32nd URSI GASS, Montreal, 19–26 August 2017

A JVLA survey of the high frequency radio emission of the massive magnetic B- and O-type stars

Sushma Kurapati*(1), Poonam Chandra(1), and Gregg Wade(2)
(1) National Center for Radio Astrophysics, Tata Institute of Fundametal research,PO Box 3, Pune 411007, India
(2) Department of Physics, Royal Military College of Canada, PO Box 17000, Kingston, Ontario K7K 7B4, Canada

Abstract

In *Kurapati et al.(2017)* [4], we conducted a survey of the radio emission properties of 7 magnetic O and 11 B-type stars with masses $M \geq 8M_\odot$ using the Karl J. Jansky Very Large Array in the 1 cm, 3 cm and 13 cm bands. We summarize the results presented in *Kurapati et al.(2017)* [4]. The survey resulted in a total of four detections, two O and two B stars. While the detected O-type stars - HD37742 and HD47129 - are in binary systems, the detected B-type stars, HD156424 and ALS9522, are not known to be in binaries. All four stars were detected at 3 cm, whereas three were detected at 1cm and only one star was detected at 13cm. The detected B-type stars are significantly more radio luminous than the majority of the non-detected B-type stars, which is not the case for O-stars. The non-detections at 13 cm are interpreted as due to thermal free-free absorption. Mass-loss rates were estimated using 3 cm flux densities and were compared with theoretical mass-loss rates, which assume free-free emission. For HD 37742, the two values of the mass-loss rates were in good agreement, possibly suggesting that the radio emission for this star is mainly thermal. For the other three stars, the estimated mass-loss rates from radio observations were much higher than those expected from theory, suggesting a possible contribution from non-thermal emission. All the detected stars are predicted to host centrifugal magnetospheres except HD 37742, which is likely to host a dynamical magnetosphere. This suggests that non-thermal radio emission is favoured in stars with centrifugal magnetospheres.

1 Introduction

Recent systematic surveys of the magnetic properties of hot stars have revealed a population of O- and B-type stars hosting significant surface magnetic fields [1, 5]. These magnetic fields are strong (from a few hundred to tens of thousands of gauss), organised (mainly dipolar) and highly stable.

Theoretical models and magnetohydrodynamical (MHD) simulations have explored the dynamical interaction of these magnetic fields with stellar rotation and mass-loss [12, 7]. Both observation and theory show clearly that the stellar wind interaction with the magnetic field leads to wind confinement and channelling, generating a long-lived circumstellar magnetosphere [9, 2]. Close to the star, the magnetic pressure dominates the kinetic pressure of the wind, forcing the wind to follow closed magnetic field lines in regions near the magnetic equatorial plane. Far from the star, the kinetic pressure dominates the magnetic pressure due to the stronger decline of the magnetic energy density compared to the wind kinetic energy density. The radius at which the energy densities become equal is defined as the Alfvén radius, which also marks the boundary of the inner magnetosphere. Beyond the Alfvén radius, the stellar wind opens the magnetic field lines and generates a current sheet in the magnetic equatorial plane. This region is the middle magnetosphere, where the electrons are accelerated to relativistic speeds and gyrosynchrotron radio emission is expected to arise [11]. The gyrosynchrotron emitting region extent is defined by these wind electrons returning to the star along the field lines. These magnetospheres were classified into two broad physical categories, namely dynamical magnetospheres (DM) and centrifugal magnetospheres (CM)[13]. This classification is based on two parameters: the degree of magnetic wind confinement characterized by the Alfvén radius (R_A), and stellar rotation characterized by the Kepler co-rotation radius (R_K). A DM results in the case of a slowly rotating star ($R_A < R_K$). In this case, wind plasma trapped in closed magnetic loops falls back onto the stellar surface on a dynamical timescale. A CM occurs in the case of a rapidly rotating star ($R_A > R_K$). In this case, wind plasma caught in the region between R_A and R_K is centrifugally supported against infall. This results in long-term accumulation of plasma and consequently higher magnetospheric plasma density[8].

