Dynamical frequency modulation as a signature of cyclotron emission of a transiting object in radio signal from its host star

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We present modelling a dynamical spectrum of a host star's cyclotron emission, which came through a magnetically active (auroral) region of a planetary magnetosphere. The resultant frequency time dependence (dynamical spectrum) has a periodic modulated character. We suggest that seeing such dynamical spectrum can be an indication of a dipole magnetic field present at the planet, and compare to available observational results.

Cyclotron maser emission is a result of unstable electron beams moving into converging magnetic fields. It is emitted in hollow cones of circularly polarised radiation, and so received as a rotationally modulated periodical signal. Magnetically active planets can emit cyclotron radiation from their magnetospheres, which is currently difficult to detect directly from Earth due to its relatively low power, low frequency (due to lower magnetic field) and highly directional nature. Detecting magnetic activity from exoplanets could be a supportive argument towards their habitability, since the magnetic field would retain the atmosphere there. While searches for direct observations of magnetic activity from exoplanets were still not successful, we propose a more 'indirect' method of detecting such cyclotron radiation, looking for its signature in its host star's cyclotron emission's dynamical spectrum. Expectations of seeing such a signature as a frequency modulation in time were based on known frequency modulations phenomena in optoelectronics, caused by nonlinear waves interaction.

The model for the local planetary emission is based on a horseshoe-type cyclotron instability (Bingham et al. 2001, Vorgul et al. 2011). We do a full electromagnetic modelling of a signal which propagated through the instability in the local magnetosphere, using 1D geometrical setting (the unstable region presented as a lane slab) but 3D fields. The later accounts for initial circular polarization in the star's radio emission before and after the interaction with the unstable region, since circular polarisation is characteristic for cyclotron maser radiation.

The field inside the unstable region with the electron beam moving in z-direction is presented as incoming and outcoming waves with time-dependent frequency. This field is connected to the incident and transmitted fields through impedance boundary conditions, taking into account the anisotropic dielectric tensor for the plasma of the unstable region.
For the incident field coming from the host star being a circularly polarized plane wave propagating in x-direction,

$$E_1 = A_1(\widehat{\hat{e}_z i} + \widehat{\hat{e}_y i})e^{-i\omega_0(t-x/v)} , \qquad (1)$$

the transmitted through the magnetically active region wave is assumed as an elliptically polarised plane wave with time-dependent frequency, $\omega(t)$,

$$E_3 = A_3\left(T_z\widehat{\hat{e}_z i} + T_y\widehat{\hat{e}_y i}\right)e^{-i(\omega_0+\omega(t))\left(t-\frac{x}{v}\right)+ik_z z} . \qquad (2)$$

In (2) k_z is the complex-value propagation constant in z-direction appearing due to the interaction with the instability and accounting for some change in direction of the incident wave as well as the local planetary magnetosphere radiation's growth rate. The growth rate is determined by the magnetically confined velocity distribution function,

$$f\left(v_{||}, v_\perp\right) = A\, e^{-\frac{m}{2T}\left(\left(\sqrt{v_{||}{}^2+(1-B/B_0)v_\perp{}^2}-v_0\right)^2+(B/B_0)\, v_\perp{}^2\right)}, \qquad (3)$$

which results from a beam of electrons with a drifting Maxwellian velocity distribution moving into stronger magnetic field (towards the magnetic poles), due to conservation of energy and magnetic momentum. The resultant from it dielectric tensor as calculated in (Vorgul et al. 2005) is used in the correspondent Maxwell's equations inside the unstable region. We used approximation of small amplitude of the frequency variations with time, compared to the star's radio frequency. After applying boundary conditions, we arrived at the frequency variations with time described by

$$\omega(t) = \frac{a_1+b_1\cos(\omega_\omega t)+c_1\sin(\omega_\omega t)}{a_2+b_2\cos(\omega_\omega t)+c_2\sin(\omega_\omega t)}, \qquad (4)$$

where $$\omega_\omega = \omega_0\left(\frac{1-\frac{\tilde{\varepsilon}_{22}^R}{|\tilde{\varepsilon}_{22}^R|}}{2\sqrt{|\tilde{\varepsilon}_{22}|}} - 1\right),$$

$\tilde{\varepsilon}_{22}$ and $\tilde{\varepsilon}^{R}_{22}$ are the dielectric tensor's diagonal element and its real part, correspondingly, and depend on k_z. The coefficients in (4) depend on the local conditions (the beam's parameters), and determine the shape of the frequency's periodic oscillations, as seen in Fig.1.

