsequently observed in this event (Fig. 1b).

Now let us consider the parameters of the unusual filament. The frequency separation between the maxima in emission and absorption (Δf_{ea}) varied from ~ 3 MHz at 230 MHz to ~ 1.4 MHz at 206 MHz, which must be related to a decrease in magnetic field strength in the source, which is determined in accordance with the well-known relationship[2,4,5] $\Delta f_{ea} \simeq f^w \simeq f_H/4 \simeq 0.7H$ (f^w is the whistler frequency and f_H is the electron cyclotron frequency), i.e.,

$$H \simeq 1{,}43 \Delta f_{ea}, \text{ G}. \tag{1}$$

We obtain $H \simeq 4.3$ G for 230 MHz and $H \simeq 2$ G for 206 MHz.

Let us check whether these values correspond to the rate of frequency drift df/dt, which varied from ~ -7.8 MHz/sec at the HF edge to ~ -3.8 MHz/sec at the LF edge of the spectrum. In accordance with the well-known relation[2]

$$H \simeq 6{,}4 (\ln f - 1{,}3)^{-2} df/dt, \tag{2}$$

we obtain $H \simeq 1.9$ G for 230 MHz and $H \simeq 1$ G for 206 MHz, i.e., about half the above values. This may only mean that in this case the group velocity $v_g{}^w$ of the whistlers, which determines the drift velocity, was directed at an angle $\alpha \approx 60°$ to the gradient of the plasma frequency (the angle α varies little over the lifetime of a filament). Then the values of the field determined from Eqs. (1) and (2) will be approximately equal if the latter is divided by cos α. A possible decrease in the frequency ratio f^w/f_H in the derivation of (1) only leads to an increase in the field that is determined by means of Δf_{ea}. A decrease in f^w/f_H may be related, for example, to the transfer of whistlers to lower frequencies as a result of differential scattering from thermal ions or electrons. Scattering from ions is slow and predominates at the altitudes of the dm range, while scattering from electrons is fast and has a lower limit at the whistler frequency $f^w \gtrsim 0.1 f_H$ for $f_p/f_H \approx 25$ (Refs. 10 and 11). We discuss the role of scattering in more detail in Sec 4.

According to the $\ell + w \rightarrow t$ scheme of filament formation,[2,4,5] absorption is due to a decrease in the level of plasma in the level of plasma waves that take part in scattering from thermal ions, i.e., in conversion into continuous emission, as they are drawn off to the process of combining with whistlers. It appears at the LF edge of a filament in emission if the later is formed at the sum frequency $\omega^{t+} = \omega^{\ell} + \omega^{w}$. It is therefore natural to assume that in the unusual filament in Fig. 1a in the HF part of the spectrum, the radiation is received at the difference frequency $\omega^{t-} = \omega^{\ell} - \omega^{w}$, due to which the absorption lies at the HF edge. Radiation at the sum frequency may not reach the earth if it emerges at a large angle to the magnetic field.

The observations under consideration are almost unique, in the sense that there is no statistics on such events. In Ref. 2 it is noted, for example, that HF absorption has been noted in only a few events in almost 20 years of observations. In confirmation of the reality of emission at the difference frequency, in Fig. 3 we present one more

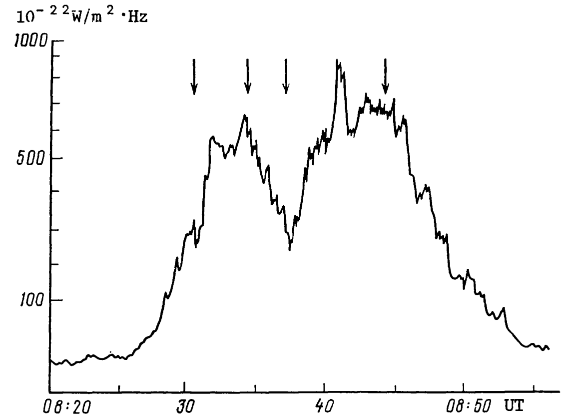

FIG. 2. Time profile of a small type IV burst on 18 May 1981 at 204 MHz. Times of appearance of filaments are marked by arrows.

example of equally unusual filaments, which form emission bands on both sides of an absorption band.[12]

Here it is natural to suggest that we are seeing radiation at both the sum and the difference frequencies, $\omega^{t\pm} = \omega^{\ell} \pm \omega^{w}$. This is a very complicated event, in the course of which varied fine structure was observed, the most interesting being the narrow-band, slowly drifting "braids" of filaments (at 10:51:10-51:17 UT in Fig. 1), which require special analysis. One interpretation of such "braids" of filaments in the model of $\ell + w \to t$ emission from a fast magnetosonic or Alfvén solitary wave source containing trapped whistlers was considered in Ref. 12. Filaments in emission on both sides of an absorption band are another feature of such "braids" (most clearly at the end of the "braid"). The unusual single filaments in this event also have almost zero frequency drift, more typical of zebra stripes.

