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Coherent radio emission from main sequence pulsar: introducing a new stellar diagnostic

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Abstract

In this paper we demonstrate how coherent radio emission observed from a subset of magnetic early type stars (called main sequence pulsars) can be used to map the magnetospheric plasma density profiles. The mechanism behind such radio emission is electron cyclotron maser emission (ECME) that gives rise to periodic, highly circularly polarized radio pulses. Here we consider the magnetic B star HD 133880, a known main sequence pulsar. We use its existing ultra wideband observation of ECME to study the dependence of the rotational phases of arrival of ECME pulses on the observing frequencies. According to current understanding, the difference in the arrival times of pulses at two frequencies (will be called 'lag') is caused by propagation effects in the stellar magnetosphere, and hence the nature of the lags is indicative of the plasma distribution in the magnetosphere. By comparing the results obtained for the ECME pulses of opposite circular polarizations, we suggest that the stellar magnetosphere has an over-dense region that is inclined towards the northern magnetic hemisphere for the parts through which the ECME radiation passes.

1 Introduction

Presence of magnetic field in an early-type star has important consequences, one of which is the formation of a magnetosphere around it. Close to the star, the wind materials are forced to follow the field lines since the magnetic field energy is stronger than the wind kinetic energy. This part of the stellar magnetosphere containing closed magnetic field loops has been named as inner magnetosphere ([12]). The magnetic equatorial radius of the largest closed field loop is called the Alfvén radius (R_A). At R_A, the wind kinetic energy equals the magnetic field energy. Far away from the star, the wind kinetic energy dominates over the magnetic field and distorts the field lines. This region is called the outer magnetosphere. The region that marks the transition from the inner to the outer magnetosphere has been named as the 'middle magnetosphere'. The middle magnetosphere contains a current sheet at the magnetic equator (Figure 1) that acts as the site of electron acceleration.

A subset of these magnetic early-type stars has been discovered to produce coherent pulsed radio emission, similar to the normal pulsars, which led to the name of main sequence pulsars for these stars (e.g. [6]). The mechanism which is behind the production of such emission is the electron cyclotron maser emission (ECME, [11, 13]). ECME is produced in auroral rings near the magnetic poles (see Figure 1) by a population of electrons with inverted energy distribution, provided the local plasma frequency is smaller than the local electron gyrofrequency ([10]). The characteristics of this emission includes high directivity and very high circular polarization. Also, in case of the main sequence pulsars, ECME is observed near the rotational phases at which the stellar longitudinal magnetic field $\langle B_z \rangle$ is zero. Such rotational phases will be called magnetic nulls. As majority of the magnetic early-type stars have near dipolar magnetic fields, the maximum number of observable magnetic nulls per rotation cycle is two, and hence ECME is observable a maximum of twice per rotation cycle for these stars. Near each magnetic null, a pair of oppositely circularly polarized pulses are observed ([7]), the different circular polarizations correspond to opposite magnetic hemispheres of the stellar magnetosphere. Whether a given magnetic polar region will produce right or left circular polarization, is determined by the magneto-ionic mode of emission. For example, in case of ECME in the extra-ordinary mode, right circularly polarized (RCP, according to the IEEE convention) pulse is produced near the north magnetic pole, and the left circularly polarized (LCP, according to the IEEE

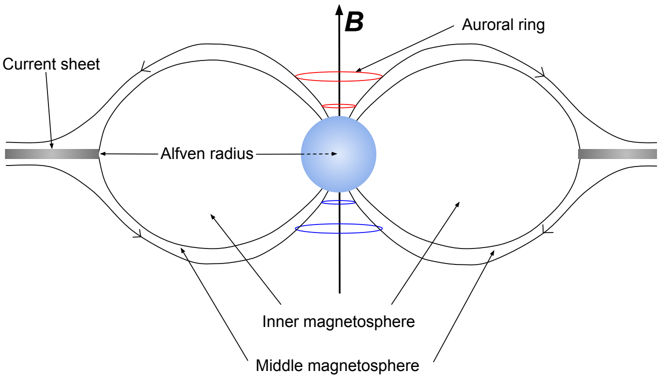

Figure 1. A cartoon diagram illustrating different parts of the magnetosphere around a hot magnetic star. The region outside the inner and the middle magnetosphere is called the outer magnetosphere. Electron cyclotron maser emission (ECME) is produced near the magnetic poles in ring-shaped regions called 'auroral rings'. For details, see §1.

