Probing the Magnetospheres of Hot Magnetic Stars Using ECME

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We discuss Electron Cyclotron Maser Emission (ECME), observed in the form of highly circularly polarized pulses, from a few hot, magnetic stars. This emission is one of the manifestations of stellar wind-magnetic field interaction. With the Giant Metrewave Radio Telescope (GMRT), we have observed ECME from four magnetic B/A-type stars. Currently, we are trying to understand certain properties of the ECME pulses and their dependence on the magnetospheric plasma. Here, we briefly review all those works which have used ECME observed from hot magnetic stars to infer some physical properties of the host stars. We finally discuss how this phenomenon can further be exploited to probe the stellar magnetosphere.

1 Introduction

Hot, magnetic stars possess strong, ordered, mostly dipolar magnetic fields, and are expected to produce radio emission via gyrosynchrotron emission or free-free emission. A small number of them are also found to produce Electron Cyclotron Maser Emission (ECME) which is coherent in nature. The emission is believed to arise near the magnetic poles in the middle magnetosphere (Leto et al., 2016), which is the transition region between the inner (the region in which magnetic field energy dominates over the wind kinetic energy) and the outer (the region in which wind kinetic energy dominates over the magnetic field field) parts of the stellar magnetosphere (see Fig.1 of Trigilio et al., 2004). The emission is highly circularly polarized and highly directed; for a mildly relativistic electron distribution, this direction is almost perpendicular to the magnetic field (Melrose & Dulk, 1982). The latter property is consistent with the fact that the ECME pulses have been observed near the rotational phase where the longitudinal magnetic field is zero, i.e. when the magnetic field axis lies in the plane of the sky (assuming a dipolar magnetic field).

The first hot, magnetic star from which ECME was discovered is CU Vir (Trigilio et al., 2000). After this discovery, there was not a second one until 2015, when Chandra et al. (2015) speculated HD 133880 to host similar emission after they observed an order of magnitude enhancement in the flux density at certain rotational phases. We confirmed it (Das et al., 2018) by observing the star at 610 MHz for one full rotation cycle using the Giant Metrewave Radio Telescope (GMRT).

One of the biggest questions about ECME from hot, magnetic stars is why this emission is not seen from most of the population. In order to be able to answer this question, we have observed a sample of hot, magnetic stars with the GMRT at $550-$ -900 MHz, near the rotational phases corresponding to the nulls of the longitudinal magnetic field $\langle B_z \rangle$. Besides performing this survey, we also study certain ECME properties which have the potential to become tools to estimate properties of the magnetospheric plasma. Here, we briefly review the already existing methods to extract information about the host star from the ECME pulses, and we also present some new directions in which this emission can become useful to probe the stellar magnetosphere.

This paper is structured as follows: in the next section (§2), we present the results of the GMRT survey. Following this section, we review how ECME has been used to study the host star, and then we present how we can further use this emission to infer plasma properties in the stellar magnetosphere (§3). We finally discuss various results and future work in §4.

2 Results from the GMRT survey

At the time of starting this survey, CU Vir and HD 133880 were the only known hot, magnetic stars producing ECME. The fact that within a span of around 17 years, only two stars were detected gives the impression that for some unknown reason, ECME is extremely rare. However, we realized that there was not any systematic search for this kind of emission, and in fact, there exist very few observations of hot, magnetic stars below 1.4 GHz. This motivated us to start a low radio frequency survey with the upgraded GMRT (uGMRT) to search for ECME. We choose band 4 ($550 - 900$ MHz) as the observing band.

So far we have made two discoveries: HD 142990 and HD 35298. Among them, HD 142990 was independently reported to be a tentative host of ECME by Lenc et al. (2018). We have also found a tentative candidate Ap star which will be further observed for confirmation. With the two confirmed stars, the current number of confirmed hot, magnetic stars capable of producing ECME is five: CU Vir (Trigilio et al., 2000), HD 133880 (Chandra et al., 2015; Das et al., 2018), HD 142990 (Lenc et al., 2018; Das et al., 2019a), HD 35298 (Das et al., 2019b) and HD 142301 (Leto et al., 2019).

In the next two subsections, we describe various characteristics of ECME observed from HD 142990 and HD 35298.

2.1 HD 142990

HD 142990 is a Bp-type star with a surface magnetic field of strength 4.7 kG (Shultz et al., 2019). Lenc et al. (2018) observed highly circularly polarized emission at 200 MHz from HD 142990 using the Murchison Wide-field Array (MWA) from which they speculated it to be a probable host of ECME. We independently observed this star as part of our ongoing survey near the rotational phases of its two magnetic nulls. The result of our observation is shown in Fig. 1[1]. We detected highly circularly polarized pulses near both magnetic nulls which confirmed the ECME origin of the pulses. HD 142990 is the most massive, hot, magnetic star ($5.7\,\mathrm{M}_\odot$, Shultz et al., 2019) from which ECME has been observed.

