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Catalogue of 1–3 GHz solar flare radio emission

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Abstract. — Solar flares frequently radiate in the 1–3 GHz range, the lowest frequency microwaves, but not much is known about the spectral shape of these emissions. We present a catalogue of selected bursts observed with a new spectrometer at ETH Zurich in the years 1989–1993. The original data set includes 268 events of various types. Featureless broadband continua generally attributed to gyrosynchrotron emission are often observed, but they are usually much weaker than the structured emissions probably caused by coherent processes. The selection emphasizes the latter class of events. The events show a rich variety of size and structures in time and frequency. Most events can be grouped into five major classes with some overlap and transitions. The samples of this catalogue have been selected to show the breadth of each class without stressing the extremes.

Key words: Sun: flares — Sun: radio radiation

1. Introduction

Little is known about the 1–3 GHz solar flare radio emission. It has been named the high-frequency part of decimetric radiation or the low-frequency part of microwaves. The two names also reflect the double nature of the range between the low-frequency (< 1 GHz) decimetric bursts (emitted by coherent processes) and the broadband continua at centimetric wavelength compatible with incoherent gyrosynchrotron emission.

The featureless, broadband gyrosynchrotron emission has been shown to extend below 1 GHz in some flares (e.g. Batchelor et al. 1984). On the other hand, early observers at single frequencies in the 1–3 GHz band (in particular Tanaka 1961, and colleagues; review by Kundu 1965) have occasionally noted spiky and highly polarized bursts which appeared differently at the few available frequencies. Of particular interest were extremely short spikes with a few tens of millisecond duration observed at 1.4 GHz (Dröge 1977) and 2.65 GHz (Slottje 1978).

Here we present the first spectrometric survey over the 1–3 GHz range. Previous broadband surveys of solar flare radio emissions concerned the 0.3–1 GHz band (Güdel & Benz 1988), the 4–8 GHz band (Allaart et al. 1990) and the 6–8.5 GHz band(Bruggmann et al. 1990). We concentrate on the relatively narrowband emissions of probably coherent origin. In agreement with earlier single-frequency observations (e.g. Enome & Orwig 1986), we find that the emission structured in time and frequency is often several orders of magnitudes more intense than the broadband microwave continuum attributed to gyrosynchrotron emission.

Coherent emissions in the 1–3 GHz range probably originate from various processes. Spectrometric observations are important information on the pertinent radiation mechanism. If plasma emission, the source density must be in the range $3\ 10^{-9} - 10^{11}\ \mathrm{cm}^{-3}$, so that the plasma frequency or its harmonic match the observed frequency range. If the radiation involves the electron gyrofrequency, the magnetic field in the source must be of the order of a few hundred Gauss. Both parameters are in the range proposed for the region of primary energy release of flares. It is therefore not surprising that some, but not all, of these radio emissions closely correlate with hard X-rays. The comparison, however, is not the aim of this presentation and will be performed separately for the different types of bursts.

This catalogue has been compiled with the aim to provide a systematic, general and complete overview of the most typical flare-related emissions in the 1–3 GHz range. It is a selection based on purely phenomenological arguments. No claim for a classification according to physical principles is made, since they are mostly unknown. Neither do we imply that bursts in the same group are the result of the same process.

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2. Observations

The *Phoenix* spectrometer near Zurich has been described by Benz et al. (1991). It has been put into operation in June 1989 to observe the full Sun at 0.1–3.0 GHz. The frequency-agile instrument measures 2000 flux densities and circular polarizations at selectable frequencies. Depending on the number of channels, the time resolution varies between 0.5 and 200 ms. Most of the data shown in this catalogue have been recorded with standard survey programs allowing resolutions of 40, 50, or 100 ms. The channel bandwidth can be selected to be 1, 3, or 10 MHz, and the channel separation can be freely chosen.

Representative events have been selected from 169 flares recorded in the period from June 1989 until May 1993. The data were selected according to the following criteria:

- radio bursts mostly in the 1–3 GHz range.
- structure in time or frequency that exclude interpretation by the gyrosynchrotron process. Some gyrosynchrotron emission, however, is often present at the high part of the frequency range.

The data exist in form of digital spectrograms. The images were calibrated and visualized on a screen in the usual spectrogram format ('dynamic spectra'). A suitably chosen background was subtracted. Subsequently, strong terrestrial interference and instrumental effects were eliminated. The flux density was logarithmically compressed to enhance weak structures, and the intensity limits were chosen for a high contrast black-and-white picture.

3. Discussion

We decided to order the various 1–3 GHz emissions into groups of similar shapes in the dynamic spectrum. Any such classification remains somewhat subjective and artificial, as long as there is no definite relation between burst type and emission process. Dynamic spectra readily yield the main structure parameters: *bandwidth* and *duration*. In addition, we have considered drift rate, substructures, grouping, and polarization.

We have found that the 1–3 GHz emissions can be assigned to four classes previously introduced for the 0.3–1 GHz emissions and a new class that has, however, been previously reported as a subclass. We will refer to these classes by the names given to the corresponding classes in the 0.3–1 GHz range: 1) type III-like bursts (incl. narrowband blips): 131 events, 2) narrowband spikes: 29 events, 3) diffuse continua: 36 events, 4) type IV events: 5) quasi-periodic pulsations: 25 events. Since several types of emissions may occur during the same flare, the total number of radio bursts (268) exceeds the number of flares (169). An event is counted once if there is no gap of emission longer than 10 minutes (except for the long-duration type IV bursts where slightly longer gaps were accepted). About 10% of the classifications were uncertain or borderline cases.

Figure 1 gives a simplified overview on the characteristic ranges of duration and bandwidth of the five classes. Note that there are more burst characteristics and that this scheme should not be used blindly. Nevertheless, the diagram may be used to classify 1–3 GHz single frequency observations in the lack of complete spectrometric information. In the following we briefly outline the five classes into which we grouped the data and suggest possible subclasses. The accompanying 29 figures show typical events stressing the diversity, but not the extremes of each class and subclass. This catalogue of representative events may help to clarify the verbal description.

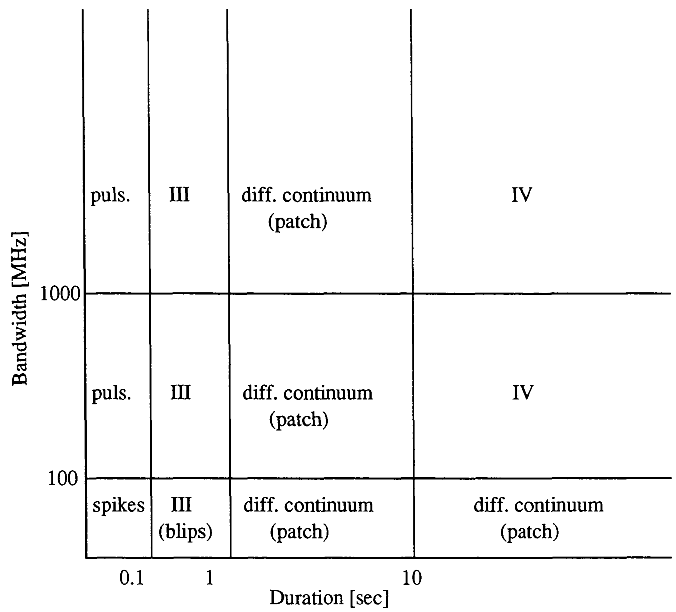

Fig. 1. Schematic overview on the five classes of 1–3 GHz bursts classified by duration and bandwidth of single bursts. The borderlines are not to be taken too literally since other characteristics must also be considered as described in the text

3.1. *Type III-like bursts*

Single type III-like bursts have short durations (0.2–1.0 s). The peak flux drifts in time and frequency. This may, however, be difficult to resolve, in particular for narrowband bursts. In the 1–3 GHz the drift rate is predominantly positive (i.e. 'reversed' in metric terminology) and usually of the order of 1 GHz/s. Type III-like bursts usually occur in groups of 10 to 1000 individual bursts starting at different frequencies. Sometimes individual bursts of a group drift in opposite directions. The polarization is usually below 20%.

3.1.1. Narrowband type III bursts

Short, unpolarized bursts of a few tens of MHz bandwidth have first been noted in the 0.3–1 GHz range and named 'blips' by Benz et al. (1981). They were later shown to have the characteristics of narrowband type III bursts (Benz et al. 1983). Type III bursts with a total bandwidth of less than 100 MHz are the most frequent type of burst in the 0.3–1 GHz range (Aschwanden 1987), where they comprise 31% of all bursts. Applying the same criterion, their ratio drops to 11% in the 1–3 GHz range, whereas the proportion of wider bandwidth type III bursts increases. This is probably an effect of higher center frequency. The typical duration of a single burst is less than 0.3 s (Fig. 2).

More than half of the narrowband type III events in the 1–3 GHz range are organized in groups of bursts at similar center frequencies (Fig. 3). They may be called 'chains' in analogy to metric chains of type I bursts. At high resolution (Figs. 4 and 5), the spectrograms reveal the existence of extremely narrowband specimens of relatively long duration.

3.1.2. Broadband type III bursts

About 20% of all type III bursts are broadband ($\gtrsim$ 0.5 GHz). Some have U-burst shape (Fig. 6). The broadband bursts are often well separated from each other (Fig. 7) with different polarizations (Fig. 8). Large groups also occur (Fig. 9).

3.1.3. Regular type III bursts

Type III bursts of intermediate bandwidth are the most frequent type of all 1–3 GHz bursts (and 55% of all type III-like bursts). Sometimes they form chains of bursts (Fig. 10). Frequently, groups of type III bursts of the same flare have drifts in opposite directions or different polarizations (Figs. 11 and 12).

3.1.4. Slow-drift type III bursts

Type III bursts with unusually low drift rates have been noted around 300 MHz by Benz and Simnett (1986). They also occur in the 1–3 GHz band (Fig. 13). Sometimes slow-drift bursts are accompanied by a continuum (Fig. 14) and normal drift bursts.