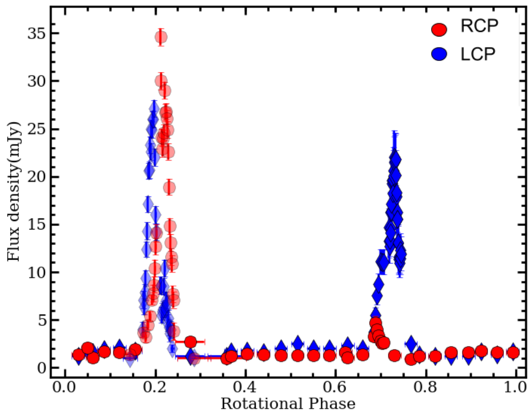

Figure 2. The 610 MHz lightcurves of HD 133880 over one full stellar rotation cycle. The ECME pulses are observed near the rotational phases of 0.2 and 0.7 cycles. The red and blue markers represent right and left circular polarization. The basal flux density is produced by gyrosynchrotron. The data used in this plot were reported in [2, 4].

convention) pulse is produced near the south magnetic polar region ([11, 8]).

Being a relatively new phenomenon, ECME from hot magnetic stars is yet to be fully characterized. In this paper, we present a strategy to study the dependence of the arrival times of ECME pulses on frequency. We then use a 3D framework ([5]) to interpret the results and demonstrate that such studies can help us 'visualize' the distribution of stellar magnetospheric plasma.

This paper is structured as follows: in §2, we describe the methodology. This is followed by results and interpretation (§3 and §4). We summarize the paper in §5.

2 Methodology

For this study, we use ultra wideband observation of ECME from the star HD 133880. HD 133880 is a known main sequence pulsar ([1, 2]). Its 610 MHz lightcurves are shown in Figure 2. There are two pairs of ECME pulses near the rotational phase 0.2 and 0.7 rotation cycles which are close to the magnetic nulls for this star. The magnetic null near which the first pair of ECME pulses is seen, will be called null 1 and the other magnetic null will be called null 2. Thus null 1 corresponds to a rotational phase of ≈ 0.2 cycle and null 2 correspond to a rotational phase of ≈ 0.7 cycle.

The data used in this work span a frequency range of $\approx 0.4-2$ GHz. We extract the LCP and RCP lightcurves near the two magnetic nulls at frequencies $\approx$ 400 MHz, 593 MHz, 781 MHz, 1 GHz, 1.1 GHz, 1.4 GHz, 1.7 GHz and 1.8 GHz. These lightcurves show enhancement in both circular polarizations, characteristic of ECME. Near null 1, however, the LCP pulses at 593 MHz and 781 MHz were only partially sampled. Also, near null 2, the RCP pulse is absent/very weak over 400–800 MHz. We hence use only the RCP pulses near null 1, and only the LCP pulses near null 2 for the analysis described below.

The aim is to obtain the difference in the rotational phases of arrival of pulses at two different frequencies. As the pulse profiles are different at different frequencies, it is non-trivial to obtain the 'lag' between a pair of frequencies. To obtain a robust estimate of the 'lag's, we cross-correlate the lightcurves corresponding to every pair of frequencies. This process essentially means that we slide one lightcurve over the other, multiplying the two at each step. The 'shift' (in the unit of rotational phase) that produces the maximum value of multiplication, is considered to be the 'lag' between the lightcurves at the two frequencies. As the measured flux densities have errorbars, the estimated lags must have meaningful errorbars too. This was achieved by following a Monte Carlo approach. For every lightcurve, we generate N number (N is a large number, we take $N = 20000$) of lightcurves by drawing N random numbers for each flux density measurement so that the mean of these random numbers is the measured flux density and the standard deviation is the errorbar in that measurement. Using these lightcurves, we obtain N number of lags for each pair of frequencies. The value with the highest occurrence frequency is taken to be the lag for the two frequencies, and one half of the interval within which 90% of the lag values fall, is assigned as the errorbar to the estimated lag.