[1]Fig. 1 was originally published as Figure 2 in Das et al. (2020a, The Astrophysical Journal, Volume 895, Issue 2, id.148, 2 pp.), which is an erratum to the article *'Detection of Coherent Emission from the Bp Star HD 142990 at uGMRT Frequencies'* (Das et al., 2019a, The Astrophysical Journal, Volume 877, Issue 2, article id. 123, 12 pp.)

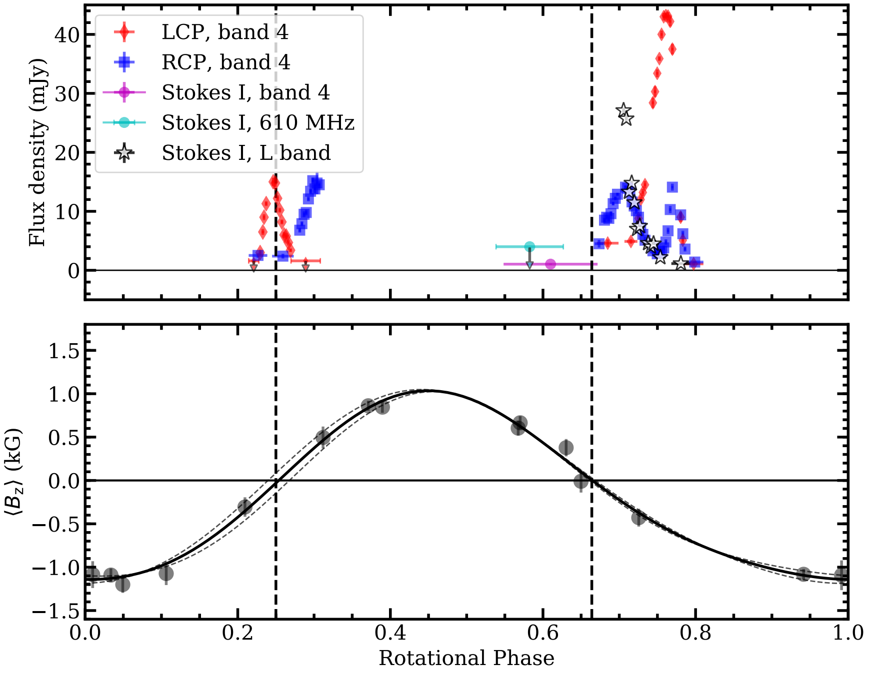

Fig. 1: The ECME pulses observed from HD 142990 (upper panel). The longitudinal magnetic field of the star is shown in the lower panel. This figure has been taken from Das et al. (2020a).

2.2 HD35298

HD 35298 is also a chemically peculiar B-type star with a nearly dipolar magnetic field of polar strength 10.8 kG (Shultz et al., 2019). The rotation period of the star is around 1.85 days (Shultz et al., 2018) which makes it the slowest host of ECME among the hot magnetic stars till now. The ECME pulses observed from this star are shown in Fig. 2[2].

3 ECME as a tool to probe the stellar magnetosphere

Since its discovery in CU Vir (Trigilio et al., 2000), the potential of ECME to become a tool to constrain various stellar/magnetospheric properties has been reported in a number of studies. We briefly review past works aimed at extracting information from the observed ECME pulses in the next subsection. Following it, we present another property of ECME, characterization of which can give us valuable information about the inner magnetosphere.

[2]Fig. 2 was originally published as Figure 1 in Das et al. (2020b, Monthly Notices of the Royal Astronomical Society: Letters, Volume 497, Issue 1, pp.L67-L68), which is an erratum to the article *'The fifth main-sequence magnetic B-type star showing coherent radio emission: Is this really a rare phenomenon?'* (Das et al., 2019b, Monthly Notices of the Royal Astronomical Society: Letters, Volume 489, Issue 1, p.L102-L107).

