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Origin of electron cyclotron maser-induced radio emissions at ultra-cool dwarfs: magnetosphere-ionosphere coupling currents

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Abstract

A number of ultra-cool dwarfs emit circularly polarised radio waves generated by the electron cyclotron maser instability. In the solar system such radio is emitted from regions of strong auroral magnetic field-aligned currents. We thus apply ideas developed for Jupiter's magnetosphere, being a well-studied rotationally-dominated analogue in our solar system, to the case of fast-rotating UCDs. We explain the properties of the radio emission from UCDs by showing that it would arise from the electric currents resulting from an angular velocity shear in the fast-rotating magnetic field and plasma, i.e. by an extremely powerful analogue of the process which causes Jupiter's auroras. Such a velocity gradient indicates that these bodies interact significantly with their space environment, resulting in intense auroral emissions. These results strongly suggest that auroras occur on bodies outside our solar system.

1. Introduction

Ultra-cool dwarfs (UCDs) are objects with spectral type later than M7, comprising the lowest mass stars and brown dwarfs. Twelve of these (out of ∼200 observed) have been found to be intense sources of radio emissions with spectral luminosities typically of order a $\mathrm{MW\ Hz^{-1}}$ (Berger et al., 2001; Hallinan et al., 2008; Antonova et al., 2007; Phan-Bao et al., 2007; McLean et al., 2012; Route & Wolszczan, 2012). The unpolarised component probably includes synchrotron emission, but the radio emission from a number of these, which have fast (∼2 h) rotation periods and strong (~ 0.1 T) magnetic fields, has been shown to be highly circularly polarised and modulated at the bodies' rotation periods (e.g. Hallinan et al., 2006). The polarised nature of the emission implicates the electron cyclotron maser instability (CMI) as the source mechanism. The presence of sustained CMI-generated radio emissions is strongly suggestive of the existence of quasi-steady auroral magnetic field-aligned currents.

Field-aligned currents arise from a divergence in field-perpendicular currents, which are, through $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$, driven by plasma velocities relative to the neutrals in the conducting outer layer of the atmosphere. Thus, strong field-aligned currents flow when there is a sharp gradient in this departure from corotation, giving rise to a strong divergence in the field-perpendicular currents. We may therefore infer from the observation of CMI-generated radio emissions from UCDs that such angular velocity gradients with auroral currents exists in the magnetospheres of these objects. Here we have developed a simple axisymmetric model of the currents arising from departure from rigid corotation in the magnetospheres of UCDs, based on that used previously to study Jupiter's auroral oval (Cowley & Bunce, 2001; Cowley et al., 2005) and to estimate the radio luminosity of fast-rotating Jupiter-like exoplanets (Nichols, 2011, 2012). We explain the properties of the radio emission from UCDs by showing that it would arise from the electric currents resulting from an angular velocity shear in the fast-rotating magnetic field and plasma, i.e. by an extremely powerful analogue of the process which causes Jupiter's or Saturn's auroras. Such a velocity gradient indicates that these bodies interact significantly with their space environment, resulting in intense auroral emissions.

2. Figures

We present here results of the model using appropriate spot values for the various model parameters. Figure 1 shows representative results, in which we employ a uniform ionospheric field strength of 0.3 T and rotation period of 2 h, in conformity with typical values obtained from the bandwidth and modulation of the UCD radio emissions (Hallinan et al., 2008). First, Figure 1a shows the angular velocity profile employed. Moving from large to small co-latitudes, the plasma angular velocity initially near-rigidly corotates, and transitions over $\sim 1°$ at $15°$ co-latitude to a quarter of rigid corotation at smaller co-latitudes. The resulting equatorward azimuth-integrated ionospheric field-perpendicular (Pedersen) current is shown in Figure 1b, increasing from small values near the pole to a value of $\sim$58 GA, before falling rapidly due to the plasma angular velocity gradient shown in Figure 1a. The resulting field-aligned current is shown in Figure 1c, which is negative, i.e. downward, near the pole and switches to a significant peak of positive, i.e. upward, field-aligned current values, reaching amplitude $\sim 0.7\ \mathrm{mA\ m^{-2}}$, centred on $15°$. This is the region of auroral field-aligned current that sustains the unstable electron distributions responsible for the CMI and thus the radio emissions. The required field-aligned voltage is then shown in Figure 1d, peaking at $\sim$11 MV, and the corresponding precipitating electron energy flux is shown in Figure 1e, peaking at $\sim 9\ \mathrm{kW\ m^{-2}}$. Integrating this energy flux and converting to spectral luminosity yields a radio power output of $\sim 1.1\ \mathrm{MW\ Hz^{-1}}$, i.e. consistent with the typical observed radio luminosities of UCDs. We also note that the bandwidth of the radio emission, equal to the electron cyclotron frequency of $\sim$8.4 GHz, is perforce similar to that observed, since the ionospheric field used is determined from the measured radio frequencies.

3. Summary and Conclusions

In this paper we have developed an axisymmetric model of the M-I coupling currents arising from departure from rigid corotation in the magnetospheres of UCDs, based on that used previously to study Jupiter's auroral oval. This simple model generates radio emissions whose power, bandwidth, modulation period and duty cycle are consistent with those observed. The implication is that these UCDs are coupling with their space environments via magnetic fields, and that this coupling reduces the angular velocity of the high latitude ionopsheric regions, thus generating intense auroral emissions including radio emissions.

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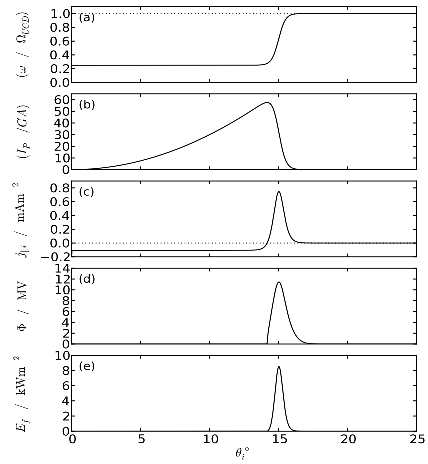

Figure 1: Figure showing profiles of model M-I coupling current system parameters, as discussed in the text.

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