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WHISTLERS IN THE SOLAR CORONA AND THEIR RELEVANCE TO FINE STRUCTURES OF TYPE IV RADIO EMISSION

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Abstract. This short report concerns a general consideration of whistler manifestations in fine structures, including possible trajectories of obliquely propagating whistlers, the role of quasilinear diffusion and an interpretation of new observations. A whistler ray tracing and kinetic whistler growth rates under arbitrary angles to the magnetic field in the solar corona were calculated. Different regimes of a whistler instability yield divers elements of fine structures: different stripes in emission and absorption or millisecond pulsations, moreover, zebra-stripes can convert into fiber bursts and inversely. A new explanation of low-frequency absorption in fibers is proposed: it is connected with an attenuation of plasma-wave instability due to the fast electron diffusion by whistlers. Rope-like chains of fiber bursts are explained by a periodic whistler instability in a magnetic reconnection region.

1. Introduction

Whistlers (w) yield a principal contribution in the fine structure radioemission (t) by means of coupling with Langmuir waves (1) at sum as well as difference frequencies: $\omega^l \pm \omega^w = \omega^t$ (Kuijpers, 1975; Chernov, 1976). Obliquely propagating whistlers essentially widen whistler manifestations in the fine structure of type IV radio emission. However, all previous calculations of a whistler instability in the solar corona were connected with the longitudinal propagation only (Kuijpers, 1975; Berney and Benz, 1978), although more real whistler behaviour must include the oblique propagation, considered for the magnetospheric plasma, e.g., in Hashimoto and Kimura (1977).

This report briefly elucidates the substances of some recent papers concerning new results including observations of unusual fine structures:

(i) wave-like zebra-stripes converting into fiber bursts and inversely;

(ii) rope-like fibers accompanied by strange fibers in absorption only and by millisecond pulsations;

and new interpretations:

(i) a new explanation of low frequency absorptions in fiber bursts;

(ii) a fan instability by whistlers at normal and anomalous Doppler cyclotron resonances;

(iii) an explanation of rope-like fibers by periodic whistler instability in a magnetic reconnection region.

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2. Possible Whistler Trajectories

In the papers by Maltseva and Chernov (1989a, b) for a whistler ray tracing in the solar corona, a standard numerical integration of the Haselgrove two-dimensional equations for magnetosphere whistlers is used. The Newkirk model of the electron density ($N_e \times 2$ and $N_e \times 5$) and the dipole dependence with altitude for the magnetic field strength above an active region are chosen. Dozens of trajectories for variable plasma parameters were obtained.

Many qualities of magnetospheric whistlers are characteristic for the solar corona, in particular, whistlers can propagate with numerous reflections. But in the corona, the whistler refractive index can be very large ($\sim 10^3$), and group propagation times between consecutive reflections may amount to some minutes. Another peculiarity of solar whistlers is the possibility of canalization along density and magnetic field inhomogeneities (ducts or magnetic traps) provided that their width does not exceed $\sim 2 \times 10^8$ cm.

In conditions of the coronal plasma in a linear adiabatic approach, the local kinetic growth rates (γ_h) and the integral amplification coefficients along trajectories (γ_Σ) were computed for whistlers propagating under arbitrary angles on the magnetic field and for a distribution function of hot electrons including a beam with loss-cone and temperature anisotropies. The three resonances (normal and anomalous Doppler cyclotrons and Cherenkov) were taken into account. According to Maltseva and Chernov (1989b), positive values of γ_h are reached by very weak beams with an energy of $E \sim 3$ keV, an energy dispersion of $\Delta E \sim 0.01$ keV and a fraction of hot electrons n_h, relative to the cold plasma density n_c, of $n_h/n_c \sim 10^{-7}$. However, long-time whistler propagation with numerous reflections and $\gamma_\Sigma > 0$ for a ratio of plasma frequency to the electron cyclotron frequency of $f_p/f_H = 20$, is possible only in a limited frequency range $f^w/f_H < 0.3$ (similarly for $f_p/f_H = 30$ on $f^w/f_H < 0.2$ and for $f_p/f_H = 40$ on $f^w/f_H < 0.12$) and with more energetic beams: $E \sim 30$ keV, $\Delta E \sim 30$ keV, $n_h/n_c \sim 10^{-5}$.

A whistler cyclotron instability at the normal Doppler resonance and upward-duct propagation causes fiber bursts. Periodic whistler wave packets generated at the anomalous Doppler resonance at arbitrary angles to the magnetic field (due to bounce-movements of hot electrons at a magnetic loop top) yield zebra-pattern stripes during nonducted propagation with reflections in low-hybrid resonance regions.