3.2. *Narrowband spikes*

Some single-frequency observers have used the term 'spike' for any short burst from a few milliseconds to a few seconds. We use the term in the restricted sense of narrowband spikes of a few tens of millisecond duration (review by Benz 1986). Spikes are a frequent phenomenon in the 1–3 GHz range (11% of all, events, Figs. 15 and 16). Some subgroups exhibit harmonic structure in frequency. A small group is enlarged in Fig. 17. A very large spike event is shown in Figs. 18 and 19. In all figures presented here the spikes are not resolved in time.

3.3. *Diffuse continua*

Diffuse continua of emission occur more frequently in the 1–3 GHz range than in other ranges and have various forms. Their characteristic duration is between one and some tens of seconds, too long for a type III burst and too short for a type IV burst. They have also been noted in the 0.3–1 GHz range and have been called 'patches' in the literature. The circular polarization is usually weak.

Narrowband (< 0.1 GHz, Fig. 20) and broadband (> 0.1 GHz, Fig. 21) diffuse continua occur at about the same rate. Some have long duration but a narrow bandwidth (Fig. 22), others are shorter but are wideband (Fig. 23). The latter two events occurred in the decay phase of hard X-ray flare emission.

Some diffuse continua may be short type IV burst caused by the same emission process. Evidence for this suspicion stems from intermediate drift structures sometimes observed in diffuse continua, a fine structure common in type IV bursts (see below).

3.4. *Type IV bursts*

Continua of many minutes duration occur in the 1–3 GHz range (Fig. 24). The emission is usually modulated in time on scales of 10 s or less, and is often strongly polarized. The spectrum sometimes shows multiple structure (Fig. 25). Fine structures, in particular parallel drifting bands (Fig. 26, also called 'zebra pattern') and intermediate drift bursts (Figs. 25 and 27, also called 'fibre bursts') occur similar to the 0.3–1 GHz range (Young et al. 1961; Bernold 1980; Slottje 1981).

3.5. *Pulsations*

Pulses of more than 100 MHz bandwidth at similar centerfrequency are called pulsations (Fig. 28). They are typically separated by 0.1 to 1 seconds and are almost periodic or irregular. Their appearance is more ordered than a group of type III bursts and their drift rate is higher. They are usually highly polarized. Fine structure, similar to type IV bursts, has been noted (Figs. 28 – 30). Sometimes the pulses occur not in emission but in absorption (Fig. 30). Such phenomena at lower frequencies have been called 'sudden reductions'.

4. Conclusions

A representative selection of 1–3 GHz spectrograms has been compiled covering the most usual shapes of bursts in our collection. Except of a few peculiar cases, five classes have been found sufficient to order most of the events: type III-like, spikes, diffuse continua, type IV, and pulsations. Compared to the 0.3–1 GHz range (Aschwanden 1987), we note that type III-like bursts are relatively less numerous (59% vs. 76%). Pulsations are relatively less abundant, and diffuse continua (patches) are relatively more abundant. A more detailed study is necessary to show whether they form only one class or are emitted by different mechanisms.

Acknowledgements. The operation of the Zurich spectrometers is a joint effort of the radio astronomy group at ETH. In particular, we would like to thank J. Brunner, T. Habermacher, W. Stehling and others. A Csillaghy has helped by developing software. The hardware construction was supported by the Swiss National Science Foundation, grant nr. 20-34045.92.

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Notes on the figures:

We did not emphasize a uniform representation, but zoomed the relevant structure. This and different recording modes result in large variations of frequency and time scales.

Dark structures mean enhanced flux density with a logarithmically compressed scale. The flux density F can be estimated from the z-range given at the top of each figure and the equation

$$F = \left(10^{z/45} - 1\right)(B + 10)[\text{sfu}], \tag{1}$$

where B is the background flux density (order of 150 sfu) in solar flux units (sfu).

Polarization images: white means left-hand circularly polarized, and black means right-hand polarized. The given z-values indicate minimum and maximum polarization in percents.

The dates are given after the figure number in the caption (year/month/day). All times are in UT.

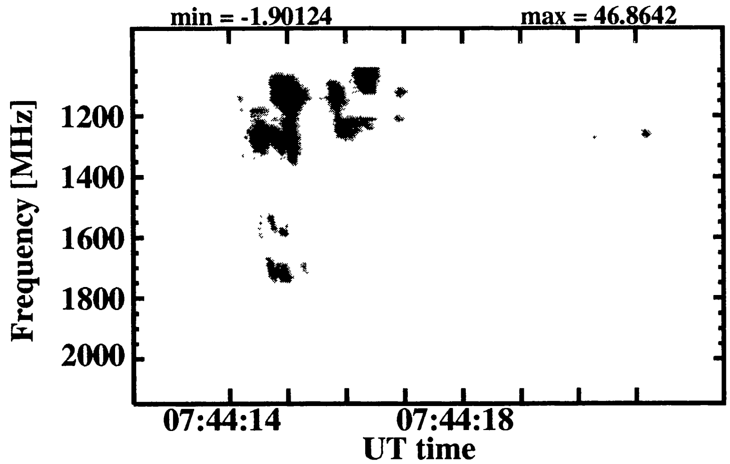


Fig. 2.

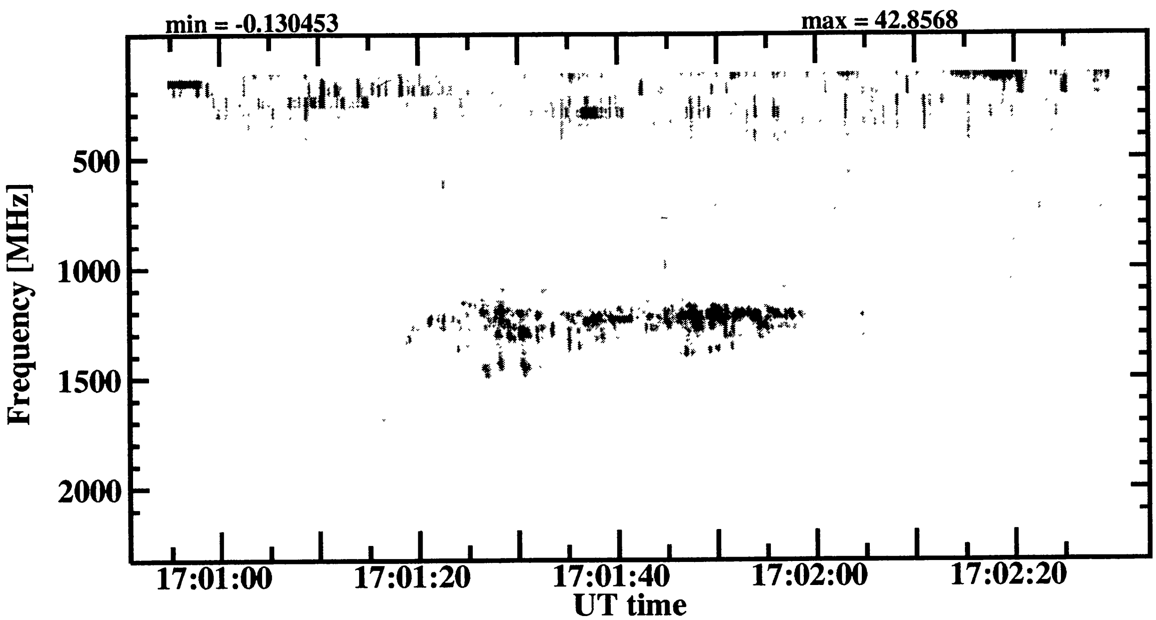
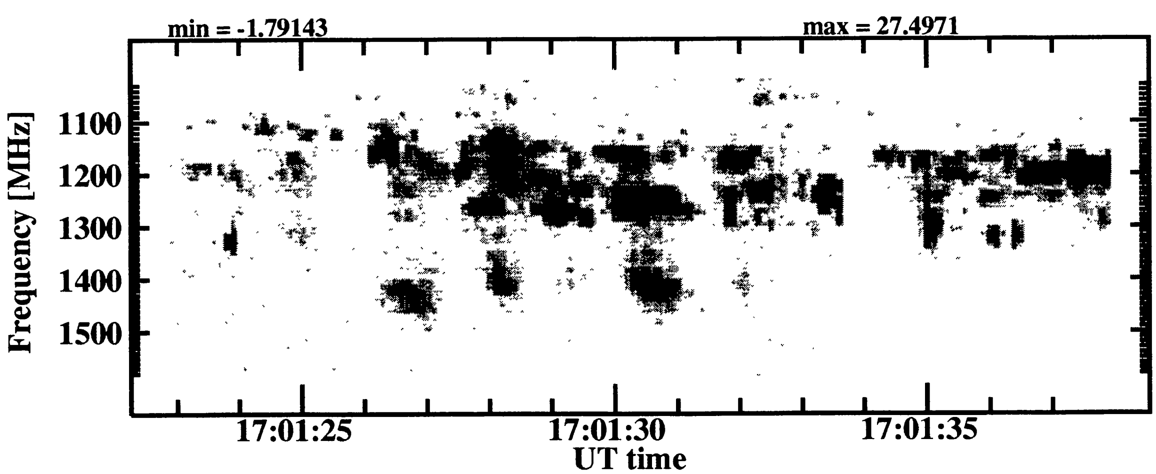


Fig. 3.



