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The Relationship between Fine Structure of the Solar Radio Emission at Meter Wavelengths and Coronal Transients

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Abstract—Features in the fine structure of type II+IV solar radio bursts that are directly related to coronal mass ejections (CMEs) are identified. Eighteen events with radio fine structure were selected for the analysis; in all cases, it was possible to reliably identify the event with some specific flare, and information about associated CMEs was available (from the SMM and R78-1 spacecraft). Unusual, slowly drifting fibers directly related to CMEs were observed in type-II bursts or in the flare continuum FCII at the impulsive stage. Sometimes braids of fibers were found to be accompanied by such unusual fibers in absorption and by wide-band millisecond pulsations in the post-maximum phase. In some events, zebra structure was observed at unusually low frequencies (to 45 MHz). Models for the radio emission of these unusual fibers that are consistent with the known properties of CMEs are examined in the framework of mechanisms for electrostatic wave instabilities and whistlers.

INTRODUCTION

Coronal transients, or coronal mass ejections (CMEs), are among the largest-scale manifestations of solar activity (Kahler 1992; Chertok 1993). They have a well-defined relation to major type II+IV radio bursts (Sheeley 1984; Robinson *et al.* 1986) and to centimeter-wavelength bursts (Chertok 1992). However, it is not yet known if CMEs have some connection with the fine structure of continuous radio flares.

The fine structure of the meter-wavelength radio emission is usually taken to include the most short-lived bursts, such as spikes and second and millisecond pulsations, as well as emission and absorption bands, which are subdivided into zebra structure and intermediate frequency drift fibers ["intermediate drift bursts" (IDB) or "fiber bursts"]. The dominant drift of the bands in these two cases is toward high and low frequencies, respectively. Continuous type-IV bursts are usually the most saturated by fine structure; in major bursts, the various types of fine structure listed above are sometimes observed nearly simultaneously in the dynamical spectrum.

The main properties of these structures are already known (Kuijpers 1975, 1980; Chernov 1976a,b, 1989a; Fomichev and Chernov 1977; Slottje 1981). However, the large variety of proposed mechanisms for the radio emission, especially for the emission and absorption bands (see Winglee and Dulk 1986), makes it clear that there is no agreement yet on this question. There is more agreement with regard to interpretations of emission and absorption pulsations on timescales of several seconds (Zaitsev *et al.* 1984; Aschwanden 1987) and milliseconds (Chernov 1989b). We assume the spikes to be merely accompanying features, noting only that they are often observed together with rapid pulsations. We will give the most attention to the least studied question of the relation of the IDB fibers and zebra structure to the processes accompanying flares and also to a search for new types of fine structure that may be produced in some source directly linked to coronal mass ejections.

The important question of properties of the radio fine structure that might be connected to coronal transients has not yet been discussed in the literature, in spite of the many papers and reviews written on related topics (Kahler 1992; Chertok 1993; Kuznetsov 1994). Only decimeter spikes accompanied by second pulsations have been discussed in this context (Karlickü'y 1984). In this last work, however, the condition that the cyclotron frequency exceed the plasma frequency ($\omega_{B_e} > \omega_{p_e}$), which is used to interpret the spikes, is too strong; in addition, in five of the seven events considered, the connection with CMEs was only proposed on the basis of observations of type II+IV radio bursts. In the rare event of November 3, 1986, a CME was observed before a flare, and accompanied type-II and type-III bursts, as well as stationary and moving type-IV bursts (Gopalswamy and Kundu 1989). However, the associated shock wave was not piston-like (at the head of the transient or a moving source, for example), but explosive (from the flare). In all the cases noted here, the instruments used by us did not permit measurement of the radio fine structure.

Although it is well known that most major type-IV bursts are accompanied by CMEs, only 45% of

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observed CMEs are accompanied by continuous type-IV bursts (Robinson *et al.* 1986), and only 41% of CME are associated with type-II bursts (Sheeley 1984). This weak inverse relation becomes understandable if we consider the fact that more than half of CMEs are behind the limb, so that the associated radio emission is not detected on Earth. It is also known that the wider and more rapid the CME, the more powerful and longer-duration the type-IV continuum, and the lower its low frequency edge. Similarly, the more powerful a type-II burst, the more rapid the associated CME (with velocities >600–800 km/s) and the larger its angular size (>60°) (Robinson *et al.* 1986). The sources of most type-IV bursts remained stationary.

The results of many years of observation of fine structure with high time and frequency resolution on the radio spectrographs of the Institute of Terrestrial Magnetism, Aeronomy, and Radio-Wave Propagation enable us to search for properties of the fine structure of type-II+IV radio bursts for which there are reliable associations with CMEs. Interpretations of such phenomena should help elucidate the nature of the fine structure and make it possible to diagnose CMEs on the basis of the associated radio fine structure, which can be detected under any weather conditions using simple ground-based instruments. However, before discussing the main issue, we will consider certain general properties of the fine structure and its relation to the accompanying flare processes.