Sometimes we observe isolated fiber bursts at rather low frequencies (~ 100 MHz) (Figure 1(a)). However, our calculations of a whistler ray-tracing show that whistler trajectories cannot go high in the corona without assuming an open magnetic configuration. Then whistlers excited, e.g., by runaway electrons at low relative frequency $f^w/f_H = 0.002$ (or $f^w = 10^5$ Hz) at the altitude $\approx 90\,000$ km (where the ratio $f_p/f_H = 6.5$ in the twice Newkirk density model), can propagate along an oblique trajectory in the high corona, but only up to the level $f_p \approx 100$ MHz (or the altitude $\approx 0.5 R_0$) where $f_p/f_H = 40$ and $f^w/f_H \approx 0.1$ (Figure 1(b)). At this level, whistlers are damped due to cyclotron damping.

A broad whistler spectrum, formed by means of coupling processes with ion-sound

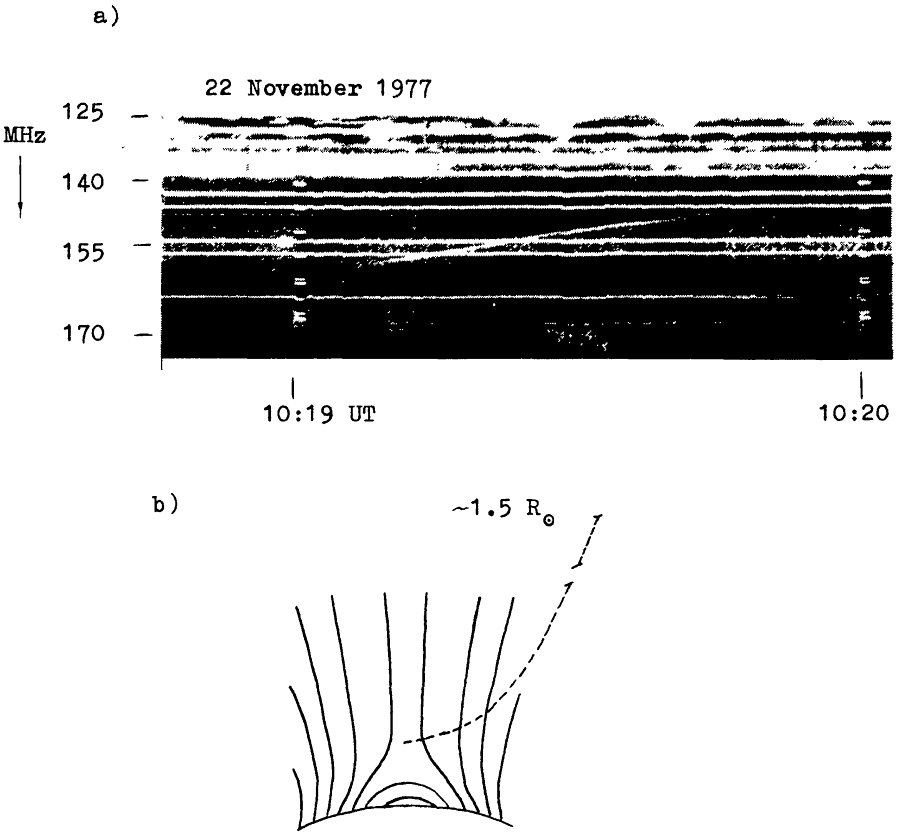

Fig. 1. An isolated fiber burst at low-frequency range (a) and a suitable possible whistler trajectory in the open magnetic field.

waves in a pulsating regime in reconnection regions, may yield millisecond pulsations and spike bursts (Chernov, 1989).

3. Manifestation of Fast Electron Diffusion by Whistlers

The calculation of whistler oblique propagation permits the discovery of a manifestation of fast electron diffusion by whistlers (at the normal and anomalous Doppler effects in the cyclotron resonance) in fine structures of type IV radio emission. Quasi-linear diffusion helps to explain the nature of low-frequency (LF) absorption in fiber bursts and a variable (wave-like) frequency drift of zebra-stripes (Figure 2(a)).

