Stars and their variability observed from space
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THE PHOTOMETRIC VARIABILITY OF MAGNETIC HOT STARS: DEVIATIONS FROM CENTERED DIPOLES

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Abstract. Magnetic O-type stars host strong, organized magnetic fields that channel their stellar winds, significantly confining their mass loss and enhancing the shedding of rotational angular momentum. The resultant mass-loss quenching and magnetic braking lead magnetic O-type stars to evolve at higher mass and slower rotation than their non-magnetic kin, making them novel laboratories for the study of high mass stellar evolution. At the root of the magnetic field-stellar wind interaction is the formation of a complex, co-rotating dynamical magnetosphere surrounding the star. The recently developed Analytic Dynamical Magnetosphere (ADM) model (Owocki et al. 2016) provides a straightforward description of the temperature, density, and velocity fields predicted to occur in these magnetospheres, allowing computationally efficient calculation of observable quantities needed for the determination of magnetospheric physical characteristics and for the testing of theoretical limitations. In earlier papers (e.g. Munoz 2019), we have exploited the ADM model to compute photometric observables of magnetic Of?p stars, to test geometric models inferred from magnetometry (for Galactic targets) and to place constraints on as-yet-undetectable magnetic fields (for extra-Galactic targets). In the following, we focus on the light curve of LMCe136-1, an Of?p-type star from the Large Magellanic Cloud, which manifests a clear asymmetry in its light curve that cannot be reproduced by an axisymmetric pure dipole model. For this purpose, we consider offset dipoles and significant quadrupoles components as possible magnetic field geometries for the star. Both topologies yield light curves that can reproduce the observed photometric variability of LMCe136-1.

Keywords: Stars: magnetic field, Stars: massive, Stars: mass-loss

1 Introduction

Stellar magnetic fields can significantly affect the evolution and fate of massive stars. For instance, their rotation rates can be substantially decreased via magnetic braking (e.g. Townsend et al. 2010) and their longevity can be substantially increased via magnetic quenching of mass loss (e.g. Petit et al. 2017). Understanding the nature of these magnetic fields is therefore an important component that plays into the general understanding of massive stars.

The magnetic properties of the known Galactic magnetic O-type stars are generally well described by an obliquely rotating, predominantly dipolar and strong magnetic field. As the star rotate, their observable quantities are expected to manifest periodic variability in accordance to the oblique magnetic rotator paradigm.

The purpose of this investigation is to gain insight on the physical processes that occur within the magnetospheres of magnetic massive stars. To this end, we attempt to model, reproduce and analyse the photometric variability of magnetic O-type stars as a means to characterise the structure and geometry of their magnetic fields.

The photometric modelling of such stars has already been analysed by Munoz et al. (2019) under the assumption of a pure dipolar field topology. Here, we consider more exotic magnetic field topologies, namely, offset dipoles and quadrupoles.

In Section 2, we describe the methodology behind the photometric and polarisation models. In Section 3, we present the light curve of LMCe136-1, a Magellanic Of?p-type star, that may be indicative of deviations from a typical dipolar field geometry. We conclude in the final section.

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2 Numerical Method

2.1 The magnetosphere model

The magnetospheres of slowly rotating O-type stars are expected to behave within the dynamical magnetosphere regime (Petit et al. 2013). Globally, such magnetospheres appear as stable, rigidly rotating structures that are held in magnetic confinement. However, locally, they are complex dynamical structures.

The complexities present in the dynamical magnetospheres of magnetic massive stars can be formally solved utilizing sophisticated 3D magnetohydrodynamic (MHD) simulations (Ud-Doula & Owocki 2002; Ud-Doula et al. 2008, 2009, 2013). However, their steady-state properties can be approximated with an analytical dynamical magnetosphere (ADM) model that was recently developed by Owocki et al. (2016).