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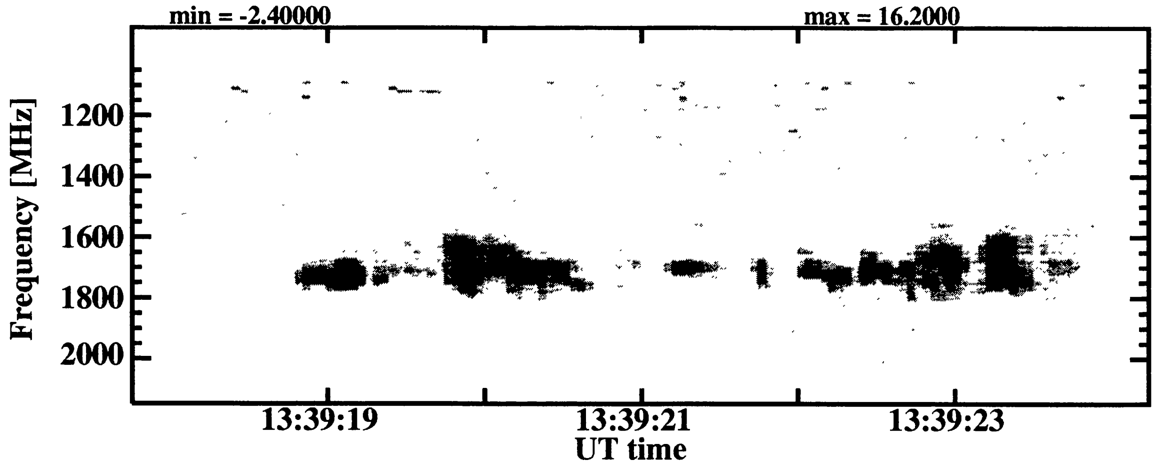

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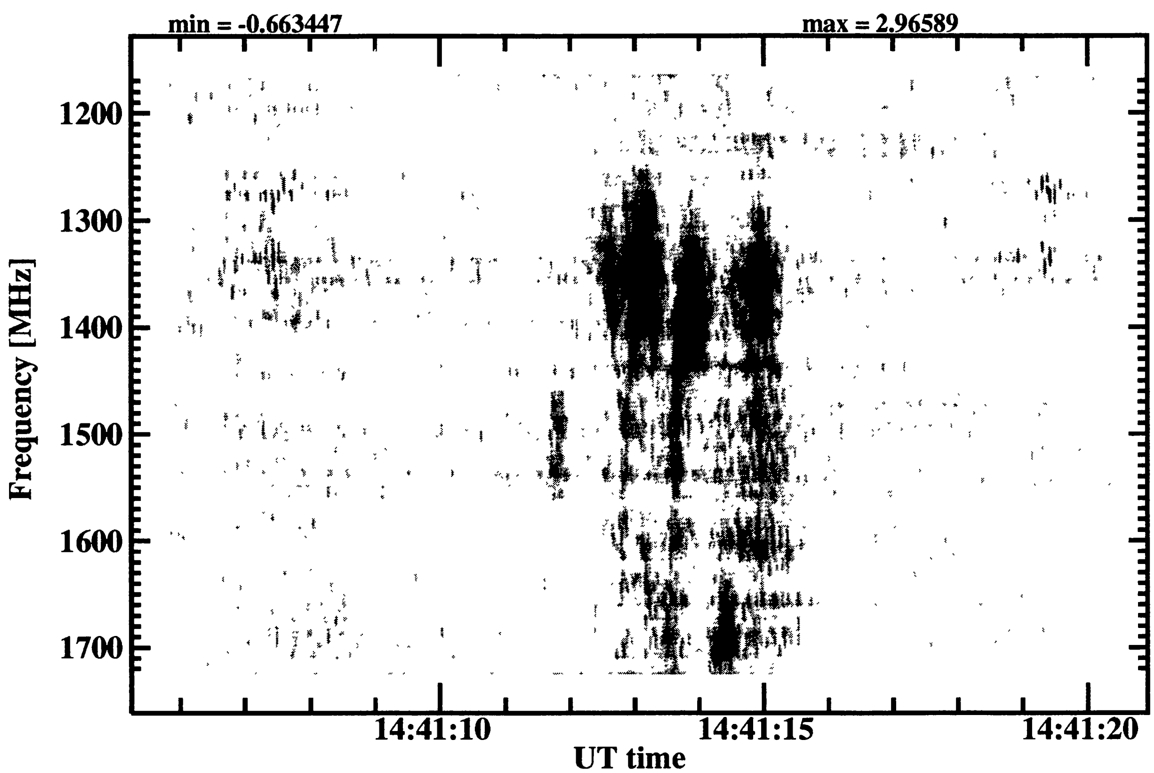
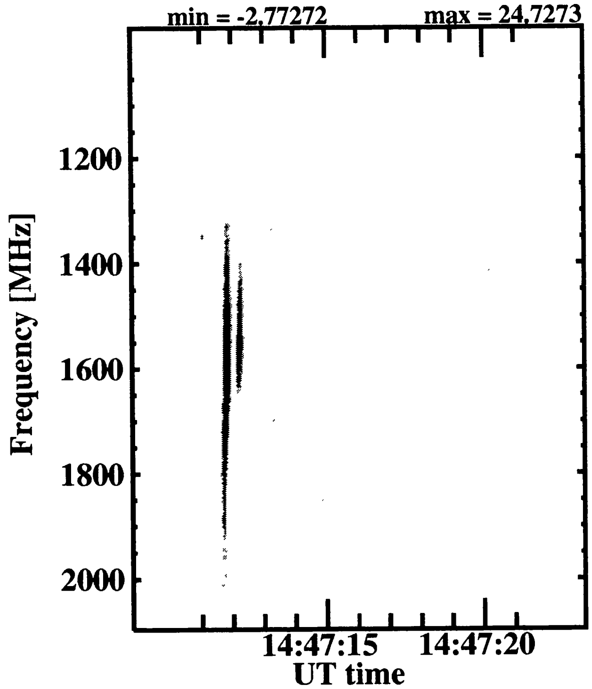


Fig. 6.

Fig. 2 – 5. *Narrowband ($\lesssim$ 100 MHz) type III bursts (blips):* – Fig. 2. 90/03/07, regular bursts, bandwidth $\approx$ 100 MHz. – Fig. 3. 89/08/15, extremely narrowband blips. They look in this representation like very small patches. – Fig. 4. Enlargement of a part of the event in Fig. 3, possibly showing multiple structure in frequency. – Fig. 5. 89/11/19, chain of extremely narrowband blips

Fig. 6. *Broadband ($\gtrsim$ 500 MHz) type III bursts:* – 91/07/18, note U-bursts at 14:41:13 and 14:41:14 UT



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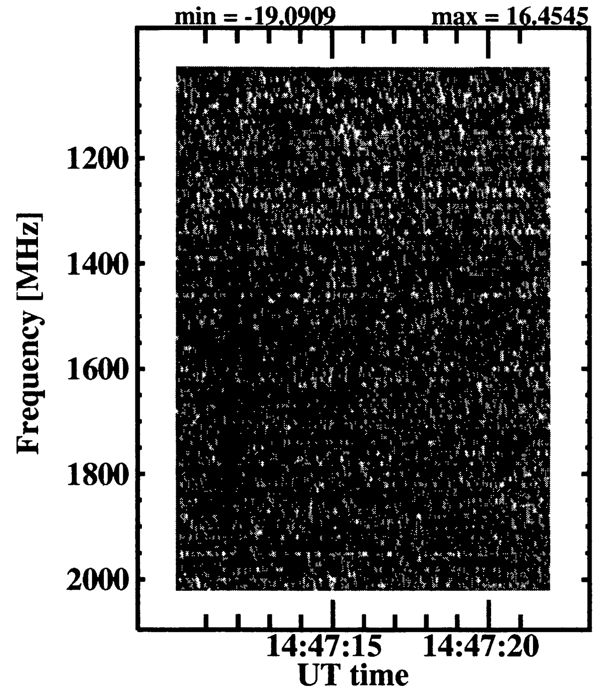


Fig. 8.

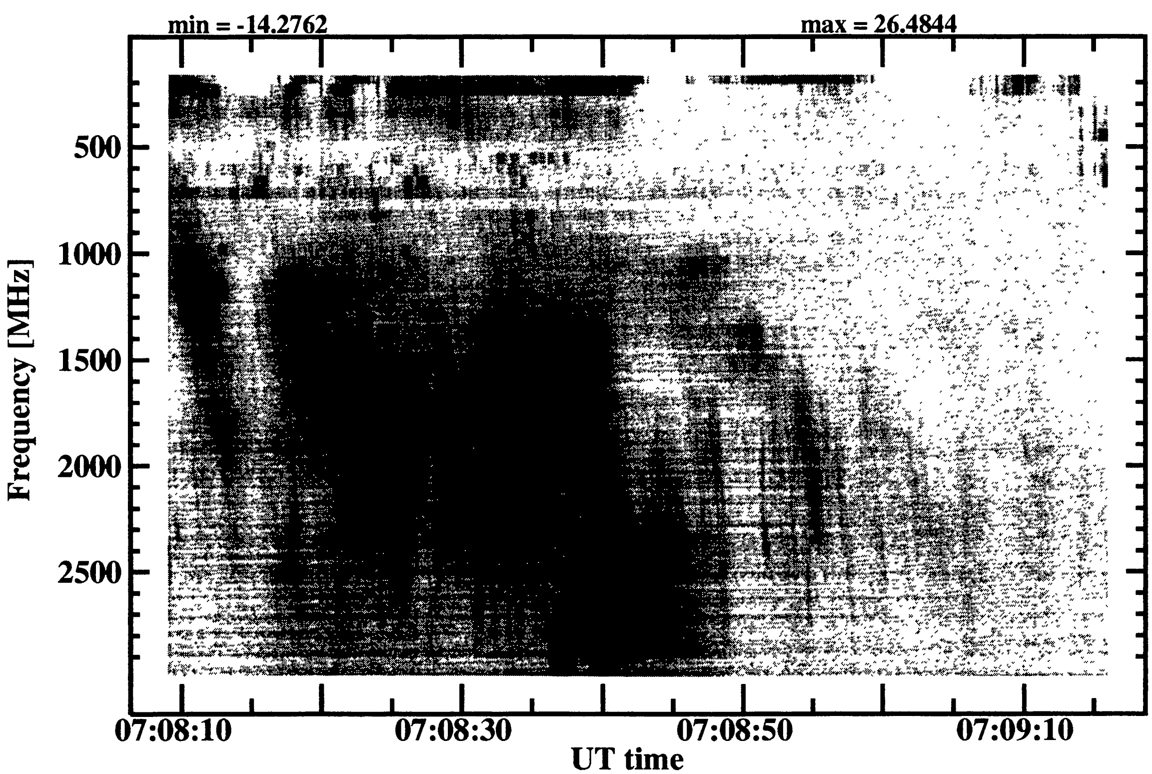


Fig. 9.