During a type IV burst, fast shocks can propagate from microflare regions and the fast shock acceleration mechanism can provide a fast electron velocity distribution of a hollow beam type (or a ring distribution) with the deficiency of slow electrons (similar to the mechanism of Potter (1981)). According to Gendrin (1981), such a distribution of an anisotropic beam type (in the usual designations),

$$F(V_\perp, V_\parallel) = C_N V_\perp^j \exp\left\{-\frac{mV_\perp^2}{2K_BT_\perp} - \frac{m(V_\parallel - V_b)^2}{2K_BT_\parallel}\right\},$$

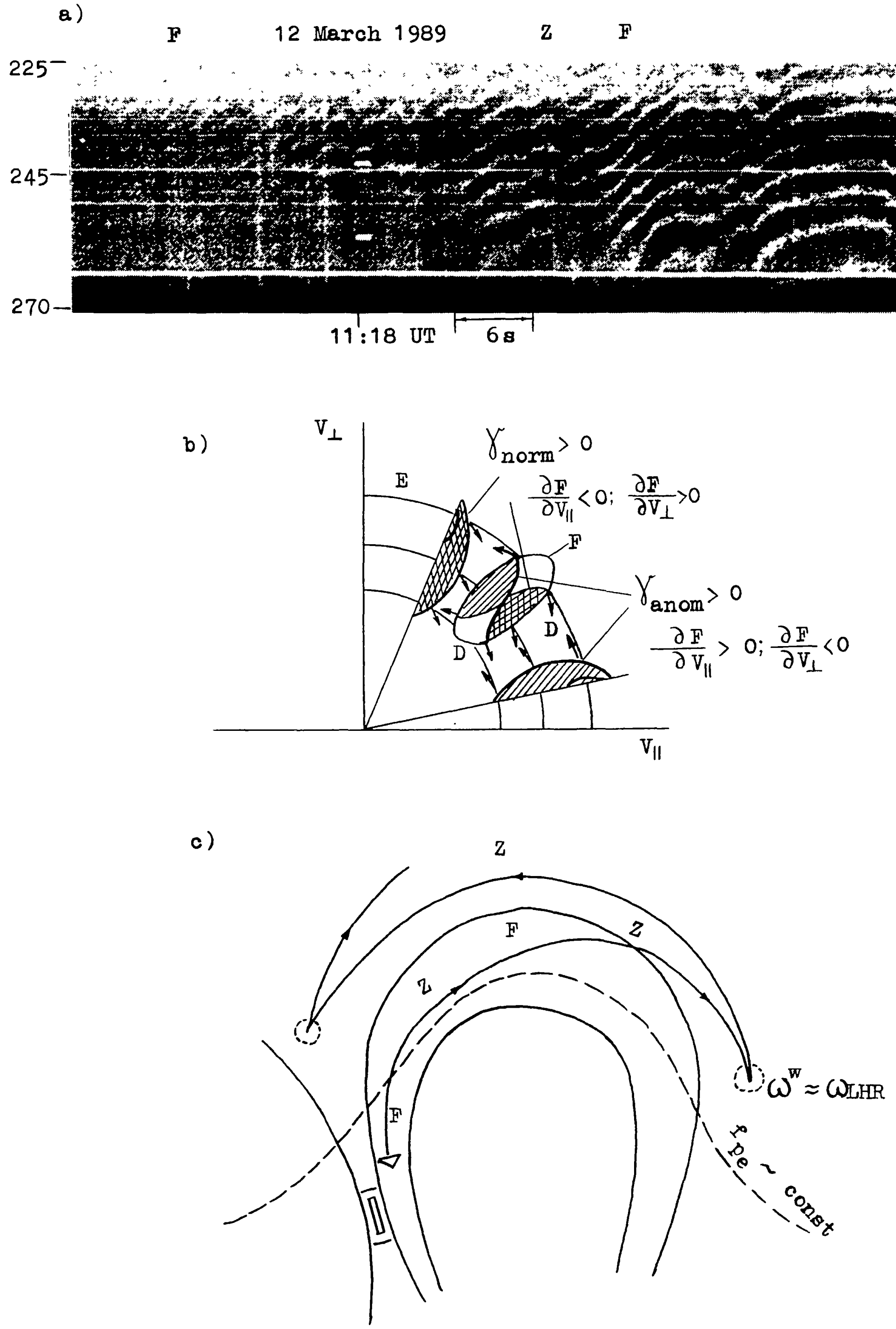

Fig. 2. (a) Unusual conversion of zebra-stripes into fiber bursts (F) and inversely; (b) switching of whistler instability from the normal Doppler cyclotron resonance ($\gamma_{\text{norm}} > 0$) into the anomalous resonance ($\gamma_{\text{anom}} > 0$) according to Gendrin (1981); F – levels of a distribution function; E – levels of equal energy; D – electron diffusion directions; c – qualitative scheme explaining the possibility of zebra-stripe conversion into fiber bursts and inversely.

can yield almost equal contributions at the normal and anomalous Doppler cyclotron resonances in a whistler instability at arbitrary angles to the ambient magnetic field (C_N, normalized constant; j, loss-cone anisotropy). Therefore, if the maximum of a fast electron distribution is located at moderate pitch angles (at the surface $(V_\parallel, V_\perp)$), a resonance switching should be possible (Figure 2(b)).

