Solar Radio Observations and Interpretations

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Solar radio observations and interpretations

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[Plates 39–43]

The recent solar radio observations related to flares are reviewed for the frequency range of a few kilohertz to several gigahertz. The analysis of the radio data leads to boundary conditions on the acceleration processes which are responsible for the fast particles which cause the radio emission. The role and cause of plasma turbulence at the plasma-frequency and at much lower frequencies is discussed in relation to the acceleration processes and the radio emission mechanisms for the various radio bursts.

1. Introduction

Solar radio astronomy has experienced an upswing in activity in the last two years, as can be judged by the large increase of observational and theoretical papers on this subject in, for example, the journal *Solar physics*. The reasons for this are twofold: a number of new, much more advanced observational techniques came into use: the Culgoora radioheliograph (Wild 1967), the Clark Lake interferometer (Erickson & Kuiper 1973), the Nançay multilobe instrument (Vinokur 1968), the compound interferometer at Nobeyama (Takakura, Tsuchiya, Morimoto & Kai 1967), the Utrecht 60-channel spectrograph (De Groot & Van Nieuwkoop 1968); satellites became available for observations at frequencies below the ionospheric cutoff and a number of non-solar instruments like the Westerbork synthesis array were used for solar work as well. Secondly, theoretical work has made considerable progress: a vast amount of work done on weak turbulence in plasma (mainly, but not only, by the Russian workers) has given more insight in the many collective processes involving particle acceleration and non-thermal radio emission. It seems that only in recent years the second generation research in this field reached the point of practical applications, where for a long time there was no essential improvement over the initial ideas of Shklovsky (1946), Haeff (1948, 1949) and Wild (1950) with regard to 'plasma radiation at the plasma frequency'.

In the following paragraphs we will try to summarize some work in recent years with particular emphasis on the unsolved problems and on all those aspects that lead to more understanding of particle acceleration processes. For summaries of preceding years we refer to the reviews given by Wild, Smerd & Weiss (1963), Wild & Smerd (1972), Zheleznyakov (1970) and Kaplan, Pikel'ner & Tsytovich (1974).

2. Microwave bursts

By the end of 1972 it seemed that the problems with the interpretation of the solar microwave emission had been solved: the slowly varying component was thought to be due to thermal bremsstrahlung from relatively hot regions in the very low corona and the same explanation was given for the gradual rise and fall bursts.

The impulsive microwave burst posed a problem for some time: they showed excellent correlation in time and intensity profile with the hard X-ray bursts (Kane & Anderson 1970). However the number of electrons necessary to explain the microwave burst by cyclotron emission was 10^2–10^3 times smaller than the number of electrons (in the 10–100 keV range) required for the hard X-rays (see, for example, Takakura 1967). This discrepancy was basically due to two assumptions:

(*a*) the ion density had to be less than $\sim 10^{10}$ cm^{-3} since otherwise the collisional energy loss time would be very short. This was thought to be unacceptable because of energy considerations;

(*b*) the magnetic field strength B had to be such that the lowest harmonics of the electron gyro frequency were of the order of a few gigahertz, where the peak emission of the microwave burst occurs.

Numerous authors (Ramaty 1973; Takakura 1973) pointed out that the microwave emission can be effectively reduced and the steep spectra explained by taking into account: (1) the inhomogeneity of the magnetic field, (2) the steepness of the electron energy distribution, (3) the free–free absorption of the microwave radiation, (4) the Razin suppression of the wave emission, and (5) the gyro-self absorption of the wave radiation.

It is not yet certain which factor is dominant and it is quite possible that for different bursts different effects play a role. However, it seems that gyro-selfabsorption is the best candidate at present. A number of authors have used much smaller ion densities to explain the hard X-ray burst than before. Therefore the Razin cutoff frequency moves towards lower frequencies as well, and hence cannot explain the observations. The free–free absorption mainly flattens the radio spectrum at the low frequency side, contrary to many observed burst spectra. We would like to note however that the observed ratio of microwave over X-ray power does not necessarily lead to discrepancies if one accepts that the X-rays are emitted in a dense medium and continuous injection of fast particles or possibly reacceleration occurs. The observed ratio

$$P\ (\text{X-rays} \gtrsim 20\ \text{keV})/P\ (\text{radio} \sim 3\ \text{cm}) \approx 10^{+2}$$

(Kane 1973); by using the simple bremsstrahlung formula for the X-ray emission and the Larmor formula for the μ-wave emission (the electrons are non relativistic) we find for the ratio of the emissivities, assuming a cospatial X-ray and microwave source

$$P\ (\text{X-rays})/P\ (\text{radio}) \approx 1.4 \times 10^{-7}\ N/B^2 \approx 1.2 \times 10^4\ \beta T_6^{-1},$$

where N is the ion density in cm^{-3}, B the magnetic field strength in gauss (10^{-4}T), β the ratio of kinetic pressure to magnetic pressure and T_6 the temperature in 10^6 K. From the observations one finds a value of 10^2 for the ratio P(X-rays)/P(radio) (Kane 1973), which leads to $\beta \approx 0.01 T_6$. Typical values of β above an active region are of the order of 0.05 (Rosenberg & Tarnstrom 1972), and hence the discrepancy discussed above is mainly caused by assuming relatively strong coronal magnetic fields and low densities.

In the last two years considerable progress has been made in the field of high resolution microwave measurements. The slowly varying component was found to contain absorption features over filaments (Kundu 1972). Hot spots were found above active regions with brightness temperatures exceeding normal quiet values (Felli, Pampaloni & Tofani 1974; Hobbs *et al.* 1974; Lang 1974). A gradual rise and fall burst was observed to have a brightness temperature of 10^8–10^9 K. (Kundu, Velusamy & Becker 1974). In this context we also want to mention that Riddle (1974) found evidence for a nonthermal component in the metric slowly varying component. All these high brightness temperatures indicate that a nonthermal process plays an important role, even under seemingly quiet conditions. The values of the observed brightness temperatures are close to the maximum brightness temperatures for gyro-selfabsorbed sources (Ramaty 1973). If higher brightness temperatures are found, we will therefore have to reconsider cyclotron radiation even at these high frequencies as the emission mechanism for those nonthermal sources. Both high spatial resolution observations and high resolution spectrography in this frequency range can give an indication whether collective radiation mechanisms and associated plasma instabilities play a role in the microwave region. Important parameters for the possible occurrence of collective effects are the number of electrons in a Debye sphere N ($N = 4 \times 10^{-15}\, v_e^3\, n_e^{-\frac{1}{2}}$, with v_e the thermal electron velocity and n_e the electron density) and the collision frequency $\nu_c \approx n_e/T^{\frac{3}{2}} \approx \omega_p/N$, with ω_p the angular plasma frequency. In the photosphere and chromosphere $N \gtrsim 1$ and $\nu_c \lesssim \omega_p$ and hence collective effects are unimportant. However, as soon as we enter the corona where the temperature rises very quickly and the density drops, $N \gg 1$, $\nu_c \ll \omega_p$ and collective phenomena can be expected. The so called microwave type IV continuum (Wild *et al.* 1963) can possibly be related to collective radiation phenomena. We will return to these continua in §3 while discussing the continua at lower frequencies.

3. Decimetric and longer wavelength solar radio bursts

The classification of solar radiobursts with frequencies below *ca.* 400 MHz has remained essentially unchanged over many years now (Wild *et al.* 1963; Wild & Smerd 1972) and is schematically shown in figure 1. The differences with former schematic spectra (Maxwell 1965; Wild *et al.* 1963) is the extension towards lower frequencies showing the dkm type III storms and their extension down to *ca.* 50 kHz. On the subclassification of the type IV continua 'there is at present no agreement on the precise characteristics..., nor on the nomenclature' (Maxwell 1965). In the following we will discuss some aspects of these different types of bursts.

(*a*) *Type I storms and dkm (and longer wavelength) type III storms*

The narrow band, short lived, highly polarized and intense type I bursts (figure 2, plate 40) remain still largely unexplained, although some efforts in the direction of an explanation have been made (Kaplan *et al.* 1974).

During a type I storm the individual type I bursts are often grouped in chains which drift slowly in frequency, usually towards lower frequencies (figure 2; Wild 1957; Wild & Tlamicha 1965; Hanasz 1966; Elgarøy & Ugland 1970; Markeev & Chernov 1971).

Both the underlying continuum and the bursts themselves are usually highly circularly polarized, probably in the ordinary mode, and the height of the source indicates emission near the local plasma frequency (Gnezilov 1970; Le Squeren 1963; Fokker 1960). The sources are often bipolar and occasionally associated with filaments (Kai & Sheridan 1974). They seldomly occur above 300 MHz, and have been observed in the dkm range. The bandwidth of the individual burst is of the order of a few megahertz, and the band over which a type I storm extends at a certain time is of the order of tens of megahertz. Finally, although occasionally a flare occurs at the onset of a type I storm, type I bursts or storms are not flare related.

These different facts all point towards a nonthermal collective emission process near the plasma frequency. The dm type III storms are always accompanied by a type I storm at higher frequencies and again are not flare related (Boischot, de la Noë & Møller-Pedersen 1970).

We therefore conclude that an acceleration process occurs in the corona, producing the electrons needed for the dkm type III storm, and it is tempting to relate the type I storm to this acceleration process. The energy can be supplied by a relaxing magnetic field configuration, which is either disturbed by a preceding flare, or which is adjusting to changing conditions in the photosphere. The fact that type I storms occur only below 300 MHz, suggests that the solar wind plays a role in this phenomena as well, possibly by opening up closed magnetic field configurations. A number of authors have invoked colliding shockwaves, Alfven waves and other modes of disturbances to explain the type I burst phenomenon (see Kaplan *et al.* 1974). But the reason for their presence or absence has remained obscure. The interaction of the solar wind with a magnetic configuration that experiences slowly varying boundary conditions, can certainly produce the weak shocks used in the theories mentioned above, but no complete physical picture is available as yet. Type I bursts should get much more attention theoretically and observationally, since they indicate particle acceleration processes high in the corona, without the many complicating dynamics in a large solar flare.

