# Auroral magnetospheric radio emission from stars and planets

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Cyclotron maser instabilities are of relevance in various astrophysical contexts including planetary auroral radio emission [1–3], astrophysical shocks [4] and recently discovered periodic radio emission from oblique-rotator stars [5]. Such sources are spectrally well defined and for the planetary cases [1-3] show a high degree of extraordinary (X-mode) polarisation within the source region. In the terrestrial auroral case, powerful radio emission has been observed from field-aligned regions of depleted plasma density ($\omega_{pe} \ll \omega_{ce}$) and it is now widely accepted that these emissions are generated by an electron cyclotron-maser instability driven by a horseshoe shaped electron velocity distribution [6]. Such distributions are formed through conservation of magnetic moment when particles descend into the increasing magnetic field of planetary / stellar auroral magnetospheres. In the terrestrial auroral case, the resultant rf emission comprises a spectrum of narrowband components, polarised in the X-mode and centred around ~300kHz. The mean output power of ~1GW corresponds to ~1% of the precipitating auroral electron flux power, in agreement with the predictions of kinetic theory for X-mode dispersion and growth due to an electron horseshoe distribution [6].

Although the generation mechanism is well established, a satisfactory explanation does not yet exist for the sporadic occurrence of these emissions and the observed field aligned beaming of the radiation out from the source region [2]. In-situ measurements of the emission from within the terrestrial auroral zone [2], and more recently from within Saturn's SKR source region [3], show the radiation to be polarised in the X-mode and generated near perpendicular to the magnetostatic field. Although quasi-optical ray tracing models have been proposed for the field aligned beaming of terrestrial AKR [2], these models assume the presence of a field aligned plasma density cavity in the source region – a structure not observed within Saturn's SKR source region [3], and not inferred for the numerous stellar candidates of the horseshoe-maser emission mechanism. In light of these issues, an alternative model of escape has been proposed comprising upward refraction of the generated radiation due to an increasing plasma density with decreasing altitude within the radiation source region [7]. In the terrestrial case, this effect would be most pronounced along a path tangential to the plasma cavity boundary for which convective growth of the cyclotron-maser instability would also be enhanced. In the case of the oblique-rotator star CU-Virginus, the model of upward refraction could also explain the observed angular frequency chirp across the precessing cone of narrowly beamed radio emission [5]. A necessary precursor for this model however is that the radiation is generated with a finite backward-wave component (negative axial wavenumber $k_z$) to facilitate propagation along a path of decreasing plasma density (increasing refractive index).

Scaled laboratory experiments and simulations (at GHz frequencies) have previously been conducted to study the magnetospheric cyclotron emission process, based on the concept that only the relative magnitudes of the plasma and cyclotron frequencies are fundamental to the dynamics of the horseshoe-maser instability [8-10]. In the current context, PiC simulations have been conducted to investigate the spatial growth of the horseshoe-maser instability in an unbounded geometry, with a view to studying the wave vector of emission, spectral properties and RF conversion efficiency. In particular, the potential for backward wave coupling was investigated as a viable precursor to upward refraction and field-aligned beaming of the radiation.

The 2D axisymmetric version of the finite-difference time domain PiC code KARAT was used to simulate the unbounded geometry with a 44cm radius region of radially increasing conductivity defined around the path of beam propagation. This represented an idealised absorber of electromagnetic radiation, inhibiting reflection and the formation of boundary resonant eigenmodes. An electron beam was injected into this simulation geometry with a predefined horseshoe distribution, comprising a pitch spread $\alpha = v_\perp / v_z$ of $0 \rightarrow 9.5$, beam energy of 20keV±5% and beam current of 14A. Other simulation parameters included a uniform axial magnetic flux density of 0.1T, grid resolution of 0.25cm, PiC particle merging factor of $3\text{x}10^6$ electrons / PiC particle and a total simulation length (beam propagation path) of 4m.

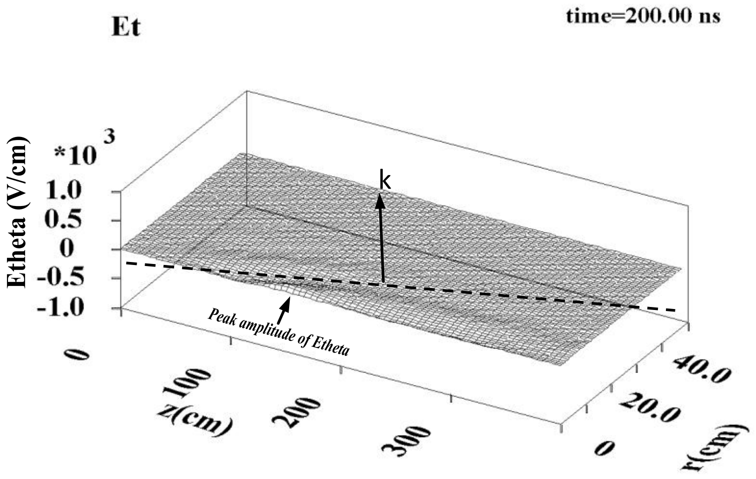

Figure 1. 3D contour plot of $E_\theta$ within the unbounded simulation geometry.