COMPARISON OF THE FINE STRUCTURE IN IMPULSIVE AND LONG-DURATION TYPE-IV BURSTS

It is important to consider this question for two reasons. First, about one-fourth of type-IV bursts with fine structure are impulsive and short-lived (~10 min), although these bursts are virtually indistinguishable in terms of their sets of fine structure elements and the parameters of these elements. Second, not all CMEs are accompanied by type-IV bursts, but the wider and more rapid the CME, the more powerful the type-IV continuum. It is, therefore, important to elucidate whether there is some property of the fine structure that can be used to infer the scale of the phenomenon. Most radio bursts with fine structure are associated with large-scale proton flares with extended energy release, which is seen primarily in the many-component nature of the accompanying centimeter-wavelength burst. In such bursts, the fine structure is usually observed in the post-maximum phase of the flare, when each appearance of zebra structure and fibers corresponds to a new brightness maximum at decimeter wavelengths. The clearest examples of such bursts are the events of July 3, 1974 (Chernov 1976a), February 3, 1983 (Bakunin *et al.* 1991), and April 24, 1985 (Aurass *et al.* 1987).

However, type-IV meter-wavelength bursts with modest flux densities and durations (~10 min) and with a developed fine structure, which was previously believed to be characteristic only of large-scale events, are sometimes observed after weak flares of magnitude ≤1*N*. In such cases, the syndrome of large flares (Kahler 1982) is not manifest in the radio fine structure. Such weak bursts are usually accompanied by modest, impulsive, centimeter-wavelength bursts (Chernov *et al.* 1987; Chernov and Kurts 1990); recall that only the most intensive impulsive bursts are accompanied by CMEs (Chertok *et al.* 1992). Note, however, an important property of these modest phenomena: most often, they are associated with active regions in which major flares have occurred several hours or several tens of hours earlier.

It is nevertheless possible to distinguish certain general qualitative criteria for both major and weaker events with fine structure. First, the accompanying multi-polar spot groups are very elongated and have a complex neutral line, suggesting the presence of arches of magnetic loops (Chernov 1976a). Second, all events with fine structure, for which a reliable association with a CME has been established (see Table 1), are accompanied by centimeter-wavelength bursts with a gradual increase and decrease (GRF) or with multiple-components (MC) with gradually increasing amplitude maxima (GRF+MC). This type of centimeter-wavelength burst, delayed relative to the meter-wavelength burst, is typical of near-limb flares, but was observed for central flares in events 3, 7, 14, and 18. Note that a gradual growth and decrease is also characteristic of many impulsive bursts with fine structure, although the flares occurred near the central meridian (for example, May 18, 1981; Chernov 1990a), and there is simply no information about observations of CMEs for most of them.

The time for the increase of centimeter-wavelength bursts is proportional to the linear size of the source (or its area) (Batchelor 1989). This may reflect a close connection with CMEs, in which the centimeter flare source gradually grows, after the transient has moved outward, independently of the heliolongitude of the flare. This growth could be attributed to the propagation of a perturbation downward from the level at which the transient arises. The amplitude of the centimeter burst does not have a well-defined lower limit at which fine structure appears at meter and decimeter wavelengths. For example, no centimeter burst was observed in the large-scale event with fine structure on June 5, 1990 (Chernov *et al.* 1994).

It is important to check for differences in the directivity of the radio fine structure in different events, since the best conditions for observing transients are realized for limb and behind-the-limb events. Figure 1 shows the distribution over the solar disk of 55 flares accompanied by fine structure, 11 of which are weak (impulsive events). No obvious differences in the fine structure of impulsive events (usually zebra structure and fibers (IDB) against the background of second pulsations) can be identified. The distribution does not reveal any appreciable directivity to heliolongitudes

~70–75°, although impulsive events are somewhat more concentrated toward the center of the disk, and there are appreciably more eastern than western and northern than southern flares. It is possible that this is not at all related to the presence of fine structure.

Thus, we cannot expect large-number statistics. Therefore, we must search for common unusual properties in the fine structure of the 18 selected events in the table that reflect their relation to CMEs.

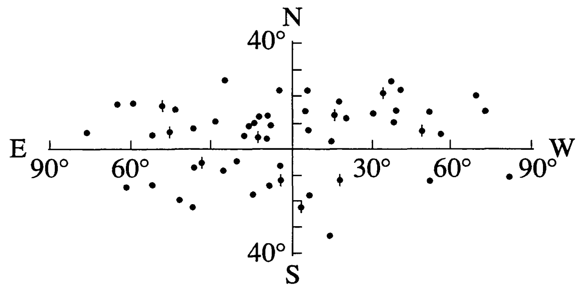

Fig. 1. Distribution over the solar disk of H_α flares reliably identified (using *Solar Geophysical Data*) with 55 events with fine radio structure at meter wavelengths over all years of observation. The vertical lines mark 11 weak impulsive events.

FREQUENCY RANGE OF THE FINE STRUCTURE AND ITS RELATION TO FLARE PROPERTIES

The appearance of one or another type of fine structure apparently depends on the specific structure of the associated active region and the development of the flare or coronal perturbation. Independent of the specific mechanism for forming the fine structure, its low-frequency boundary is probably determined by the maximum height of magnetic loops (or arcades) in the corona; this property is usually invoked in models of the zebra structure, fibers, and pulsations. Although the low-frequency boundary is not strictly constant, it is most often in the range from 150–160 MHz (Slottje 1981).

One widely accepted model for type-IV radio sources is a magnetic trap, with the radio emission tied to the local plasma frequency. Therefore, the condition for the existence of magnetic loops (the approximate equality of the magnetic and kinetic plasma pressures; plasma parameter $\beta \le 1$) must be satisfied at the associated plasma levels in the corona. Often, other plasma parameters determined from the fine structure must satisfy, first and foremost, precisely this condition (for more detail, see Chernov 1990a). Therefore, it is important to take note of any appreciable decrease in the low-frequency boundary of the fine structure, if it is indeed associated with a CME that is rising high in the corona. In the table, the low-frequency boundary is presented in the third column, in the second line (Fr. MHz), after the type of the fine structure (F = fiber, P = pulsation, Z = zebra structure).