The ADM model is capable of quickly computing the density, velocity and temperature structure of dynamical magnetospheres. Although the model was initially designed for pure magnetic dipoles, we have recently extended the model to consider offset dipoles and (linear) quadrupoles. Figure 1 showcases the density structure

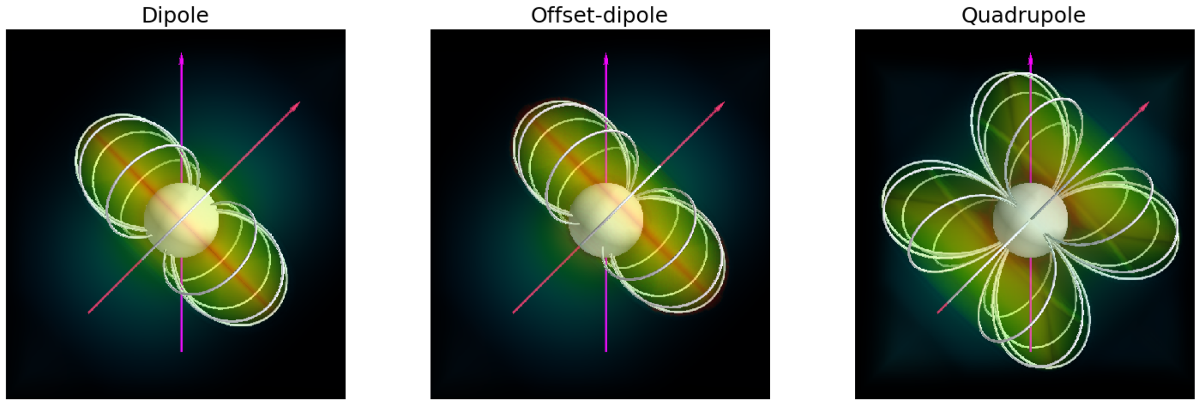

Fig. 1. 3D rendering of the density structure computed with the ADM model for three simple magnetic field topologies: Pure dipole, offset-dipole and linear quadrupole (from left to right). In each panel, the magnetic field axis (inclined pink arrow) is tilted by 45° with respect to the rotation axis of the star (vertical purple arrow) and the field lines of the magnetic topology are overplotted. Red regions are high in density while green regions are low in density.

computed with ADM for three magnetic field geometries: a pure dipole, a decentered dipole and a quadrupole. In all cases the magnetic field axis (shown in pink) is inclined by 45° with respect to the rotation axis (shown in purple). The density structure is computed with input parameters based on the prototypical magnetic massive star HD 191612: $T_{\rm eff} = 35\,{\rm kK}$, $R_* = 14.5\,R_*$, $M_* = 30\,M_*$, $v_\infty = 2700$ km s^{-1}, $\dot{M}_{B=0} = 10^{-6}\,M_\odot{\rm yr}^{-1}$ and $B_{\rm d} = 2.5 \pm 0.4\,{\rm kG}$. In all three cases, we can see over-density structures along the apex of each closed loop. This is an expected result. As material follows the magnetic field lines, they collide and deposit matter near the magnetic equator.

2.2 The photometric and linear polarisation model

The photometric variability of an oblique magnetic rotator is expected to arise from the periodic occultations of its own magnetosphere. For hot stars, the amount of occulted light can be quickly estimated in the single-electron scattering regime. In such a case, the amount of occultation is predominantly determined by the column density along the line-of-sight of the observer. In order to estimate the optical depth, we exploit the ADM model as a means to quickly obtain the density structure of the magnetosphere.

Figure 2 shows sample light curve morphologies expected from the different magnetic field topologies illustrated in Fig. 1. For a pure dipole, the light curves are either single-dipped (if $i + \beta < 90°$) or double-dipped (if $i + \beta > 90°$). An axisymmetric magnetic field topology will always yield a symmetric light curve (i.e. the light curve is mirrored across the rotational phase 0.5). Deviations from this paradigm may be attributed to more exotic magnetic field topologies. For instance, a dipole offset or a significant quadrupolar component may cause asymmetries to be present in the light curve. Under certain configurations, a light curve produced from an offset-dipole topology may be degenerate from one produced from a dipole plus quadrupole topology. This is

