Stars and their variability observed from space
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MAGNETIC OB[A] STARS WITH TESS: PROBING THEIR EVOLUTIONARY AND ROTATIONAL PROPERTIES - THE MOBSTER COLLABORATION

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Abstract. In this contribution, we present the MOBSTER Collaboration, a large community effort to leverage high-precision photometry from the Transiting Exoplanet Survey Satellite (*TESS*) in order to characterize the variability of magnetic massive and intermediate-mass stars. These data can be used to probe the varying column density of magnetospheric plasma along the line of sight for OB stars, thus improving our understanding of the interaction between surface magnetic fields and massive star winds. They can also be used to map out the brightness inhomogeneities present on the surfaces of Ap/Bp stars, informing present models of atomic diffusion in their atmospheres. Finally, we review our current and ongoing studies, which lead to new insights on this topic.

Keywords: Techniques: photometric, Stars: magnetic field, Stars: rotation

1 Introduction

Magnetism is found in stars across the Hertzsprung–Russell diagram. However, while low-mass stars generate magnetic fields contemporaneously via strong surface dynamos powered by rotation and convection, stars across the OBA spectral type range lack the ingredients actively to create and sustain a large-scale magnetic field. Despite that fact, as evidenced by results from recent large spectropolarimetric surveys (e.g. MiMeS, BOB, BinaMiCS and LIFE; Wade et al. 2016; Morel et al. 2015; Alecian et al. 2015; Martin et al. 2018), a small fraction ($\lesssim 10\%$) of these stars exhibits the presence of strong, globally-organized magnetic fields on their surfaces. Even more remarkably, this incidence rate appears to be flat across a wide range of stellar masses, and the magnetic characteristics of these stars appear to be uncorrelated with their physical properties. The prevailing hypothesis to explain these observations is that the field is of *fossil* origin, meaning that it was formed at an earlier stage of evolution (Borra et al. 1982), although there remains a debate as to what that earlier stage might be (Neiner et al. 2015).

The presence of a surface magnetic field influences several aspects of OBA stars that are crucial to their evolution. In the more massive O- and early B-type stars magnetism can spin the star down significantly (e.g. ud-Doula et al. 2009) and confine its wind, leading to much lower effective mass-loss rates (ud-Doula & Owocki 2002). These effects greatly impact the evolution of magnetic OB stars, and are starting to be included in evolutionary codes (e.g. Keszthelyi et al. 2019). The latter effect might even provide a possible channel to form heavy stellar-mass black holes (e.g. Liu et al. 2019), such as those whose coalescence was detected by LIGO (Abbott et al. 2016), at solar metallicity (Georgy et al. 2017; Petit et al. 2017).

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In later B- and A-type stars, magnetic fields affect atomic diffusion processes in the atmosphere, leading to anisotropic chemical abundances on the stellar surface. This causes spectral peculiarities, as noted in the spectral types of many of these objects: the so-called “Ap/Bp” stars. When compared to other stars of similar spectral type, they are found to exhibit slower rotation rates as a population (Abt & Morrell 1995). In both cases, a further examination into the detailed interaction between magnetic fields and the atmospheres (and extended atmospheres) of these stars will constrain better their overall evolution and observable properties.

To this extent, we propose to take full advantage of the unique opportunity offered by the Transiting Exoplanet Survey Satellite (*TESS*; Ricker et al. 2015). While it was originally designed, as its name suggests, for the detection and characterization of exoplanets via the transit method, the high-precision, high-cadence data that it provides for objects covering ∼85% of the sky represent a veritable treasure trove for the field of stellar astrophysics. Below we describe briefly what kind of photometric signatures can be expected from magnetic massive and intermediate-mass stars, what kind of physical insights we can expect to gain by analyzing *TESS* data, and the ways in which we can increase that gain by combining them with various other observational diagnostics.

2 General phenomenology

Magnetic OBA stars tend to present a common photometric behaviour. Their light curves are recognizable owing to periodic rotational modulation. For the earlier spectral types, that is due to the magnetically confined wind material which scatters continuum light. Since this material is distributed non-axisymmetrically around the star and the magnetic and rotation axes are generally not aligned, a varying column density intersects the line of sight throughout a rotational cycle.

However, as already mentioned, slightly cooler magnetic stars have abundance patches on their surfaces. Flux redistribution (Krtička et al. 2007) also leads to brightness inhomogeneities on the stellar surface which appear and disappear as the star rotates, causing periodic photometric variations.