In stars with high mass-loss rates, radio emission is usually produced by thermal free-free emission from the ionised stellar wind. However, in the presence of magnetic field and relativistic electrons, non-thermal synchrotron emission may dominate the radio spectrum. Electrons can be accelerated to relativistic speeds, either by magnetic reconnection near the current sheet in the middle magnetosphere [14] or through Fermi acceleration in strong shocks in the inner magnetosphere [6, 3]. Some numerical simulations [15] suggest that one requires both a magnetic field and a binary companion to explain the non-thermal radio emission from massive stars.

To homogenize the study of the physics of magnetospheres of hot stars, we have carried out a systematic survey of the radio emission properties of the 18 known magnetic O and B type stars (with masses $M \geq 8 M_{\odot}$) using the Karl J. Jansky Very Large Array (JVLA). Our results of this survey has been published in *Kurapati et al.(2017)* [4]. Here, we summarize the results presented in *Kurapati et al.(2017)* [4]. We describe the observations briefly. We compare the properties of detected and non-detected stars and explore their properties.

2 Observations

The JVLA observations were taken between 2014 March 8 to 2014 August 1 during the 14A semester in the 13 cm (S), 3 cm (X) and 1 cm (Ka) bands. The data were collected in an 8-bit sampler mode for the S band, and in a 3-bit sampler mode for the X and Ka bands. Thus the bandwidths for S, X and Ka bands observations were 2 GHz (frequency range 2–4 GHz), 4 GHz (frequency range 8–12 GHz) and 8 GHz (frequency range 29–37 GHz), respectively. The observations were taken in VLA A, D and A→D configurations. All the calibration and data reduction were carried out using standard tasks in the Common Astronomy Software Applications (CASA) Package.

3 Results

The survey resulted in a total of four detections in the X band. The detected stars are HD 37742 (O9.5 Ib), HD 47129 (O7.5 III), HD 156424(B2 V) and ALS 9522 (B1.5 V). Three of the stars detected in the X band were also detected in the Ka band (i.e. all except for ALS 9522). Only one of them, HD 37742, was also detected in the S band. The non-detections in the S band are probably due to free-free absorption. This is because, due to the wavelength-squared dependence of the free-free opacity [16], the size of the radio photosphere increases with wavelength resulting in high free-free absorption at S-band frequencies compared to the X and Ka bands. The mass-loss rates were estimated from our radio observations, and were compared with the mass-loss rates calculated from theoretical models which are based on free-free emission. This may allow us to understand the emission processes and estimate the thermal versus non-thermal contributions to the radio emission. If the radio radiation is purely thermal, we would expect that the mass-loss rates estimated from observations to match those expected from theoretical models. If the radio emission has an important non-thermal contribution, then our estimates based on the thermal emission assumption are likely to be overestimates. In 3 of the detected stars, we found that for HD 47129, HD 156424, and ALS 9522, the mass-loss rates derived from radio observations are many times higher than those expected from the theoretical models. This could suggest a significant contribution of radio emission by various mechanisms, e.g. non-thermal radio emission or radio emission from colliding wind binary. For HD 37742, the mass-loss rate obtained from radio observations matches the value obtained using the theoretical model. This result could be evidence for a thermal origin of its radio emission, which is also consistent with the positive spectral index. For the non-detected stars, upper limits on estimated mass-loss rates (from 3σ upper limits on the radio flux) are consistent with the theoretical mass-loss rates for those stars, i.e. the theoretical model predicts radio fluxes that are below our detection threshold.

4 Summary and Conclusions

We summarize the results obtained in *Kurapati et al.(2017)* [4]. Results of JVLA observations of 18 magnetic O- and B-type stars with masses greater than 8 $M_{\odot}$ were presented. The JVLA observations were taken at random rotational phases in the S, X and Ka bands. We have detected X band radio emission from 2 out of 7 magnetic O-type stars and 2 out of 11 magnetic B-type stars in our sample. The detected O-type stars, HD 37742 and HD 47129, are in binary systems. The detected B-type stars, HD 156424 and ALS 9522, are not known to be in binaries. Two other O-type stars, which are known to be in (much longer-period) binary systems (HD 108, HD,191612) were not detected. Only HD 37742 is detected in the S band. The general lack of detections of our targets in the S-band is probably due to free-free absorption by the free-streaming stellar wind. Three stars, HD 37742, HD 47129 and HD 156424, were detected in the Ka band. The radio flux of HD 37742 and HD 47129 in the Ka band is consistently higher compared with that in the S and X bands. This can be explained by a dominant contribution of thermal flux.

