Contrib. Astron. Obs. Skalnaté Pleso **48**, 175 – 179, (2018)

Rotation, Emission, & Evolution of the Magnetic Early B-type Stars

M. Shultz[1], G.A. Wade[2], Th. Rivinius[3], C. Neiner[4], O. Kochukhov[1] and E. Alecian[5]

[1] *Department of Physics and Astronomy, Uppsala University, Box 516, Uppsala 75120, (E-mail: matt.shultz@gmail.com)*

[2] *Department of Physics, Royal Military College of Canada, Kingston, Ontario K7K 7B4, Canada*

[3] *European Southern Observatory, Casilla 19001, Santiago 19, Chile*

[4] *LESIA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universits, UPMC Univ. Paris 06, Univ. Paris Diderot, Sorbonne Paris Cit, 5 place Jules Janssen, 92195 Meudon, France*

[5] *Univ. Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France*

Received: November 8, 2017; Accepted: January 5, 2018

Abstract. We report the results of the first population study of 51 magnetic early B-type stars, based upon a large database of high-resolution spectropolarimetry assembled by the MiMeS and BinaMIcS collaborations. Utilizing these data, rotational periods were determined for all but 5 of the sample stars. This enabled us to determine dipole oblique rotator model parameters, rotational parameters, and magnetospheric parameters. We find that the ratio of the Alfvén radius to the Kepler corotation radius is highly predictive of whether or not a star displays Hα emission from a Centrifugal Magnetosphere (CM), as expected from theoretical considerations. We also find that CM host stars are systematically younger than the general population, as expected given that CM emission requires rapid rotation and a strong magnetic field, and a strong magnetic field will lead to rapid magnetic braking. We conclude that emission-line magnetic early B-type stars are, almost without exception, strongly magnetized, rapidly rotating, and young.

Key words: stars: magnetic field – stars: rotation – stars: early-type – stars: evolution – stars: massive

1. Introduction

Thanks to extensive spectropolarimetric surveys, in particular the Magnetism in Massive Stars (MiMeS) survey, the number of early-type stars with detected magnetic fields has increased dramatically during the past decade (Wade et al., 2016). Approximately 10% of early-type stars are magnetic (Wade et al., 2016; Grunhut et al., 2017), a fraction that is approximately constant for stars with radiative envelopes. Magnetic stars earlier than about type B5 sometimes possess Hα emission originating in their corotating magnetospheres. Petit et al.

(2013) showed that emission-line magnetic hot stars can be classified as possessing either Dynamical Magnetospheres (DMs) or Centrifugal Magnetospheres (CMs), depending on whether the centrifugal force arising from corotation of the magnetically confined plasma with the stellar surface is strong enough to prevent gravitational infall. While this division was approximately succesful in separating stars with and without detectable Hα emission, when first proposed there was significant uncertainty regarding the combination of magnetic, rotational, and stellar parameters necessary for a star's magnetosphere to become detectable. In addition, the presence or absence of Hα emission had not been determined for many of the stars examined by Petit et al. (2013).

In order to more precisely explore the boundaries between stars with and without emission, we assembled a sample of 51 magnetic stars with spectral types between B5 and B0, i.e. essentially all known such objects. The study is based upon a large database of high-resolution ESPaDOnS, Narval, and HARPSpol spectropolarimetry, principally obtained by the MiMeS Large Programs (LPs), but also including data obtained by the Binarity and Magnetic Interactions in various classes of Stars (BinaMIcS) and BRITE spectropolarimetric survey (BRITEpol) LPs (Alecian et al., 2015; Neiner et al., 2016), as well as various individual observing programs. In total 1159 spectropolarimetric sequences were obtained, yielding 792 magnetic measurements after removal of bad data and, when appropriate and necessary, temporal binning. Longitudinal magnetic field $\langle B_z \rangle$ measurements (Mathys, 1989) were obtained from Least-Squares Deconvolution (LSD) profiles (Donati et al., 1997; Kochukhov et al., 2010) and H lines. The $\langle B_z \rangle$ measurements, supplemented in some cases by spectroscopic or archival Hipparcos photometric data, were used to obtain rotational periods $P_{\rm rot}$. The empirical analysis of these data were presented by Shultz et al. (2018). These data also enabled us to evaluate the Hα emission status of all stars. Here, we discuss some of the principle conclusions that can be drawn about the differences between magnetic early B-type stars with and without optical emission lines.