Fig. 7 – 9. *Broadband (≳ 500 MHz) type III bursts:* – Fig. 7. 90/02/20, well separated bursts. – Fig. 8. Polarization of the event in Fig. 7. – Fig. 9. 89/09/22, large group, reversely drifting

Fig. 10 – 12. *Intermediate bandwidth (a few hundred MHz) type III bursts:* – Fig. 10. 93/01/18, upwards drifting chain of downward drifting individual type III bursts. – Fig. 11. 92/09/06, individual groups, largely dispersed up to 3 GHz. – Fig. 12. Polarization of the event in Fig. 11. Note that the group at high frequencies has a polarization opposite to the group around 1 GHz at 11:51:00 UT!

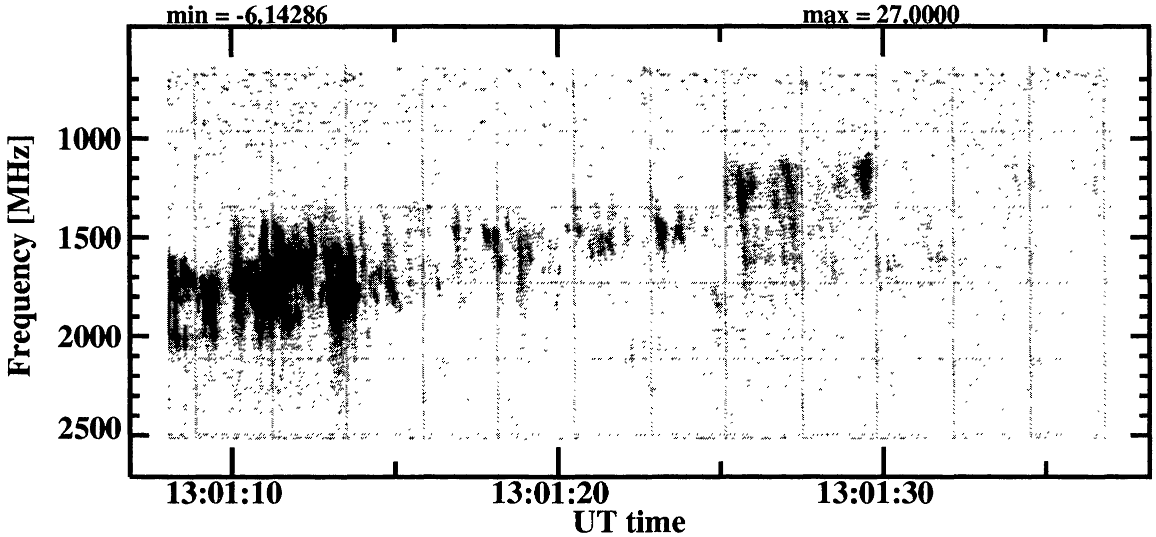


Fig. 10.

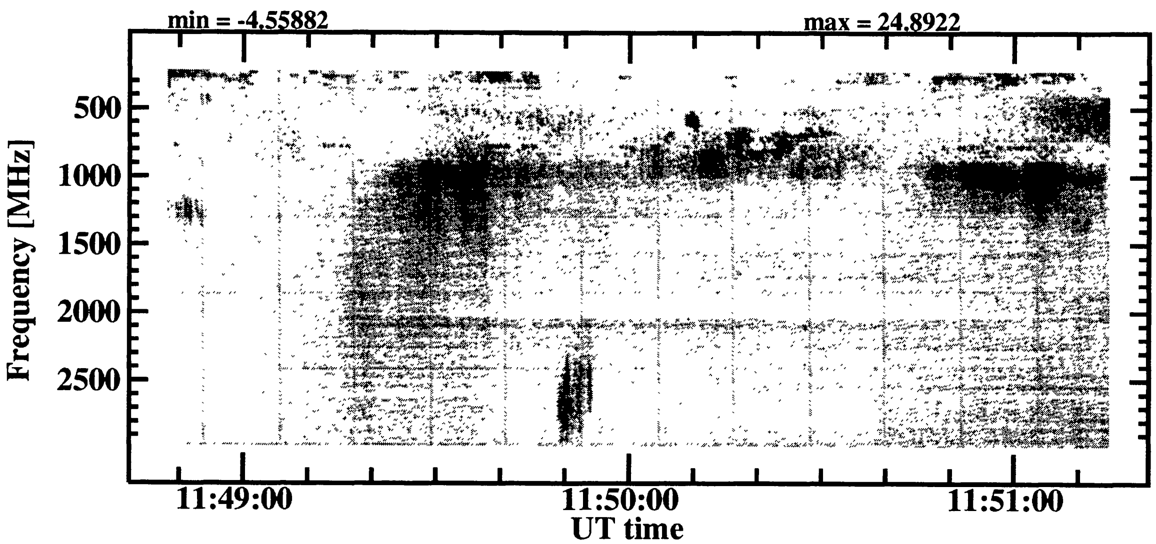


Fig. 11.

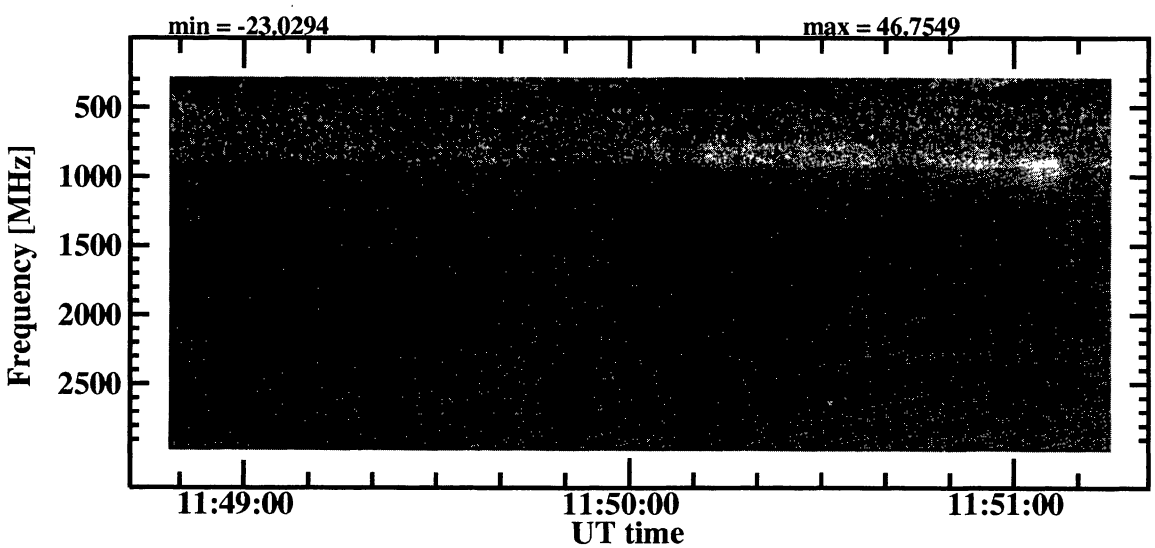


Fig. 12.

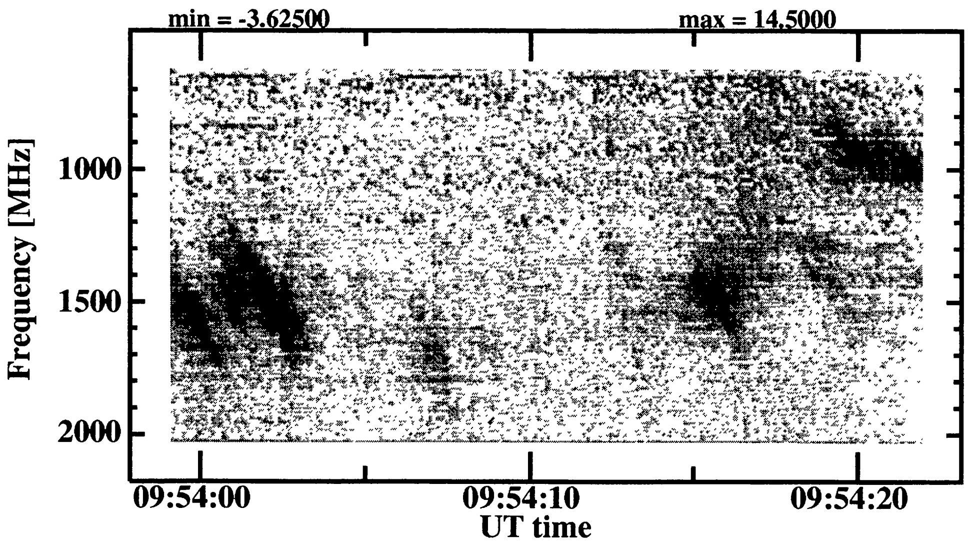


Fig. 13.