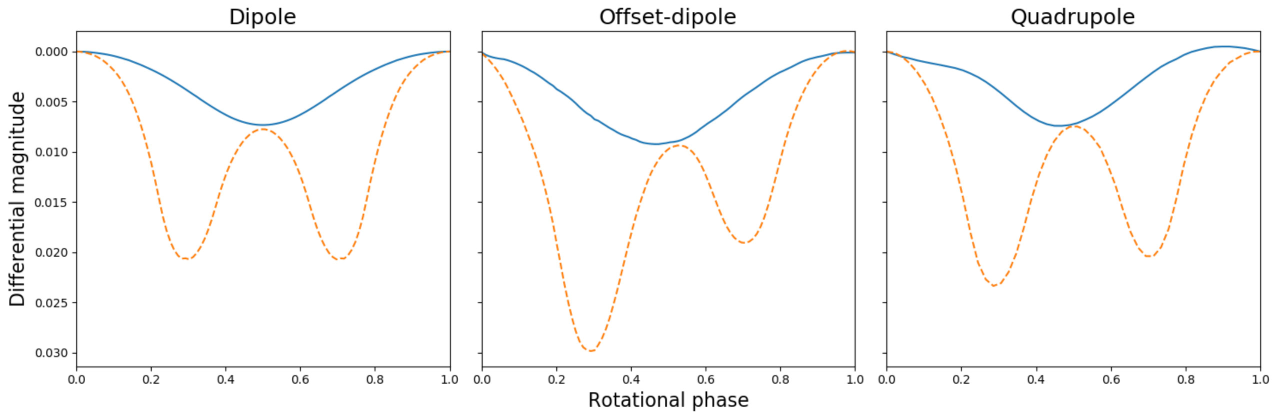

Fig. 2. Photometric variability obtained from the configurations shown in Fig. 1. The solid (blue) curve corresponds to an inclination of $i = 15°$ while the dashed (orange) curve corresponds to an inclination of $i = 75°$. In all cases, the magnetic obliquity is fixed to $\beta = 45°$.

problematic as it may not always be possible to discern the magnetic topology from the observed photometric variability.

3 Application to LMCe136-1

LMCe136-1 was recently identified as an Of?p type star in the Large Magellanic Cloud by Neugent et al. (2018). A photometric light curve was obtained from the Optical Gravitational Lensing Experiment (OGLE) project which revealed a distinctive periodic signal of 18.914 ± 0.004 d.

The phased light curve for LMCe136-1 is displayed in Fig. 3. Since a definitive ephemeris is not yet constrained for this star, the rotational phase $\phi = 0$ was arbitrarily placed to correspond to a maximum in photometric brightness. An interesting feature in the phased light curve is a clear asymmetry present near $\phi = 0.4$ and $\phi = 0.6$.

To account for the asymmetry present in the phased light curve, we attempt to model the photometric variability with a decentered dipole. The curve of best-fit is shown in Fig. 3 (left panel, red curve) with best-fitted parameters listed in Table 1. The photometric variability can be well reproduced with a dipole offset of $a = -0.21^{+0.03}_{-0.03}\,R_*$ (perpendicular to the magnetic axis), a dipolar field strength of $B_{\rm d} = 5.6^{+4.1}_{-1.9}$ kG, an inclination angle of $i = 57^{+21\circ}_{-19}$ and a magnetic obliquity of $\beta = 51^{+20\circ}_{-21}$.