Now let us compare how the conservation laws are satisfied for processes at the sum and difference frequencies: $\ell + w \to t$ and $\ell \to t + w$. In Ref. 9 it was shown that the $\ell + w \to t$ process proceeds for wave numbers $k^w = -k^{\ell}$, both for $k^w/k^{\ell} > 1$ and for $k^w/k^{\ell} < 1$. The possibility of the $\ell \to t + w$ process was not verified, however.

It is clear[10] that this process will not proceed for large ratios $\omega_H/\omega_p \approx 1$. Let us therefore test whether the conservation laws $\omega^{\ell} = \omega^{t-} + \omega^{w}$ and $\overline{k}^{\ell} = \overline{k}^{t} + \overline{k}^{w}$ are satisfied for the typical values of ω_H/ω_p for decimeter-and meter-wave radio emission in the solar corona.

Radio emission at the frequency $\omega^{t-} = \omega^{\ell} - \omega^{w}$ escapes from the plasma if ω^{t-} is higher than ω_p. This requires that the contribution to the plasma frequency in the dispersion relation for Langmuir waves be higher than the whistler frequency, i.e., with allowance for the term that is related to the magnetic field, we must test whether the inequality

$$\omega_p\left(\frac{\omega_H^2 \sin^2\vartheta^l}{2\omega_p^2} + \frac{3}{2}\frac{V_{T_e}^2 k^{l2}}{\omega_p^2}\right) > \omega^w, \qquad (3)$$

is satisfied, where V_{T_e} is the electron thermal velocity and ϑ^{ℓ} is the angle between k^{ℓ} and the magnetic field. It is seen that for any actual conditions in the corona ($\omega_p/\omega_H \approx$ 10-30 and ϑ^{ℓ} from 0 to 90°), the first term in (3) is much smaller than the second. Retaining only the second term, therefore, we easily obtain

$$\frac{\omega_p}{\omega_H} > \frac{\omega_p^2}{6k^{l2}V_{T_e}^2} \approx \frac{1}{6}\frac{V_{\parallel}^2}{V_{T_e}^2}, \qquad (3')$$

which can be satisfied over a wide range of altitudes in the corona; for $V_{\parallel} \approx 5\cdot10^9$ cm/sec and $V_{T_e} \approx 5\cdot10^8$ cm/sec ($T_e \approx 1.6\cdot10^6$ K), for example, it yields $\omega_p/\omega_H > 16.7$. It is also clear that large wave numbers are required to satisfy (3), $k^{\ell} > (\omega_p/\sqrt{3}V_{T_e})\,[\omega_H/2\omega_p - (\omega_H^2/\omega_p^2)\sin^2\vartheta^{\ell}]^{1/2}$ for $\omega^w = \omega_H/4$, i.e., under the previous conditions and $\omega_p/2\pi = 300$ MHz, $\sin\vartheta^{\ell} \approx 1$, and $k^{\ell} > 0.35$ cm^{-1}.

For a detailed verification of the values of ω^{t-} and k^{t-} in accordance with the conservation laws and with allowance for the angles of propagation of the interacting waves, we consider a graphic solution of the well-known dispersion relations for electromagnetic (ordinary (o), extraordinary (x), and slow extraordinary (z)) and Langmuir (ℓ) waves (by analogy with Fig. 5 of Ref. 4),

$$\left\{1 - \frac{3V_{T_e}^2}{c^2}N^2 - \frac{\omega_p^2}{\omega^2}\right\}\left\{(1-N^2)\left(1+\frac{\omega_H}{\omega}\cos\vartheta\right) - \frac{\omega_p^2}{\omega^2}\right\}$$
$$\times\left\{(1-N^2)\left(1-\frac{\omega_H}{\omega}\cos\vartheta\right) - \frac{\omega_p^2}{\omega^2}\right\} = \frac{\omega_H^2}{\omega^2}\sin^2\vartheta\left(1 - N^2 - \frac{\omega_p^2}{\omega^2}\right) \qquad (4)$$

and for whistlers,

$$\omega^w = \frac{\omega_H|\cos\vartheta^w|}{\omega_p^2 + k^{w2}c^2}k^{w2}c^2 \qquad (5)$$