Most of the events in the table are characterized by low-frequency boundaries that are significantly lower than 160 MHz, and for three major events with low-frequency boundaries ~200 MHz, there are simply not complete spectral data at lower frequencies. The only common property in most of the events that are listed is the presence of a flare continuum, which follows immediately after a type-II burst [an FCII continuum in the classification of Robinson (1985)], against the background of which fibers and zebra structure were observed. In this case, the decrease in the low-frequency boundary of the fine structure is due to the location (and possibly the movement) of the FCII continuum source high in the corona, in close relation with a CME. This is very important, since we considered only the post-maximum phase of the flare evolution in the Hα line.

Indeed, we see that, in a number of the events, each new fine structure series corresponds to new formations in flare exposures in the Hα wings. For example, in the event of May 16, 1981, bright nodes in the penumbra of spots appeared prior to the onset of the second-long pulsations. This process was accompanied by a shift in the centimeter-wavelength spectrum toward higher frequencies, suggesting the birth of a new centimeter source with a hard spectrum (Ishkov *et al.* 1985). In the same event, and also the event of February 3, 1983, the peaks of arcs brightened or new arcs appeared immediately before the appearance of series of zebra structures (Bakunin *et al.* 1991). This provides evidence for the additional injection of rapid particles into coronal magnetic traps. These times usually coincide with the birth of new decimeter sources.

PROPERTIES OF THE FINE STRUCTURE IN EVENTS ASSOCIATED WITH CMES

Together with the 14 major events associated with CMEs in the table, we have included four events that do not show obvious evidence for a connection with a CME but have certain other general properties, most importantly, the presence of unusual fibers at low frequencies in the FC II continuum. The appearance of their centimeter bursts also agreed with those for the other events: they were either multiple-component (MC) or gradually increasing and decaying (GRF). There were no coronograph observations for the 2nd and 16th events, and events 3 and 13 were associated with flares at the disk center, where the conditions are not favorable for detecting weak CMEs. It appears that the unclear connection of CMEs with type-II bursts noted above is due to the incompleteness of our data. As noted by Gopalswamy and Kundu (1994), transients usually form at large heights, when the corresponding type-II burst caused by a piston-like shock begins at low frequencies, at the poorly studied decameter wavelengths (2–20 MHz).

Fine Structure (FS) of Type-II+IV Radio Bursts Associated with CMEs

No.	Date; spectrum	Time, UT; type of FS; Fr., MHz	Hα, UT; magnitude; coordinates	Brightness, sfu; profile	CME: UT	CME: Location; width, deg.	CME: type	CME: V_{CME}, km/s V_{sh}, km/s	Ref.
1	12.01.74 IV	1030 F+P, 48	1028 1B S18 E82	20 Imp	1144	124 350	MIS	 350	Munro *et al.* 1979; Munro and Sime 1985
2	10.07.78 II+IV	0630 Z, 55	0618 3B N19 E60	1530 MC+GRF		No observations			
3	10.11.79 II+NS	0643 F, 55	0642 1B S15 W13	607 Imp, MC		None			
4	20.08.79 II	0930 F, 54	0904 2B N06 E77	2000 MC+GRF	1041	S15E 90	MS, A, Y	1260 650	Cane *et al.* 1987
5	21.08.79 II+IV	0615 F 57	0611 1B N15 W38	None	0651	N50 70	MS	680 910, 780	Robinson *et al.* 1986
6	3.04.80 II+IV	0718 F, P 55	0655 1B N24 W19	1440 MC+GRF	0700	N80 60	L, B	860 770	Sheeley 1984; Robinson *et al.* 1986
7	16.05.81 II+IV	0836 F, P 60	0809 3B S15 E09	1250 GRF	1042	360 360	H, A, Y	>1200 1070	Cane *et al.* 1987
8	12.10.81 II+IV	0641 F, Z 190	0620 3B S18 E31	2300 GRF	0913	360 360	H, A, Q	>650 1070	Cane *et al.* 1987
9	3.06.82 II+IV	1142 F 48	1141 2B S09 E71	1207 Imp+MC	1203	N20 ±30 – *E*		1330 840	Sheeley *et al.* 1985
10	9.07.82 II+IV	0758 F 45	0742 3B N18 E76	1200 Imp+MC	<1252	N20E 140	R, B, Q	>490 830	Cane *et al.* 1987
11	12.07.82 II+IV	0923 F, S, 180	0906 3B N11E36	1100 MC+GRF	1203	S10E 180	R, B, Y	>730 1350	Cane *et al.* 1987
12	19.07.82 II+IV	0932 F 48	0821 1N N23 W09	28 Imp	0942	S30 100		890 670	Sheeley *et al.* 1985
13	16.12.82 II+IV	1009 F, Z 102	0955 1B S11 E04	250 Imp		None			
14	3.02.83 II+IV	0612 F, Z 95	0543 2B S17 W07	3500 GRF	0642	360 360	H, A, Y H, A, Y	830 1100	Cane *et al.* 1987
15	24.04.85 II+IV	1050 F, P 225	0855 3B N06 E17	3400 GRF	0936	60 80	BL		Cyr and Burkepile 1990
16	4.02.86 IV	0738 F, Z 80	0737 3B S06 E18	100 MC		None			
17	6.02.86 IV	0700 Z, P 108	0622 2B S06 W10	1300 MC+GRF	0641	289 78	DES		Cyr and Burkepile 1990
18	12.03.89 IV	0858 Z 200	0803 2B N29E07	313 MC	0601 1149	284, 19 64, 25	MF FC		Cyr and Burkepile 1990