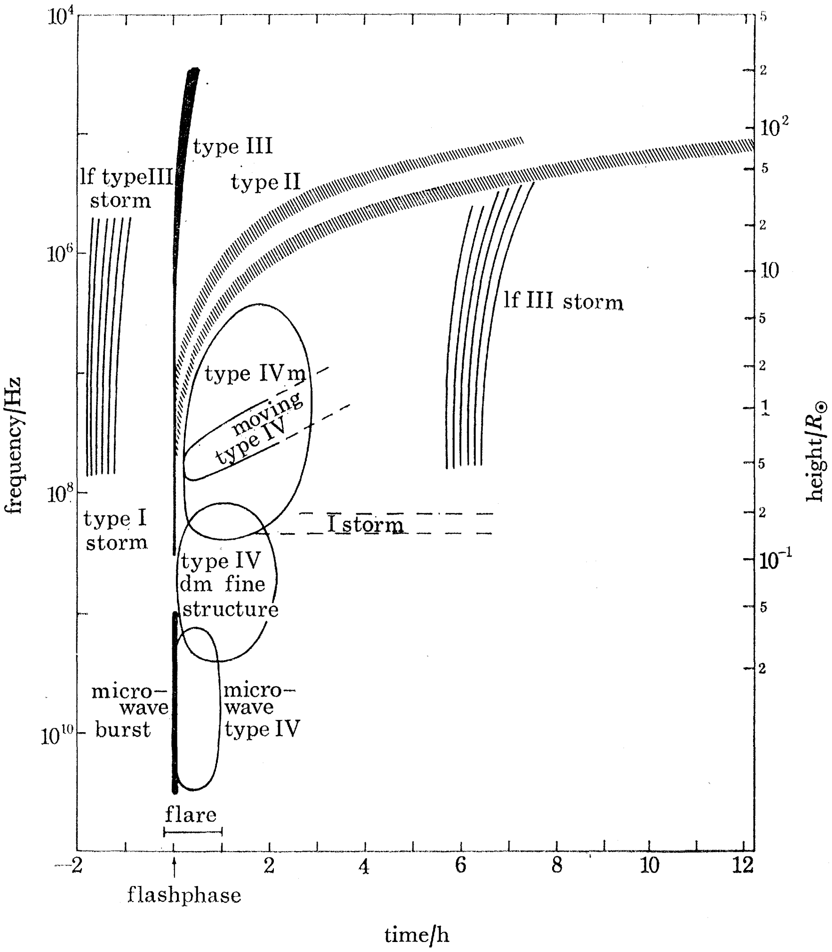


Figure 1. (*a*) Schematic representation of the radiospectrum during and after a large flare. The low frequency type III storms and the type I storms preceding and following the flare are not necessary ingredients. Only one type III burst has been drawn, although usually a group of approximately ten occurs at the flash phase. Only the envelopes of the respective type IV bursts have been drawn: usually only part of them is filled. The height scale on the right hand side corresponds to the plasma level of the frequency scale on the left hand side.

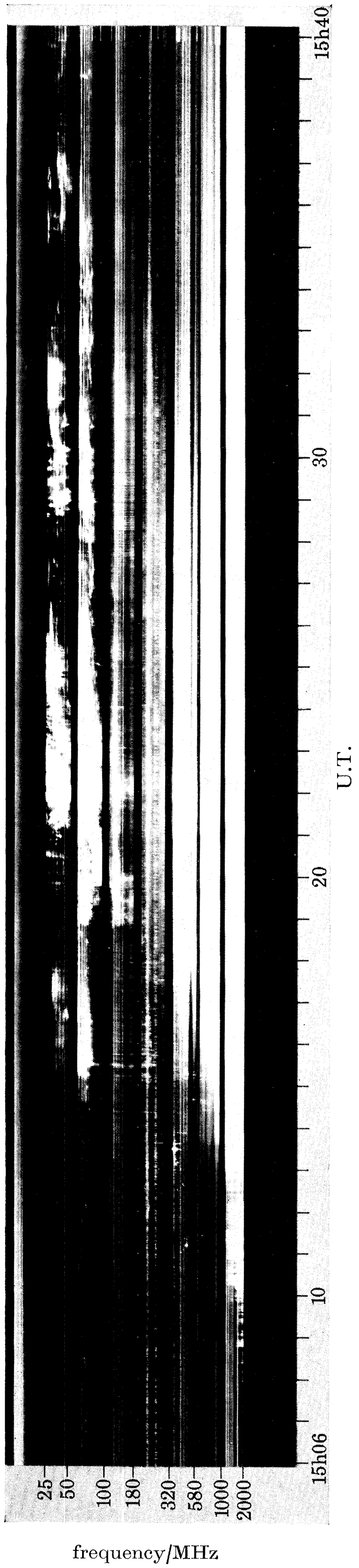
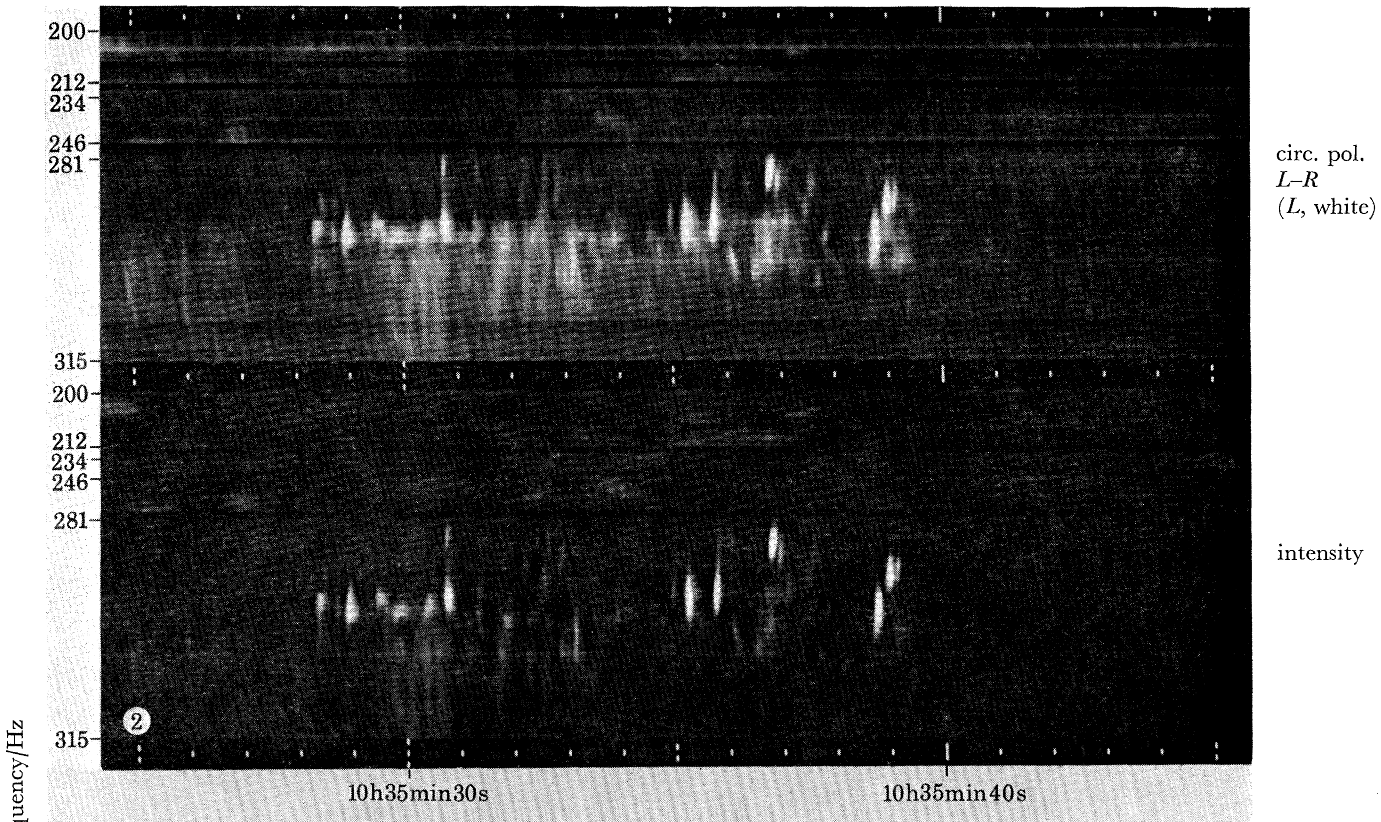


FIGURE 1*b*. Radio spectrum of the large outburst of 7 August 1972. Various types can easily be recognized by comparison with figure 1*a*. Courtesy of Dr A. Maxwell, Harvard Radio Astronomy Station, Fort Davis, Texas.



