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Magnetospheres around high mass stars revealed by polarimetry

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Abstract. About 10% of the known massive stars have a magnetic field of relevant strength. Combined with the star's fast rotation, the magnetic field may be able to trap the expelled material, forcing it to corotate with the star, creating the so-called magnetospheres. The *Rigidly Rotating Magnetosphere* (RRM) model was created for the case of strong magnetic fields and high rotation velocity. However, it is not able to simultaneously reproduce the photometry and polarimetry of the archetype star σ Ori E's magnetosphere. An alternative model, named *Dumbbell plus Disk* (D+D) was proposed, which allows a good fit of the data and the determination of basic parameters of the magnetosphere. We present the results of a polarimetric survey of massive magnetic stars at Pico dos Dias Observatory (OPD), where observations of 18 stars were carried out int the V and R filters. We improved the D+D model, coupling the original routine to the *emcee* algorithm of the Monte Carlo Markov Chain method, making possible a more robust statistical analysis of the data. The objetive of the project is to obtain linear polarization data of massive magnetic stars throughout their rotation period, and thus apply the D+D model to study their magnetospheres. We report the detection of four new magnetospheres by polarimetry, in the stars σ Ori E, HD 35502, HD 142990, HR 7355 and HR 5907. We applied the model to observational data, and improved the results of σ Ori E. Of the new detections, two stars, HD 35502 and HD 142990 had good fits, making it possible to determine the parameters of their magnetospheres. HR 7355 and HR 5907 had marginal fits, which can be caused by the low modulation of the intrinsic polarization, or by the inadequacy of the D+D for these objects. An analysis was also made to investigate existing relations between the properties of the magnetosphere and its host star. We found that the mass of the magnetosphere increases with the strength of the magnetic field.

Resumo. Aproximadamente 10% das estrelas massivas conhecidas possuem campo magnético de força relevante. Combinado a uma rápida rotação da estrela, campos magnéticos podem ser capazes de aprisionar o material expelido, o forçando a corrotacionar com a estrela, criando as chamadas magnetosferas. O modelo *Rigidly Rotating Magnetosphere* (RRM) foi criado para o caso de campos magnéticos muito fortes e altas velocidades de rotação. Ele, porém, não é capaz de reproduzir simultaneamente a fotometria e polarimetria da estrela arquétipo σ Ori E. Um modelo alternativo, chamado *Dumbbell plus Disk* (D+D) foi proposto, que permite um bom ajuste dos dados polarimétricos e a definição de parâmetros básicos da magnetosfera. Apresentamos o resultado de um monitoramento polarimétrico de estrelas massivas magnéticas no Observatório Pico dos Dias, onde foram realizadas observações de 18 estrelas nos filtros V e R. Aprimoramos o modelo D+D, acoplando a rotina original ao algoritmo *emcee* do método de Monte Carlo via Cadeias de Markov, tornando possível uma análise estatística mais robusta dos dados. O objetivo do projeto é obter dados da polarização linear de estrelas massivas magnéticas durante todo seu período de rotação, e assim aplicar o modelo D+D para estudar suas magnetosferas. Reportamos a detecção de quatro novas magnetosferas por polarimetria, nas estrelas HD 35502, HD 142990, HR 7355 e HR 5907. Aplicamos o modelo aos dados observacionais, onde aprimoramos os resultados de σ Ori E. Das novas detecções, duas estrelas, HD 35502 e HD 142990 tiveram bons ajustes, tornando possível determinar os parâmetros de suas magnetosferas. HR 7355 e HR 5907 tiveram ajustes marginais, que podem ser causados pela baixa modulação da polarização intrínseca, ou pela inadequação do D+D para estes objetos. Também foi feita uma análise para investigar relações existentes entre as propriedades da magnetosfera e sua estrela. Encontramos que a massa da magnetosfera aumenta com a força do campo magnético.