The smooth switching of the predominant contribution from the anomalous to normal Doppler resonances (and inversely) occurs in accordance with the sign of an operator $\hat{\Lambda}$ in the growth rate expression (Gendrin, 1981; Bespalov and Trahtengerts, 1980):

$$\hat{\Lambda} = \frac{s\omega_H}{\omega V_\perp} \frac{\partial}{\partial V_\perp} + \frac{k_\parallel}{\omega} \frac{\partial}{\partial V_\parallel} \bigg|_{V_\parallel = (\omega - s\omega_H)/k_\parallel}$$

It is known that in the normal Doppler effect, particles and waves propagate in the same direction, but in the anomalous Doppler effect, they propagate in opposite direction. The resonance switching must operate with a periodicity defined by a diffusion time $t_D \sim D_\alpha^{-1}$, where D_α is a pitch-angle diffusion coefficient which is moreover equal to about a few seconds in the solar corona. This effect provides a smooth change of the whistler propagation direction and, consequently, a smooth change of the frequency drift of stripes in emission and absorption. This effect is called the turn of the beam due to diffusion (Shapiro and Shevchenko, 1987). It corresponds to a fan instability in the tokamak plasma diagnostics (Parail and Pogutse, 1981).

A slow resonance switching during whistler propagation permits us to understand the smooth conversion of zebra-stripes into typical fiber bursts, and inversely, shown in Figure 2(a). A qualitative scheme of applicable whistler trajectories is shown in Figure 2(c).

But because of diffusion, the velocity distribution begins to level out and the plasma-wave instability reduces in the particle beam volume. This attenuation is the main reason for low frequency absorption in fiber bursts and in zebra-stripes.

We observed unusual fibers in type II bursts (Figure 3). These fibers are distinct from the usual fibers by the absence of LF-absorption. This was also the case with the isolated fiber shown in Figure 1(a). In the above hypothesis concerning the nature of LF-absorption, in this case, a magnetic trap is absent before a shock front. Therefore, whistlers and particles propagate in different directions and diffusion does not occur.

4. Rope-Like Fiber Bursts

During the solar type IV radio burst on 24 April, 1985, a new fine structure, "slowly drifting chains of narrowband fiber bursts" (or rope-like fiber), was first observed by the IZMIRAN 200–250 MHz spectrograph (Figure 4(a)) (Mann *et al.*, 1989). For these rope-like fibers, a model of critical loss-cone instability was elaborated. Numerical calculations show that this instability only appears for loss-cone angles greater than the critical one through the influence of the thermal ions: $\alpha_{cr} \approx 3.6°$ for the ratio of the plasma frequencies $f_{pe}/f_{H_e} = 15$ and velocities of electrons $V = 10^{10}$ cm s^{-1} or $\alpha_{cr} \approx 8°$ for $V = 1.5 \times 10^9$ cm s^{-1}. However, in order to produce quickly (for ~ 0.16 s) a sufficient wave energy level, it is necessary to use sufficiently high fractions of hot electrons $n_h/n_c \sim 10^{-2}$, which are difficult to expect in the high corona. But under