Mass-loss rates were estimated for the detected stars using X band radio flux densities and were compared with the expected mass-loss rates from the theoretical models. However, there are some caveats in theoretical prediction of mass-loss rates as binarity and the presence of magnetic field were not taken into account. In addition, the theoretical estimates assume smooth density profiles, while clumping factors of order 10 are measured in O-type star winds. However, the clumpiness of the medium is not expected to change the mass-loss rate by more than a factor of 3 [10], much less than the discrepancy we note. For HD 37742, the theoretical estimate matches with that of observational one, suggesting that the radio emission is mostly thermal. The thermal nature of the HD 37742 radio emission is also supported by the spectral index we measure. For the remaining 3 stars, mass-loss rates estimated from radio observations were orders of magnitude higher compared to those predicted by theory. This may indicate significant contribution of the radio emission from other mechanisms than only thermal free-free emission. In magnetic stars, middle magnetosphere can give rise to non-thermal gyrosynchrotron emission. However, in case of binary systems, the stellar wind from both the stars may interact and produce thermal and non-thermal emission. The detected B- stars in our sample are not known to be in binary system, thus the additional mass-loss rate is likely to have contribution from the non-thermal emission of the magnetosphere. However, HD 47129 is a close binary system and emission from colliding stellar winds could play a significant role.

All the detected stars host centrifugal magnetospheres except for HD 37742, which hosts a dynamical magnetosphere. However, the radio emission of HD 37742 is unambiguously thermal. This suggests that non-thermal radio emission seems to favour centrifugal magnetospheres. In addition, binary wind interactions may also play a role.

We were unable to evaluate the nature of emission or variability of radio flux as we have a adopted snapshot approach to identify the stars that are emitting radio radiation. In order to understand the emission mechanisms and flux variability over the rotation period, we need to observe the detected stars simultaneously over all the frequencies. The detectability of the O-type stars seem to be sensitivity limited. With the upcoming SKA, we expect to achieve a significant sensitivity and detect a larger fraction of the O star sample.

References

[1] Wade, G. A., Neiner, C., Alecian, E., et al. 2016, mnras, 456, 2

[2] Babel, J., & Montmerle, T. 1997, aap, 323, 121

[3] Eichler, D., & Usov, V. 1993, apj, 402, 271

[4] Kurapati, S., Chandra, P., Wade, G., et al. 2017, mnras, 465, 2160

[5] Morel, T., Castro, N., Fossati, L., et al. 2014, The Messenger, 157, 27

[6] Owocki, S. P., & Rybicki, G. B. 1984, apj, 284, 337

[7] Owocki, S., Townsend, R., & Ud-Doula, A. 2008, Revista Mexicana de Astronomia y Astrofisica Conference Series, 33, 80

[8] Petit, V., Owocki, S. P., Wade, G. A., et al. 2013, MNRAS, 429, 398

[9] Shore, S. N., Brown, D. N., Sonneborn, G., Landstreet, J. D., & Bohlender, D. A. 1990, apj, 348, 242

[10] Smith, N. 2014, araa, 52, 487

[11] Trigilio, C., Leto, P., Umana, G., Leone, F., & Buemi, C. S. 2004, A & A, 418, 593

[12] ud-Doula, A., & Owocki, S. P. 2002, ApJ, 576, 413

[13] Ud-Doula, A., Owocki, S. P., & Townsend, R. H. D. 2008, mnras, 385, 97

[14] Usov, V. V., & Melrose, D. B. 1992, ApJ, 395, 575

[15] van Loo, S., Runacres, M. C., & Blomme, R. 2005, A & A, 433, 313

[16] Weiler, K. W., Panagia, N., Montes, M. J., & Sramek, R. A. 2002, araa, 40, 387