HARMONIC EMISSION AND POLARIZATION OF MILLISECOND RADIO SPIKES*

A. O. BENZ and M. GÜDEL

Institute of Astronomy, ETH, Zürich, Switzerland

Abstract. The spectral distribution of millisecond radio spikes observed by the Zürich spectrometers in the 200–1100 MHz range has been studied. In one event out of a total of 36 we have found clearly developed harmonic structure. The ratio between the two bands of emission was 1:1.39 ± 0.01. We have also determined the sense of circular polarization of the spike events and compared it to the magnetic polarity of the leading spot of the flaring active region. According to the 'Leading Spot Rule' the majority of the events (10 out of 13) were emitted in the ordinary mode.

1. Introduction

Millisecond radio spikes have brightness temperatures up to $10^{15}$ K (cf. review by Benz, 1986). For this reason the very efficient electron cyclotron instability (often referred to as 'maser') has been evoked as the cause of emission. The first quantitative theories (Holman et al., 1980; Melrose and Dulk, 1982) predict emission at the lowest harmonics of the electron-cyclotron preferentially in the extraordinary mode. This model and predictions are similar to auroral kilometric radiation, where usually (but not always) x-mode is observed and there is evidence for harmonics (Benson, 1984). More recent calculations, however, yield ordinary mode emission at plasma densities expected in solar flares. Although there is no alternative emission process proposed, the maser model for solar spikes needs to be observationally confirmed. The goal of this study was to search for harmonics predicted by the above theory and to study the mode.

2. Observations

Spike events can be readily identified in the film recordings of the Zürich analog spectrograph (DAEDALUS) and analyzed from digital recordings of the Zürich frequency-agile spectro-polarimeter (IKARUS). Both instruments have operated in the 100–1100 MHz range during the past solar cycle (Perrenoud, 1981). The resolution of the digital instrument varied in frequency from 1–3 MHz and in time from 25–100 ms. The analog instrument observes the full spectrum is a continuous sweep, whereas the digital spectrometer only observes in certain bands selected for their absence of interference.

We have selected 36 spike events for further analysis, excluding fine structure of type IV events. All of these events were associated with type III activity at lower frequency. An example of a digital registration is shown in Figure 1. The selection contains both small groups of spikes as investigated by Benz et al. (1981) as well as large


© 1987 by D. Reidel Publishing Company
© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
groups containing some ten thousand spikes. As much as we could confirm from hard X-ray and Hα observations, they all occurred during the impulsive phase of flares.

3. Harmonics

We have inspected the 36 selected events for harmonic structures both in the analog and the digital data. We frequently noticed the spikes to form clusters in frequency and time. The clusters usually do not seem to be related to each other and do not occur simultaneously. Only one case, presented in Figure 2, showed a clear splitting in frequency. Terrestrial interference at constant frequency has been removed for clarity. Weak type III activity is visible at frequencies below 450 MHz. The spikes occurred during the rise of the impulsive phase of a major flare which later produced type IV emission. The two bands of spikes have also been digitally recorded and are displayed in Figure 3. There seems to be a correspondence between the global structures in the two bands indicating that they are related to each other. A frequency ratio can be determined between corresponding clusters of spikes in the two bands of Figures 2 and 3. It is 1:1.39 ± 0.01 in frequency. The scatter of this value is surprisingly small and excludes any chance coincidences.
We have also noted a correlation between single spikes in the two bands. Their frequency ratio, however, seems to be less stable.