3 Results

The results of the exercise described in the preceding section are shown in Figure 3. We plot the absolute values of the lags against the quantity $X = \lambda_1^2 - \lambda_2^2$ (λ represents wavelength). The reason for plotting the lag values against this quantity is that if we ignore the refraction within the inner magnetosphere, and consider only the refraction that the radiation suffers at the time of entering the inner magnetosphere (from their site of origin, i.e. the auroral ring in the middle magnetosphere), then, over a small range of frequencies, the lag values should vary with $X = \lambda_1^2 - \lambda_2^2$ as a straight line passing through the origin (Equation 2 of [3]). Here we find that the variation of lag with X is clearly nonlinear. This is probably not surprising since we are dealing with a wide range of frequencies. Interestingly, we find that the ranges within which the values of lie are similar for the RCP and LCP pulses, however, the deviation of linearity of the relation between lag and X is higher for the RCP pulses than that for the LCP pulses.

In the next section, we attempt to qualitatively understand the significance of the observed difference in the variation of lag with X for pulses of opposite circular polarizations.

4 Significance of the non-linear variation of lags with $X = \lambda_1^2 - \lambda_2^2$

Das et al. [5] presented a 3D framework to obtain ray path traced by ECME for any kind of density distribution in the

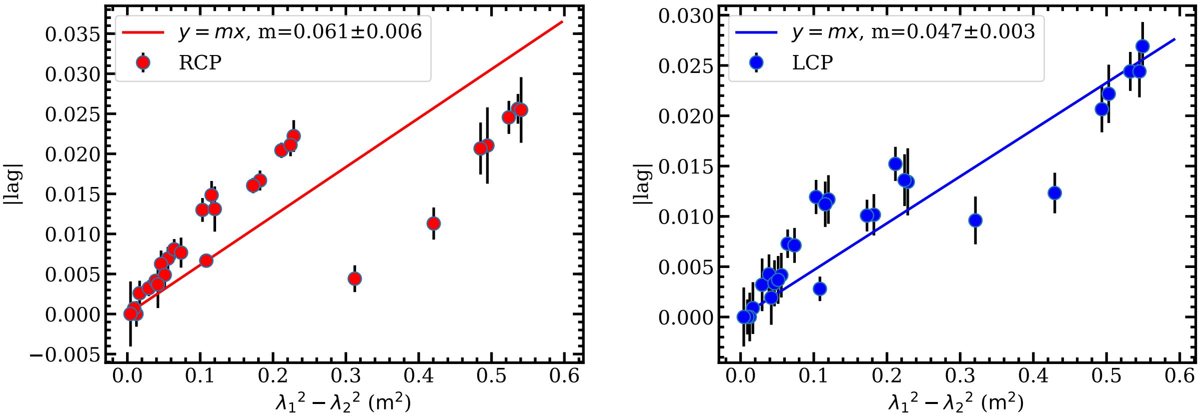

Figure 3. The variation of lag between ECME pulses at two frequencies with the quantity $\lambda_1^2-\lambda_2^2$, where λ_1 and λ_2 are the wavelengths corresponding to the two frequencies. The RCP pulse considered, (left) was observed near null 1 and the LCP pulse considered (right), was observed near null 2. The linear relation (shown by straight lines) is expected for small frequency ranges and for the case when refraction insider the inner magnetosphere is negligible.

stellar magnetosphere. We use this framework to qualitatively understand what can cause the observed difference between RCP and LCP pulses. We consider a density distribution that is symmetric about the magnetic dipole axis. A slice of this distribution is shown in Figure 4 (the z axis lies along the magnetic dipole axis). It is characterized by a background radially decreasing plasma density superposed by an over-dense region at the magnetic equator. Such a distribution is influenced by the prediction of the analytical 'Rigidly Rotating Magnetosphere' (RRM) model of Townsend et al. [9].