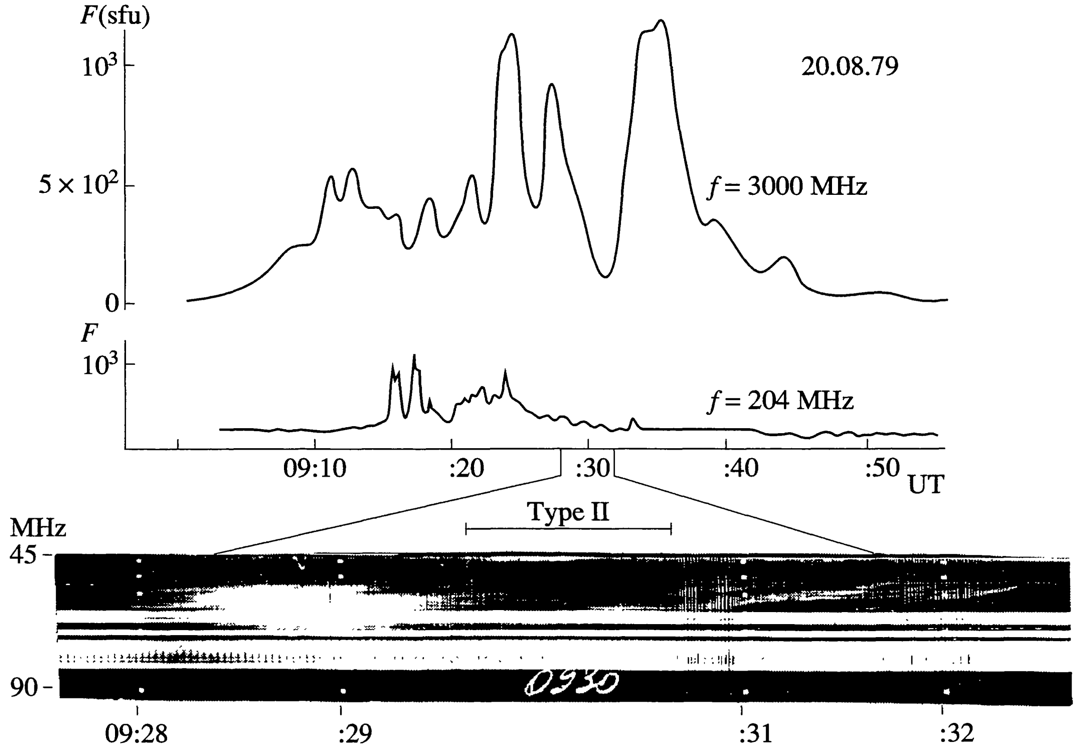

Fig. 2. Slowly drifting fibers in the type-II burst of August 20, 1979 in a dynamical spectrum from 45–90 MHz (below) and the time profiles of the flux density F of the meter- and centimeter-wavelength radio bursts in solar flux units (1 sfu = 10^{-22} W/m^{2}Hz). The burst at 10 cm shows developed multiple components (MC) and a strong delay of the maximum relative to the meter burst.

Events 2 and 17 are included because of the presence of zebra structure at low frequencies. Nearly horizontal zebra structure bands were observed over three hours in the period between two CMEs in event 18; the position of the first CME above the active fiber at 06:03–07:36 UT coincided with the radio source of the fine structure at 236 MHz.

The most remarkable unusual fine structures in the table are slowly drifting fibers (F) in the flare continuum, which are directly related to type-II bursts (in 15 events). Some properties of such fibers have been discussed in the literature [see Fig. 9 of Ishkov *et al.* (1985), Fig. 5 of Gnezdilov *et al.* (1981), and Figs. 3 and 4 of Chernov (1990b), for example] but without accenting the well-defined association with CMEs. Their main difference from the usual fibers (fiber bursts) in type-IV bursts is their wider instantaneous bandwidth (~3 MHz at 100 MHz), order-of-magnitude lower frequency drift $df/dt \sim -0.1$ to -0.2 MHz/s, and substantially longer duration (to 70 s).

One unifying property of all these unusual fibers is a slow or wave-like frequency drift. Although the structures of these fibers are different in each event and require individual examination, most of them have a forward drift, characteristic of type-II bursts, and do not exhibit low-frequency absorption. Typical examples are the events of August 20, 1979 (Fig. 2), February 3, 1983 [Fig. 9 of Bakunin *et al.* (1991)], and October 12, 1981 (Fig. 3). In the event of April 24, 1985, we observe a braided fiber (fiber burst) in close connection with slowly drifting absorption fibers and with millisecond pulsations in the post-maximum phase of the flare (Fig. 4a).