Both of these phenomena manifest themselves in a light-curve periodogram as a well-defined peak in a reasonable frequency range that might be associated with the rotation of the star; there is at least one harmonic (typically the first one; Bowman et al. 2018), although occultation by magnetospheric material can, in some cases, lead to the presence of more harmonics and a rather complex light-curve (Townsend 2008). This phenomenology can be used to select highly probable magnetic candidates (Buysschaert et al. 2018). However, the method must be used with caution since other mechanisms can lead to a similar observational signature (e.g. eclipsing binaries, ellipsoidal variations, etc.), and should be ruled out before the frequencies are ascribed to a rotational origin.

3 Physical insights obtained from photometry

3.1 O and early B stars

The circumstellar *magnetospheres* formed by the interaction between a surface magnetic field and a strong stellar wind around OB stars have been studied in great detail over the past two decades. State-of-the-art magnetohydrodynamic simulations (ud-Doula & Owocki 2002; ud-Doula et al. 2008, 2009) have provided us with unprecedented insights into their structure and their influence on a star. Simpler parametrizations have also been developed, both for fast (Townsend & Owocki 2005) and slow (Owocki et al. 2016) rotators, which enable us to define a density and velocity at any given point in the magnetosphere. Coupled with an appropriate radiative transfer scheme (e.g. Hennicker et al. 2018), these models can reproduce a large swath of multi-wavelength observations to great accuracy (e.g. Nazé et al. 2014; David-Uraz et al. 2019a). They can also be confronted with optical photometry, as was done with great success with MOST data to explain the light-curve of σ Ori E (Townsend et al. 2013). Ongoing efforts also aim to derive magnetospheric parameters using photometry (Munoz et al. 2019). Measuring period changes in magnetic OB stars can validate or challenge our current understanding of their rotational evolution (e.g. Townsend et al. 2010; Mikulášek et al. 2011; Shultz et al. 2019a).

3.2 Late B and A stars

Photometric time-series can be used to map brightness spots on the surface of a star using various light-curve inversion techniques, as exemplified by the work that Weiss et al. (2016) have done with BRITE data to map the surface of α Cir. The maps can then be compared to elemental abundance maps derived from applying

Doppler Imaging to well-sampled time-series of high-resolution spectroscopy (e.g. Khokhlova & Riabchikova 1975). Furthermore, information about the abundance and vertical stratification of different chemical elements can be obtained by performing a detailed analysis of their line profiles, as has been achieved by the VeSElkA project (Khalack et al. 2017). There is a clear synergy between that endeavour and the core goals of the MOBSTER Collaboration, leading to a more complete picture of the atmosphere of Ap/Bp stars – as evidenced by studies conducted in common by both groups (Khalack et al. 2019).

4 Progress to date

To date our collaboration has published three refereed articles; more are planned. Paper I (David-Uraz et al. 2019b) looked at the morphology of the photometric variations for known magnetic B- and A-type stars in sectors 1 and 2, and concluded that most were compatible with rotational modulation. It also derived refined periods for them.

In Paper II (Sikora et al. 2019) we detected rotational modulation in the light-curves of many A-type stars observed by *TESS* in sectors 1 to 4. Interestingly, the properties of the variations (e.g., period and amplitude) appear to differ between the population of stars identified as chemically peculiar (Ap) and the population of stars that are not identified as such. This might be providing us with a clue as to the underlying physical mechanisms.

In Paper III (Shultz et al. 2019b) we discuss the puzzling case of an eclipsing B-type binary system, HD 62658. Careful modelling of its light-curve, and examining its spectroscopic and spectropolarimetric data, suggests that only one of the stars is magnetic, even though the mass ratio is almost unity and the stars appear otherwise to be nearly identical. This poses a particular challenge to theories of the origin of magnetic fields in such stars . . . The plot thickens even further.

5 Conclusions, and future work

The MOBSTER Collaboration groups both observers and theorists together with the goal of maximizing the scientific output of the *TESS* mission with respect to magnetism in massive and intermediate-mass stars. As elaborated above, the high-precision light-curves produced by *TESS* enable us to constrain the physics of the atmosphere and winds of these stars, leading to a deeper understanding of their evolution. While some work has already been done, there remain many questions to be answered. So far we have only skimmed the surface of this data bounty; we have focused mainly on 2-minute cadence data (which are obtained for somewhere between 200,000 and 400,000 objects), but full-frame image data (30 minute cadence) should be available for over 500 million point sources (Stassun et al. 2018). Much work thus remains to unlock the truly transformative potential of the MOBSTER project in the field of magnetism in OBA stars.

