Low-frequency GMRT observations of the magnetic Bp star HR Lup (HD 133880)

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Abstract. We present radio observations of the magnetic chemically peculiar Bp star HR Lup (HD 133880) at 647 and 277 MHz with the GMRT. At both frequencies the source is not detected but we are able to determine upper limits to the emission. The 647 MHz limits are particularly useful, with a 5σ value of 0.45 mJy. Also, no large enhancements of the emission were seen. The non-detections, along with previously published higher frequency detections, provide evidence that an optically thick gyrosynchrotron model is the correct mechanism for the radio emission of HR Lup.

Keywords : magnetic fields – radio continuum: stars – stars: chemically peculiar

1. Introduction

Sources of stellar radio emission can be split by the presence of non-thermal emission. Thermal emission is seen in massive stars (Wolf-Rayet, O- and early B-type stars) that have strong radiatively driven stellar winds (Wright 1975). These winds are ionized and radiate via free-free emission. A number of early type stars also show a non-thermal component and this is usually due to shock-acceleration associated with colliding stellar winds in binary systems (De Becker 2007). Several types of lower mass stars also show detectable radio emission, often non-thermal in nature. Examples include the Sun, RS CVn stars (Slee et al. 2008), dMe stars (Osten et al. 2006), dwarf stars and brown dwarfs (Berger et al. 2006). This emission is usually associated

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with coronal emission and flare activity, is often time variable and also requires the presence of magnetic fields.

Late B-type stars and early A-type stars have neither strong stellar winds nor substantial outer convective zones and so were not expected to be strong radio emitters. Magnetic chemically peculiar (MCP) stars have been known as radio emitters in the centimetre range since the mid 1980s. MCP stars are a class of peculiar A and B stars (referred to as Ap or Bp stars) with strong (kGauss) magnetic fields. The class is characterized by large abundance anomalies in a range of elements which suggested that the photospheres of these stars are highly stable (with the turbulent motions stabilized by the magnetic field) allowing diffusion to take place. The origin of the magnetic fields in these stars is still unclear, with possibilities including either a fossil-field from the original collapse to form the star, or possible dynamo action either in the radiative zone or at an earlier stage of evolution (Arlt 2008). Although sub-surface convection zones in massive stars, associated with the iron opacity bump, could be associated with magnetic field generation, this mechanism is thought to not work for the late B-type stars considered here (Cantiello 2011).

There is one MCP star that is of particular interest at radio wavelengths – CU Vir (A0p). This nearby star has a period of 0.52 days and a strong magnetic field. From optical variability timing, Pyper et al. (1998) reported on a peculiar change in the optical (and presumably rotational) period. CU Vir also shows periodic, polarised outbursts as well as quiescent emission. The burst emission has been attributed to electron cyclotron maser emission. The outbursts are seen over a wide range of frequencies (see (Lo et al. 2012); (Trigilio et al. 2011); (Ravi et al. 2010); (Stevens & George 2010) and references therein).

There have been a small number of radio observations of late B and early A-stars. Drake et al. (1987) observed 34 sources detecting only 5 at 5 GHz with the Very Large Array (VLA). They interpreted the observed radio emission as being due to gyrosynchrotron emission from the magnetosphere of the star due to a continuously injected population of mildly relativistic particles that are trapped in the magnetosphere. Wilson et al. (1988) also using the VLA at 5 GHz surveyed 16 M dwarf stars detecting one source, Gliese 735. A more recent VLA survey of MCP stars at 5 GHz by Leone et al. (1994) extended this to cover 40 stars, of which only 8 were detected.

MCP stars on average show moderate circular polarisation, with radio properties similar to that of active cool stars such as RS CVns. They show periodic changes in the detected magnetic field over the stellar rotation period (Borra & Landstreet 1980). The magnetic field topology of this kind of star is generally taken as a magnetic dipole tilted with respect to the rotation axis (Babcock 1949), though in the case of HR Lup the field is quadrupolar in nature (see below). In a few cases, MCP stars possess an anisotropic stellar wind as a consequence of the wind interaction with the dipolar magnetic field (Shore et al. 1990). In about 25% of MCP stars non-thermal radio emission is observed and the rate of detection seems to be correlated with the effective stellar temperature (Linsky et al. 1992; Leone et al. 1994).

