Contrib. Astron. Obs. Skalnaté Pleso **48**, 149 – 153, (2018)

The Of?p stars of the Magellanic Clouds: Are they strongly magnetic?

M. Munoz[1], **G. A. Wade**[2], **Y. Nazé**[3], **S. Bagnulo**[4] and **J. Puls**[5]

[1] *Queen's University, Kingston, Ontario, Canada*
(E-mail: 16msm5@queensu.ca)
[2] *Royal Military College, Kingston, Ontario, Canada*
[3] *Université de Liège, 4000 Liège, Belgium*
[4] *Armagh Observatory, Armagh BT61 9DG, Northern Ireland, UK*
[5] *Universitätssternwarte, D-81679 München, Germany*

Received: November 11, 2017; Accepted: November 15, 2017

Abstract. All known Galactic Of?p stars have been shown to host strong, organized, magnetic fields. Recently, five Of?p stars have been discovered in the Magellanic Clouds. They posses photometric (Nazé et al., 2015) and spectroscopic (Walborn et al., 2015) variability compatible with the Oblique Rotator Model (ORM). However, their magnetic fields have yet to be directly detected. We have developed an algorithm allowing for the synthesis of photometric observables based on the Analytic Dynamical Magnetosphere (ADM) model by Owocki et al. (2016). We apply our model to OGLE photometry in order to constrain their magnetic geometries and surface dipole strengths. We predict that the field strengths for some of theses candidate extra-Galactic magnetic stars may be within the detection limits of the FORS2 instrument

Key words: stars: massive – stars: magnetic fields – stars: rotation – stars: chemically peculiar

1. Introduction

Of?p stars are a rare class of chemically peculiar O-type stars. They are characterized by the presence of strong N III λ4634-41 and C III λ4686 emission lines. In Nazé et al. (2008), the Galactic sample of Of?p stars were shown to display phase-locked spectroscopic and photometric variability that is reminiscent of a magnetic oblique rotator model. Searching for Magnetism in Massive Stars (MiMeS), the MiMeS survey confirmed magnetic detections in all Galactic Of?p stars (Grunhut et al., 2017), thus linking their anomalous surface abundances to the presence of magnetic fields.

Recently, a small sample of extra-Galactic Of?p stars have been detected in the Small and Large Magellanic Clouds (Walborn et al., 2015). Similar to the Galactic sample of Of?p stars, the Magellanic Of?p stars also possess phase dependent spectroscopic and photometric variability (Nazé et al., 2015). It is therefore highly suspected that the Magellanic Of?p stars host magnetic fields as well. Despite a first attempt to detect these proposed magnetic fields using the FORS2 instrument at VLT, none were detected due to poor weather conditions and non-optimal observing times (Bagnulo et al., 2017).

Therefore, we propose an indirect method to infer the magnetic field properties of magnetic massive stars via modeling of the photometric variations caused by the rotation-phase-dependent scattering of their photospheric light by their magnetospheres. Since stars residing in the Magellanic Clouds have intrinsically lower metallicities than those from the Milky way, this investigation may provide useful insight on the impact of metallicity on the ORM paradigm.

In Sect.
refsec:model, we will describe the numerical method allowing for the light curve synthesis and consider the effect of metallicity on some sample light curves. In Sect. 3, we will first apply our algorithm to archival Hipparcos photometry of the thoroughly-studied Galactic Of?p star HD 191612 (Wade et al., 2011) as a proof of concept, and then on the recent OGLE photometry of the Magellanic Of?p stars (Nazé et al., 2015). Finally, we will summarize our results in the last section.

2. The model light curves

2.1. The algorithm

For a wind dominated by electron scattering (which is appropriate for hot massive stars), the photometric variability will be modulated by the amount of plasma occulting the star's surface along the line-of-sight of an observer. This is parametrized via the α angle corresponding to the inclination of the magnetic equator with respect to the observer's line-of-sight. The projection of such an angle is

$$\cos\alpha = \cos\phi\sin\beta + \cos\beta\cos i, \tag{1}$$

where i is the inclination angle (angle between the observer's line-of-sight and the rotation axis), β is the magnetic obliquity (angle between the magnetic axis and the rotation axis) and ϕ is the rotational phase.

At each rotational phase, the differential magnitude due to an optically thin single electron scattering wind is given by

$$\Delta m = \Delta m_0 + (2.5\log e)\tau, \tag{2}$$

where Δm_0 is a constant magnitude shift and τ is the Thompson scattering optical depth. For an observer arbitrarily placed on the z axis, the line-of-sight optical depth will be related to the magnetosphere density, ρ, as follows

$$\tau = \frac{\alpha\sigma_e}{m_p}\int \rho dz, \tag{3}$$

where σ_e is the Thompson cross section, α is the free electron baryon mass and m_p is the mass of a proton. For a completely ionized gas composed of helium, that is suitable for hot massive stars, $\alpha = 0.5$.

The density structure surrounding the star is provided by the Analytic Dynamical Magnetosphere (ADM) model from Owocki et al. (2016). The ADM model is capable of characterizing the density, temperature and wind flow structures via analytical prescriptions. For simplicity, it assumes a dipolar field geometry which is observationally consistent with the well-known Galactic Of?p stars (Grunhut et al., 2017). Traditionally, magnetosphere models were obtained using computationally expensive MHD simulations. As the ADM model is vastly more computationally efficient and was shown to be in good agreement with more sophisticated MHD simulations (Owocki et al., 2016), we have chosen to implement the ADM formalism.