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References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, Phys. Rev. Lett., 116, 061102

Abt, H. A. & Morrell, N. I. 1995, ApJS, 99, 135

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

Borra, E. F., Landstreet, J. D., & Mestel, L. 1982, ARA&A, 20, 191

Bowman, D. M., Buysschaert, B., Neiner, C., et al. 2018, A&A, 616, A77

Buysschaert, B., Neiner, C., Martin, A. J., et al. 2018, MNRAS, 478, 2777

David-Uraz, A., Erba, C., Petit, V., et al. 2019a, MNRAS, 483, 2814

David-Uraz, A., Neiner, C., Sikora, J., et al. 2019b, MNRAS, 487, 304

Georgy, C., Meynet, G., Ekström, S., et al. 2017, A&A, 599, L5

Hennicker, L., Puls, J., Kee, N. D., & Sundqvist, J. O. 2018, A&A, 616, A140

Keszthelyi, Z., Meynet, G., Georgy, C., et al. 2019, MNRAS, 485, 5843

Khalack, V., Gallant, G., & Thibeault, C. 2017, MNRAS, 471, 926

Khalack, V., Lovekin, C., Bowman, D. M., et al. 2019, MNRAS, 490, 2102

Khokhlova, V. L. & Riabchikova, T. A. 1975, Ap&SS, 34, 403

Krtička, J., Mikulášek, Z., Zverko, J., & Žižňovský, J. 2007, A&A, 470, 1089

Liu, J., Zhang, H., Howard, A. W., et al. 2019, arXiv e-prints, arXiv:1911.11989

Martin, A. J., Neiner, C., Oksala, M. E., et al. 2018, MNRAS, 475, 1521

Mikulášek, Z., Krtička, J., Henry, G. W., et al. 2011, A&A, 534, L5

Morel, T., Castro, N., Fossati, L., et al. 2015, in IAU Symposium, Vol. 307, New Windows on Massive Stars, ed. G. Meynet, C. Georgy, J. Groh, & P. Stee, 342–347

Munoz, M. S., Wade, G. A., Nazé, Y., et al. 2019, MNRAS, 2573

Nazé, Y., Petit, V., Rinbrand, M., et al. 2014, ApJS, 215, 10

Neiner, C., Mathis, S., Alecian, E., et al. 2015, in IAU Symposium, Vol. 305, Polarimetry, ed. K. N. Nagendra, S. Bagnulo, R. Centeno, & M. Jesús Martínez González, 61–66

Owocki, S. P., ud-Doula, A., Sundqvist, J. O., et al. 2016, MNRAS, 462, 3830

Petit, V., Keszthelyi, Z., MacInnis, R., et al. 2017, MNRAS, 466, 1052

Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, JATIS, 1, 014003

Shultz, M., Rivinius, T., Das, B., Wade, G. A., & Chandra, P. 2019a, MNRAS, 486, 5558

Shultz, M. E., Johnston, C., Labadie-Bartz, J., et al. 2019b, MNRAS, 490, 4154

Sikora, J., David-Uraz, A., Chowdhury, S., et al. 2019, MNRAS, 487, 4695

Stassun, K. G., Oelkers, R. J., Pepper, J., et al. 2018, AJ, 156, 102

Townsend, R. H. D. 2008, MNRAS, 389, 559

Townsend, R. H. D., Oksala, M. E., Cohen, D. H., Owocki, S. P., & ud-Doula, A. 2010, ApJ, 714, L318

Townsend, R. H. D. & Owocki, S. P. 2005, MNRAS, 357, 251

Townsend, R. H. D., Rivinius, T., Rowe, J. F., et al. 2013, ApJ, 769, 33

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

ud-Doula, A., Owocki, S. P., & Townsend, R. H. D. 2008, MNRAS, 385, 97

ud-Doula, A., Owocki, S. P., & Townsend, R. H. D. 2009, MNRAS, 392, 1022

Wade, G. A., Neiner, C., Alecian, E., et al. 2016, MNRAS, 456, 2

Weiss, W. W., Fröhlich, H. E., Pigulski, A., et al. 2016, A&A, 588, A54