($N = kc/\omega$ is the refractive index and ϑ (with the appropriate indices t, ℓ, and w) is the direction of wave propagation with respect to the magnetic field). In Fig. 4 we show the dispersion curves and a graphic representation of the interaction of ℓ, w, and o waves for the typical conditions in the corona: $\omega_p/\omega_H = 30$ and $T_e = 10^6$ K. The branches of whistlers for $\vartheta^w = 0$ and 30° are cut off at the frequency $\omega^w = 0.37\,\omega_H$, since for $\omega_p/\omega_H = 30$ strong cyclotron damping sets in at higher frequencies,[4] and ω^w does not exceed $0.17\omega_H$ for $\vartheta^w = 80°$. The interaction of waves at the sum frequency ω^{t+} is shown schematically by dashed lines. The sum values ω^{t+} and k^{t+} calculated in Ref. 4 for different frequencies ω^w are denoted by dots on the branches of o waves. The intervals of values of k^{ℓ} and k^w for which the conservation laws are satisfied at the difference frequency $\omega^{t-} = \omega^{\ell} - \omega^{w}$ are denoted by segments on the wave-number axes. These values of k^w fall on the whistler branches at large angles between the wave vectors $\overline{k}^w$ and the magnetic field, $\vartheta^w \approx$ 70-80°. The domains of values of ω^{t-} and k^{t-} determined from the expression $k^{t-2} = k^{\ell 2} + k^{w2} - 2k^{\ell}k^{w}\cos\vartheta^{\ell,w}$ are encircled by dashed curves on the branches of o waves. For the interaction at the difference frequency the vectors $\overline{k}^{\ell}$ and $\overline{k}^w$ must be in the same direction at very small angles to each other, $\vartheta^{\ell,w} < 1°.3$. The direction of the vectors $\overline{k}^{t-}$ can be either positive (along the field) or negative, depending on the direction and relative magnitude of the vectors $\overline{k}^{\ell}$ and $\overline{k}^w$. The right-hand boundary of the k^{ℓ} segment is determined by

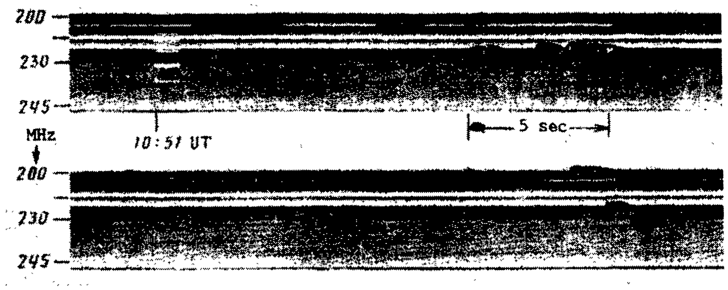

FIG. 3. Slowly drifting braids of filaments (top) and single filaments in the major event on 24 April 1985, displaying emission bands on both sides of the absorption band.

Landau damping for ℓ waves, which increases with k^ℓ. It is about an order of magnitude smaller than the Debye number $k_d = \omega_p/V_{T_e} \approx 4.8\ \mathrm{cm}^{-1}$, and the smallest possible k^ℓ and k^w are determined by the minimum frequencies ω^{t-}_{min} at which radio emission can freely escape from the source ($\omega^{t-}_{min} \approx \omega_p + 0.05\ \omega_H$ in the given case).

Using the simplified dispersion relations and conservation laws, it is easy to estimate the angles ϑ^{t-} for the most efficient $\ell \to t + w$ interaction, $\vartheta^{t-} < \pm \cos^{-1} 2\omega^w/\omega_H$, i.e., for $\omega^w/\omega_H = 0.2$ radio emission can escape at angles $\vartheta^{t-} < 66°.4$. For the opposite angles $\vartheta^{t-} > \pi/2$ we have the restriction $\vartheta^{t-} < 90° + \vartheta^w$, related to the fact that the angles ϑ^w and ϑ^ℓ are always less than $\pi/2$ (i.e., angles $\vartheta^{t-} \approx 180°$ do not occur). Besides these constraints on ω^{t-} and ϑ^{t-}, in the $\ell \to t + w$ decay process a significant constraint is imposed on the range of wave numbers k^w and $k^\ell \approx 0.35$-$0.45\ \mathrm{cm}^{-1}$.

These very factors may explain the rare appearance of radio emission at the difference frequency. It is also clear that one other reason for the lower efficiency of $\ell \to t + w$ decay in comparison with $\ell + w \to t$ combining may be the predominant direction of the wave vectors $\bar{k}^w$, provided by the generation mechanism and by the slower process of backscattering of whistlers from ions than in the case of ℓ waves.[10] Thus, in the generation of whistlers in cyclotron resonance, $\omega - k_\parallel V_\parallel \pm \omega_H = 0$, the directions of $\bar{k}^w$ and of the electron velocity $V_\parallel$ coincide, i.e., they also coincide with the direction $\bar{k}^\ell$ only for the anomalous Doppler effect (the "+" sign), which is what yields whistlers at large angles to the magnetic field. For the normal Doppler effect the directions $\bar{k}^w$ and $\bar{k}^\ell$ are opposite and favor the $\ell + w \to t$ combining process. From the diagram in Fig. 4, however, one can see that for small angles ϑ^{t+} and $k^\ell > k^w$ the $\ell + w \to t$ combining also has a frequency limit, $\omega^w < (0.1$-$0.15)\ \omega_H$.