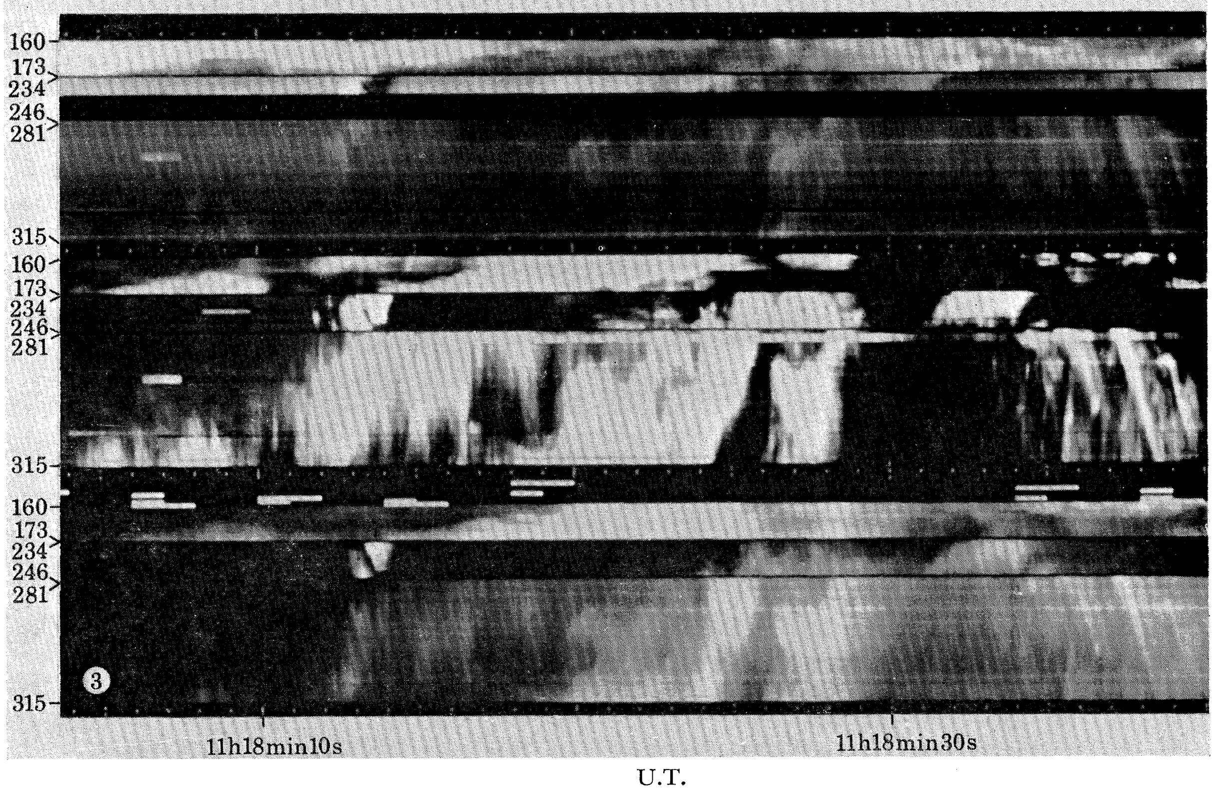
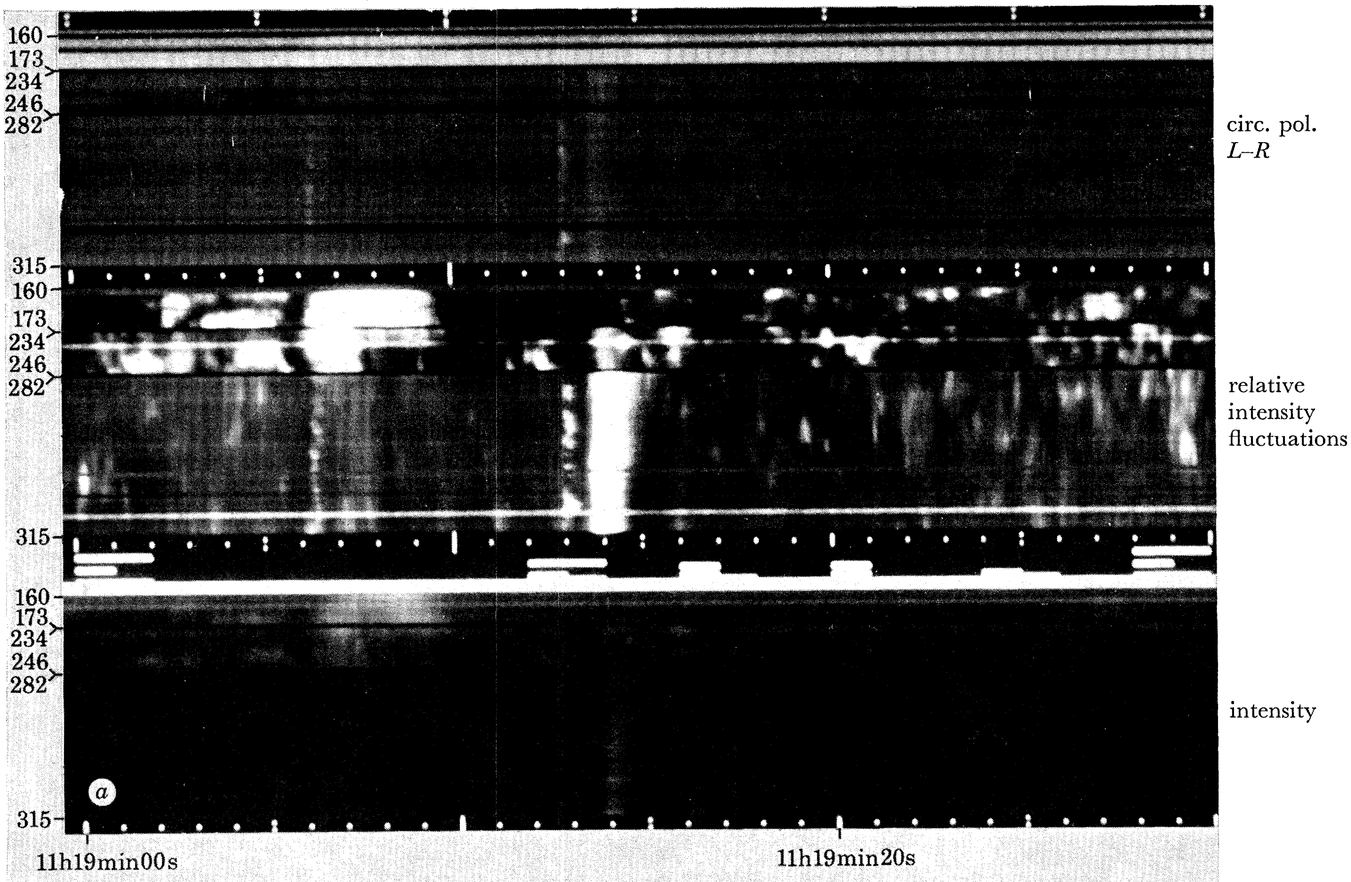


Figure 2. High resolution spectrum of a type I burst chain on 11 July 1974. 60 channel Utrecht radiospectrograph of Solar Radio Observatory, Neth. Foundation of Radio Astronomy, Dwingeloo, Netherlands.

Figure 3. Detail of a type II burst on 6 March 1972. Note the absence of fine structure in the fundamental band (160–173 MHz) and the short duration, wide band fine structure in the harmonic band. 60 channel radiospectrograph.



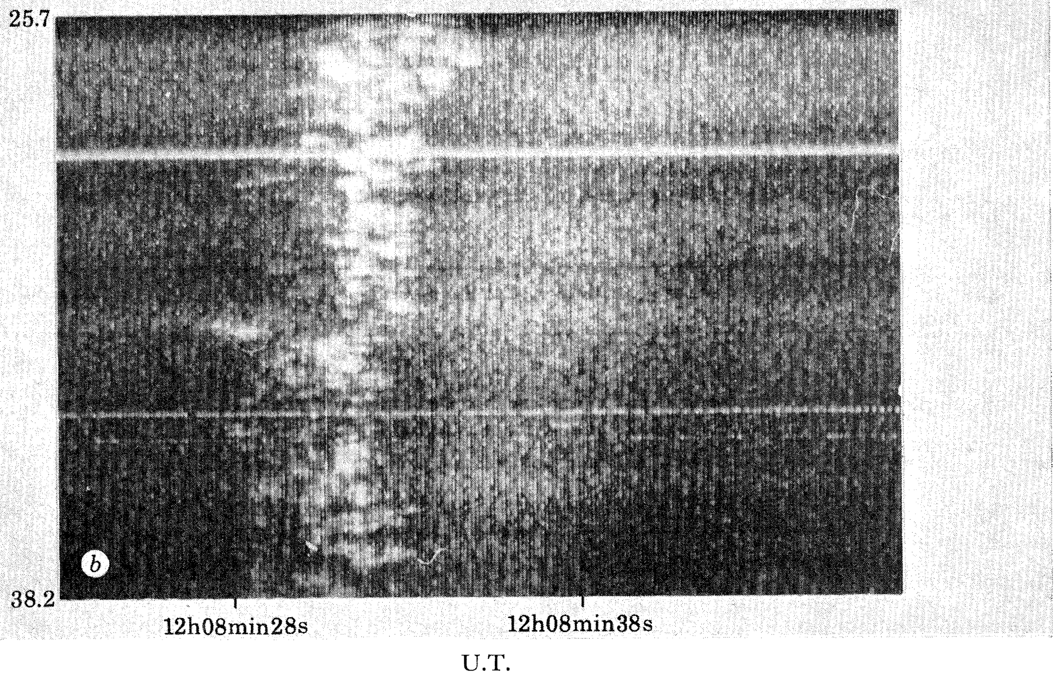


Figure 4*a*. High resolution observation of a type III pair on 10 March 1973. Note the circular polarization at the start of the type III bursts, and the great amount of fine structure in time and frequency. 60 channel Utrecht radio spectrograph.

Figure 4*b*. Example of a high resolution observation of a type IIIb burst on 19 December 1974. Courtesy of Dr J. de la Noë, Decametric Radio Group, Meudon Observatory at Nançay Station, France.