2.2. The effect of metallicity

Studying stars outside the Milky Way presents a unique opportunity to investigate the effect of varying metallicity (Z). To anticipate this effect, we will synthesize and compare model light curves at three different metallicities: solar ($Z_\odot$), $0.5\,Z_\odot$ for the Large Magellanic Cloud (LMC) and $0.2\,Z_\odot$ for the Small Magellanic Cloud (SMC). Using stellar and magnetic parameters from Wade et al. (2011), the original light curve, at solar metallicity, will be based upon the prototypical Galactic Of?p star, HD 191612. The subsequent light curves will be computed with adjusted mass-loss rates and wind terminal velocities that are scaled according to Z using Vink et al. (2001) prescriptions.

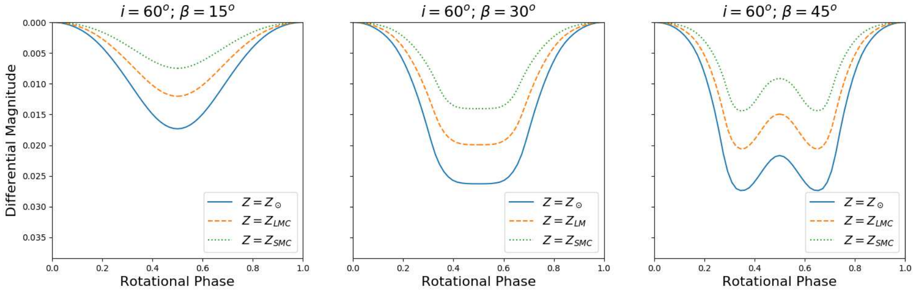

Figure 1. Model light curves with constant inclination. The different panels show curves of increasing obliquity: 15° (left), 30°(middle) and 45° (right). Over-plotted on each panel are curves of decreasing metallicity: $Z_\odot$ (solid), $0.5\,Z_\odot$ (dashed) and $0.2\,Z_\odot$ (dotted).

Figure 1 illustrates the effect of decreasing Z for a selection of $i + \beta$ angles. Panels from left to right, show increasing angles of $i + \beta$. Overplotted on each panel are curves of decreasing Z. We notice that curves with $i+\beta = 90°$ are flat bottomed and mark the transition from single peaked curves ($i + \beta < 90°$) to double peaked curves ($i + \beta > 90°$). This is because at high $i + \beta$, the magnetic equator, corresponding to the densest region of the magnetosphere, crosses the observer's line-of-sight twice during one rotational cycle. Furthermore, we can see that curves with lower metallicities have linearly scaled down occultation depths. This is to be expected as lowering the metallicity will lower the star's mass-loss rate and thus the magnetosphere density as well. As a decrease in density effectively yields a decrease in opacity, the overall light curve depth will diminish. Therefore, a change in metallicity can only account for linear scalings. In contrast, the increase of $i + \beta$ can morphologically change the light curve shape that is essentially related to the double peak separation.

3. Applications

3.1. HD 191612

HD 191612 is a well-known Galactic Of?p star with observationally constrained magnetic field strength and field geometry. From longitudinal magnetic field measurements, a dipolar field strength of $B_d = 2\,450 \pm 400\,\mathrm{G}$ was obtained satisfying the general set of solutions characterized by $i + \beta = 95 \pm 10\,°$. While tentative Monte Carlo radiative transfer light curve models have been computed for this star, no genuine fit has ever been performed to its light curve. Using the same stellar parameters from Wade et al. (2011), we attempt to fit a light curve to the Hipparcos photometry. The fitting procedure is accomplished via a Python implementation of Markov chain Monte Carlo (MCMC) method using the `emcee` package from Foreman-Mackey et al. (2013). We obtained $B_d = 3.8^{+0.9}_{-1.8}\,\mathrm{kG}$ and $i + \beta = 92^{+5}_{-5}\,°$. It is reassuring to see that, within uncertainty, the best-fitted parameters are compatible with the previous findings obtained from direct measurements of the magnetic fields.

3.2. LMC and SMC Of?p stars

Among the five recently reported Of?p stars from the Magellanic Clouds, only four stars have accurately determined photometric periods. We first utilized published prescriptions in order to deduce their wind parameters (Vink et al., 2001). The remaining stellar parameters were determined via spectroscopic modeling using FASTWIND. The best-fit parameters are listed in Table 1. We notice that the dipole field strengths are unusually high in comparison to the Galactic sample of Of?p stars. This is because the light curve depths from Magellanic Of?p stars are comparable to those of the Galactic Of?p stars, while the former have inherently lower mass-loss rates due their the sub-solar metallicities. It is therefore required for the dipole field strength to be increased in order to compensate for the reduced density in the magnetosphere.

Table 1. Best-fit i, β couple and B_d for the Magellanic Of?p stars.

	SMC 159-2	LMC 164-2	2dFS 936	BI 57
$i + \beta\,[^\circ]$	88^{+4}_{-3}	100^{+5}_{-5}	86^{+3}_{-3}	66^{+3}_{-4}
$i - \beta\,[^\circ]$	42^{+18}_{-24}	50^{+23}_{-13}	44^{+23}_{-16}	22^{+15}_{-24}
B_d [kG]	7^{+2}_{-2}	6^{+1}_{-2}	13^{+4}_{-5}	$3.1^{+0.8}_{-0.9}$

4. Discussion and conclusion

To summarize, we described a simple prescription allowing for the light curve synthesis of magnetic massive stars. We apply this model to the OGLE photometry of the first-candidate Of?p stars from the Magellanic clouds and predict the magnitude and geometry of their suspected magnetic fields. We note that these stars have already previously been observed with FORS2 (Bagnulo et al., 2017). However, due to unfavorable weather conditions and non-optimal observing times, no surface fields could be confirmed with certainty. We suspect that SMC 159-2, in particular, will be detectable with the FORS2 instrument and is scheduled to be re-observed in the coming year.

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