The spikes of the 16 May, 1981 event were weakly circularly polarized. As in all weakly polarized spike events the polarization at peak flux scatters considerably from spike to spike. The average polarization of the spikes in the low-frequency band was significantly higher (16.4 ± 3% left) than in the high-frequency band (7.6 ± 5% left). The sense of polarization (left) was independently confirmed by observations of the Trieste Observatory (courtesy Dr P. Zlobec). It corresponds to ordinary mode according to the Leading Spot Rule (cf. next section).
4. Leading Spot Rule

In 13 out of the 36 events we were able to determine a well defined sense of circular polarization as well as the position of the associated Hz flare. For the remaining bursts we either did not have polarization data, the polarization was close to zero, or no Hz flare was reported. The magnetic field polarity of the leading spot was looked up in Solar-Geophysical Data using mainly Kitt Peak observations. The Leading Spot Rule suggests that the leading polarity of the active region determines the magnetic field direction of the source. This rule would predict that radio sources emitting extraordinary mode are left circularly polarized for negative (S) leading polarity and vice versa. Applying the rule to these spike data, however, would indicate that 10 out of the 13 events were polarized in the ordinary mode.

In this set of observations the Leading Spot Rule suggests ordinary mode also for the associated type III bursts in 10 cases out of 12 which could be measured. The associated type III bursts generally have the same polarization as the spikes (Benz et al., 1982).

5. Discussion

These observations of spikes contradict early theories of maser emission. However, they do not exclude maser emission in general for the following reasons:
The observed ratio of the harmonic structure in a spike event cannot be the result of two integer multiples of the electron gyrofrequency unless unreasonably high harmonics are assumed. However, maser emission does not occur exactly at the harmonics of the gyrofrequency. Particularly the fundamental is shifted to higher frequency due to refraction. Fundamental and second harmonic \((n = 2)\) of the \(X\)-mode have a frequency ratio of \(1:1.39\) for a ratio of plasma frequency to gyrofrequency of 0.52 (Aschwanden and Benz, 1987). This possibility does not seem to exist for \(O\)-mode emission, which is suggested by the Leading Spot Rule. There is an alternative: the discrepancy would disappear if one of the bands is assumed to be the result of electrostatic waves at the upper hybrid frequency \(\omega_{uh}\) (sometimes referred to as \(Z\)-mode) which are also well-known under similar conditions. They can emit radio waves at their second harmonic by coalescence. The observed ratio then is given by

\[
\frac{\omega}{2\omega_{uh}} = \frac{n\Omega_e}{2\Omega_e (1 + \omega_p^2/\Omega_e^2)^{1/2}} = \begin{cases} 1.39 \\ 1/1.39 \end{cases},
\]

where \(n\) is the harmonic of the maser, \(\Omega_e\) and \(\omega_p\) are the electron cyclotron and the plasma frequency, respectively. The two cases refer to the \(Z\)-mode emission being at the lower-frequency band (top) or at the higher frequency band (bottom), respectively. E.g., for \(n = 2\) the ratio \(\omega_p/\Omega_e\) is 0.967 for the second case, the first case having no real solution.

The Leading Spot Rule is not a compelling proof of the mode of emission. It has produced consistent results for type I bursts (90% ordinary mode, cf. Elgarøy, 1977, and references therein) and decimetric pulsations (extraordinary mode, Aschwanden, 1986). The results for type III (predominantly ordinary mode) are less clear (cf. Krüger, 1979, and references therein). A detailed analysis of \(U\)-bursts by Benz et al. (1979) has given further evidence for ordinary mode emission of electron beams. The emission mode of spikes determined by the leading Spot Rule may thus be taken as an indication requiring further corroboration. Most importantly, however, preferential emission in the ordinary mode is predicted for the maser instability at \(\omega_p/\Omega_e \gtrsim 0.4\) for \(n = 1\) and \(\omega_p/\Omega_e \gtrsim 1.4\) for \(n = 2\) by recent calculations (Sharma and Vlahos, 1984; Melrose et al., 1984). The predominant maser mode in sources at wave saturation is a topic of ongoing theoretical research and of great importance for any quantitative model.

Acknowledgements

This work has profited from various discussions at the 1986 CESRA workshop in Aubigny. In particular we thank M. J. Aschwanden and one of the referees for constructive criticism and suggestions, and P. Zlobec for supplementary data. The construction of the Zürich spectrometers is being financially supported by the Swiss National Science Foundation (Grant No. 2.211–0.84).
References