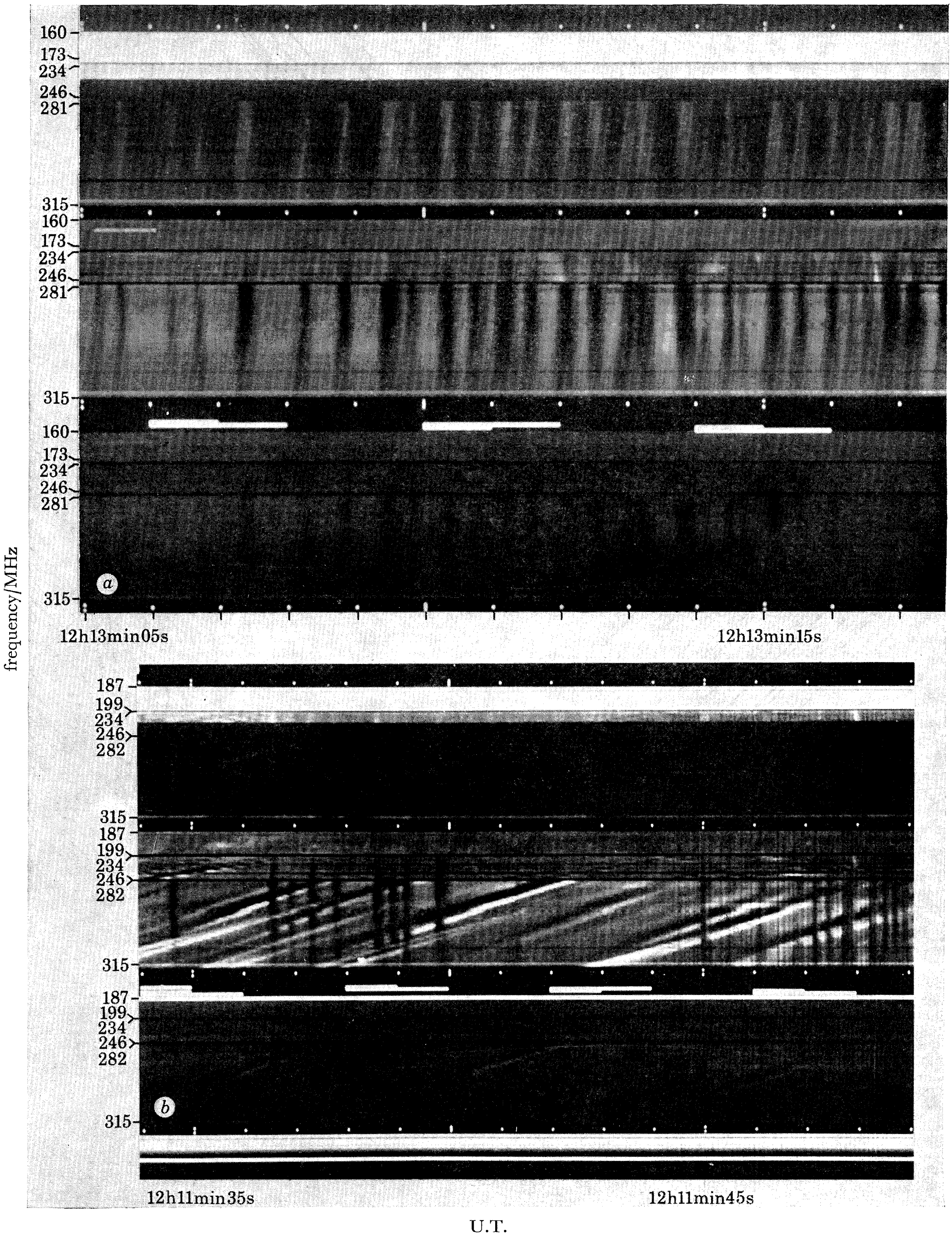


FIGURE 5. Type IV fine structure. (*a*) Pulsating structure in a type IV burst on 6 March 1972. 60 channel Utrecht radiospectrograph. (*b*) Intermediate drift bursts or fibre bursts on 6 March 1972. 60 channel Utrecht radiospectrograph.

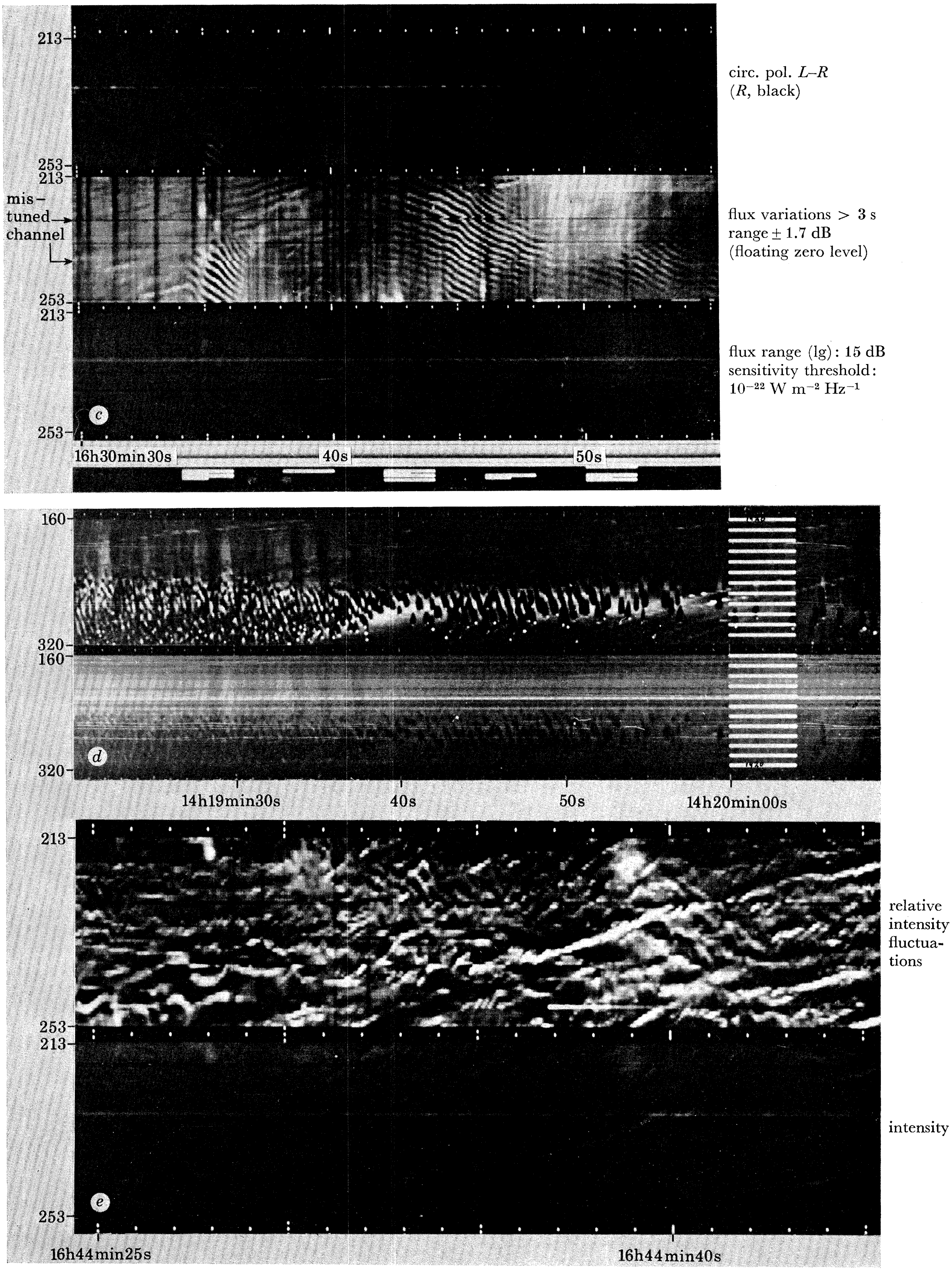


FIGURE 5. Type IV fine structure. (*c*) Parallel drifting bands or zebra structure on 26 June 1971. 60 channel Utrecht radiospectrograph. (*d*) 'Tadpole' structure on 2 March 1970. 60 channel Utrecht radiospectrograph. (*e*) Highly complex, not classified structure in a type IV burst on 29 June 1971. 60 channel Utrecht radiospectrograph.

(*b*) *Type II bursts*

The type II burst (figure 3, plate 40) is closely related to Athay-Moreton waves observed optically during a flare (Moreton 1964; Harvey, Martin & Riddle 1974) and there is good agreement between type II bursts, interplanetary shocks and geomagnetic disturbances particularly if the type II burst is accompanied by a type IV burst (Hundhausen 1972*a*). Hence the crude model of a shock wave moving away from the flare region and producing electromagnetic radiation at the fundamental and harmonic of the plasma frequency seems correct. Some problems remain however: Type II bursts usually start at frequencies below 200 MHz, i.e. much higher than where the shock wave originates. Many single type II bursts are probably harmonic bursts with the fundamental emitted below the ionospheric cutoff. Hence the necessary conditions for emission of electromagnetic waves are mainly met high in the corona and not close to the flare site. It is not clear what this condition is: there is no strong correlation between starting frequency (starting height) and velocity, the latter having a wide spread and being ≈ 1000 km/s on the average. Hence, the Alfvenic Mach number is not a very likely candidate, although Smith (1972*b*) found that a necessary and sufficient condition for production of electromagnetic radiation was an Alfvenic Mach number of approximately 2–3. Uchida (1974) traced the raypaths of a small amplitude mhd wave front starting from the flare region. He found that these paths followed regions of low Alfven velocity and that the type II brightness coincided with the predicted regions. Therefore the positional information seems to support the idea of a weak shock.

Most theories of type II bursts try to explain the radio emission by plasma-electrons turbulence which is set up by drifting inside the shockfront (Smith 1971, 1972*a*, *b*; Zaitsev 1966; Kaplan *et al.* 1974). If the drift velocity is high enough a beam plasma instability develops, and plasma waves grow with frequency ω_p in the frame of the electrons. In the laboratory frame however, the frequency of the excited waves is much less than the plasma frequency and hence this process cannot explain the observed electromagnetic radiation at ω_p (Smith & Krall 1974).

The actual situation must be more complicated: possibly only a small fraction of the electrons is being accelerated, in which case the excited plasma waves are carried by the remainder of the electron plasma (which remains at rest) and therefore have frequency ω_p. More insight in the detailed processes might be obtained from the wealth of fine structure shown in high resolution spectra (figure 3*b*), in which many fast drift structures are present.