The radio emission is generally interpreted as gyrosynchrotron emission from mildly relativistic electrons. These electrons are accelerated in current sheets, formed when the gas flow

brakes the magnetic field lines, close to the magnetic equator and the electrons propagate along the magnetic field lines towards the inner magnetospheric regions (Havnes & Goertz 1984).

X-ray studies have found that MCP stars are weak X-ray emitters with a detection rate of just over 10% (Drake et al. 1994). The X-ray emission of MCP stars does not correlate with other stellar properties. Their radio properties also do not follow the Guedel-Benz scaling law as this would imply X-ray luminosities as high as 10^{33} erg s^{-1} (Guedel & Benz 1993). The only X-ray detections of MCP stars are not particularly bright ($L_x > 10^{30.5}$ erg s^{-1}; Drake et al. 2006).

In this paper we focus on low frequency observations of one specific object (HR Lup) which may give some insights into the processes going on in the star.

2.   HR Lup

HR Lup (HD 133880, HR 5624; RA: 15 08 12.124, Dec: −40 35 02.15) is a rapidly rotating B-type chemically peculiar star of spectral type B8 Ivp.

The star is rapidly rotating ($v \sin i \approx 103$ kms^{-1}) and has a rotational period of 0.8777 days, which is observed in optical photometry, magnetic field measurements and radio flux (Bailey et al. 2012; Schmitt et al. 2005).

The inferred stellar parameters for HR Lup are $M_* = 3.2 M_\odot$, $R_* = 2.01 R_\odot$, $T_{eff} = 13000$ K and age of 15.8 Myr (derived from the fact that it is a member of the Upper Cen Lup association; Landstreet et al. 2007). HR Lup has a very strong magnetic field, typically 2.4 kG (Schmitt et al. 2005). This magnetic field varies from about 4 to +2 kG (Landstreet et al. 1990). Unlike most MCP stars the magnetic field is not dipolar, but quadrupolar (and this has consequences for the observed radio variability). The rotational and magnetic axes are misaligned (Bailey et al. 2012).

HR Lup is a photometric variable with variations on the order of 0.15 mag in the U - band, which is probably the result of the large magnetic field and surface abundance anomalies (Waelkens 1985).

HR Lup is a known radio source, previously observed with the Australia Telescope Compact Array (ATCA). At 5 GHz Lim et al. (1996) demonstrated that both the total intensity and circular polarisation of the source varied significantly and coherently according to the known rotational period. The total intensity varied from ~ 1 mJy to ~ 5 mJy with the degree of circular polarisation reaching up to 20%. They noted that the emission shows broad peaks (suggesting a dipole contribution to the field) and narrower peaks at the predicted phases of a quadrupole contribution to the magnetic field. At 8 GHz the source is seen to have a flux density of 4.08 ± 0.16 mJy though no indication of any variability is presented (Drake et al. 2006). Bailey et al. (2012) have re-reduced the ATCA radio data of Lim et al. (1996) but there are no significant differences in the reduced data.

In this paper we present observations at 647 and 277 MHz with the intention of finding if there is any lower frequency emission and help to find if there is a cut-off frequency.

3.   Observations and data reduction

The Giant Metrewave Radio Telescope (GMRT) is located near Pune, India and consists of thirty 45 m diameter radio dishes. The GMRT has a maximum and minimum baseline of 25 km and 100 m, and has operating receivers at 150, 235, 325, 610 and 1400 MHz.

We observed HR Lup with the GMRT on 2009 December 5th and 7th simultaneously at both 647 and 277 MHz, implying only total intensity maps were constructed. At 647 MHz a bandwith of 16 MHz was used and at 277 MHz a bandwith of 6 MHz was used (both observations used 128 channels). An integration time of 16 seconds was used. The total time on source was 4.67 hours over the two nights. During the observations 27 antennas were used. The observations consisted of flux density and bandpass calibration using 3C 286 at the start and end of the observations, and phase calibration using VSOP J1501–3918 every 30 minutes.

Each spectral window was calibrated and imaged separately using the Common Astronomy Software Applications package (CASA[1]). Any interference in the data was removed by manual inspection. Several rounds of phase only self-calibration were completed on the target data. During these iterations any visibility measurements that showed unusual phase excursions were rejected. The final image used for analysis below was primary beam corrected and has a central rms of 90 μJy at 647 MHz and 6 mJy at 277 MHz.