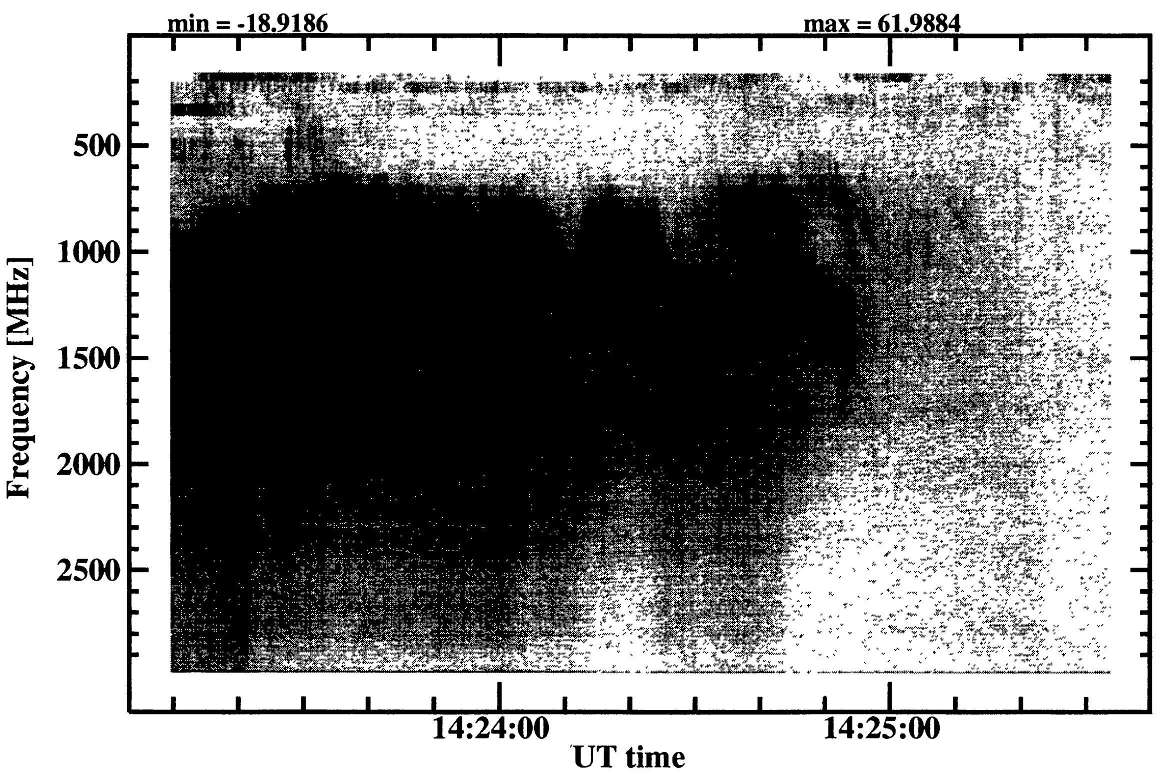
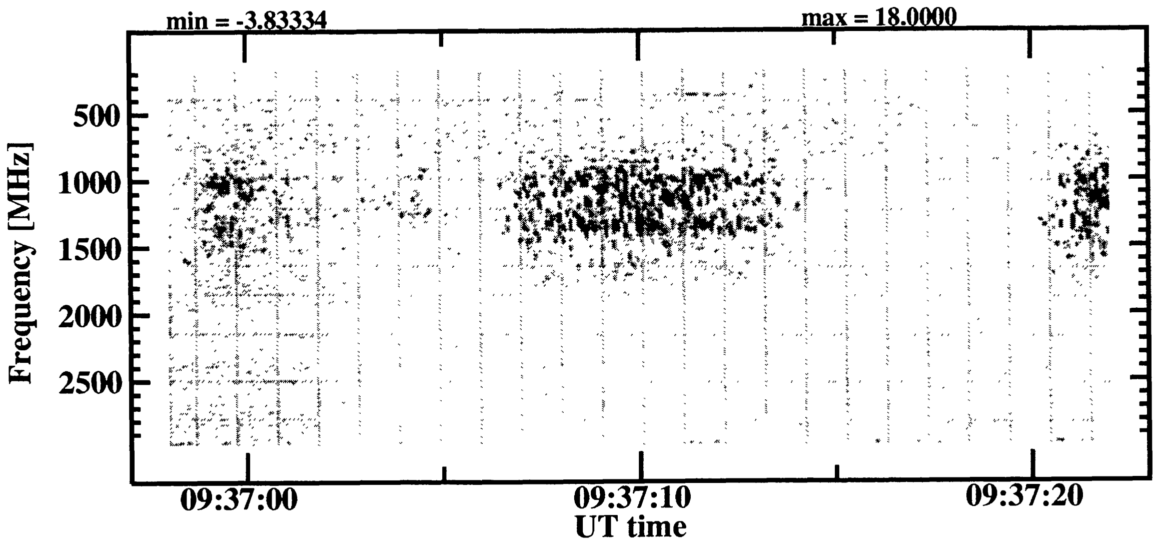


Fig. 14.

Fig. 13 – 14. *Slow drift, intermediate bandwidth type III bursts:* – Fig. 13. 92/10/30. – Fig. 14. 89/08/09, slow drift bursts (in the range 0.7 – 1.1 GHz), together with regular drift type III bursts at frequencies above and below

Fig. 15 – 17. *Narrowband spikes:* – Fig. 15. 90/12/25, a sequence of clusters of spikes. – Fig. 16. Polarization of the event in Fig. 15 – Fig. 17. 90/06/10, a small group (chain)



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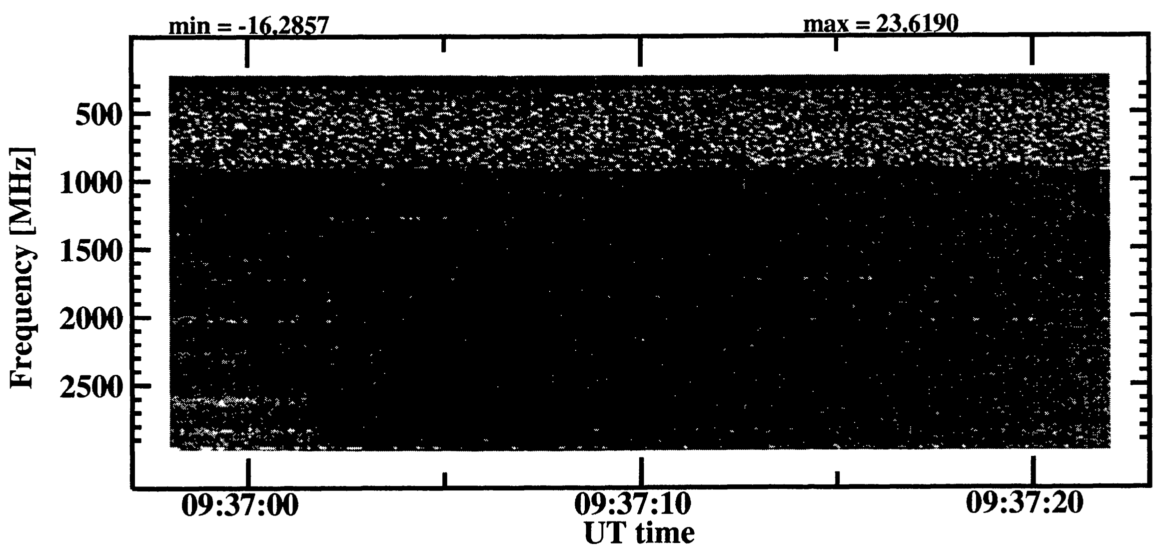

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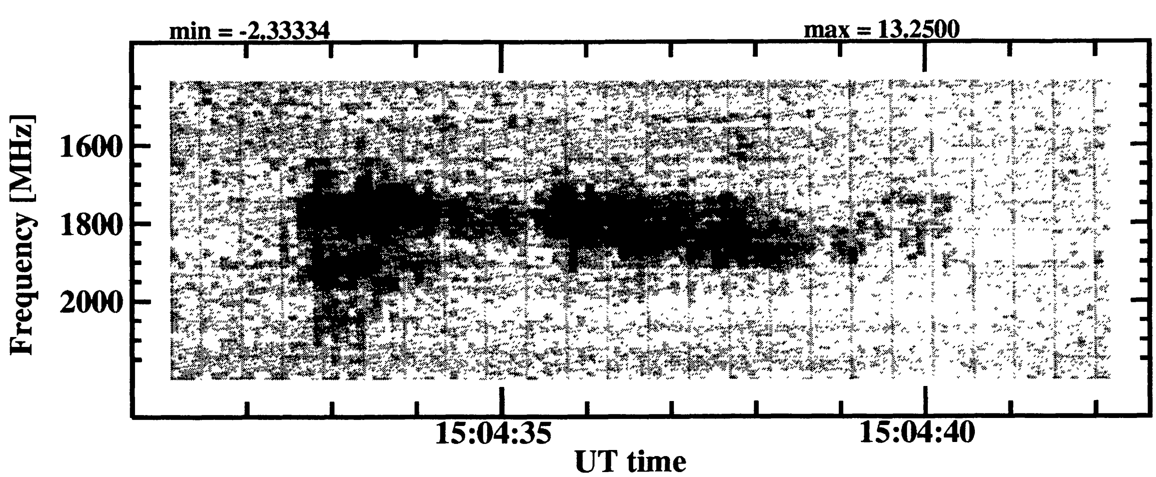
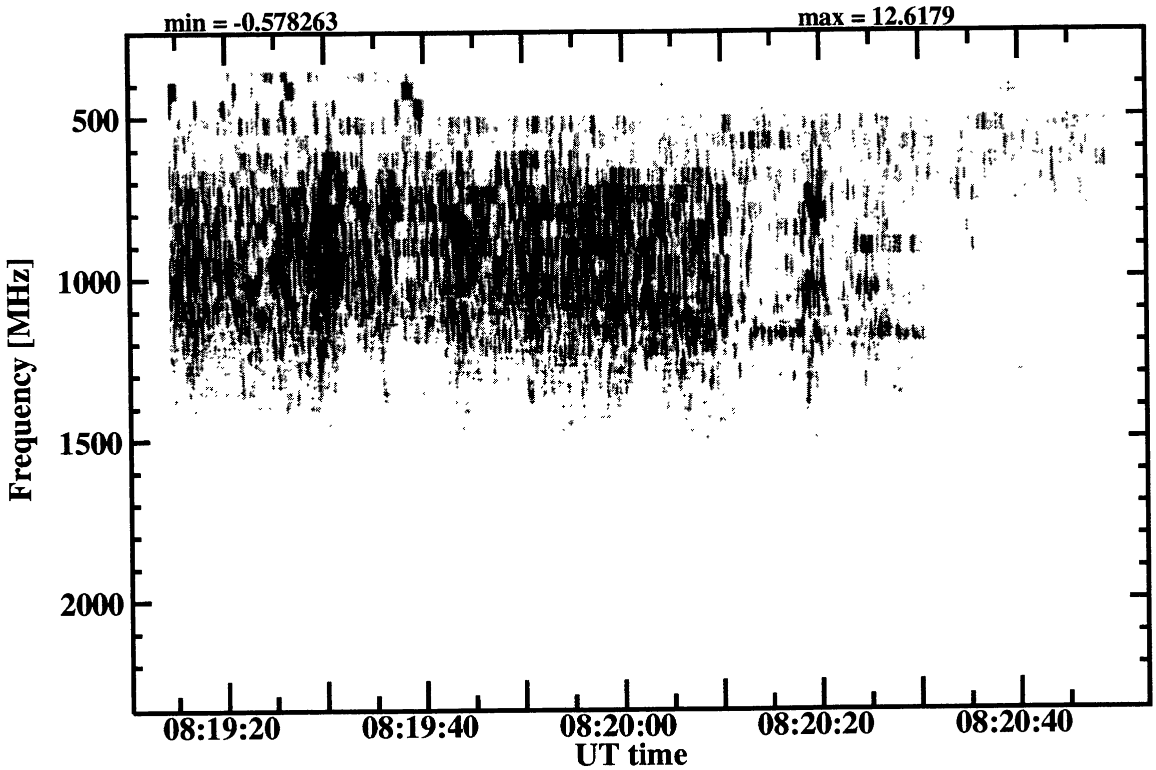


Fig. 17.