INTERPRETATION OF THE SLOWLY DRIFTING FIBERS

Series of Fibers in Type-II Bursts

Our first, natural suggestion about the nature of the unusual fibers in type-II bursts is that they are associated with the existence of ordered, elongated, dense regions or narrow loops in the corona. In this case, the fibers could arise during the propagation of shocks through a system of such loops which are extended along the force lines at various angles to $\mathbf{f}_{p_e}$. The increased density in the loops would maximize the generation of radio emission there, and their structure could explain the discreteness and frequency drift of the fibers.

However, certain repeating type-II bursts do not support such a picture. For example, the burst of August 20, 1979, which directly preceded a type-II burst, had an usual, clumpy structure at the same frequencies (Gnezdilov *et al.* 1981). Since the formation and disruption of dense, extended loops cannot occur in only a few seconds, we would suggest that in each case the

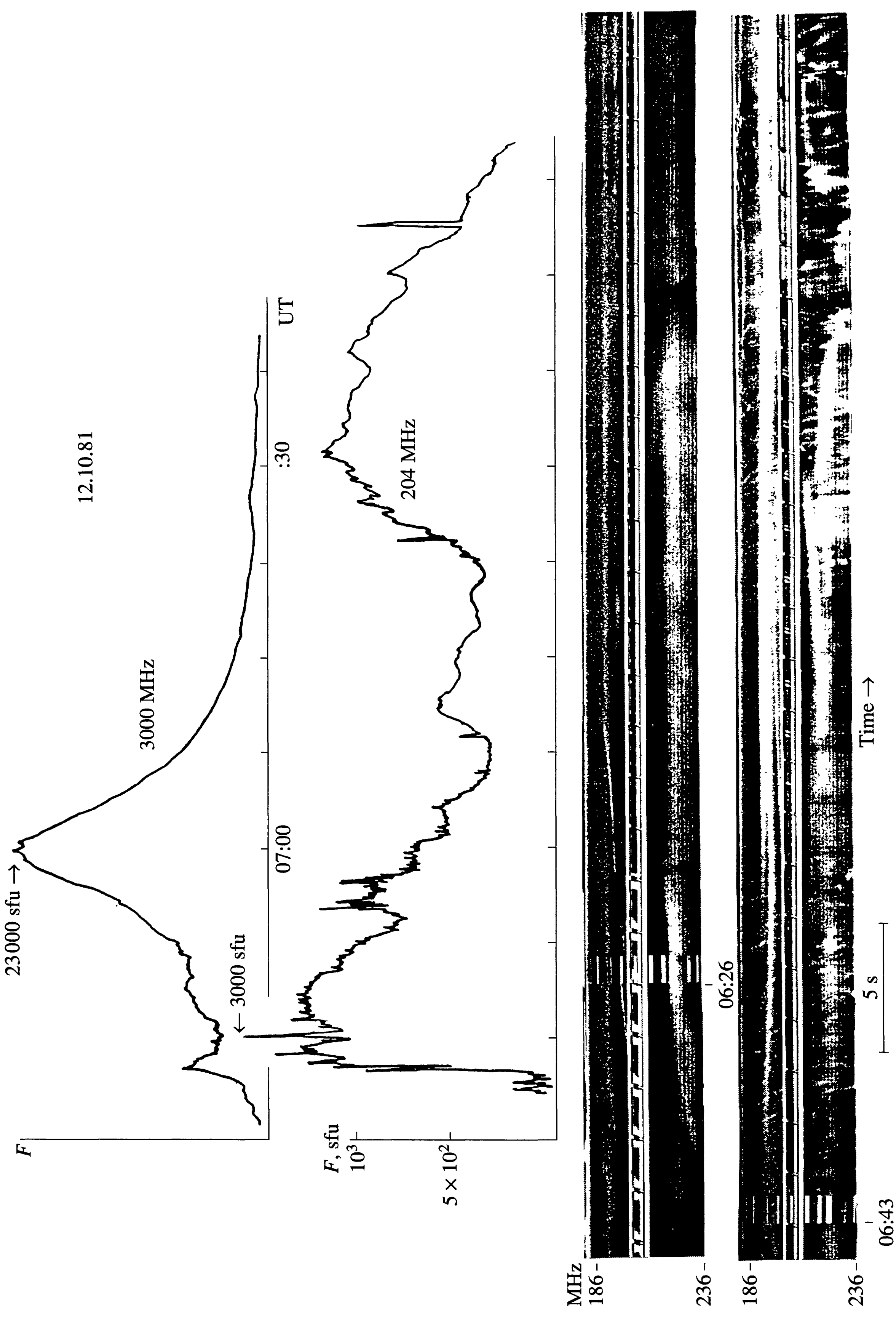

Fig. 3. Slowly drifting fibers in the flare continuum (after a type-II burst at 0626 UT) and the zebra structure background (at 0643 UT, below) in a high-resolution spectrum from 186–236 MHz in the major burst of October 12, 1981. The maximum of the centimeter-wavelength burst gradually grows and decays (GRF), and is appreciably delayed relative to the burst maximum at 204 MHz.