2. Results

Basic stellar parameters (radius R_*, mass M_*, age t, and fractional main sequence age $\tau_{\rm TAMS}$) were determined from the effective temperatures $T_{\rm eff}$ (determined spectroscopically either via spectral modelling, where this was available, or via EW ratios, where it was not), log luminosities $\log(L_*/{\rm L}_\odot)$ (determined photometrically), and log surface gravities $\log g$ (determined via spectral modelling of Hβ and Hγ). For each star, overlapping positions on the Hertzsprung-Russell Diagram and $T_{\rm eff}$-$\log g$ diagrams were determined, and stellar parameters then obtained via interpolation within the rotating evolutionary tracks and isochrones calculated by Ekström et al. (2012). For stars belonging to clusters or OB associations (about half the sample), stellar parameters were further

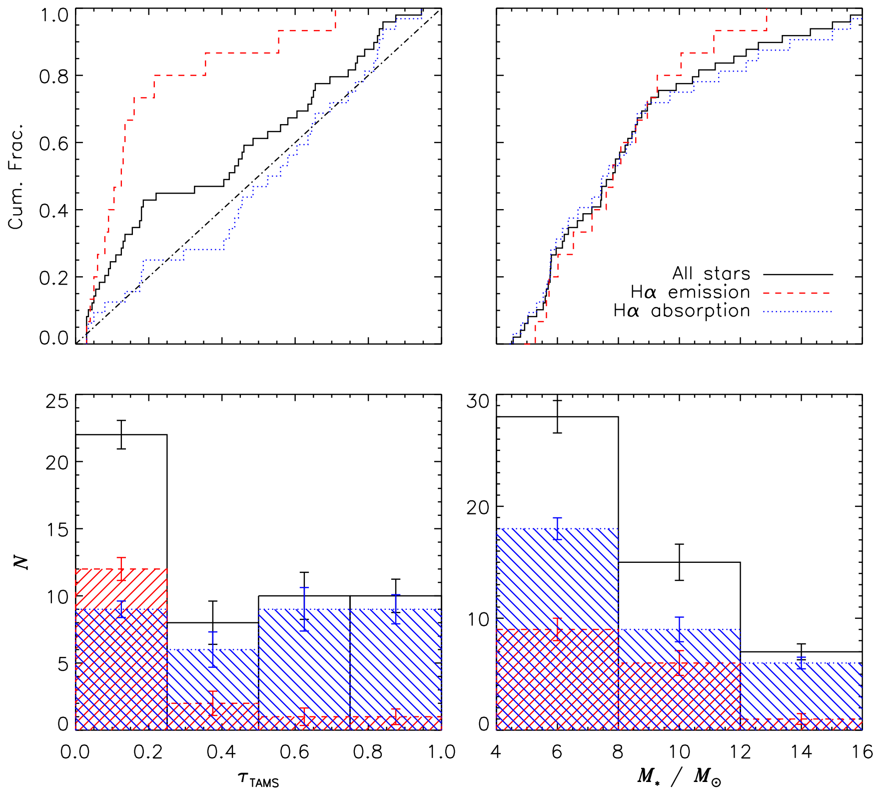

Figure 1. Cumulative distributions (top) and histograms (bottom) of fractional main sequence age $\tau_{\rm TAMS}$ (left) and mass M_* (right) for stars with (dashed red) and without (dotted blue) Hα emission. Emission-line stars are systematically younger than absorption-line stars. The dot-dashed line indicates a flat age distribution, with which the absorption-line stars are consistent. No such dichotomy is apparent for stellar mass.

required to be consistent with the cluster ages determined via main-sequence turnoffs, thus improving the precision of age determination.

Figure 1 shows cumulative distributions and histograms of $\tau_{\rm TAMS}$ and M_* for stars with and without emission. While Hα emission-line stars comprise only about 25% of the overall sample, they are a majority (57%) of stars with $\tau_{\rm TAMS} < 0.25$. The two-sample K-S test probability that the emission- and absorption-line stars belong to the same age distribution is 0.002. By way of contrast, there is no difference in the mass distributions (K-S test probability of 0.95 to belong to the same distribution). From this we conclude that emission-line stars are systematically younger than stars without emission.

Stellar magnetospheres are characterized by two length scales: the Alfvén

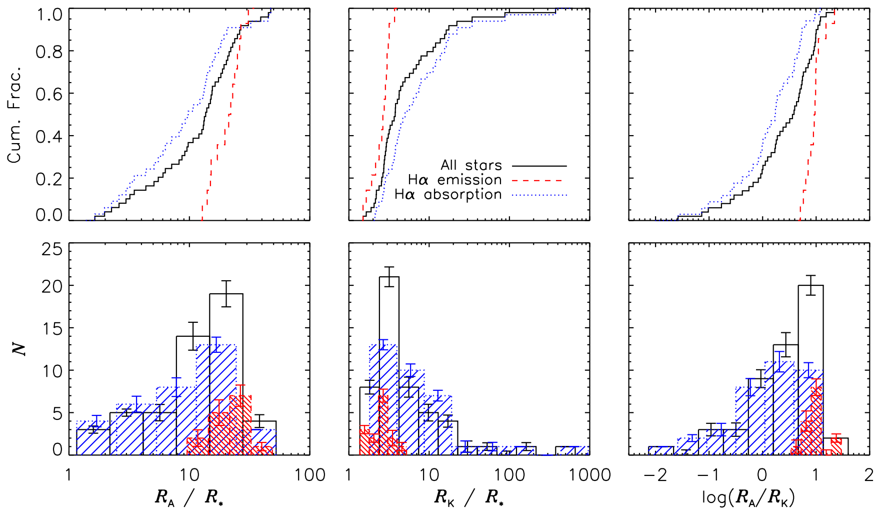

Figure 2. Cumulative distributions (top) and histograms (bottom) of Alfvén radius $R_{\rm A}$ (left), Kepler corotation radius $R_{\rm K}$ (middle), and $\log{(R_{\rm A}/R_{\rm K})}$ (right), for stars with (dashed red) and without (dotted blue) Hα emission. While there are clear differences in the distributions of $R_{\rm A}$ and $R_{\rm K}$ between emission and absorption-line stars, $\log{(R_{\rm A}/R_{\rm K})}$ provides a superior separation of the two populations.