If the whistler spectrum is assumed to be fairly narrow, then radio emission at the frequencies ω^{t+} and ω^{t-} will escape only at certain angles. Therefore, returning to Fig. 1, we can assume that the emission at the sum frequency in the HF part of the unusual filament escaped at a large angle to the magnetic field and to the line of sight toward the earth. As the whistlers traveled upward along a curved field line, emission at the difference frequency, which is directed at a sharper angle to the magnetic field, no longer reached the earth.

The presence of an absorption band is thus most characteristic of filaments. Filaments in ansorption are observed considerably more often than filaments only in emission. This is explained naturally by the directivity of the emission. Filaments only in absorption will be observed in a case in which emission at the frequencies ω^{t+} and ω^{t-} does not reach the earth. Absorption may not be noticeable where the size of the region of the $\ell + w \to t$ and $\ell \to t + w$ interactions is small in comparison with the size of the entire region emitting at these frequencies. Filaments will be formed only in emission in this case, especially if the whistler power is high.

For the filaments in Fig. 3 the scheme for the source must provide, first of all, for the possibility of obtaining different frequency drifts (for whistler motion almost parallel to levels of equal density, for example) and the simultaneous simultaneous escape of emission at the frequencies ω^{t+} and ω^{t-}. An alternative explanation for filaments with oscillating drift may be the trapping of whistlers in an inhomogeneity like a fast magnetosonic or Alfvén wave traveling at the Alfvén velocity $v_a \ll v_g^w$ at the top of a magnetic arch. In that event one may observe filaments only in emission, if there is no pronounced density inhomogeneity of the plasma in the source and absorption is not formed due to screening, or only in absorption, if such absorption occurs and the emission does not reach the earth.

3. INSTANTANEOUS EMISSION BANDWIDTH OF FILAMENTS AND THE WHISTLER SPECTRUM

For the estimates here we use the instantaneous bandwidth b_t at the half-power level, so it is approximately equal to the intrinsic emission bandwidth b_i (without allowance for broadening of the band due to drift).[2,3] It is well known that the instantaneous bandwidth b_t increases with observing frequency from about ~ 1.1 MHz at 150 MHz to ~ 3.6 MHz at 500 MHz (Ref. 2, Table V), i.e., the ratio b_t/f remains almost constant, ~ 0.007. Further into the dm range this ratio increases to ~ 0.013 at 600 MHz and to 0.015 at 900 MHz (Ref. 3, Table X).

As is well known, the bandwidth b_t must be defined by the expression[5]

$$b_t \approx \Delta f^l + L^w \,\mathrm{grad}\, f_p + \Delta f^w, \tag{6}$$

where Δf^ℓ is the natural width of the spectrum of plasma waves at the given level in the corona, L^w is the size of the whistler wave packet, and Δf^w is the width of the whistler spectrum. The first term in (6) cannot provide the increase with fre-

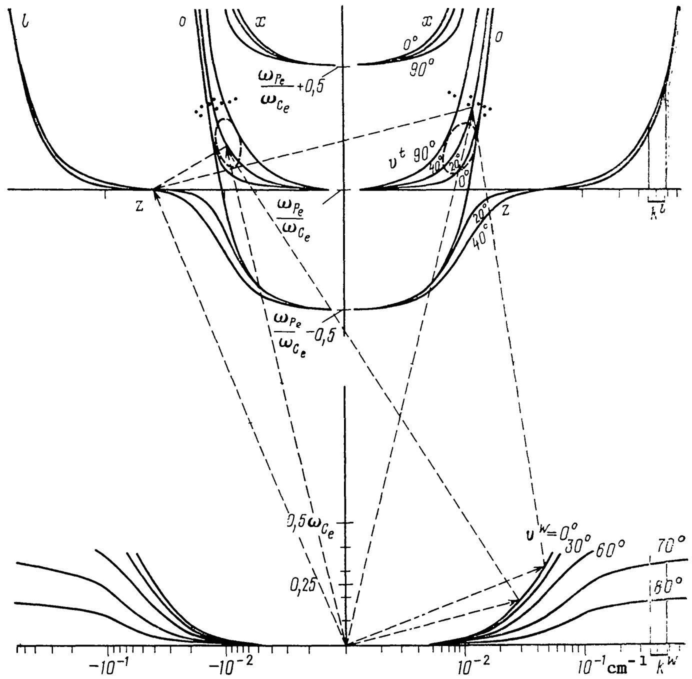

FIG. 4. Dispersion curves for electromagnetic (o and x) and plasma (ℓ) waves (top) and whistlers (bottom) for different propagation angles ϑ with respect to the magnetic field. A graphic diagram of the $\ell + w \rightarrow t$ interaction at the sum frequency is shown by dashed lines for two whistler wave numbers and $\vartheta^w \approx 0°$. On the branches for the ordinary wave the domains of values of ω^{t-} and k^{t-} for the $\ell \rightarrow t + w$ process at the difference frequency are encircled by dashed curves. The corresponding values of k^ℓ and k^w are marked by segments on the branches of ℓ waves and whistlers.