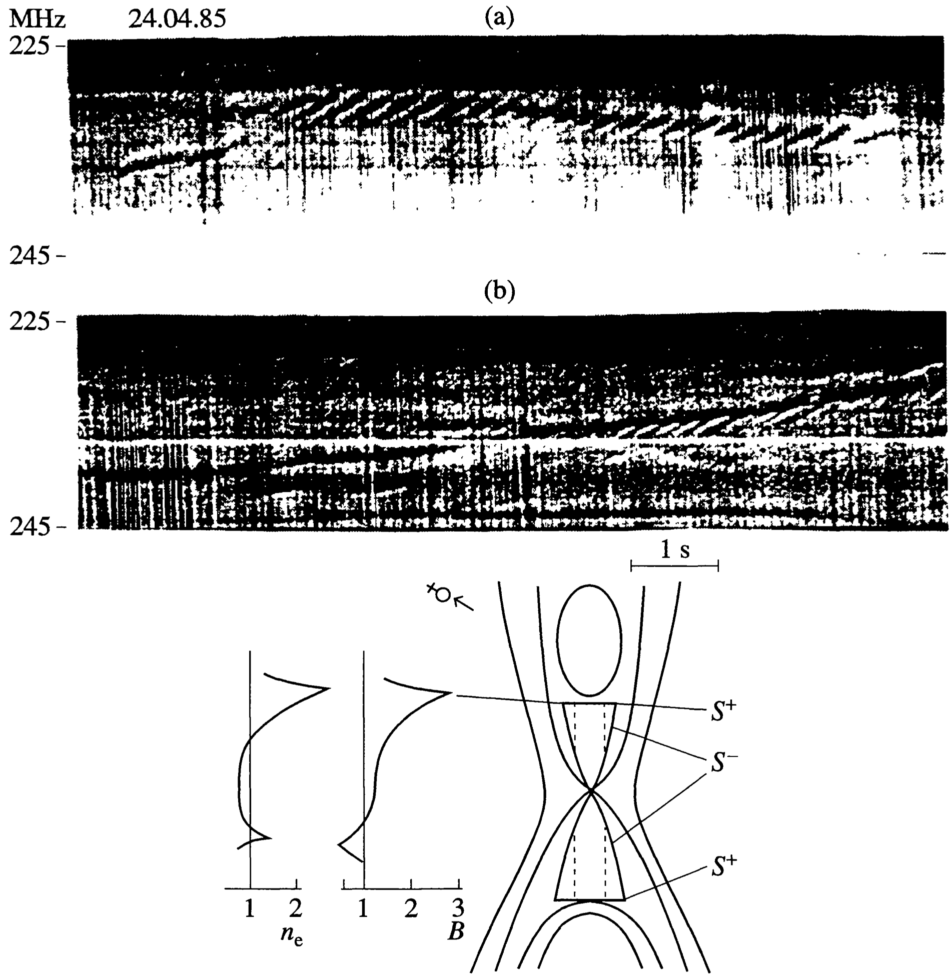

Fig. 4. (a) Braids of fibers (fiber bursts) at the post-maximum phase of the major event of April 24, 1985, accompanied by unusual, slowly drifting absorption fibers and millisecond pulsations. (b) Qualitative picture of quasi-stationary reconnection with an X point during the establishment of the magnetic configuration after the outward movement of a transient (CME). The dashed lines represent possible trajectories of whistlers trapped between the rapid S^+ and slow S^- shock fronts. The curves to the left show the rough variations of the magnetic field B and the electron number density $\mathbf{n}_e$ along the trap—the rarified region between the fronts [according to the model of Sidneva and Semenov (1985)].

fibers are created by an emission mechanism, rather than by the structure of the corona.

A number of data sets on interplanetary shock waves (Richter *et al.* 1985; Tokar *et al.* 1984) and the Earth's shock wave (Galeev 1988) indicate the presence of plasma waves and whistlers ahead of the shock fronts. An analogous model with a source of plasma waves ahead of a shock front has been considered for type-II radio bursts, which are associated with shocks with Mach numbers <2 (Holman and Pesses 1983). It is, therefore, logical to consider the fiber structure of type-II bursts to be the result of the propagation of whistlers through clumps of plasma waves ahead of a shock front. The plasma waves could be emitted by the same electrons (reflected from the shock front) that emit the whistlers. The frequency drift of the fibers is determined by the direction of propagation of the whistlers relative to the electron density gradient.

The main peculiarity of these fibers is attributable to the absence of any obvious absorption at the low-frequency edge and to their varying durations (from 5 to 70 s). There are no trapped rapid particles (in general) ahead of the front of a collisionless inclined shock wave; therefore, the interaction of the whistlers and the rapid particles cannot be long in duration.

After each impulsive injection of particles, whistlers excited in the normal Doppler resonance will move toward the particles and the shock front, while the whistlers excited in the anomalous resonance will move at a large angle in the direction of motion of the particles. Judging from the negative frequency drift of the fibers, whistlers should be excited in the anomalous resonance and propagate forward from the front or remain nearly stationary relative to it. The possibility of the presence of whistlers ahead of a shock front was first discussed by Helliwell (1969).

Thus, a particle beam with conical anisotropy moves along the magnetic field lines, and whistlers propagate at large angles to the field, interacting with plasma waves after some isotropization. The absence of bounce motions of the particles ahead of the shock front explains the lack of strict periodicity of the fibers. In each case, there are essentially no quasi-linear whistler effects, and they should weaken the instability of the plasma waves, which also determines the low-frequency absorption (Chernov 1990b). However, there cannot be absorption at the low-frequency edge without diffusion of the rapid particles in the whistlers, as confirmed by the observations.