Another problem which remains is the question whether we are dealing with a blast wave or a piston driven shock in the case of a type II burst (Hundhausen 1972*a*). Although the type II burst starts at the flash phase, the interplanetary shock wave structure shows that the energy release is not confined to the flash phase, but lasts at least as long as the optical flare and possibly considerably longer. Such a continuous driving force puts less limitations on the energy release mechanism in the flare than an impulsive release during the flash phase only.

Finally, the fact that during the Skylab mission many coronal transients have been observed, which did not produce strong type II bursts, shows that the simple fact of a disturbance is not enough to yield radio emission. Although all those transients probably produce low frequency turbulence, apparently only a few produce the high frequency turbulence near the plasma frequency, which is necessary to produce any observable electromagnetic radiation. (MacQueen *et al.* 1974).

(*c*) *Type III bursts*

Extensive reviews have recently been published on type III bursts (Solar radio group Utrecht 1974; Smith 1974; Fainberg & Stone 1974; Lin 1974), and in this paper we only discuss a few aspects.

A clear distinction should be made between the type III bursts occurring singly or in small groups ($N \lesssim 10$), which are flare related and have starting frequencies above 100 MHz and the low frequency (80 MHz to tens of kilohertz) type III storms which are not flare related and which last for hours or days. The latter are closely associated with type I storms (see §3*a*). The low frequency type III storms give evidence that particle acceleration is not confined to flares in the low corona or high chromosphere, but occurs in the high corona as well.

The low frequency type III bursts are all emitted at the harmonic of the local plasma frequency (Fainberg & Stone 1974), but in the case of high-frequency type III bursts many cases of fundamental harmonic bursts have been reported. This has caused considerable problems in explaining type III bursts (Smith 1974). It seems that most of this can be resolved by arguing that the majority of the fundamental-harmonic pairs are in fact two type III bursts following each other within a second, and which are both emitted at the harmonic of the plasma frequency (Rosenberg 1975). Type III bursts are thought to be due to an electron beam travelling outward through the corona and locally exciting plasmawaves by the beam-plasma instability. The growth rate of the instability is very large and leads rapidly to destruction of the beam; this caused numerous publications on the stabilization problem (Smith 1974). However, Melrose (1974*b*) probably solved the problem by showing that it is not the thermal noise in plasma waves which is being amplified in the instability, but the plasma waves which are spontaneously emitted by the beam electrons. This put a much less restrictive condition on the electron density in the beam, and increased the destruction time to approximately the observed type III duration. In this model the beam density is low and the source size large, that is, approximately equal to the observed size. Scattering effects should therefore be minimal, which is in accordance with emission at the harmonic frequency and with observations (Mercier & Rosenberg 1974).

High resolution observations have shown some remarkable results. Figure 4*a*, plate 41, shows an example of a metric type III burst with a highly polarized front (Slottje 1974). The discussion on whether this is due to propagation effects or intrinsic source characteristics is still unfinished (Riddle 1975). Figure 4*b* shows an example of fine structure in a decametric type III*b* burst, a subclassification of the type III bursts (De la Noë & Boischot 1972). Whereas normal low frequency type III bursts have a tendency to occur around central meridional passage, the type III*b* bursts show a preference for occurrence at the limb (De la Noë 1974; Møller-Pedersen 1975).

A different form of directivity in type III bursts pairs was observed during the Steréo experiment at 160 MHz, in which the preceding member of the pair was much more directive than the following member (Caroubalos, Poquérusse & Steinberg 1974). The directivity data indicate that scattering cannot be as important as has been assumed formerly, which is in agreement with the discussion on fundamental harmonic pairs mentioned above. The fine structure is still largely unexplained, although Zheleznyakov & Zlotnik (1971) suggested that double resonance effects in regions where $\omega_p = n\omega_{gyro}$ is important, and Rosenberg (1973) argued in favour of coupling of Bernstein waves at harmonics of the electrongyrofrequency and plasma waves.

(*d*) *Type IV bursts*

The classification of broadband continua from solar radio spectra alone has been far from unique (Wild *et al.* 1963; Maxwell 1965; Fokker 1963) and more insight is obtained when positional information is available as well. In that case the moving type IV continua, usually following a type II burst are a clearly identificable class. We feel that at present one best distinguishes between the following categories:

(1) Flare continua: broad band, highly complex continua during and shortly after the flare and following the type III and type II bursts at low frequencies, while occasionally preceding these bursts at high frequencies. The frequency range can be from several tens of GHz down to the ionospheric cutoff. Out of such a continuum two separate classes can develop:

(2) Type IV bursts with a height close to the plasma level. This includes most of the so called stationary type IV bursts (Weiss 1973). They often show a wealth of fine structure (see figure 5, plates 42 and 43). They can last for hours or possibly days and can develop into type I storms.

(3) Type IV bursts with position far above the plasma level. These include all moving type IV bursts (Weiss 1963; Schmahl 1973) and possibly some stationary type IV bursts as well. In these bursts the so called pulsating structure has been observed (Young, Spencer, Moreton & Roberts, 1961; Rosenberg 1970; McLean, Sheridan, Stewart & Wild 1971).

At present it is not clear whether the flare continuum belongs to class 2 or class 3; more positional information is certainly needed. The above classification offers the advantage that it is probably not just a phenomenological classification but also a division in emission mechanism.

Synchrotron radiation is severely affected by the Razin effect, which leads to a peak frequency of the emission at $\approx 1.5\,\gamma\omega_{\mathrm{p}}$, where $\gamma = E/m_0\,c^2$ (E the energy of the electrons). In practice the largest contribution arises from the fastest electrons present, with typical values for γ of about 10 (Ramaty & Lingenfelter 1968; Rosenberg 1975). Hence synchrotron radiation sources are expected to lie high above the plasma level, and because of the wide band nature of the emission, fine structure is only expected in time not in frequency. Therefore class 3 type IV bursts are best associated with synchrotron sources.

On the other hand, most emission processes involving plasma turbulence at the plasma frequency and other lower characteristic frequencies of the plasma should radiate at frequencies close to the plasma frequency. Furthermore we expect considerable narrow band fine structure in these sources (see below). Therefore class 2 type IV bursts are best associated with a collective emission mechanism.

Several problems remain with respect to the interpretation of both class 2 and class 3 type IV bursts. During part of their lifetime moving type IV bursts (belonging to class 3 or elevated type IV bursts) show a high degree of circular polarization (Schmahl 1973). This is then taken as an indication that we are dealing with emission at low harmonics of the electron gyrofrequency (Dulk 1973) leading to magnetic field strengths of about 1 mT, which is very high for these heights in the corona. Furthermore, the field has to be highly aligned in order to yield the observed degree of polarization. Neither the dynamic structure of such a plasmoid or the emission mechanism is fully understood; if the Razin effect is important, the derived magnetic field strength is much lower, however in that case it is difficult to explain the observed degree of circular polarization.

In these elevated type IV sources, the spectrum shows occasionally pulsating structure (figure 5*a*). Rosenberg (1970) tried to explain this by magnetohydrodynamic oscillations of the radiating magnetic field configuration which cause magnetic field strength variations and therefore wide band variations in the emitted synchrotron radiation. This interpretation leads to a pulsating source size of only 1000 km, which seems very small. A more refined analysis, to be published elsewhere, showed that because of the Razin effect the number of fast particles needed for the radio emission is much larger than assumed before. In that case the relativistic particle pressure exceeds the coronal gas pressure, but is still less than the magnetic pressure. In such a magnetoplasma very fast magnetohydrodynamic waves exist (Parker 1965) which are carried by the magnetic field and the fast particles instead of the coronal plasma. This leads to much larger pulsating source sizes in agreement with the observations. It was found that in the non fluctuating part of the type IV source $p(\text{magnetic}) > p(\text{fast particles}) > p(\text{corona})$ whereas in the pulsating part $p(\text{magnetic}) \approx p(\text{fast particles}) > p(\text{corona})$. In an inhomogeneous magneto plasma, where locally $p(\text{magnetic}) \sim p(\text{fast particles})$ a flute like instability should develop, causing fluctuations of the magnetic field strength and releasing fast particles in the surrounding source.

In class 2 or plasma level type IV sources a large variety of fine structure has been observed (Young *et al.* 1961; Maxwell 1965; Slottje 1972, 1973) (figure 5).

Intermediate drift bursts or fibre bursts (figure 5*b*), with typical drift rates between those of type II and type III bursts. Kuijpers (1973, 1975) has suggested that these bursts can be explained by nonlinear coupling of whistler waves and plasma waves, which are both excited by a loss-cone type electron velocity distribution. The whistlers have a tendency to be excited at lower levels, and propagate upward. In their course they couple nonlinearly with the plasma waves thus producing an enhancement of the radiation at the sum frequency and a depletion of the emission at the plasmafrequency, as is observed.

Parallel drifting bands (figure 5*c*) suggest immediately an explanation in the form of harmonics of some basic frequency and the most likely candidate is the electron gyro frequency. Several models have been proposed:

(*a*) nonlinear coupling of Bernstein waves at harmonics of the electron gyro frequency and upper hybrid waves (Rosenberg 1972; Chiuderi, Giachetti & Rosenberg 1973) or nonlinear coupling between Bernstein waves (Zheleznyakov & Zlotnik 1975), where both mechanisms occur within a homogeneous source;

(*b*) emssion in regions where double resonance occurs of the upper hybrid frequency and a harmonic of the electron gyro frequency (Kuijpers 1975; Zheleznyakov & Zlotnik 1975). The instability that grows at the double resonance frequency is again of the loss-cone type. Whereas in case (*a*) the frequency separation between the bands yields direct information on the electron gyrofrequency and hence the magnetic field strength, in case (*b*) one only obtains an upper limit for these quantities from the frequency separation.

'*Tadpoles*' or short lived, narrow band absorption-emission features (figure 5*d*). Zheleznyakov & Zlotnik (1975) give a detailed analysis of the growth and damping rates in the interval between two subsequent harmonics of the electron gyrofrequency. Above the lower harmonic the Bernstein mode is unstable, over the remainder of the interval this wave is damped, while in a very narrow bandwidth just below the upper harmonic a relativistic instability arises. This corresponds well with the observed frequency structure; the time structure is still largely unexplained.