quency, since it is well known that

$$\Delta f^l/f \approx 3(V_{Te}/V)^2(\Delta V/V).$$

For $V_{T_e}/V \approx 10^{-2}$ and a particle velocity spread $\Delta V/V \approx 0.1$ we obtain a small value $\Delta f^\ell/f \approx 0.003$ and, most importantly, it hardly varies with frequency. It would be difficult to suggest that the term L^w grad f_p varies much with altitude.

It is therefore natural to relate the broadening of b_t with frequency to an increase in the width Δf^w of the whistler spectrum. The cyclotron frequency f_H does not appear directly in (6), but its increase, together with the ratio f_H/f_p, with depth in the corona means an increase in b_t. According to Fig. 4 in Ref. 4, the conditions for the generation of longitudinal whistlers by conical instability with electrons at velocities $V \approx 7 \cdot 10^9$ cm/sec for $f_p/f_H \approx 10$ (i.e., at 200-300 MHz) provide a whistler spectral width $\Delta f^w \approx 0.08\ f_H$, and in the dm range ($f_p \approx$ 600-800 MHz, $f_p/f_H \approx 10$) for a loss cone with a wide angle the spectral width broadens to about $0.25\ f_H$. Thus, when the observing frequency is approximately tripled, the whistler spectral width also approximately triples, which explains the constancy of the ratio b_t/f in the meter range and the small increase in the dm range.

It should be noted that, although the whistler spectrum is about three times broader in the dm range (from $0.45f_H$ to $0.2f_H$), the whistler group velocities at the ends of this spectral range are almost the same as that at the maximum at $0.25f_H$, which eliminates the group spreading of the whistler wave packet that is typical of the spectra of magnetospheric whistlers. At meter wavelengths, the whistler spectrum is very narrow (sharp maxima of increments) and, although v_g^w is not the same at its ends, group spreading is weakly manifested during the life of one filament (∿ 10 sec). The velocity spread decreases sharply as v_g^w deviates from the magnetic field.[5] Group spreading causes only minor broadening of the emission bandwidth of a filament toward the boundary with the LF absorption. Allowance for the whistler spectrum in the scheme of filament formation in Ref. 5 means a transition from the scheme of Fig. 4b to that of Fig. 4a in Ref. 5 with different values of ω^w at the LF and HF edges of the filament. Thus, the term L^w grad f_p in (6) varies little, especially since grad f_p decreases with altitude in the corona with the increase in L^w due to spreading.

4. DETERMINATION OF THE MAGNETIC FIELD USING FILAMENTS

The reliability of estimates of the magnetic field in the corona using filaments has often been doubted.[2] Let us try to understand in more detail the reasons for this doubt, in order to increase the reliability of the estimates.

Recall that along with the above-mentioned methods of determining the field from the frequency separation Δf_{ea} between the maxima in emission and absorption (Eq. (1)) and from the rate of frequency drift (Eq. (2)), there is another possibility for verifying the values obtained, using the necessary condition for the existence of a magnetic arch,

$$\beta = nk_B T/(H^2/8\pi) = 1, \qquad (7)$$

and using the appropriate values $n = n_e + n_i$ and $T = 1.5 \cdot 10^6$ K (k_B is the Boltzmann constant). Condition (7) corresponds to a ratio $f_p/f_H \approx 32$. A determination of the field from the intrinsic bandwidth of a filament,[2] $H = 3.6b_i$, must be acknowledged to be fairly coarse, since the relation $b_i \approx \Delta f^w \approx 0.1f_H$ taken in Ref. 2 actually depends strongly on the observing frequency. In Eq. (1), however, we must also verify the correctness of the choice of the ratio $f^w/f_H \approx 1/4$, which is usually justified by

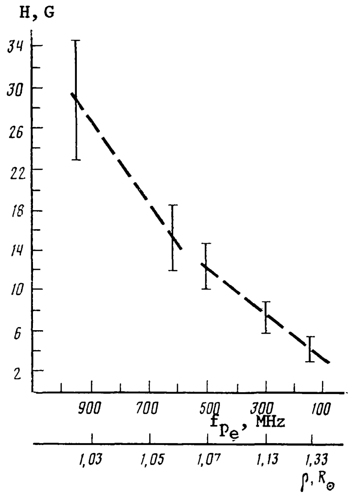

FIG. 5. Distribution of magnetic field strength with altitude in the corona, obtained using the frequency separation Δf_{ea} between absorption and emission in filaments. This relation is close to that of the model proposed in Ref. 15, $H = 0.5(\rho - 1)^{-1.5}$.

the fact that whistlers have the maximum group velocity at this frequency.