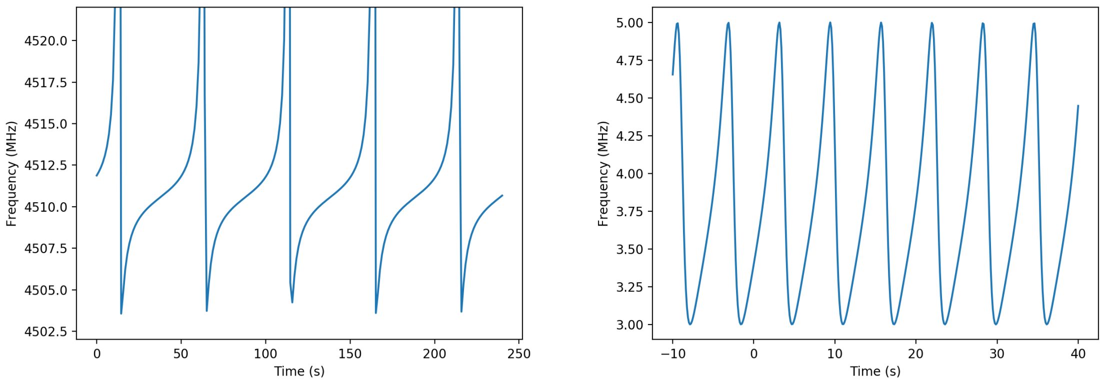

Fig.1. Typical temporal variations of the frequency of the transmitted signal for different combinations of coefficients in (4).

While the solution does not provide a straightforward way to determine local parameters by the transmitted wave's frequency modulation, it indicates that periodic variations of the frequency with time is a signature of the non-linear interaction with local active magnetosphere.

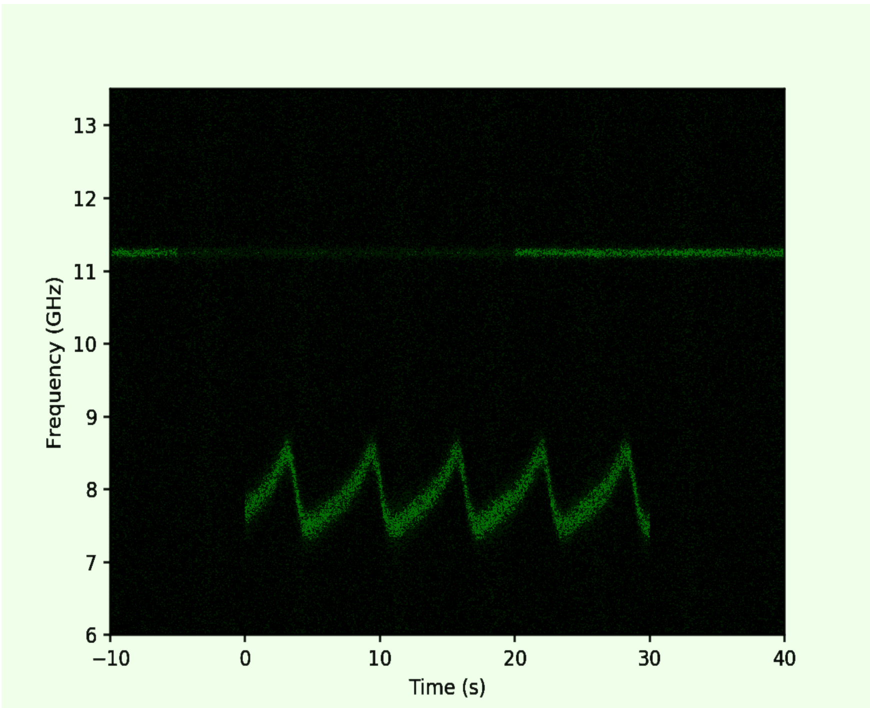

Fig.2. Simulated dynamical spectrum of a cyclotron signal coming through a magnetically-active region

Fig.2 presents a simulated dynamical spectrum (with added noise) of the transmitted cyclotron emission of a host star during a transit of a magnetically-active planet. The straight line corresponds to the initial undisturbed frequency. During the interaction with the local instability, the periodically modulated signature appears. It can however start either earlier or later (as in Fig.2) than the gap in the main frequency signal happens. This is due to a slight change in direction of the propagating signal (non-zero k_z).

The change of the signal's direction can play a vital role in detection of also non-transiting planets and in the cases when the radio emission from the host star is not detected on its own, due to the geometry of its rotation (i.e. when the radiation cone rotates with the star in a way that it never points towards Earth). We suggest that the periodical lines in dynamical spectrum received from Ross 128 (Emilio Enriquez et al. 2019), without any single-line spectrum emission received from it, could possibly be an indication of the star's cyclotron emission being deflected by its orbiting planet's, Ross 128b, magnetic activity, with its frequency being periodically modulated in time. Since the planet orbits in the habitable zone around its star, suspecting seeing a magnetic activity there would bring up the arguments on it having an atmosphere. Being 10.89 light years away, a 4^0 change in the original emission's direction could bring the ray of radiation, normally missing Earth, 0233 parsecs closer and make the resultant transformed emission observable (non-linear lensing effect).

Acknowledgements. MTW acknowledges support of Royal Society of Edinburgh's Cormack Vacation Research Scholarship 2018, which enabled him to work on this research as a summer project.

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