ON THE HARMONIC STRUCTURE OF SOLAR RADIO SPIKES

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Abstract. This paper analyzes the frequency structure of the bands of electron-cyclotron maser instability. The calculations show that each term of the series describing the growth rate provides a double-peak structure, if we accept a nonthermal electron distribution with a 'two-side' loss-cone. The ratio of central frequencies is found to be non-integer in general case. We conclude that the harmonic structure of solar radio spikes observed in a number of events can be imitated by electron-cyclotron maser emission of mildly relativistic electrons with a power-law momentum distribution.

1. Introduction

Solar millisecond radio spikes reveal many interesting features. The harmonic frequency structure recorded a few times by Güdel (1990) is one of them. It is commonly assumed that millisecond radio spikes appear under the action of an electron cyclotron maser (ECM) (Benz, 1986), while several alternative mechanisms still exist (Zheleznyakov and Zaitsev, 1975; Tajima et al., 1990; Wentzel, 1991). Experimental study of the sense of polarization in the radiation (Güdel and Zlobec, 1991) has shown that the X-mode dominates in spiky emission for most of the events. This fact has a natural explanation within ECM theory. Nevertheless, extensive calculations with several model electron distribution functions (Melrose and Dulk, 1982; Sharma, Vlahos, and Papadopoulos, 1982; Sharma and Vlahos, 1984; Wu 1985; Louarn, Le Queau, and Roux, 1987; Winglee, Dulk, and Pritchett, 1988; Aschwanden, 1990) have not provided a comparable value of linear growth rates of normal modes at various harmonics. Thus, the observed harmonic structure of solar radio spikes up to $s = 6$ (Güdel, 1990) gives a challenge to EMC theory. Melrose (1991) has proposed coalescence of $Z$-modes (processes $Z + Z \rightarrow t$, $Z + t' \rightarrow t$) as a possible mechanism for harmonic production. However, his evaluations show that this mechanism cannot provide emission with $s > 4$ for typical conditions.

This paper demonstrates that mildly relativistic electrons with power-law momentum distribution (and loss-cone angular distribution) can ensure an imitation of harmonic structure at least up to $s = 6$ near the fundamental and second harmonics of the gyrofrequency.
2. Calculations

2.1. Initial Distribution Function

Previous investigations of linear growth rates considered quasi-maxwellian distributions of fast electrons with loss-cone (Melrose and Dulk, 1982; Aschwanden, 1990), hollow-beam (Wu, 1985), DGH (Sharma, Vlahos, and Papadopoulos, 1982; Sharma and Vlahos, 1984; Louarn, Le Queau, and Roux, 1987; Winglee, Dulk, and Pritchett, 1988), etc. Aschwanden and Güdel (1992) have shown that radio spikes appear always together with HXR bursts. Temporal dependencies of HXR and spiky emission agree quite well, while the latter has a 2–5 s delay. Judging by HXR spectra, accelerated electrons usually have power-law energetic spectra with various indices. For this reason we have chosen the following electron distribution function:

\[
f(p) = \frac{\xi - 3}{2\pi p_0^3} \left( \frac{p_0}{p} \right)^\xi F(\mu), \quad p_0 < p < p_{\text{max}},
\]

where \( p \) is the particle momentum, \( \xi \) is the spectral index of the distribution and \( F(\mu) \) the angular distribution of the particles. Generally speaking, the shape of the function \( F(\mu) \) depends on microscopic processes forming the anisotropy. So far, several model distributions have been used, e.g., an empty loss-cone or sin-distributions (Wu, 1985; Aschwanden, 1990). A general form of the distribution can be represented by an asymmetric loss-cone with two limiting cases of one-side loss-cone and symmetric two-side loss-cone. Unfortunately, we still have no detailed observational data on the real angular distributions of nonthermal electrons in solar flares. The respective theoretical models (see, e.g., Hamilton and Petrosian, 1990) do not allow us to determine the distribution reliably.

However, we would like to note that the results obtained in the paper are not qualitatively sensitive to the exact form of the distribution, though the presence of a two-side loss-cone (symmetric or asymmetric) as well as the power-law momentum distribution are important for the conclusions made. We expect that \( F(\mu) \) has a nonzero value at each pitch-angle in any physical system. The simplest distribution that fits this requirement is a gaussian distribution over pitch-angles:

\[
F(\mu) = \frac{1}{N} \exp\left(-\frac{\mu^2}{\mu_0^2}\right), \quad \int_{-1}^{1} F(\mu) \, d\mu = 1,
\]

where \( \mu = \cos \vartheta \), and \( \vartheta \) is the electron pitch-angle. We suppose that this distribution can approximate real loss-cones in some cases at least.

3. Linear Growth Rates

A fully relativistic expression for growth rates of transverse waves (Akhiezer et al., 1974; Wu, 1985) can be written in the form (Fleishman and Yastrebov, 1994)