If the values of the field determined using Δf_{ea} turn out to be larger than those determined from df/dt, this may mean, as noted above, that Eq. (2) must be divided by cos α (a is the angle between $v_g{}^W$ and grad f_p). This does not increase the estimate of the field by much (by a factor of 1.4, for example), however, since the actual values of α may be in the range of $\lesssim 45°$ (or somewhat larger for values of df/dt considerably lower than average).

But if the values of the field determined from Eqs. (1) and (2) coincide and satisfy condition (7), then these values can be considered reliable. Otherwise (and when (1) gives lower values than (2)) the conclusion that the actual values of f^W/f_H are < 0.25 suggests itself. Thus, the value $f^W/f_H = 0.03$ was taken in Ref. 14. In this connection we note that the value of f^W/f_H for filaments can scarcely be close to 0.023 (i.e., to the frequency of lower hybrid resonance), since in that case whistlers are reflected in the plasma, whereas channeled propagation must be assumed for filaments. Moreover, the maximum increments for the typical parameters of the coronal plasma fall at higher frequencies,[4] $f^W \approx (0.1\text{-}0.3) f_H$.

The values of the field determined above for the filament in Fig. 1 in the LF part of the spectrum do not satisfy condition (7). The multichannel profiles of filaments that are given in Ref. 3 enable us to determine Δf_{ea} with high accuracy. Using Eq. (1) (for the filament in Fig. 32 of Ref. 3, for example), we obtain very low fields at 260 MHz, $H \approx$ 1-2 G. It is therefore clear that at meter wavelengths the whistler frequency f^W/f_H must be less that 1/4 and the determined by the actual mechanism of excitation of whistlers and by their propagation in the corona.

In the dm range Δf_{ea} usually hardly varies during the life of one filament.[3] However, f^W/f_H and H in (1) can vary. But if f^W decreases simultaneously with f_H, the cutoff of filament emission must be related not to reaching the level of cyclotron damping of whistlers (where $f^W \approx 0.4 f_H$) but to quasilinear effects. The increase in f^W/f_H with upward travel for several seconds may be compensated for by transfer of whistlers to lower frequencies due to their differential scattering from thermal ions, since this process is considerably slower than scattering of plasma waves, and it becomes efficient in relatively strong fields. According to Ref. 10, Sec. 4.10, predominant scattering of whistlers from ions requires a limit on the Alfvén velocity,

$$v_a > (m_e/m_i)^{1/4} V_{T_e} \simeq 0{,}15 V_{T_e},$$

which corresponds to the actual limit on the ratio of plasma frequencies for the dm range, $f_p/f_H < 12$. The electron pitch angle increases with an increase in the field, so the electron energy distribution function in the dm range should have a broad loss cone. In this case, the maximum of whistler generation falls at frequencies $f^W \approx f_H/4$ (Ref. 4, Fig. 4), and this value should hardly vary with allowance for whistler scattering from ions during the life of a filament.

At meter wavelengths ($f_p/f_H \approx 30$) the exciting particles should have a narrow loss cone and the generation maximum will fall at frequencies $f^W \approx 0.1 f_H$ (Ref. 4). Scattering from ions does not operate in this case, and scattering from electrons turns out to be differential with respect to frequency (and faster than for scattering from ions) and integral with respect to angle.[11] For meter waves, therefore, f^W/f_H is determined by the mechanism of generation and differential transfer over the spectrum with a decrease in frequency to $f^W/f_H \approx 0.1$, and it does not vary appreciably over the life of a filament. It is clearly more reliable to determine the field at the start of a filament (on the HF edge) and to verify it from Eq. (2).

Thus, in the m range (at 150-300 MHz) instead of (1) we must use the equation

$$H = 3{,}57 \Delta f_{ea}, \tag{8}$$

which increases the field strengths by a factor of 2.5.

These corrected values of the field, obtained from the mean values of Δf_{ea} for the m range (Ref. 2, Table VIII) and for the dm range (Ref. 3, Fig. 45), are presented in Fig. 5. The spatial spread of the field strengths corresponds to the observed distributions of Δf_{ea} in different events. These field strengths satisfy condition (7) that the magnetic pressure exceed the kinetic pressure. The field increases faster with frequency in the dm than in the m range, in accordance with the well-known distributions of Ref. 12. The distance scale in the m range is set up in accordance with Newkirk's double model of density (here the field strengths are close to those of the model proposed in Ref. 15: $H = 0.5(\rho - 1)^{-1.5}$), and the scale in the dm range is set up in accordance with the proposed models, which correspond to numerous observations.[5,13]

5. EXPLANATION OF THE DEFICIT OF FILAMENTS WITH REVERSE DRIFT BY THE DIRECTIVITY OF EMISSION AT THE FREQUENCIES ω^{t+} and ω^{t-}

Filaments with reverse drift are observed almost as rarely as absorption on the HF edge of a filament in emission. Let us try to determine whether this is related to the same cause, i.e., to the directivity of emission in the $\ell + w \rightarrow t$ and $\ell \rightarrow t + w$ interaction processes.