Figure 1 contains a 3D contour plot of $E_\theta$ over the simulation geometry after a 200ns run. An electromagnetic wave sourced at z ~ 1.45m is evident propagating near perpendicular to the electron beam with a small negative axial wavenumber. The observed backward propagation angle of a few degrees represents a sufficient precursor for the proposed upward refraction model in the terrestrial auroral case [7]. A plot of the corresponding radial Poynting flux is presented in figure 2a measured in a plane at r = 3.5cm. A DC offset is present in the measurement due to low frequency EM field components associated with the electron beam propagation. After 180ns a peak rf output power of ~3kW was measured corresponding to an rf conversion efficiency of 1.1% - comparable to the estimate of ~1% for the astrophysical phenomena [11,12]. The corresponding output spectrum is presented in figure 2b, showing a well-defined spectral peak at 2.68GHz. This represents a 1.1% downshift from the relativistic electron cyclotron frequency of 2.71GHz, consistent with the slight backward wave character observed in figure 1.

In conclusion, PiC simulations have been conducted to investigate the electrodynamics and directional coupling of the cyclotron-maser instability attributed to numerous astrophysical radio sources [1-5]. Computations demonstrate a well-defined cyclotron emission process, with RF output showing a small negative axial wavenumber corresponding to a backward wave angle of a few degrees – consistent with minimum estimates required for a model of upward refraction and field aligned beaming of the radiation [7]. The corresponding RF conversion efficiency of 1.1% is comparable to earlier waveguide bounded simulations [8] and consistent with estimates of ~1% for the astrophysical phenomena [11,12].

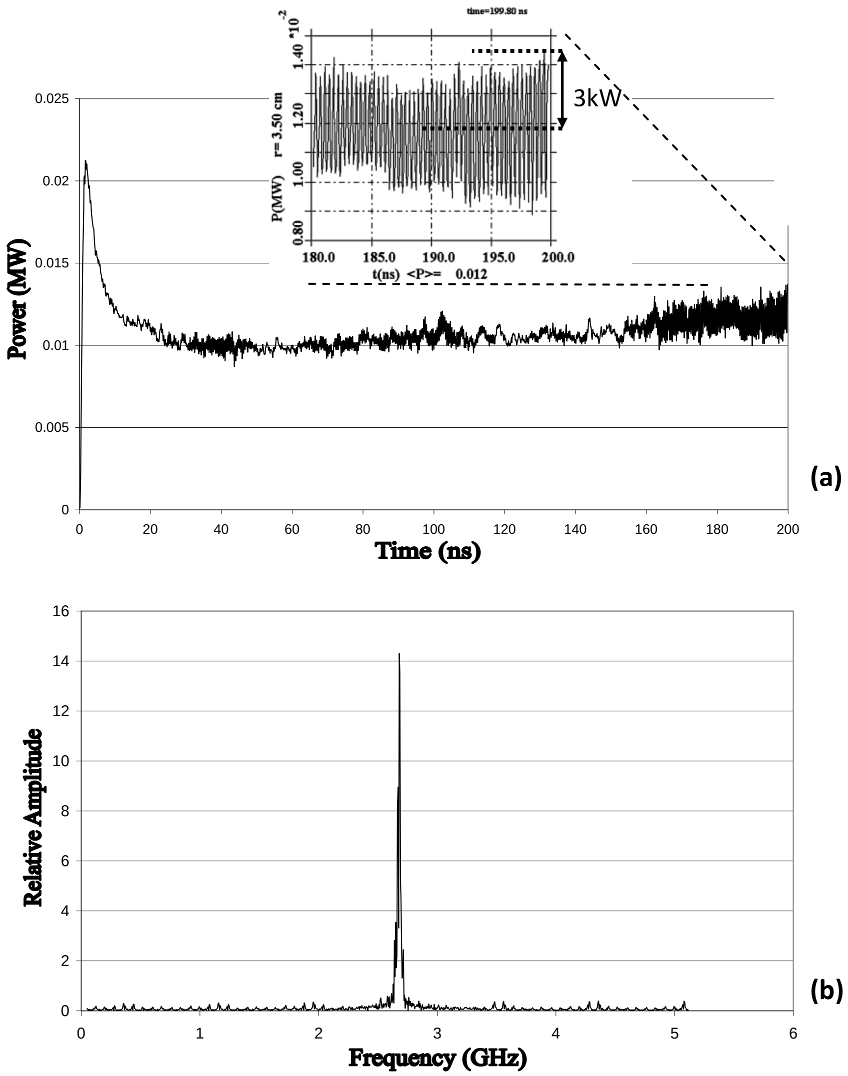

Figure 2: (a) Temporal evolution of the radial Poynting flux measured in a plane at r = 3.5cm spanning the length of the simulation. (b) Fourier transform of $E_\theta$ from t = 0 →200ns at z = 1.9m.

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## References

[1] A P. Zarka, Advances in Space Research, **12**, 99 (1992).
[2] R.E. Ergun et al., Astrophys. J. **538**, 456 (2000).
[3] L. Lamy et al., J. Geophys. Res. **113**, A07201 (2008).
[4] R. Bingham et al., Astrophys. J. **595**, 279-284 (2003).
[5] B.J. Kellett et al., ArXiv Astrophysics, 0701214 (2007)
[6] R. Bingham and R. A. Cairns, Phys. Plasmas, **7**, 3089 (2000).
[7] J.D. Menietti et al., J. Geophys. Res., **116**, A12219 (2011).
[8] S.L. McConville et al., Plasma Phys. Controlled Fusion, **50**, 074010 (2008).
[9] D.C. Speirs et al., Phys. Plasma, **17**, 056501 (2010).
[10] A.V. Vodopyanov et al., JETP **104**, 296 (2007).
[11] P.L. Pritchett and R.J. Strangeway, J. Geophys. Res., **90**, 9650 (1985).
[12] D.A. Gurnett, J. Geophys. Res., **79**, 4227 (1974).