The general emission of the continuum in the low-lying type IV sources has received considerable attention, most of which is focused on the production of Langmuir turbulence and subsequent transformation of this turbulence into electromagnetic waves at frequencies close to the plasma frequency (Kuijpers 1974). Loss-cone type electron distribution functions are certainly good candidates for the production of the Langmuir turbulence. The exact mechanism, and in particular the question whether one is dealing with instantaneous or continuous injection of the fast particles is still largely unknown.

4. Particle acceleration

From the preceding paragraphs we can draw the following conclusions with regard to the particle acceleration processes:

(*a*) During the flash phase acceleration of a great number of electrons to energies in the 10–100 keV occurs within time scales of 1 s. These electrons are responsible for the type III bursts, the hard X-ray bursts, the microwave bursts. The acceleration can occur in relation to solar flares, but it must also happen high in the corona not related to a flare, in order to explain the low frequency type III storms and the type I storms. Whereas in the case of flares the acceleration process probably does not last longer than the flare (10–30 min) in the coronal case conditions for particle acceleration are present for days.

(*b*) The acceleration to high energies (proton events, electrons with energy > 1 MeV) is confined to large flares, accompanied by type II bursts, and macroscopic motions. The elevated type IV bursts, in which synchrotron radiation by electrons with these energies is important, are evidence for this secondary acceleration mechanism. It occurs after the flash phase and following the type II burst and although typical acceleration times are difficult to determine a rough guess is 5–10 min.

A vast amount of literature has appeared on the subject of particle acceleration both by plasma turbulence and by the macroscopic Fermi process (Melrose 1974*a*; Tsytovich 1970; Kaplan *et al.* 1974). In combination with this we stress two points:

(*a*) Radio spectra as discussed above show the presence of plasma turbulence, whether at low frequencies or at the plasma frequency, with brightness temperatures of the order of 10^9–10^{10} K and higher. This turbulence is capable of accelerating electrons up to equivalent energies, i.e. $\approx$ 100 keV on very short time scales.

(*b*) The macroscopic Fermi process involving magnetohydrodynamic disturbances has a low efficiency for slow thermal particles and is not a very fast process. It is however capable of accelerating particles to very high energies.

We therefore suggest that during the flash phase of a flare and in type I sources low frequency plasma turbulence arises as the result of a magnetohydrodynamic instability, the latter being unspecified but a good candidate is the tearing mode instability (Coppi & Friedland 1971). This turbulence has large growth rates (growth times usually much less than 1 s) and can quickly accelerate electrons to energies equivalent to the brightness temperature of the turbulence. In large flares where macroscopic motions occur, Fermi acceleration can then take place, accelerating the preheated electrons to much higher energies.

This qualitative picture needs a lot more quantitative analysis. A present it is not clear which magnetohydrodynamic instability is responsible for the low frequency turbulence. Therefore, it is also difficult to calculate the expected spectrum of the turbulence and hence the efficiency of the particle acceleration. In particular the nonlinear effects which saturate the instability are virtually unknown. Nevertheless, the framework sketched above fits the observations and provides a guideline for further research.

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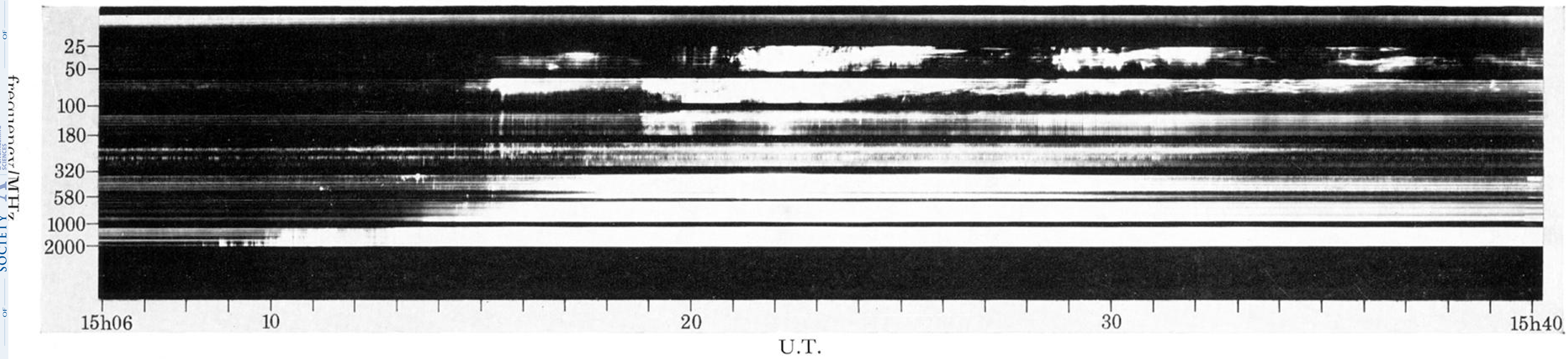
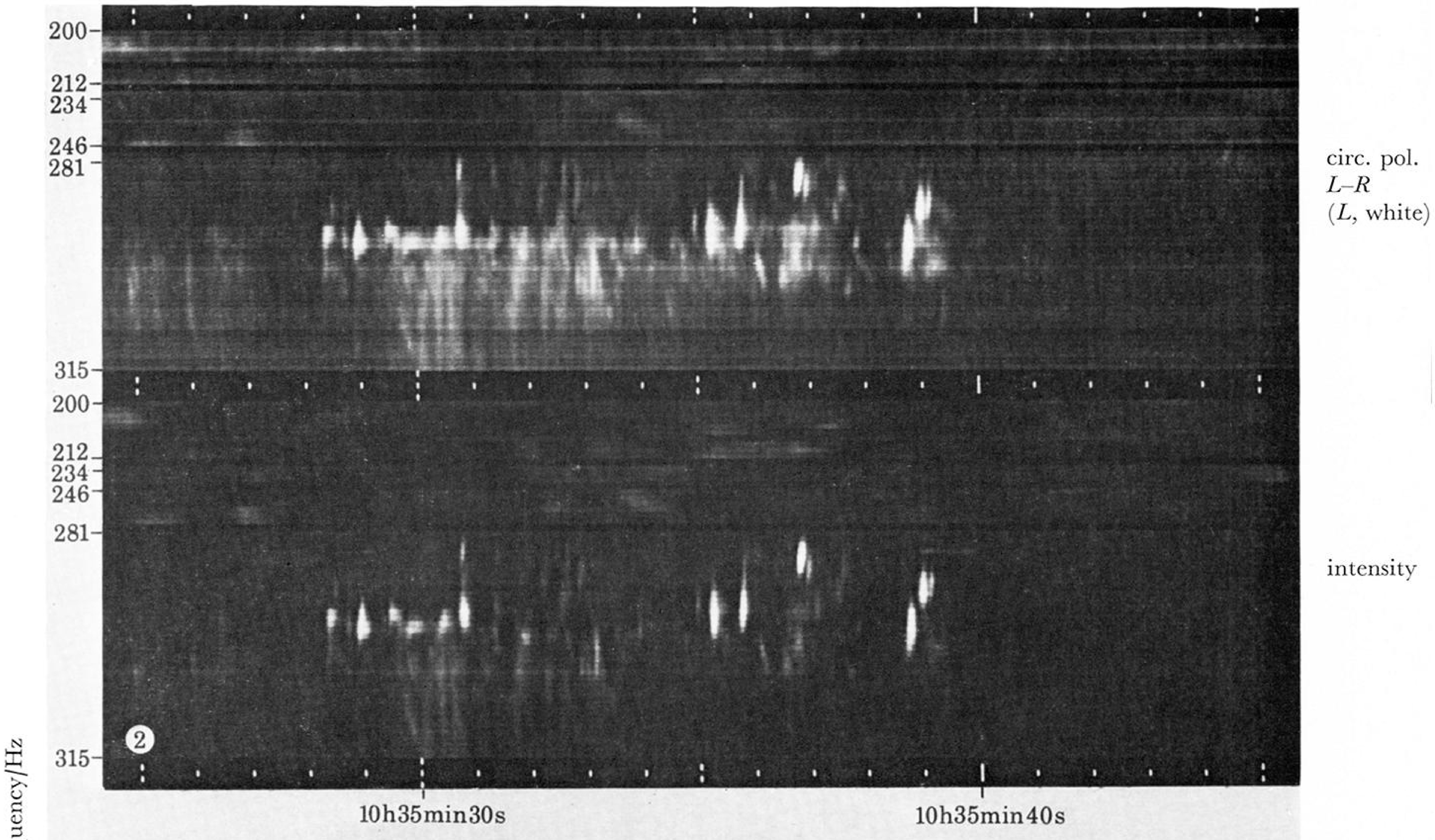


Figure 1*b*. Radio spectrum of the large outburst of 7 August 1972. Various types can easily be recognized by comparison with figure 1*a*. Courtesy of Dr A. Maxwell, Harvard Radio Astronomy Station, Fort Davis, Texas.