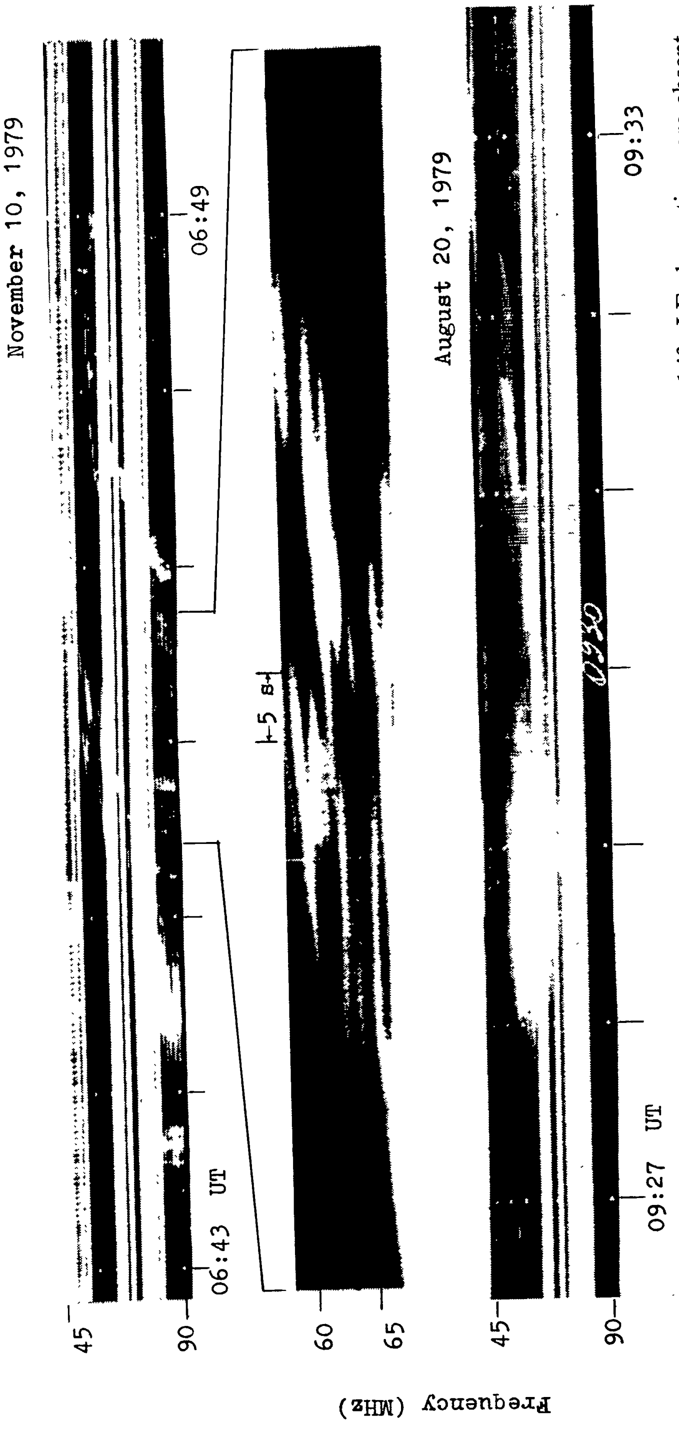

Fig. 3. Type II bursts with unusual fiber structures. The fibers have a very slow frequency drift, LF absorptions are absent.