radius $R_{\rm A}$, giving the distance to which the stellar wind remains magnetically confined; and the Kepler corotation radius $R_{\rm K}$, giving the distance at which centrifugal and gravitational forces balance. Only stars with $R_{\rm A} > R_{\rm K}$ possess CMs. $R_{\rm K}$ is calculated from $P_{\rm rot}$, M_*, and R_* (Townsend & Owocki, 2005). $R_{\rm A}$ is calculated from the surface magnetic dipole strength $B_{\rm d}$, R_*, the mass-loss rate $\log{\dot{M}}$, and the wind terminal velocity v_∞ (ud-Doula & Owocki, 2002), where we obtained $B_{\rm d}$ from dipole oblique rotator models based upon $\langle B_z \rangle$ curves, and wind parameters were calculated using the theoretical predictions of Vink et al. (2001).

Petit et al. (2013) suggested that $\log{(R_{\rm A}/R_{\rm K})} > 0.8$ may be a minimum condition for Hα to go into emission. Figure 2 shows cumulative distributions and histograms for $R_{\rm A}$, $R_{\rm K}$, and $\log{(R_{\rm A}/R_{\rm K})}$, for stars with and without Hα emission. Emission-line stars possess systematically higher $R_{\rm A}$ and lower $R_{\rm K}$ than absorption-line stars: the median value of $R_{\rm A}$ for emission-line stars is 22 R_* vs. 9 R_* for absorption-line stars, and for $R_{\rm K}$ the respective medians are 2.7 R_* vs. 4.8 R_*. However, there is substantial overlap in both cases, with 9% of absorption line stars having $R_{\rm A}$ above the median value for emission-line stars, and 13% having $R_{\rm K}$ below the emission-line median. $\log{(R_{\rm A}/R_{\rm K})}$ provides a superior separation, with emission- and absorption-line medians of 0.97 and 0.23, and only 6% of absorption-line stars being above the emission-line median. The two-sample K-S test probabilities for $R_{\rm A}$, $R_{\rm K}$, and $\log(R_{\rm A}/R_{\rm K})$ are respectively 10^{-3}, 10^{-5}, and 10^{-7}.

3. Conclusions

Magnetic B-type stars hosting detectable CMs are without exception rapidly rotating and strongly magnetized, and almost invariably young. The youth of Hα-bright stars makes sense given that strong magnetic fields should lead to rapid magnetic braking. This suggests that young stellar clusters should be the best places to look for more CM hosts, and that any such object will have a magnetic field of at least several kG, and $P_{\rm rot}$ below about 1.5 d.

References

Alecian, E., Neiner, C., Wade, G. A., et al. 2015, in IAU Symp., Vol. **307**, *New Windows on Massive Stars*, ed. G. Meynet, C. Georgy, J. Groh, & P. Stee, 330–335

Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., & Collier Cameron, A. 1997, *Mon. Not. R. Astron. Soc.*, **291**, 658

Ekström, S., Georgy, C., Eggenberger, P., et al. 2012, *Astron. Astrophys.*, **537**, A146

Grunhut, J. H., Wade, G. A., Neiner, C., et al. 2017, *Mon. Not. R. Astron. Soc.*, **465**, 2432

Kochukhov, O., Makaganiuk, V., & Piskunov, N. 2010, *Astron. Astrophys.*, **524**, A5

Mathys, G. 1989, *Fundamentals of Cosmic Physics*, **13**, 143

Neiner, C., Wade, G., Marsden, S., & Blazère, A. 2016, *ArXiv e-prints* [arXiv:1611.03285]

Petit, V., Owocki, S. P., Wade, G. A., et al. 2013, *Mon. Not. R. Astron. Soc.*, **429**, 398

Shultz, M. E., Wade, G. A., Rivinius, T., et al. 2018, *Mon. Not. R. Astron. Soc.*, accepted, *ArXiv e-prints* [arXiv:1801.02924]

Townsend, R. H. D. & Owocki, S. P. 2005, *Mon. Not. R. Astron. Soc.*, **357**, 251

ud-Doula, A. & Owocki, S. P. 2002, *ApJ*, **576**, 413

Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2001, *Astron. Astrophys.*, **369**, 574

Wade, G. A., Neiner, C., Alecian, E., et al. 2016, *Mon. Not. R. Astron. Soc.*, **456**, 2