Positive frequency drift indicates to us that the whistler wave vectors $\bar{k}^W$ are directed toward the sun. This indicates at once that emission at the difference frequency $\omega^{t-} = \omega^\ell - \omega^W$ will also be directed downward and cannot be received, since, in accordance with the explanations to Fig. 4, emission does not escape at the opposite angles $\vartheta^t \approx 180°$ in this case. It is also clear that whistler with $\bar{k}^W$ directed away from us can be excited at cyclotron resonance with the normal Doppler effect, $\omega^W - k_\parallel{}^W V_\parallel - \omega_H = 0$, by particles that are traveling upward. But, first, according to observations of large flares, particles travel predominantly downward. And second, in accordance with Fig. 4, the conservation laws for the $\ell + w \rightarrow t$ process (for $k^\ell > k^W$) are satisfied mainly at large angles ϑ^t, so we will not receive radiation at the frequency ω^{t+} with vectors $\bar{k}^{t+}$ directed toward us. Also for small angles there is a limit on the whistler frequency, $\omega^W \lesssim 0.1\omega_H$, i.e., the conditions for satisfying the conservation laws do not occur at all in the dm range.

But if the whistlers and plasma waves are excited by electrons that are injected downward, which yield downward-directed $\bar{k}^W$ and $\bar{k}^\ell$ by the anomalous Doppler effect, then we find a deficit of the $k^\ell \approx -k^W$ required for combining. In this case, the numbers $k^\ell = -k^W$ are obtained as a result of differential scattering from ions, which forms the two-dimensional spectrum of ℓ waves. The wave numbers are then transferred to smaller k^ℓ, however, and their interaction with k^W no longer occurs with the formation of $\bar{k}^t$ directed toward the sun (see the diagram of the $\ell + w \rightarrow t$ interaction on the hight-hand side of Fig. 4).

Thus, the reason for the deficit of filaments with reverse drift is the directivity of emission at the frequencies ω^{t+} and ω^{t-}. They are observed too rarely, however, in the m range, where the emission maximum falls at frequencies $\omega^W = 0.1\,\omega_H$, even with allowance for this effect. In this connection, we need to address the fact that when whistlers propagate toward increasing density and magnetic field, they deviate from the magnetic field lines. According to data on the magnetospheric propagation of whistlers, which are confirmed by calculations of whistler trajectories on the sun, whistlers at frequencies $\omega^W \approx 0.1\,\omega_H$, close to 0.023 ω_H, deviate rapidly as they approach ω_{LHR}, where they are reflected. In this case, therefore, the whistlers escape rapidly from the source of continuous emission.

6. STRONG TURBULENCE OF WHISTLERS

In Ref. 4 it was already shown that the usually observed fluxes filaments, $\sim 5 \cdot 10^{-17}$ W/m²·Hz, for example, are explained in the context of weak turbulence for a ratio of the wave field to the background field $H/H_0 \approx 0.7 \cdot 10^{-4}$ and a plasma-wave power $W^\ell \approx 3.6 \cdot 10^{-5}$ erg/cm³. Here the optically thick source with respect to the $\ell + w \rightarrow t$ combining process provides the observed brightness temperature $T^t \approx 8.5 \cdot 10^{11}$ K.

As a result of a more detailed analysis of the $\ell + w \rightarrow t$ combining of waves with random phases, it was found in Ref. 9 that the observed filament fluxes 10^{-19} W/m²·Hz and brightness temperatures $\sim 10^{14}$ K for $W^\ell \approx 10^{-5}$-10^{-6} erg/cm³ require a whistler power $W^W \approx 2 \cdot 10^{-10}$ erg/cm³, which is only four to five orders of magnitude higher than the thermal noise of the whistlers and as many orders of magnitude lower than the energy of the plasma waves.

Observations of filaments in very strong type IV bursts against the background of the continuum, $\sim 10^4 \cdot 10^{-22}$ W/m²·Hz, however, are stimulating many authors to employ strong turbulence of whistlers. On the basis of an expression for the functional form of a one-dimensional soliton of whistlers obtained in Ref. 16, for example, it was proposed in Refs. 3, 6, and 7 that all the energy of the whistlers is concentrated in such solitons. This model subsequently encountered new difficulties. It turns out that the emission of $\sim 10^{14}$ solitons from a volume of $\sim 10^8$ km³ is required to explain the observed filament fluxes. The absorption cannot be explained in the usual way in this case, since the individual solitons in such a volume cause emission (and absorption) at frequencies that differ too much, due to their very small size. Screening of the continuous emission by density inhomogeneities within such a volume is therefore used to explain the absorption.