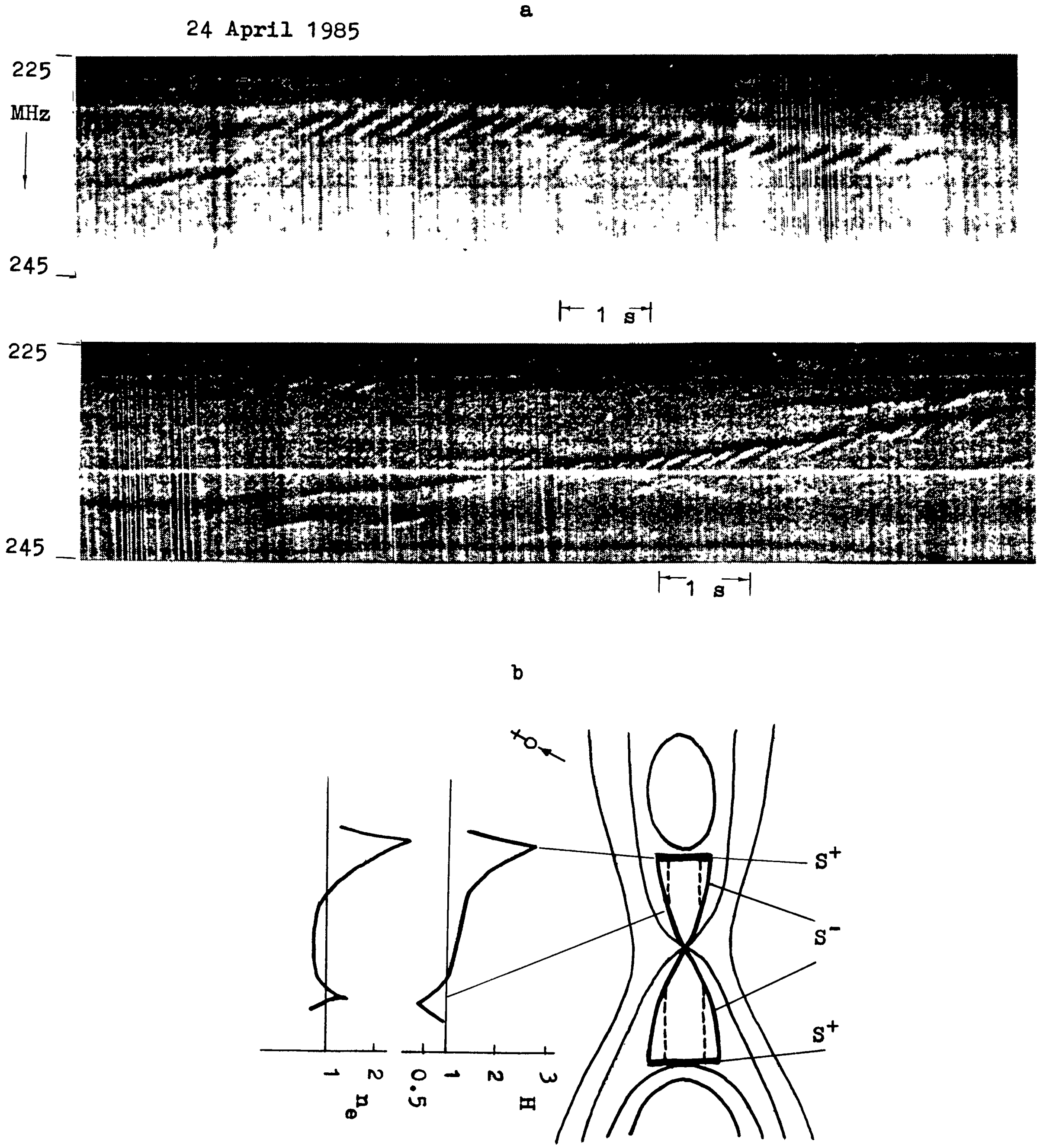

Fig. 4. Rope-like chains of fiber bursts in the range 225–245 MHz (a). (b) qualitative scheme of a quasi-stationary reconnection with a type X neutral point during magnetic loop restoration after a flare (Forbes and Priest, 1983) and the approximate variation of density and magnetic field strength in a reconnection region (see Sidneva and Semenov, 1985); S^- – slow shock fronts, S^+ – fast shock fronts; dashed lines --- whistler wave packet trajectories.

normal conditions for more real fractions $n_h/n_c \sim 10^{-6}$, a whistler instability at the same energy level $W^w/nT \sim 10^{-6}$–10^{-7} may develop if the loss-cone angle reaches a high value, $\sim$45–80°, in a magnetic trap (Berney and Benz, 1978).

Therefore, another possible source of a periodic loss-cone instability may be the region of reconnection during the annihilation of magnetic islands in a vertical current sheet after a flare (model of Forbes and Priest (1983)). During a quasi-stationary reconnection with a neutral type X point, two pairs of slow shocks and two fast shocks are formed*. Between the fast shock fronts, a new magnetic trap is produced. Near a fast shock front, the magnetic field grows to more than twice its size, maximum whistler increments may reach sufficiently high values $\gamma_h/\omega_{H_e} \sim 10^{-2}$, and the periodic whistler instability develops, due to the bounce motions of the fast electrons between two fast shock fronts at a distance of about $\sim 10^9$ cm. Hence, there follows a higher periodicity of fibers in one rope ~ 5–$6\ \mathrm{s}^{-1}$, than in the usual ~ 1–$2\ \mathrm{s}^{-1}$. Whistler wavepackets can propagate from the fast front up to the slow shock front where the magnetic field strength sometimes decreases and the whistlers decay by cyclotron damping. This distance (~ 2–3×10^8 cm) defines the bandwidth of rope-like chains (~ 2–3 MHz) (see the model of Sidneva and Semenov (1985) and Figure 4(b)). The proposed scheme not only explains rope-like fibers, but also other accompanying fine structures, such as slow drifting fibers in absorption (due to the screening of the emission from rarefaction regions by the slow shock fronts) and millisecond pulsations according to the model of a pulsating regime of whistler and ion-sound waves in a reconnection region (Chernov, 1989).

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* See also Forbes (1988) and Hick and Priest (1989).