The relative rarity of the appearance of fibers in type-II bursts suggests that the whistlers and plasma waves are often not cospatial ahead of the shock front. However, the conditions for forming fibers could be easily satisfied if a type-II burst is accompanied by a transient, whose outward movement is associated with magnetic reconnection and extended energy release in a vertical current sheet (Kuznetsov 1994). Particles accelerated during the reconnection excite the plasma waves which are responsible for the FCII continuum, and the conditions for fiber formation are realized against the background of this continuum. In such a picture, we can understand the general conditions for the formation of fibers in most type-II bursts associated with CMEs (in events 1, 3–7, 9–14, and 16 in Table 1).

Long-lived, Slowly Drifting Fibers in the Flare Continuum

The slowly drifting fibers in the FCII continuum in the events of February 3, 1983 (Bakunin *et al.* 1991), and October 12, 1981 (Aurass and Chernov 1983), are distinguished by their long durations, small numbers (single fibers with duration 0.5–2 min), and weak absorption at the low-frequency edge. In the former event, the FCII flare continuum had a sharp, drifting, high-frequency cutoff. Taking into account the overall picture of the source, with forward and reverse shocks with tangential discontinuities between them (Bakunin *et al.* 1991), we suggest that, in the event of February 3, 1981, we observed a whistler wave packet trapped between the forward shock front and a tangential discontinuity. The trapping of rapid particles in this region and their diffusion in the whistlers can explain the weak absorption at the low-frequency edge. The sharp, high-frequency cutoff of the continuum can be explained by the propagation of the reverse shock through the "body" of the transient, toward lower electron densities.

In this event, zebra structure at rather low frequencies (90–120 MHz) was observed together with the unusual fibers. The presence of two scales for the frequency division between the bands of the zebra structure suggests that the emission from the different bands is from sources with different magnetic field strengths before and after the tangential discontinuity, i.e., directly connected to the CME.

Braids of Fibers with Intermediate Frequency Drift

The braids of fibers accompanied by long-lived absorption fibers in the event of August 24, 1985, (Fig. 4a) require special consideration, since they were observed for more than an hour in the post-maximum phase of the flare (Aurass *et al.* 1987). Our subsequent, more-detailed analysis revealed a number of similar braids in the event of October 12, 1981, as well, also lasting more than an hour after the flare maximum, although this event was included in the table because of the obvious presence of unusual fibers in the flare continuum at the maximal phase (Fig. 3).

One published theory (Mann *et al.* 1989) is based on a threshold for the activization of the whistler conical instability when the critical angle of the loss cone is exceeded due to additional perturbation of the magnetic trap by a rapid magneto-acoustic wave. This scheme can be applied to CME models that include the disruption of the equilibrium of magnetic formations in the corona under the action of perturbations propagating from the flare region, e.g., magneto-acoustic waves [see Fig. 9 in the review by Kuznetsov (1994)]. However, it is applicable only in the case of injection of a large relative number of energetic particles ($\mathbf{n}_h/\mathbf{n}_c \sim 10^{-2}$) into a magnetic trap with a large stopper ratio.

A whistler excitement threshold in terms of the loss cone angle that is realized only when we take into account the contribution of thermal ions in the dispersion relation is of general importance for sources of type II–IV radio emission; however, we must stretch the theory to explain the more rapid repetition of the fibers in braids, the deep modulation of the continuum, and certain other properties. In addition, this picture does not include the most important elements accompanying the braids—the slowly drifting absorption fibers and the millisecond pulsations.

We will, therefore, consider another probable fiber braid source, which is directly related to the reconnection CME model of Anzer and Pneuman (1982) and which is located in a vertical current sheet with X points. The multiple formation of magnetic islands along an elongated current sheet with X points high in the corona was calculated by Forbes and Priest (1983). Beginning with the stationary phase, here is a reconnection between the magnetic islands and the lower closed loop.

With the onset of nonstationary reconnection with an X point (Fig. 4b), two pairs of slow shock waves (S^-) and two rapid shock fronts (S^+) move outward from the reconnection region (Sidneva and Semenov 1985; see also Fig. 1 in Xu and Forbes 1992). There is a reconnection of force lines across the region surrounded by the slow fronts. The rapid shock fronts form here, because streams of plasma flowing from the rarified region upward and downward from the X point with the Alven velocity run into a transverse field (analogous to the situation with planetary head shock waves). Rapid shock fronts in regions of reconnection were first predicted by Yang and Sonnerup (1976); this prediction was later confirmed in the calculations by Podgornii and Syrovatskii (1981).

The subsequent computations by Forbes (1988) and Robertson and Priest (1988) suggest that the fiber braid source is located between shock fronts in the rarified region around the X point. The numerical calculations of explosive reconnection (after which the CME occurs) of Sakai and Ohsava (1987) indicate that the magnetic field triples in the rapid front, and that the ions and electrons undergo quasi-periodic acceleration by the induced electric field with a period $\sim 10\Omega_{B_i}^{-1}$.

Note that the multiple formation and destruction of magnetic islands in the vertical current sheet is also possible in the process of establishing magnetic structures after the outward movement of the transient. This could correspond to the unusual fibers in the post-maximum phase of an event. The rapid and slow fronts are compression waves, but while the magnetic field is roughly tripled in a rapid front, it is weakened in a slow front, so that rarefactions form in the region surrounded by the shock fronts, as shown in the calculations of Somov *et al.* (1987) and Karlickü'y (1988). In the quasi-stationary reconnection stage, the X point moves smoothly with a velocity $\sim 0.1\mathbf{V}_a$, where $\mathbf{V}_a$ is the Alfvén velocity.