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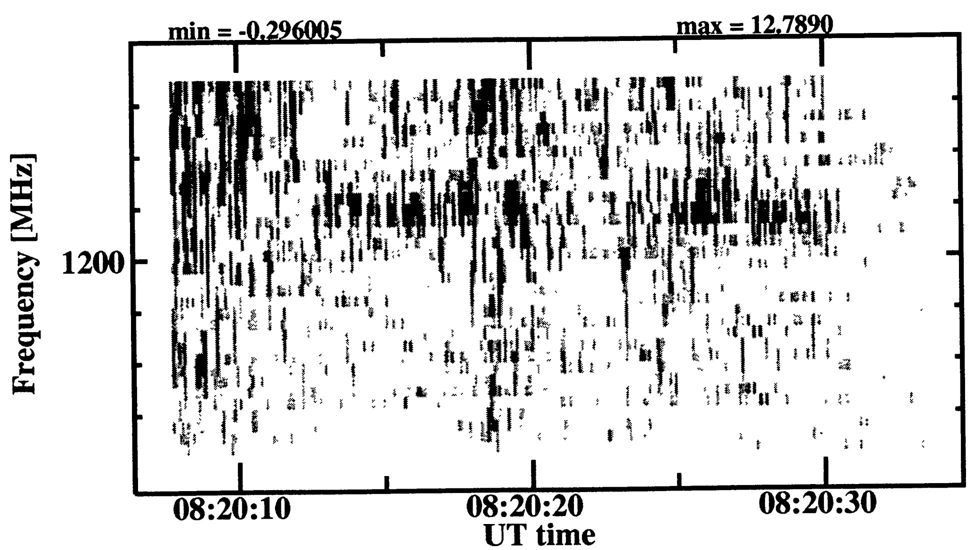


Fig. 19.

Fig. 18 – 19. *Narrowband spikes:* – Fig. 18. 90/06/24, a large cluster, with a downwards drifting chain at the end. – Fig. 19. Enlargement of the chain at the end of the event of Fig. 18

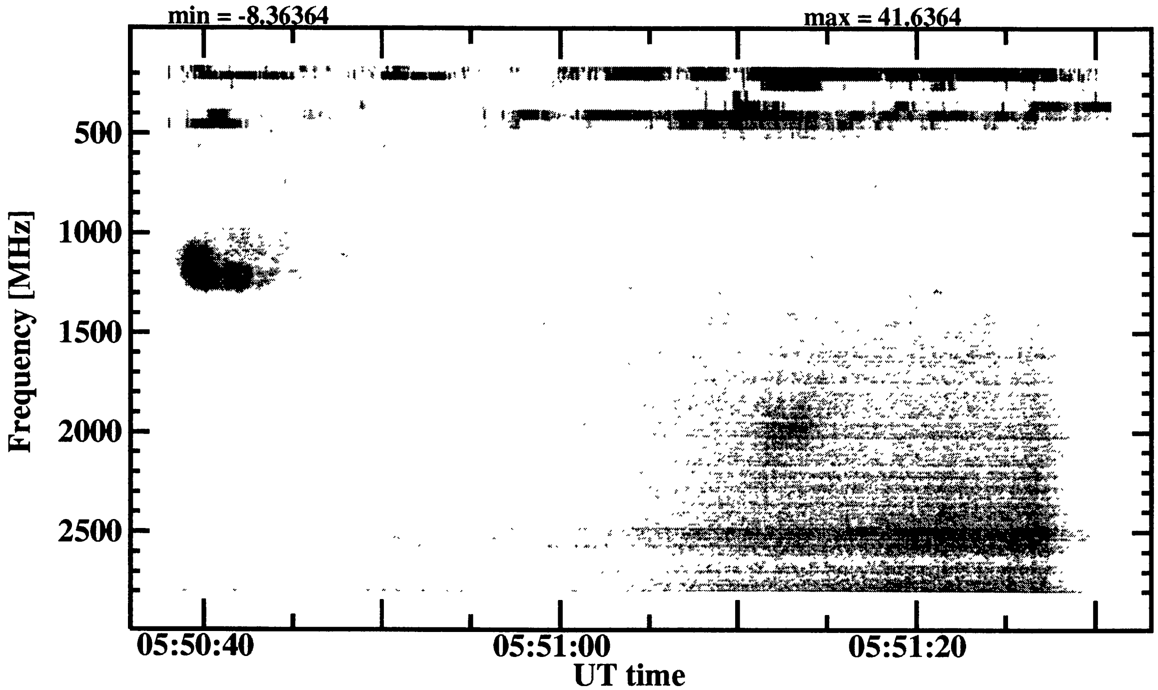


Fig. 20.

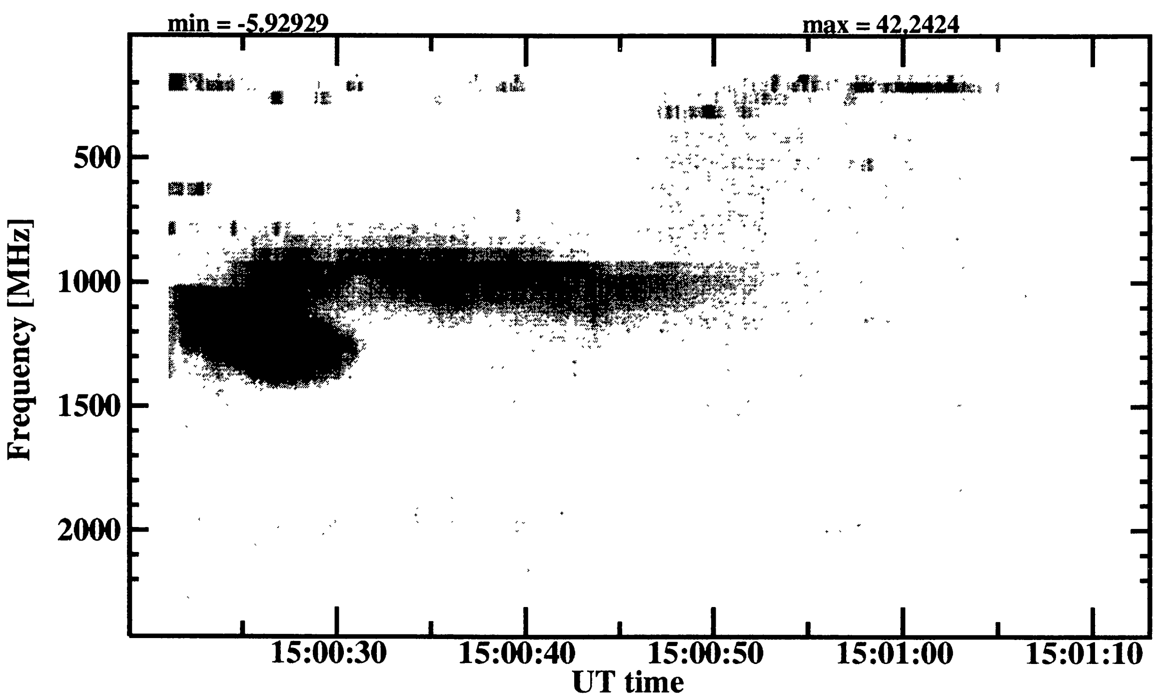
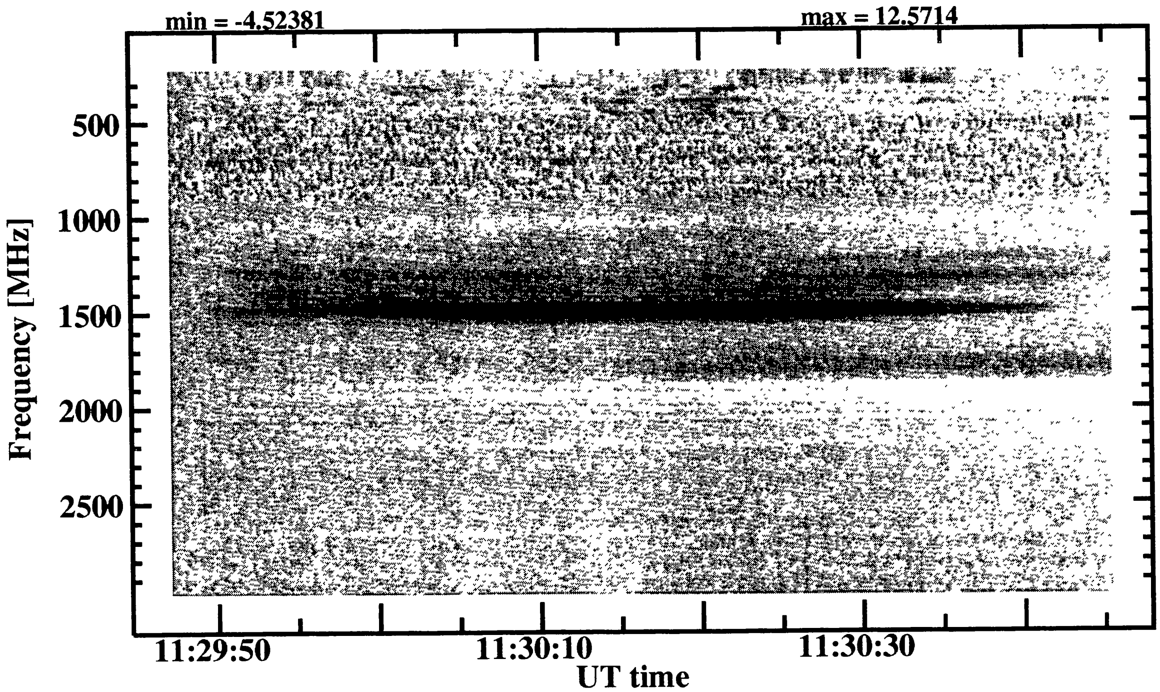


Fig. 21.