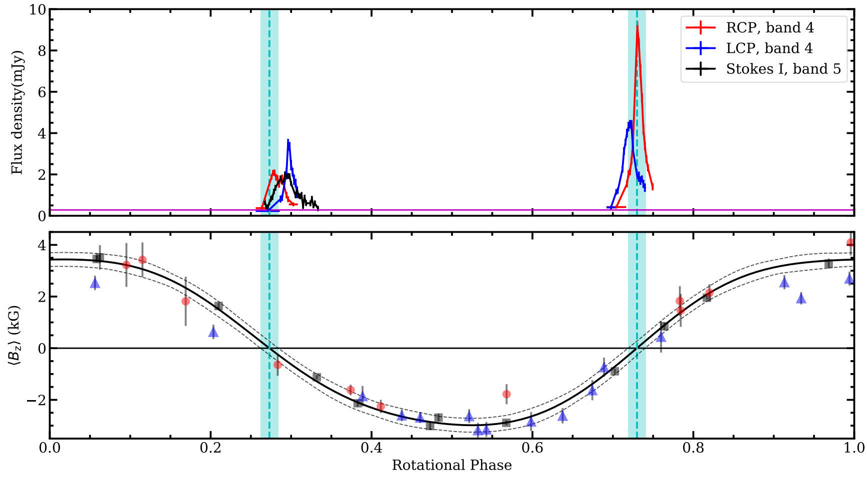

Fig. 2: The ECME pulses observed from HD 35298 (upper panel). The longitudinal magnetic field of the star is shown in the lower panel. This figure has been taken from Das et al. (2020b).

3.1 Past work

Because of the high directivity, ECME pulses have been used to estimate the change in stellar rotation period (e.g. Trigilio et al., 2008). The principal idea is that if a star is rotating with a constant period, the ECME pulses will always arrive at the same rotational phases. Using this property, Trigilio et al. (2008) proposed a spin-down of CU Vir. However, Pyper et al. (2013) reported that the period change indicated by radio data is inconsistent with that obtained from optical photometry and suggested that the radio emitting region is probably not in synchronous rotation with the photosphere. Two alternate explanations to the shift of the radio pulses are that the emission region is itself drifting or that the emission region is unstable (Ravi et al., 2010).

Another important piece of information that we can extract about the stellar magnetosphere from ECME pulses is the magneto-ionic mode of emission. The mode of emission determines the circular polarization of the pulses. This is shown in the cartoon diagram Fig. 3[3]. If we detect ECME from both magnetic hemispheres and the longitudinal magnetic field $\langle B_z \rangle$ of the star is known, we can infer the mode of emission (Leto et al., 2019). This is useful as it helps us to constrain the plasma density at the site of emission. If the ratio between plasma frequency (ν_p) to the electron cyclotron frequency (ν_B) is less than $0.3-0.35$, the mode of emission is extra-ordinary (X-) mode and above it, the mode will be ordinary (O-) mode. (Melrose et al., 1984; Sharma & Vlahos, 1984).

An interesting property of ECME is that the pulses at different frequencies arrive at slightly different rotational phases. This was attributed to propagation effect by Trigilio et al. (2011). Based on this model, Lo et al. (2012) successfully reproduced

[3]Fig. 3 was originally published as Figure 1 in Das et al. (2019a, *'Detection of Coherent Emission from the Bp Star HD 142990 at uGMRT Frequencies'*, The Astrophysical Journal, Volume 877, Issue 2, article id. 123, 12 pp.)

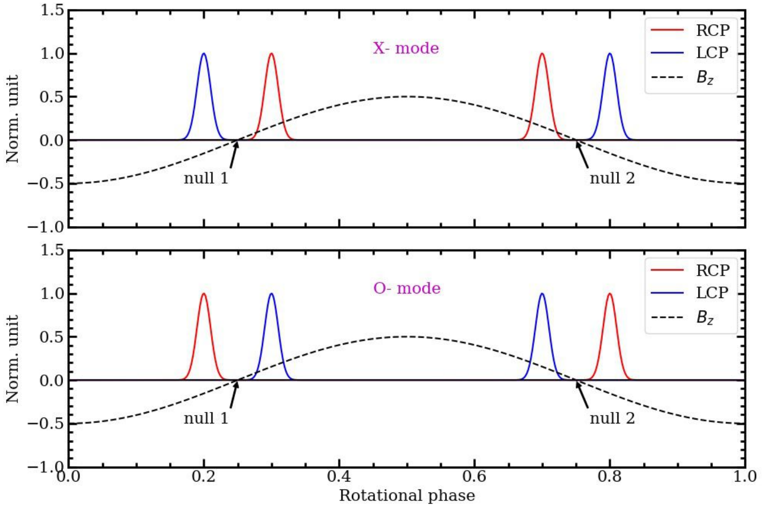

Fig. 3: A cartoon diagram illustrating the difference in the ECME light curves between X-mode (upper panel) and O-mode (lower panel). This figure has been taken from Das et al. (2019a).

the pulse arrival sequence of ECME at 20 cm and 13 cm. The salient features of this model are (Trigilio et al., 2011; Lo et al., 2012):

- ECME is emitted perpendicularly to the magnetic dipole axis as well as the local magnetic field line irrespective of the frequency of emission.
- Density in the inner magnetosphere is constant.
- There is only a single refraction at the boundary between middle and inner magnetospheres at the time of entering the latter. Refraction at the time of exiting the inner magnetosphere is neglected.

In the next subsection we show how we can use this simple model to derive a relation between pulse arrival time and frequency.