In this connection, we must note, first of all, that the conditions suggested in Refs. 3,6, and 7 for attaining strong turbulence at the reflection points of whistlers can be used only for lower-hybrid solitons. First, $\omega^W \approx \omega_{LHR} \approx \omega_H/43$ at the reflection points, and the condition $\omega^W \gtrsim \omega_H/4$ must be satisfied for the formation of whistler solitons. Second, a simple decrease in the group velocity cannot result in the formation of whistler solitons. Multiple reflections of whistlers are observed in the earth's magnetosphere, but solitons are not recorded. The reflection of whistlers occurs with a gradual reversal of k^W through the interaction with the electrostatic mode. A strong wave can therefore result in the formation of lower-hybrid solitons, which propagate perpendicular to the magnetic field and can interact with upper-hybrid waves. This latter process has been analyzed quite thoroughly in Ref. 3.

All observations of filaments indicate to us, however, that the motion of whistlers is predominatly channeled along magnetic field lines. Under the conditions of propagation in a magnetic trap they should be rapidly damped by fast trapped particles (over the lifetime of a filament).

It is thought that the level of strong turbulence of whistlers (and strong Langmuir turbulence, incidentally) may be reached in powerful events. But the analysis of the linear stage of modulation instability in Ref. 16 does not at all mean that all the energy of whistlers is concentrated in solitons. For filaments it is necessary to consider the nonlinear stage of modulation instability, and even more its saturation. Such a two-dimensional problem was solved numerically in Ref. 17. The estimates of three-dimensional modulation instability in Ref. 17 are of particular interest. They show that the field of a powerful wave is concentrated in two types of narrow structures drawn out along field lines: fast magnetosonic waves with decreased density and magnetic field, propagating at a velocity $v_g{}^W$, and slow magnetosonic waves with increased density, moving at a very slow velocity ($<V_{T_e}/43$). The first two structures containing density cavities can be used to interpret the usual classic filaments, and the slow magnetosonic structures can be used to interpret unusual slowly drifting bands in emission and absorption.

7. CONCLUSION

Our analysis of certain aspects of filament emission (fiber bursts) has shown that a multitude of features can be explained by a detailed analysis of the directivity of emission in the $\ell \pm w \to t$ mechanism in the context of channeled propagation of whistlers upward along a magnetic trap.

The position of the absorption on the HF side of the band in emission is related to the reception of radiation at the difference frequency $\omega^{t-} = \omega^{\ell} - \omega^{w}$. The conservation laws for the $\ell + \omega \to t$ and $\ell \to t + w$ processes were verified graphically, which enables us to use more general expressions for the dispersion relations of the interacting waves and allow for the directivity of the emission at the sum and difference frequencies ω^{t+} and ω^{t-}. Emission at the frequency ω^{t-} will escape from the source under the condition $\omega_p/\omega_H \gtrsim 17$, which is satisfied over a wide range of meter and decimeter wavelengths.

The broadening of the instantaneous bandwidth of filament emission with an increase in observing frequency is explained by the natural increase in the spectral width of the excited waves (whistlers) with a decrease in the ratio ω_p/ω_H.

An analysis of extensive experience in determining magnetic field strength from filaments has shown that, in accordance with the mechanism of whistler generation at the altitudes of meter-wavelength radio waves, the ratio $f^W/f_H \approx 0.1$ must be used to estimate the field using the equality[2)] $\Delta f_{ea} = f^W$. This makes it possible to increase the field estimates by a factor of 2.5 and bring them into agreement with other models and with the condition $\beta \lesssim 1$.

The directivity of emission at the frequencies ω^{t+} and ω^{t-} explains the deficit in observations of filaments with reverse frequency drift.

It is noted that a level of strong turbulence of whistlers may be reached in powerful type IV bursts, but it cannot be analyzed in the context of a one-dimensional soliton solution. This question requires a detailed analysis on the basis of numerical results for the nonlinear stage of a saturated modulation instability.[16] Along with strong turbulence of whistlers as applied to filaments, and to other fine structure of type IV bursts, incidentally, it is necessary to consider strong turbulence of plasma waves.

[1)] A type IV source consists of a magnetic trap. A structure of the filament type will not be washed out due to averaging over the cross section under the actual condition that wave packets of whistlers occupy almost the entire transverse size of a trap ($\sim 10^8$ cm) (see Ref. 5 for more detail).

[2)] Transfer of the whistler spectrum due to scattering from thermal electrons was analyzed in detail in Refs. 10 and 11. Local increments for whistlers and the gain along propagation trajectories in the corona were calculated in Ref. 18 on the basis of the well-known methods that are used for magnetospheric whistlers.[19,20]

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