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Electron cyclotron maser model of solar radio zebras

Jan Benáček[1] and Marian Karlický[2]
[1]Technical University of Berlin, Center for Astronomy and Astrophysics, Germany (benacek@tu-berlin.de)
[2]Astronomical Institute, Czech Academy of Sciences, Czech Republic

Solar radio zebras, occurring as fine structures in radiograms during Type IV bursts, are an excellent tool for plasma diagnostics during solar flares. The main model of zebras is the electron cyclotron maser instability based on double plasma resonance between electron cyclotron and plasma frequencies and an unstable wave in the presence of an unstable type of velocity distribution is necessary, e.g., a loss-cone. The radio emission occurs in the electromagnetic Z-mode along the magnetic field or at the first harmonic of the X-mode in the perpendicular direction. However, it is still unclear where and how the instability evolves and how the locally captured electrostatic waves are converted to escaping radio waves. To obtain the instability evolution, we calculated its growth rates and saturation energies as functions of cyclotron-to-plasma frequency ratio, loss-cone density, cold background temperature, hot electron thermal velocity, and loss-cone angle by using analytical calculations and particle-in-cell simulations. We found that the growth rates and saturation energies form maxima, approximately located at the harmonic numbers of cyclotron frequency. The maxima shift to lower frequencies with increasing the plasma temperature, they broaden and decrease with increasing the harmonic number. We also estimated electromagnetic energy densities in the emission region and the conversion efficiency to the radio waves.