Fig. 20 – 21. *Diffuse continua (patches):* – Fig. 20. 89/07/17, a relatively narrowband, short-duration event. – Fig. 21. 89/09/27, two slowly drifting, long-duration events



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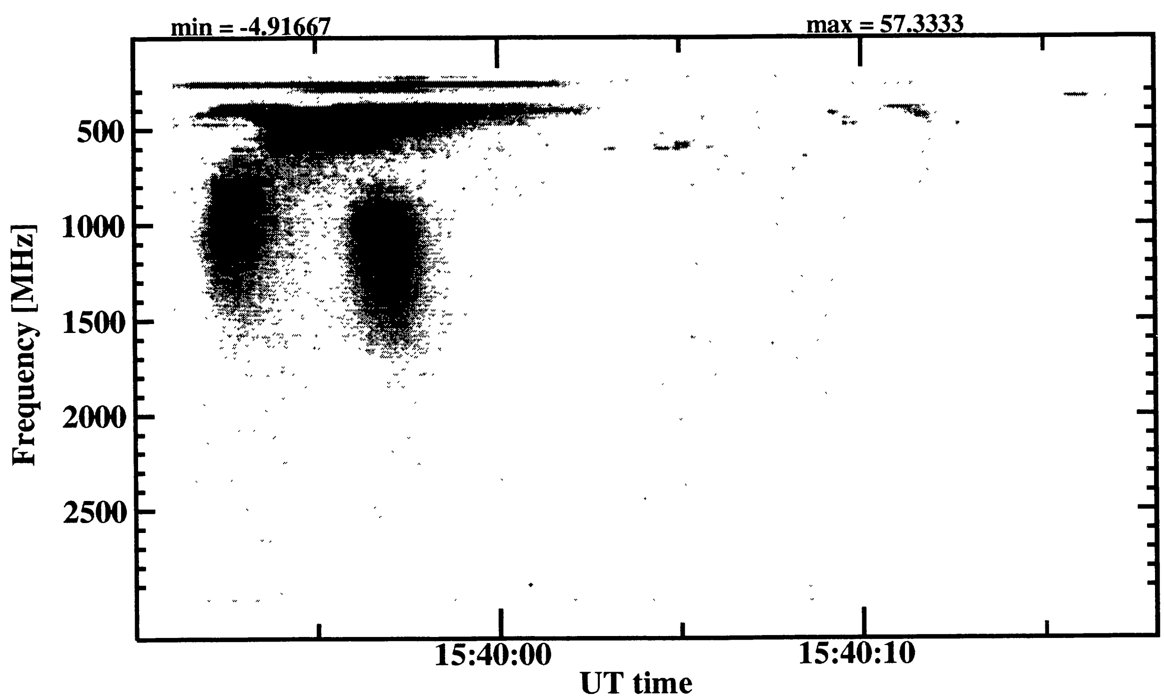


Fig. 23.

Fig. 22 – 23. *Diffuse continua (patches):* – Fig. 22. 92/09/05, an extremely narrowband, long-duration event. – Fig. 23. 92/09/12, two broadband events of short duration

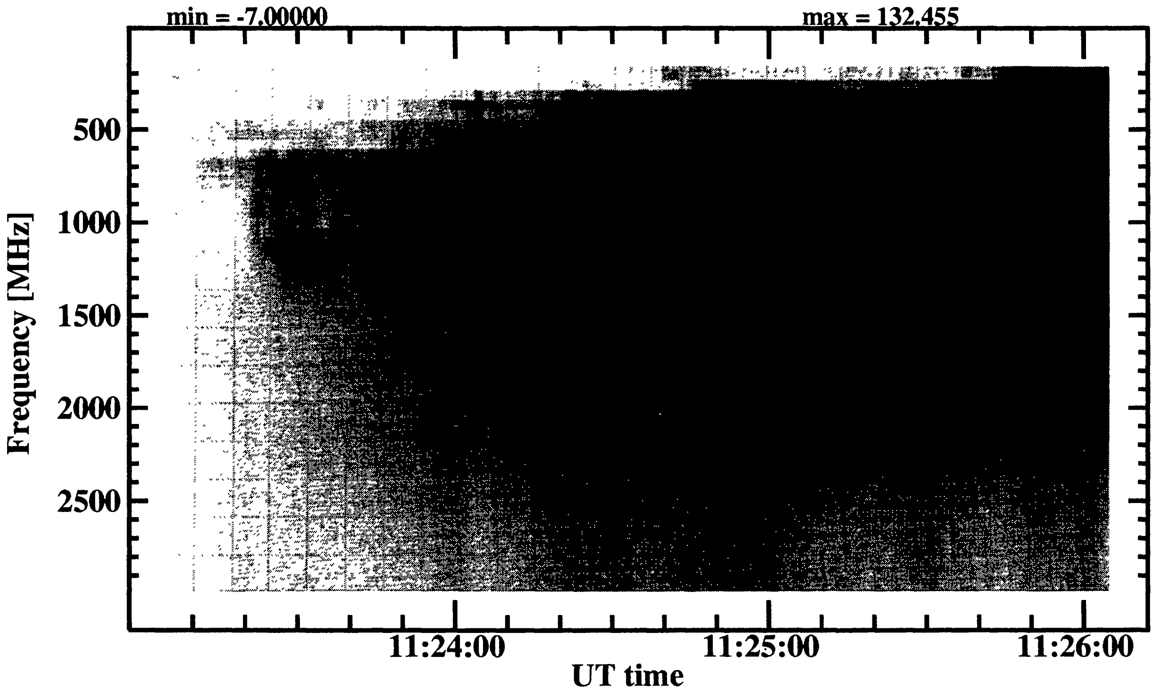


Fig. 24.

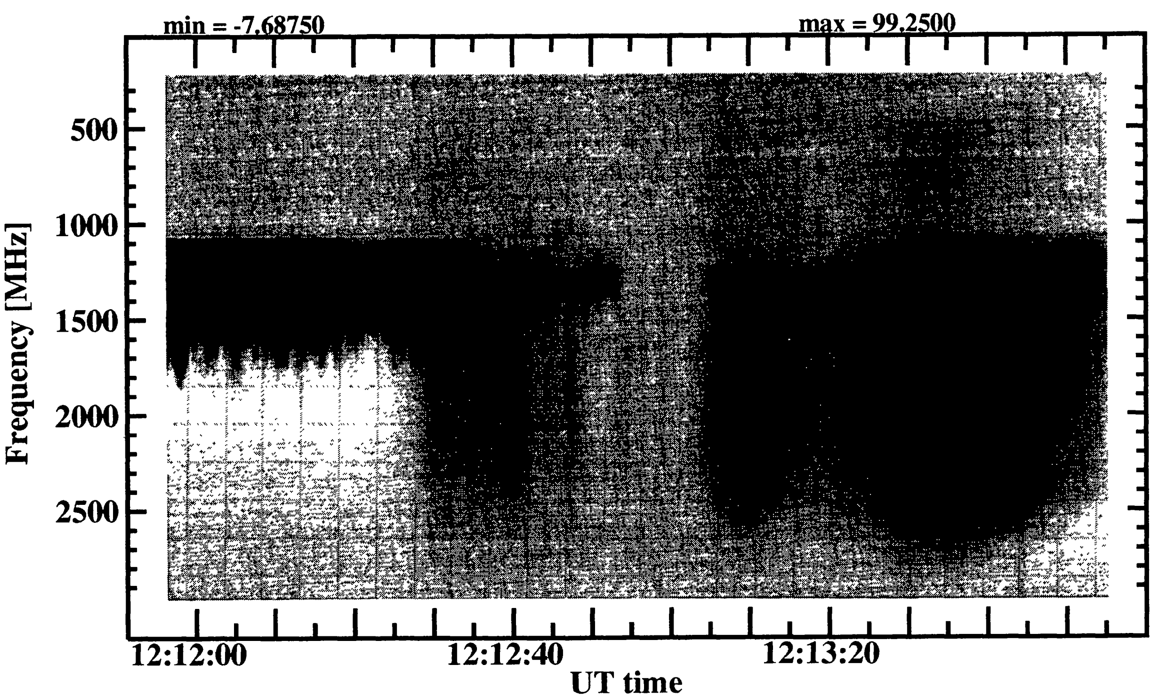


Fig. 25.