The most obvious and necessary effect in this picture is the lowering of the continuous emission from the rarified regions due to screening by the shock fronts. Because of this screening, the slowly-moving rarified regions should give rise to slowly-drifting absorption fibers, which are in fact the most characteristic features accompanying fiber braids. Their bandwidth of ~2–3 MHz corresponds to the height of the rarified region along $\mathbf{f}_{p_e}$ in the corona, ~2–3 × 10^8 cm.

The fiber braid radio source should not be associated with the oscillatory structure of the rapid fronts, since these fronts are very narrow, at most $\sim c/\omega_{p_i} \sim 7$ m (for $\omega_{p_i} = (2\pi \times \frac{3}{43}) \times 10^8$ Hz). However, the accelerated rapid particles could be reflected off the rapid fronts and could form a conical distribution with a large loss cone angle near the front. The particles become captured in a small trap between the upper and lower rapid fronts S^+, near which there is a sharp increase in the conical instability of the whistlers.

While the distribution function for the electrons reflected from the front correspond to an anisotropic beam (with conical anisotropy), the maximum contribution to the instability is given by the cyclotron resonance in the anomalous Doppler effect, and the whistlers propagate together with particles toward the slow front until cyclotron damping becomes important (when ω_w is close to $0.5\,\omega_{B_e}$). The cyclotron damping gradually increases, since the relative frequency of the whistlers $x = \omega_w/\omega_{B_e}$ smoothly grows with decrease in the field. Instantaneous cyclotron damping at the minimum field acts only in the slow shock front $\mathbf{S}^-$. Using the above estimate for the size of the rarified region ~10^8 cm, we can roughly estimate the time for propagation of the whistlers between the rapid and inclined slow fronts with group velocity ~5 × 10^8 cm/s [for $\omega_{p_e}/\omega_{B_e} \sim 15$ and $x = 0.03$, determined for this event by Mann *et al.* (1989)]. The result is ~0.5 s, which corresponds to the observed duration of separate fibers in a braid.

The whistlers propagate toward decreasing density, which explains the observed negative frequency drift of the individual fibers in a braid. The periodicity of the fibers is associated with the bounce motions of particles in the small trap between the rapid fronts. This leads to the higher periodicity of the fibers in a braid ~5–6 s^{-1} compared to the usual periodicity of fibers ~1–2 s^{-1}.

According to the calculations of Mal'tseva and Chernov (1989), the instability of whistlers in this model grows to a rather high level at substantially lower rapid particle densities ($\mathbf{n}_h/\mathbf{n}_c \sim 10^{-4}$–$10^{-5}$), which are more realistic high in the corona. The occasional appearance of continuous emission at the high-frequency edge of the absorption fiber could be associated with the emission of escaping electrons. Because of the strong directivity of the fiber radio emission from the merging of plasma waves and whistlers, only a small fraction of the radio emission from the small magnetic trap is directed toward the Earth.

Taking into account that the loss cone is emptied twice over the bounce period between the stoppers at either end of the trap and that the periodicity of the braid fibers is ~0.2 s and assuming a particle velocity of ~2 × 10^9 cm/s, we estimate the size of the region between the rapid fronts to be ~2 × 10^8 cm. This indeed corresponds to the width of the absorption fibers due to the screening of the continuous emission from this area by the shock fronts. The diffusion of rapid particles in whistlers in the small magnetic trap should weaken the instability of the plasma waves, i.e., it should lead to the usual high-frequency absorption of individual fibers in a braid. Series of braids correspond to a sequence of reconnections with X points in a vertical current sheet.

In this picture, the plasma in the reconnection region should not be isothermal ($T_e > T_i$), primarily due to the predominant heating of electrons in the shock fronts. Therefore, a mechanism in which the millisecond pulsations are the result of a pulsating merging regime and the decay of whistlers in ion-acoustic waves should work (Chernov 1989a,b). The ion-acoustic waves should encompass a large height interval in the vertical current sheet, so that the millisecond pulsations appear at a wide range of frequencies.

Thus, this picture for the fiber braids should work in direct association with a CME. It can explain not only all the main properties of the braids but also a number of accompanying features of the radio fine structure.

CONCLUSION

Our analysis of the radio fine structure in 18 bursts, for which the information about associated CMEs was available, indicates the presence of (1) slowly drifting fibers in type-II bursts or in the associated flare continuum in the impulsive phase or (2) unusual braids of fibers accompanied by slowly drifting absorption fibers and millisecond pulsations at the post-maximum phase. Zebra structure at unusually low frequencies (to 45 MHz) is also observed.

We have examined possible schemes and models for the radio emission of these special features of the fine structure in the framework of known emission mechanisms, taking into account the direct connection between the radio sources and CMEs, which, in fact, form the basis for this study. The statistics of this relation are limited by the impossibility of observing CMEs at the center of the solar disk, when the conditions for observing radio fine structure are optimal.

The specific fine structure noted above was observed both in short-lived (sometimes impulsive) and long-duration radio bursts, but in different events, the corresponding centimeter-wavelength bursts either gradually grew and decayed or had multiple components, providing evidence for extended energy release high in the corona. The corresponding active regions in both cases were multi-polar and elongated. The distribution of all events over the solar disk does not reveal any unusual features, except for the absence of limb events, in connection with the directivity of the radio emission.

The detection of unusual, slowly drifting fibers in emission and absorption and low-frequency zebra structure can be used as a radio-based diagnostic for CME events.

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