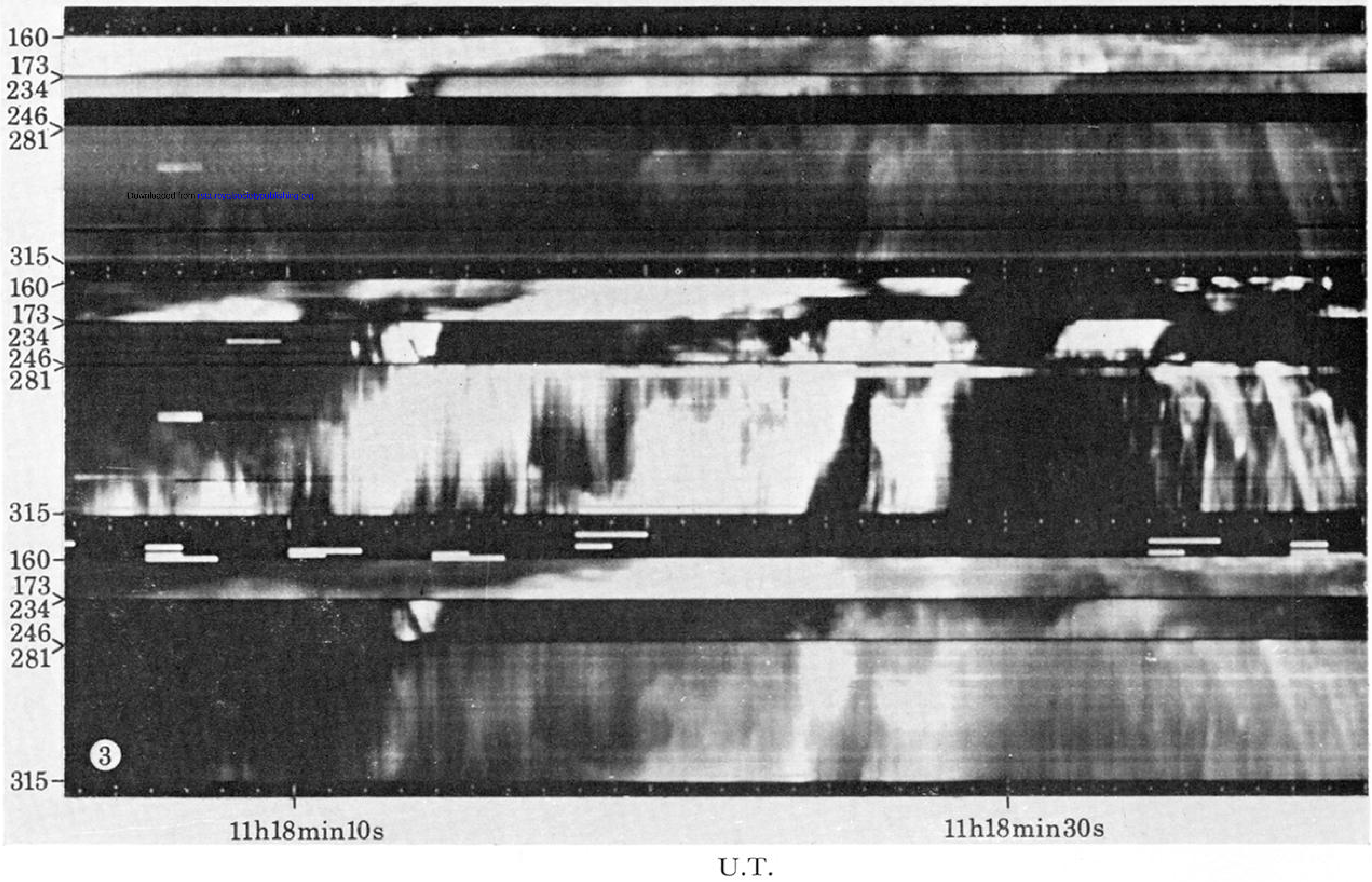
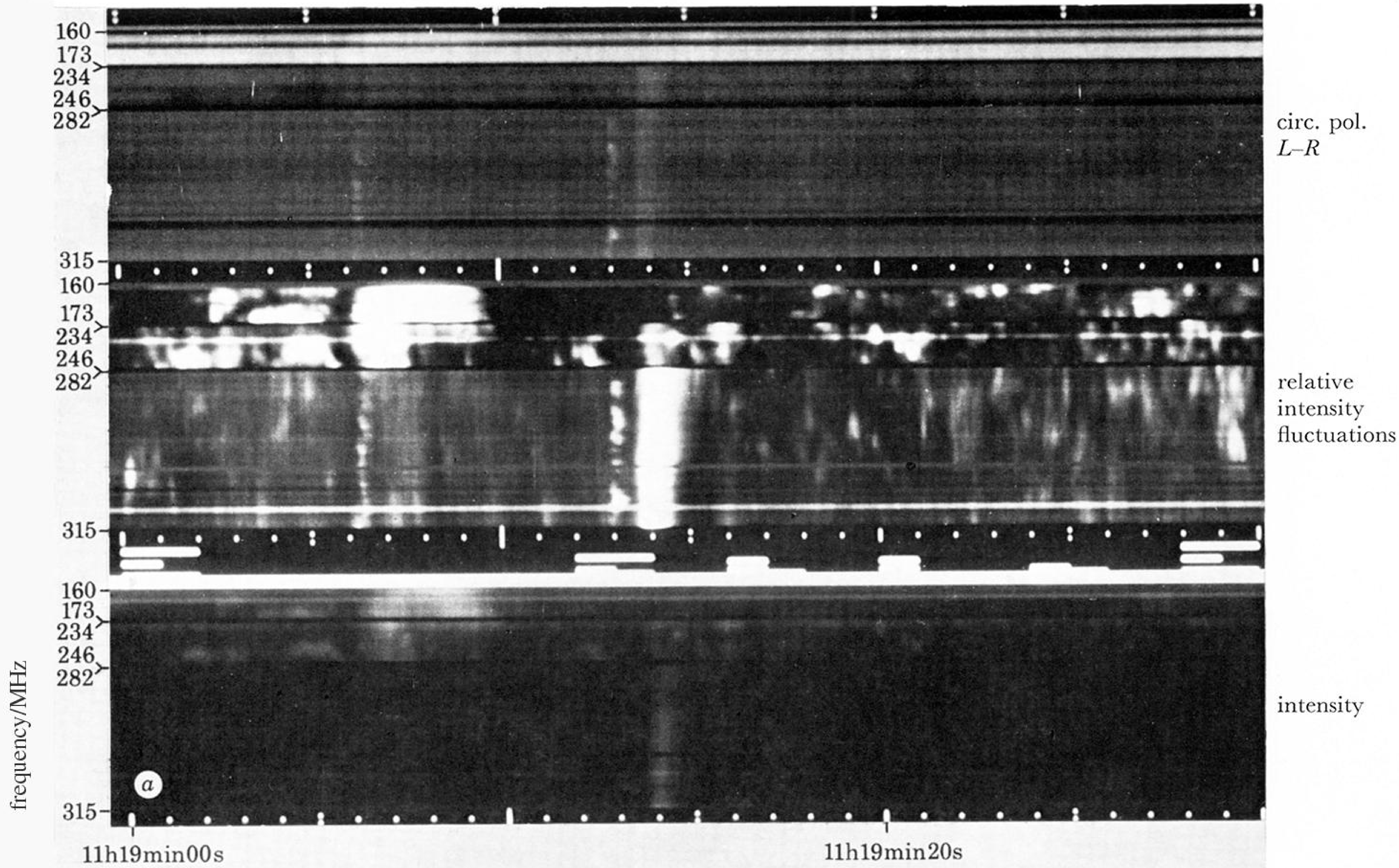


FIGURE 2. High resolution spectrum of a type I burst chain on 11 July 1974. 60 channel Utrecht radiospectrograph of Solar Radio Observatory, Neth. Foundation of Radio Astronomy, Dwingeloo, Netherlands.

FIGURE 3. Detail of a type II burst on 6 March 1972. Note the absence of fine structure in the fundamental band (160–173 MHz) and the short duration, wide band fine structure in the harmonic band. 60 channel radiospectrograph.