3.2 Frequency dependence of pulse arrival time: a new way to estimate plasma density

The aim of this work is to quantify the dependence of pulse arrival time on frequency. We derive a mathematical relation between the difference in rotational phases of pulse arrival at two frequencies (i.e., lag, denoted by τ_{12}) and the two frequencies ν_1 and ν_2 for the model of Trigilio et al. (2011). Assuming $\nu_\mathrm{p}/\nu_\mathrm{B} \ll 1$, we can write the refractive index as $\mu = \sqrt{1 - \frac{A\nu_\mathrm{p}^2}{\nu^2}}$, where A is a constant that depends on the magneto-ionic mode and harmonic number. At the time of entering the inner magnetosphere, the emission gets refracted and the angle of refraction (θ_r) can be obtained using Snell's law. For an angle of incidence of θ_i, the difference in angle of

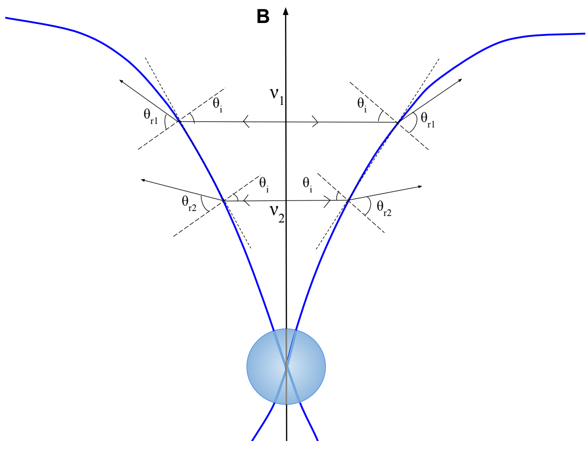

Fig. 4: The geometry of the stellar magnetosphere assumed while deriving Eq. 2. The blue shaded circle represents the star and the blue curved lines represent the boundary of the inner magnetosphere. The vertical arrow represents the magnetic dipole axis. ECME is emitted at a right angle to the magnetic field axis and is incident on the boundary between inner and middle magnetospheres at angle θ_i. This angle is assumed to be same for both the frequencies ν_1 and ν_2, with $\nu_1 < \nu_2$. The angle of refraction for the two frequencies are determined by the corresponding refractive indices μ_1 and μ_2; the angle of refractions are θ_{r1} and θ_{r2} respectively. Note that the deviations of the rays are exaggerated for clarity.

refractions at two frequencies is given by

$$\theta_{r2} - \theta_{r1} = \sin^{-1}\left(\frac{\sin\theta_i}{\mu_2}\right) - \sin^{-1}\left(\frac{\sin\theta_i}{\mu_1}\right) . \tag{1}$$

The various angles used in this equation are shown in Fig. 4. The corresponding lag is expected to be proportional to this difference. If we further assume that the lags are small, then to leading order, we get

$$\tau_{21} \propto \theta_{r2} - \theta_{r1} = C\frac{\nu_2^2 - \nu_1^2}{\nu_1^2\nu_2^2} = \tilde{C}(\lambda_1^2 - \lambda_2^2) . \tag{2}$$

The constant C is a function of the plasma density in the inner magnetosphere and $\tilde{C} = C/c^2$, c being the speed of light. Thus, if we have wide band observations (simultaneous, to avoid the complexity that can arise due to change in rotation period and/or a drifting/unstable emission region), we can obtain the lags, and from the observed lags we can estimate the inner magnetospheric density.

4 Discussion

It is not known yet why the magnetospheres of some of the hot, magnetic stars can produce ECME and why others cannot. We are trying to solve this problem by systematically observing a sample of magnetic B-type stars with known magnetic properties with the uGMRT near their magnetic nulls. We detected ECME from two of them.

ECME pulses have a number of interesting properties which have the potential to become probes for the stellar magnetosphere. Here we demonstrate the potential of one such property which is the frequency dependence of pulse arrival time. This exploits the refractive index of the inner magnetosphere and hence constrains the density in the inner magnetosphere. Note that for this method to give a reliable estimate, it is important to ensure that the data at different frequencies are near-simultaneous.

Currently, our understanding about ECME from hot, magnetic stars is highly limited. In addition to the fact that we do not know yet which subset of these stars can produce this type of emission, we also do not know the cut-off frequencies. Besides, ECME pulses are often found to be offset from their expected rotational phases; the reason for this is again unclear, although complex magnetic field topology is speculated to be at its root (e.g. Leto et al., 2019; Das et al., 2019a). Both spectropolarimetric observations and radio observations over a wide frequency range will be needed to answer these questions.

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Matt Shultz.

Pier-Emmanuel Tremblay, Pierre Bastien, Georges Michaud (from left).