Fig. 24 – 25. *Type IV bursts:* – Fig. 24. 89/09/29, the beginning of a very broadband event lasting 15 minutes and drifting slowly to lower frequencies. – Fig. 25. 93/03/20, an event that is interrupted in the middle of the image and consists of two continua at different frequencies, each with fine structures (pulsations and intermediate drift bursts). In the second part, the weaker, high-frequency continuum is of opposite polarization than its low-frequency counterpart

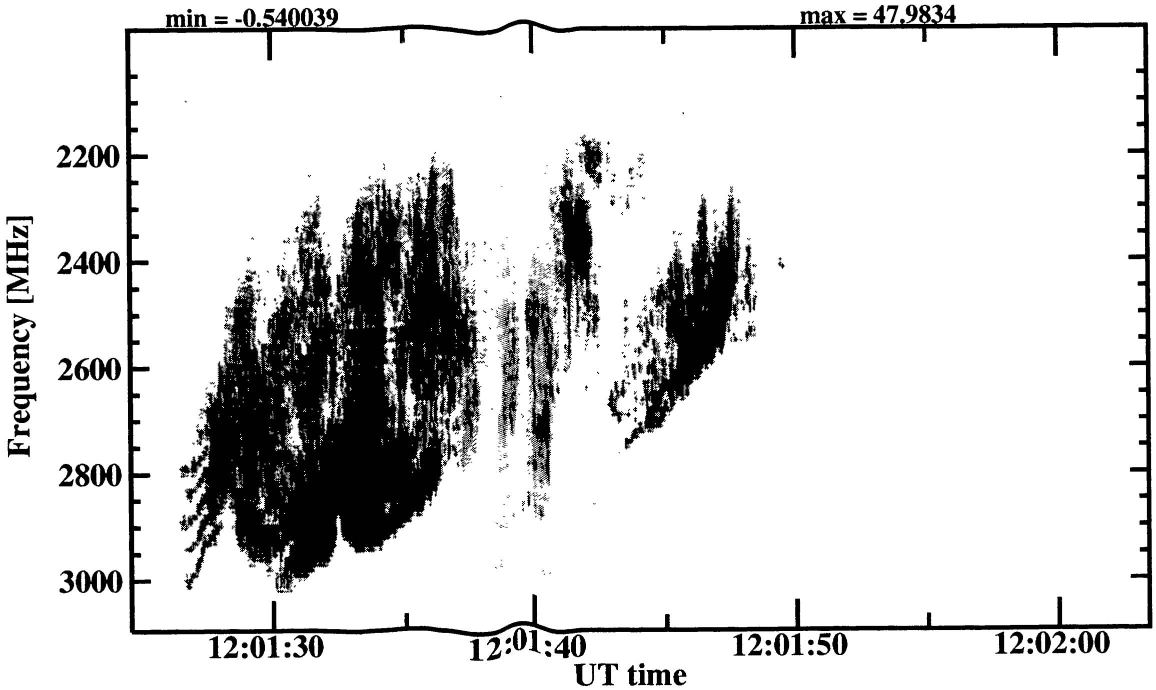


Fig. 26.

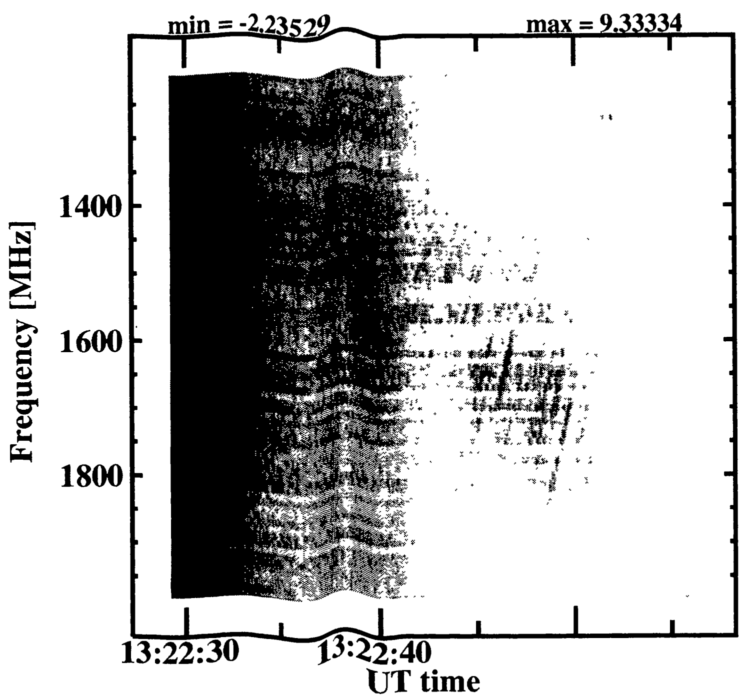


Fig. 27.

Fig. 26 – 27. *Type IV bursts:* – Fig. 26. 91/07/10, an event modulated in time, with parallel drifting bands. – Fig. 27. 90/04/04, with intermediate drift bursts

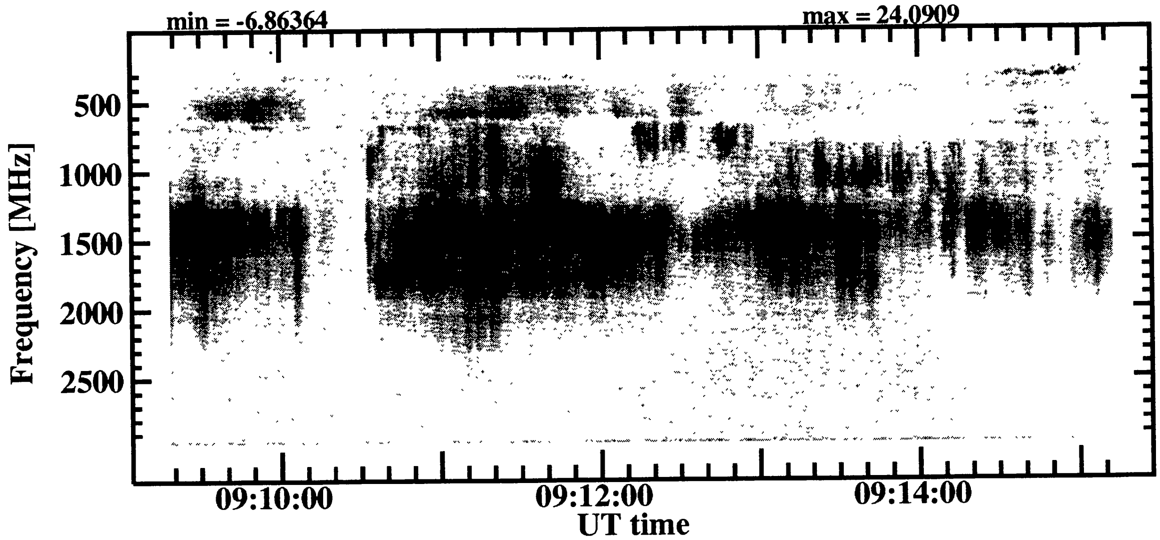
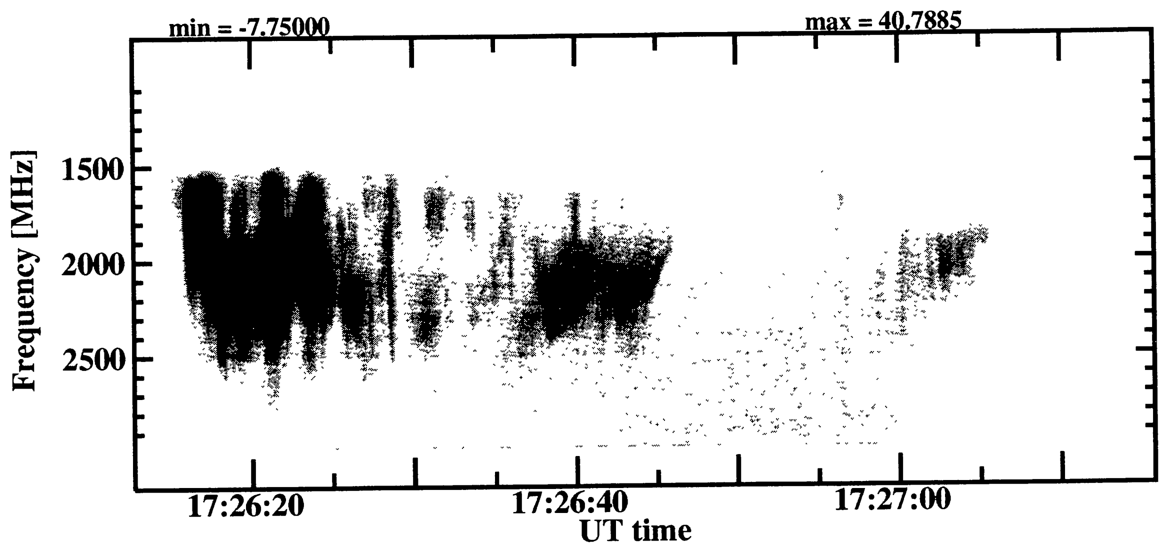


Fig. 28.



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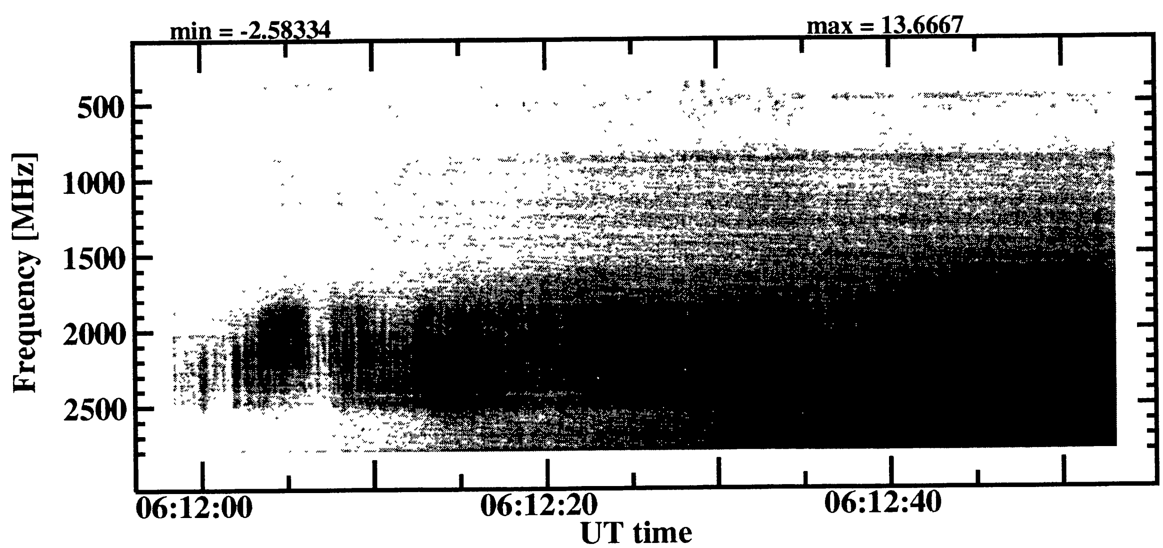

Fig. 30.

Fig. 28 – 30. *Pulsations:* – Fig. 28. 93/01/07, a typical event consisting of several parts at different frequencies. Note also intermediate drift structures. – Fig. 29. 89/08/16, with parallel drifting bands. – Fig. 30. 89/09/01, pulsations partly in absorption