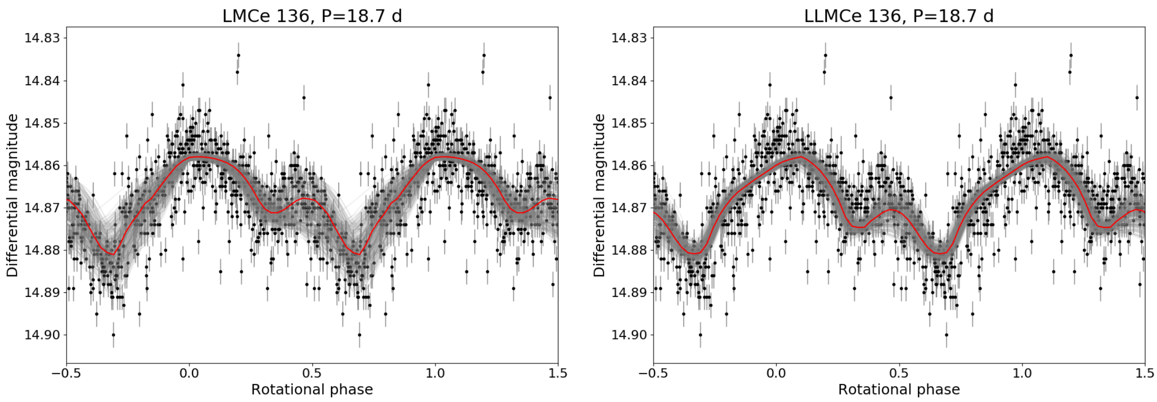

Fig. 3. The photometric variability of LMCe136-1. **Left:** Offset-dipole model. **Right:** Dipole plus quadrupole model. The curves of best-fit are overplotted in red (bold solid lines). Curves that span the 1 σ error bars on the best-fit parameters are overplotted in gray (thin solid lines).

Another magnetic field geometry to consider is a dipole plus quadrupole model. With this configuration, the parameters of best-fit are: $i = 70^{+7\circ}_{-7}$, $\beta_1 = 35^{+9\circ}_{-6}$, $\beta_2 = 30^{+8\circ}_{-6}$, $\Delta\phi = 0.25^{+0.06}_{-0.08}$, $B_{\rm d} = 5.0^{+0.6}_{-0.8}$ kG and

Table 1. Best-fit parameters to the OGLE photometry with an offset-dipole and dipole + quadrupole model

Model	i [deg]	β_1 [deg]	β_2 [deg]	$\Delta\phi$	B_d [kG]	B_q [kG]	Δm_0 [mmag]	a [$R_\odot$]
Offset-dipole	57^{+21}_{-19}	51^{+20}_{-21}	-	-	$5.6^{+4.1}_{-1.9}$	-	14858^{+1}_{-1}	$a = -0.21^{+0.03}_{-0.03}$
Dipole + quadrupole	70^{+7}_{-7}	35^{+9}_{-6}	30^{+8}_{-6}	$0.25^{+0.06}_{-0.08}$	$5.0^{+0.6}_{-0.8}$	$6.5^{+1.5}_{-1.5}$	14860^{+2}_{-2}	-

† Δm_0 corresponds to a vertical offset in the differential magnitude (assumed constant).

$B_\mathrm{q} = 6.5^{+1.5}_{-1.5}$ kG (see Fig. 2 and Table 1). Here, β_1 is the magnetic obliquity of the dipolar component, β_2 is the magnetic obliquity of the quadrupolar component, $\Delta\Phi$ is a rotational phase shift between both components, B_d is the dipolar magnetic field strength and B_q is the quadrupolar field strength. Although we can obtain an adequate fit for the photometric variability of LMCe136-1, we obtain a magnetic field strength for the quadrupolar component that is greater than the dipolar component which is unprecedented.

4 Conclusions

To summarise, we have explored the photometric variability produced from a pure dipole, an offset dipole and a dipole plus quadrupole. The light curves were synthesised under the single-electron scattering limit while utilizing the density structure computed from the ADM model. For a pure dipole, the light curve is symmetric about rotation phase $\phi = 0.5$. The implementation of an offset dipole or a significant quadrupolar component introduces asymmetries in the light curve.

For the Of?p-type star LMCe136-1 in the Large Magellanic Cloud, its photometric variability cannot be explained under the assumption of a pure dipolar magnetic field topology. Instead, the light curve could be reproduced with a dipole offset of $a \sim -0.21\,R_*$ or with a quadrupolar field strength of $B_q \sim 6.5$ kG. Unfortunately, we could not rule out one geometry over the other. This is not unexpected, as degeneracy between these two field topologies has been noticed when trying to model longitudinal fields or the magnetic field modulus in Ap-type stars (e.g. Landstreet 1980).

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