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Kinetic simulation of the electron-cyclotron maser instability: effect of a finite source size

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The electron-cyclotron maser instability is widespread in the Universe, producing, e.g., radio emission of the magnetized planets and cool substellar objects. Diagnosing the parameters of astrophysical radio sources requires comprehensive nonlinear simulations of the radiation process taking into account the source geometry. In this work, we simulate the electron-cyclotron maser instability (i.e., the amplification of electromagnetic waves and the relaxation of an unstable electron distribution) in a very low-beta plasma. The model used takes into account the radiation escape from the source region and the particle flow through this region.

We developed a kinetic quasi-linear code to simulate the time evolution of an electron distribution in a radio emission source. The model includes the terms describing the particle injection to and escape from the emission source region. The spatial escape of the emission from the source is taken into account by using a finite amplification time. The unstable electron distribution of the horseshoe type is considered. A number of simulations were performed for different parameter sets typical of the magnetospheres of planets and ultracool dwarfs.

We have found that the generated emission (corresponding to the fundamental extraordinary mode) has a frequency close to the electron cyclotron frequency and propagates across the magnetic field. Shortly after the onset of a simulation, the electron distribution reaches a quasi-stationary state. Under the conditions typical of the sources of terrestrial and Saturnian auroral radio emissions, the dominant factor affecting the electron distribution is the particle escape from the emission source region. As a result, the electron distribution in a quasi-stationary state does not differ significantly from the horseshoe-like distribution of the injected electrons. The conversion efficiency of the particle energy flux into waves is typically a few percent. We have found good agreement of our model with the in situ observations in the source regions of auroral radio emissions of the Earth and Saturn.

Under the conditions that seem to be typical of the magnetospheres of ultracool dwarfs, the electron distribution may become nearly flat due to the wave-particle interactions, while the conversion efficiency of the particle energy flux into waves reaches $10-20\%$. Therefore we expect the electron distributions in the stellar magnetospheres to look similar to Maxwellian or kappa distributions, which are only slightly distorted by the parallel electric field and magnetic mirroring. Nevertheless, even these small deviations from an equilibrium distribution seem to be sufficient to produce an intense radio emission.