We examine how the lag variation changes due to an overall increase in the density, and due to increase in the width (vertically) of the overdense region. We find that the latter effect can explain the observed discrepancy between RCP and LCP pulses; i.e. the range of the lag values remain the same, but the deviation from the linear relation with X increases upon increasing the width of the overdense region. Such a situation happens, if the overdense region is inclined towards the north magnetic pole (Figure 5). This is a plausible explanation since analytical model also predicts that for stars like HD 133880 in which the rotation and the dipole axes are misaligned, the overdensity will not be symmetric about the dipole axis.

We would like to clarify that there might be other possible explanations for the observed behaviour of lags. The density distribution function that we use here has several parameters that one can play with. We choose only the two quantities: absolute density and the density gradient that we intuitively think to take major role in affecting the ray paths.

5 Summary

In this paper we demonstrate that ECME pulses observed from a few hot magnetic stars can be useful in studying the stellar magnetosphere. We present a technique to estimate

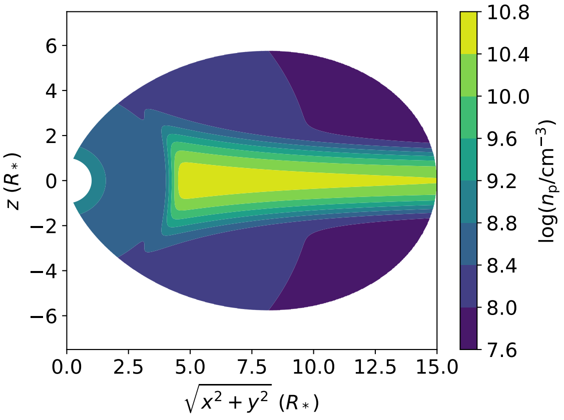

Figure 4. A slice of the inner magnetosphere that shows the density distribution we use to simulated the lags. The z axis lies along the magnetic dipole axis.

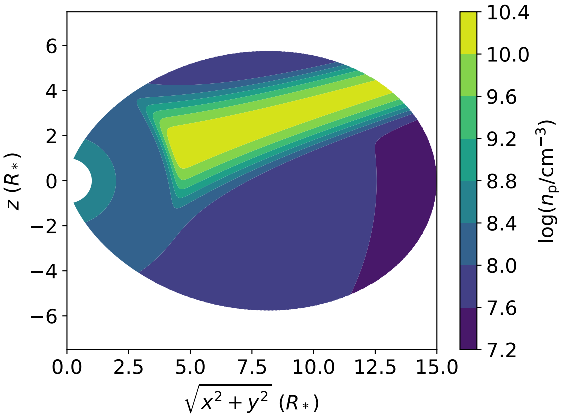

Figure 5. A cartoon diagram illustrating a density distribution inside the inner magnetosphere in which the overdense disk is inclined towards the northern magnetic hemispheres.

the differences in the rotational phases of arrival (lag) of the pulses at different frequencies. We show that the lags vary with the quantity $X = \lambda_1^2 - \lambda_2^2$ in a non-linear, non-monotonic fashion. For the star HD 133880, we find this variation to be non-identical for the RCP and LCP pulses. By using the 3D framework of Das et al. [5], we show that the observed difference can happen if the star's magnetosphere has an overdense disk that is not symmetrical about the magnetic dipole axis. This inference is consistent with the prediction of the RRM model of Townsend et al. [9].

The primary point that we would like to convey from this work is that the estimation of the 'lag's for the ECME pulses is a useful exercise which can act as the proxy for the density structure in the stellar magnetosphere. To the best of our knowledge, this is the only technique that has the potential to become a probe for obtaining quantitative information (once we optimize the parameters of simulation to match the observed lags) about the plasma distribution. In the future, it will be interesting to make similar studies for other main sequence pulsars, as well as other objects (like brown dwarfs) that emit ECME.

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