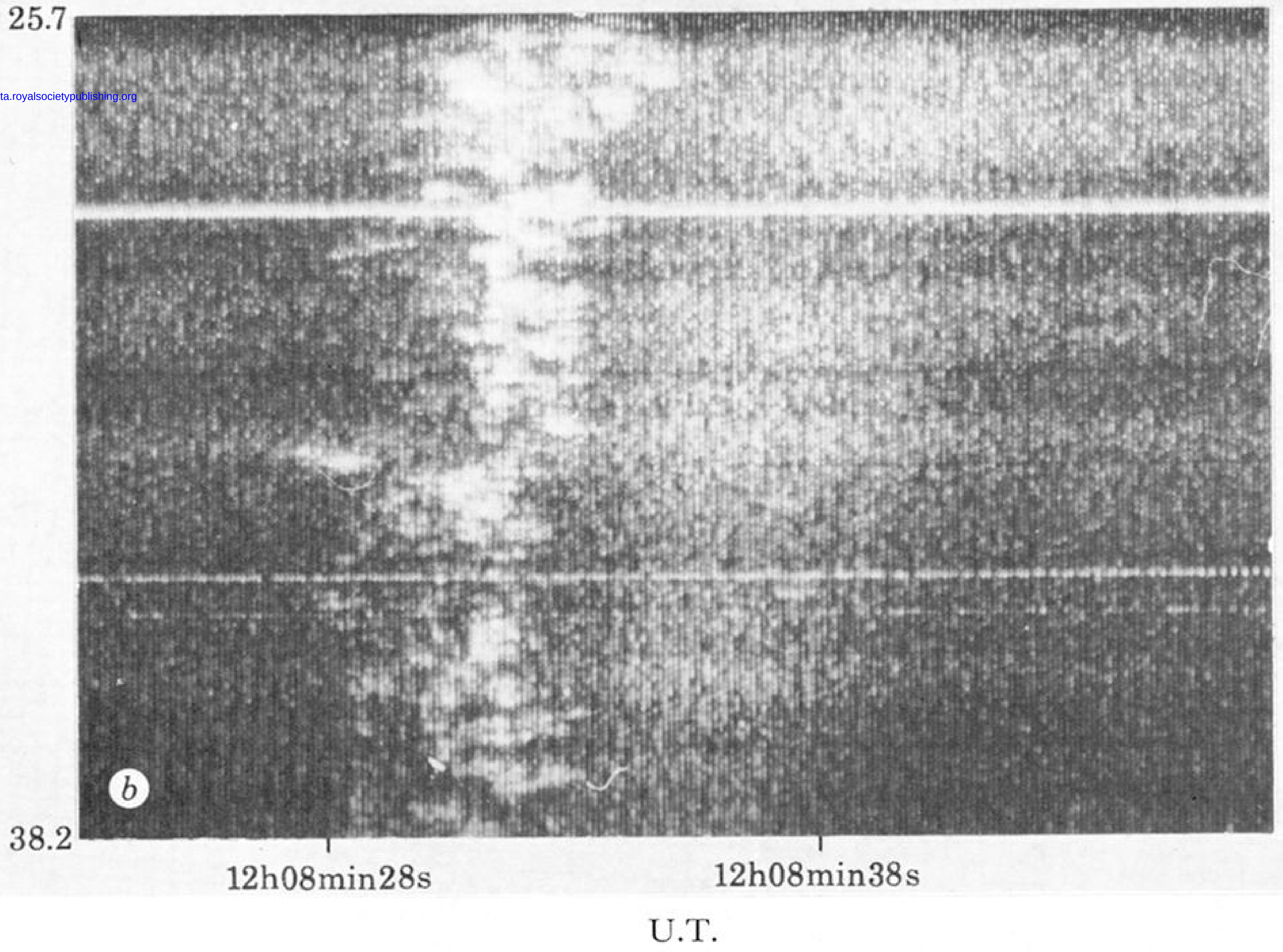


FIGURE 4*a*. High resolution observation of a type III pair on 10 March 1973. Note the circular polarization at the start of the type III bursts, and the great amount of fine structure in time and frequency. 60 channel Utrecht radio spectrograph.

FIGURE 4*b*. Example of a high resolution observation of a type IIIb burst on 19 December 1974. Courtesy of Dr J. de la Noë, Decametric Radio Group, Meudon Observatory at Nançay Station, France.

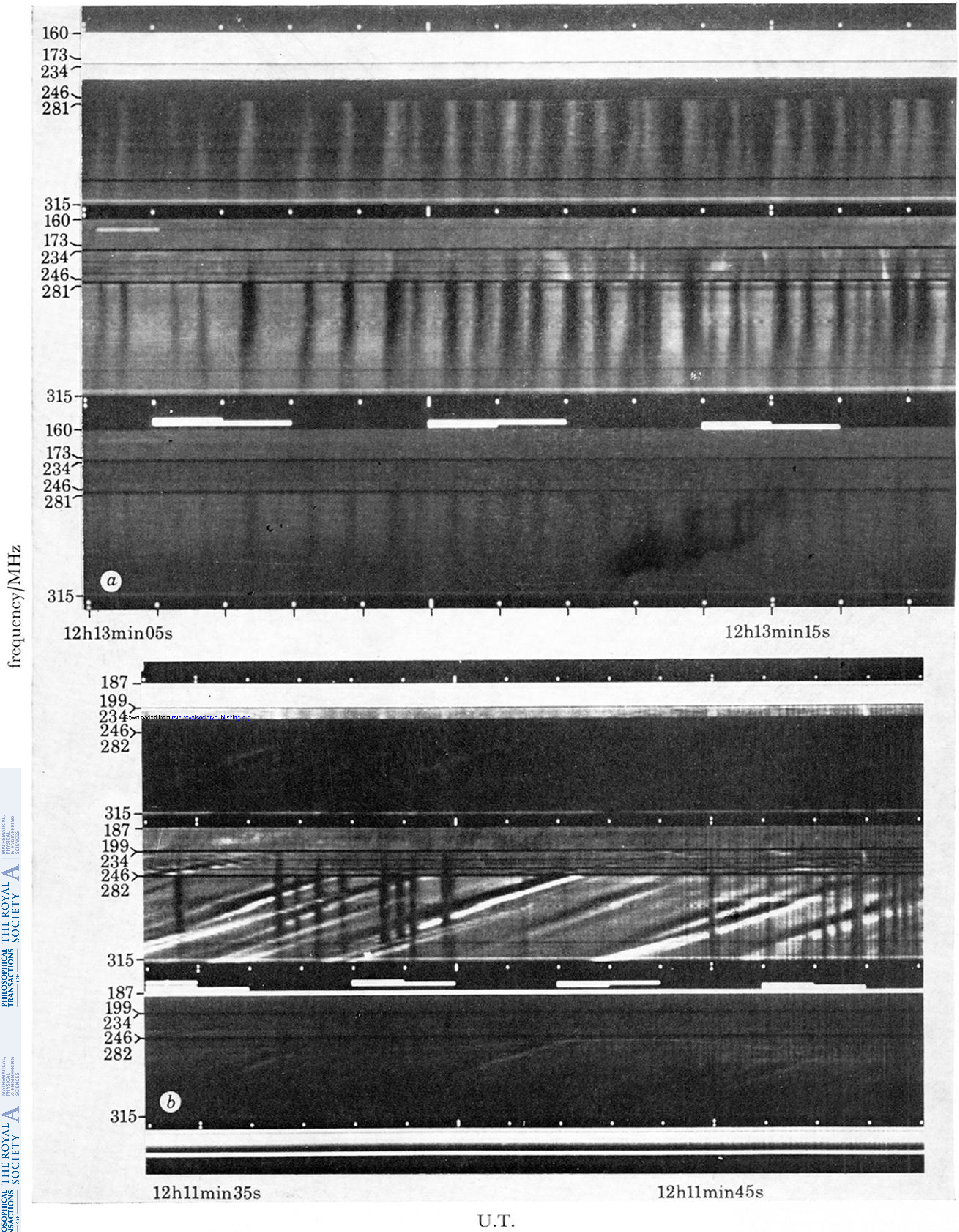


FIGURE 5. Type IV fine structure. (*a*) Pulsating structure in a type IV burst on 6 March 1972. 60 channel Utrecht radiospectrograph. (*b*) Intermediate drift bursts or fibre bursts on 6 March 1972. 60 channel Utrecht radiospectrograph.

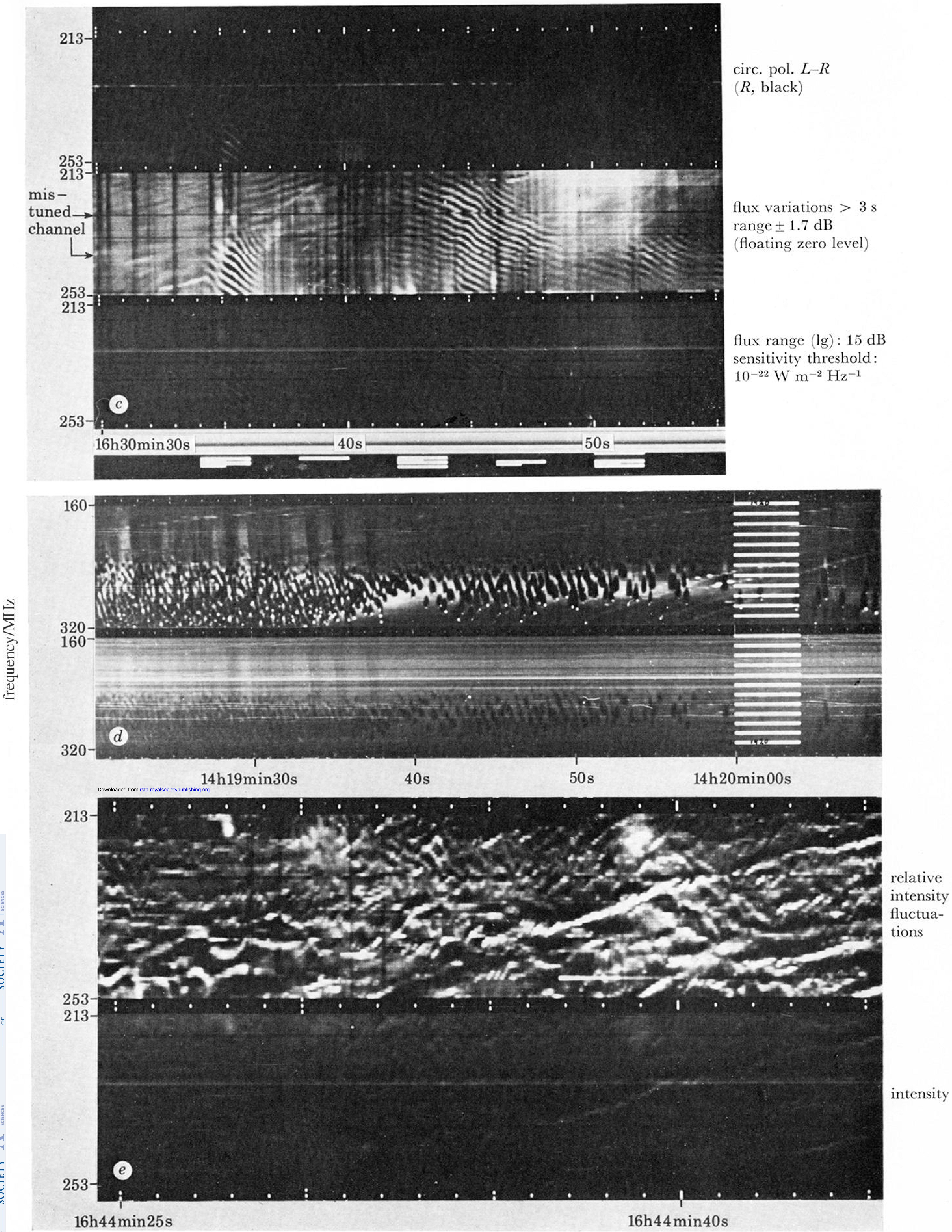


FIGURE 5. Type IV fine structure. (*c*) Parallel drifting bands or zebra structure on 26 June 1971. 60 channel Utrecht radiospectrograph. (*d*) 'Tadpole' structure on 2 March 1970. 60 channel Utrecht radiospectrograph. (*e*) Highly complex, not classified structure in a type IV burst on 29 June 1971. 60 channel Utrecht radiospectrograph.