The source positions for the brighter sources were matched with that of the Sydney University Molonglo Sky Survey (SUMSS) at 843 MHz (Mauch et al. 2003). No significant source position offset was found between the GMRT data and this survey.

4.   Results and Discussion

At 647 MHz we do not detect the source. At the 5σ level this gives us an upper limit of the flux density of 0.45 mJy. Also, at 277 MHz we do not detect the source. At the 5σ level this gives us an upper limit of the flux of 30 mJy. The data were also cut into shorter time-scales (at 120 seconds and the scan length $\sim$ 600s) and imaged. No significant time variation was seen at the position of the source thus ruling out any bright bursts.

Bailey et al. (2012) have produced the most recent and accurate ephemeris for HR Lup, combining several data sets to yield:

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[1]http://casa.nrao.edu/

$$JD_{min} = 2445472.000(10) + 0.877476(9) \cdot E, \tag{1}$$

where zero phase corresponds to minimum photometric brightness and also the minimum of the longitudinal magnetic field. With this ephemeris the principal radio maxima at GHz frequencies occur at phase $\phi = 0.0$ and 0.5.

From this, we can determine the phase of our observations. The observations are on two separate days and they cover phases of 0.93–1.06 and 0.15–0.35 respectively. Thus the observations cover at least one of the periods of radio maxima previously observed. Using the 3σ period errors quoted by Bailey et al. (2012) we estimate an uncertainty in the phase for these observations of around 0.1.

Since we compared our positions to that of SUMSS it is worth noting that no source is given in their catalogue at the position of HR Lup, though investigation of the SUMSS mosaics indicates that there is a possible enhancement with a peak of 4.5 mJy/beam at the optical position of HR Lup. This source is below the detection threshold of 10 mJy/beam.

If indeed there is a source corresponding to 4.5 mJy/beam at 843 MHz then this would imply an extremely steep cut-off between the 843 and 647 MHz observations (i.e. $\alpha \geq 7$, for $S_\nu \propto \nu^\alpha$, which seems rather extreme). Though with no formal detection in the SUMMS maps this does not discount the possibility that the cut-off frequency is not located somewhere between 647 MHz and the previous detections at 5 GHz. If we discount the SUMSS point, then the implied limit on the spectral index between 647 MHz and the previously reported 5 GHz points is $\alpha > 1$. These sources are possibly variable in time (although the ATCA observations show only a factor 2–3 variability across the rotational period) over longer time-scales.

The non-detection, particularly at 647 MHz, implies that the radio emission region intersecting the line of sight has a finite extent which is consistent with the optically thick gyrosynchrotron model of Linsky et al. (1992). The radio spectrum from this model will have a frequency (ν_{peak}) where the emission peaks, the location of which depends on the wind density/geometry and the magnetic field properties. The radio spectrum then falls away on either side of this peak frequency, and the spectral slope on either side of the ν_{peak} with the electron energy spectrum. It is likely that ν_{peak} lies somewhere between 647 MHz and 5 GHz, and observations with a much broader bandwidth will be important to fully constrain the detailed shape of the emission.

5. Summary

In summary, we present non-detections of the MCP star, HR Lup with the GMRT at 647 MHz and 277 MHz. No significant time variation was seen at the position of the source thus ruling out bright bursts, as seen in CU Vir, in this dataset. We consider that these non-detections provide evidence that the emission mechanism for this star is optically thick gyrosynchrotron emission. We suspect that the peak emission frequency lies between 647 MHz and 5 GHz. Follow-up observations at frequencies in this range would be particularly useful to constrain the spectral model

Table 1. The GMRT observations of HR Lup in UT at 647/277 MHz. Given are the start and end times of the observing and the range of phase covered by these observations, using the ephemeris of Bailey et al. (2012).

Start Observing	End Observing	Phase range
04:35:10.9 05 Dec 2009	07:22:40.4 05 Dec 2009	0.93–1.06
03:23:28.3 07 Dec 2009	07:35:41.3 07 Dec 2009	0.15–0.35

and indeed provide constraints on the energy injection of electrons in the stellar magnetosphere. Broad-band observations (covering both the GHz and sub-GHz regimes) are necessary to constrain the emission mechanisms in MCP stars and coverage of the entire rotational period are necessary to detect the presence of short-lived intense bursts, which may well be a feature of the radio emission from the strongly magnetic stars.

Acknowledgements

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