Keywords. Magnetic fields – Polarization – Surveys

1. Introduction

New generations of spectropolarimeters have directly revealed that, in addition to low-mass stars, for which magnetic fields are known, magnetic fields also occur in massive stars. The observational consortium known as MiMeS *Magnetism in Massive Stars* collected over 4800 circularly polarized spectra of 560 O and B stars and the results show that about 10% of the stars observed have a reliable magnetic field detection (Wade et al., 2016). The magnetic field of massive stars tend to be strong, raging from 0.1 to 15 kG, stable, not changing over years to decades, and have an important dipolar component that dominates the field. Since observed fields have large-scale, quasi-static, stable configurations, which are not correlated with the star's characteristics such as rotation, it is believed that the field has a fossil origin (Braithwaite & Spruit, 2004).

Magnetohidrodynamical simulations show that a dipolar magnetic field of large scale can trap the stellar winds in closed loops along the magnetic fields lines (Owocki et al., 2002). Rotation adds a layer of complication to the problem, as the wind material is forced by the magnetic field to corotate with the star (ud-Doula et at., 2008). The classification for magnetospheres was proposed by (Petit et al., 2013), and is based on the relatives values for the Keplerian corotation radius R_K and the Alfvén radius R_A.

If $R_\mathrm{K} > R_\mathrm{A}$, the star has a *dynamical magnetosphere* (DM), characterized by weak rotation and/or magnetic confinement, with the effects of rotation limited to some modest enhancement in equatorial density. In general any magnetically confined material falls back to the star in a dynamical timescale.

If $R_\mathrm{K} < R_\mathrm{A}$, the strong magnetic confinement combined with a sufficiently rapid rotation can support the material against infall near the Keplerian corotation radius. The magnetic field and centrifugal force both hold the material in nearly rigid-body rotation, and keep it confined against the tendency of the material to escape the system, building a much denser magnetosphere. In this case, we have a *centrifugal magnetosphere* (CM).

The model that more reliably reproduces CMs of high-mass, highly magnetic stars is the Rigidly-Rotating Magnetosphere

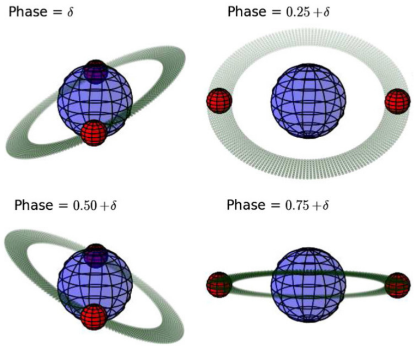

Figure 3. Geometric conception of the "dumbbell + disk" model to scale.
(A color version of this figure is available in the online journal.)

Figure 1. Geometric conception of the Dumbbell plus Disk model ($i = 70°$). δ indicates the phase shift between the photometric and polarimetric minima (Carciofi et al., 2013).

Table 1. Phase coverage of the magnetic magnetic OB stars from our sample.

Star	Phase coverage	Star	Phase Coverage
σ Ori E	100%	HD 35502	100%
HR 5907	100%	HR 7355	100%
HD 142990	100%	HD 64740	60%
HD 37776	30%	HD 37017	60%
δ Ori C	60%	θ^1 Ori C	20%
HD 148937	80%	HD 151018	10%
σ Lup	50%	HD 345439	10%
τ Sco	80%	HD 57682	10%
HD 191612	70%	HD 96446	70%

(RRM, Townsend & Owocki, 2005). The RRM model was created on the notion that the plasma flowing along the magnetic field lines experiences an effective potential arising from a combination of the stellar graviational field the centrifugal forces due to corotation. The plasma, flowing along the field lines, settles in the vicinity of the points where the potential undergoes a local minimum.

The B2IV star σ Ori E is by far the most studied star of its class. The discovery of σ Ori E's magnetic field was the first evidence that early-type stars can also have a significant magnetic field (Landstreet & Borra, 1978). The presence of two circumstellar clouds situated at the intersection of the magnetic and rotational equators causes an observed modulation of its Hα Balmer line, helium absorption line, photometry, 6 cm radio emission and polarization (Carciofi et al., 2013). The RRM model was first applied to the archetype star σ Ori E, and was able to reproduce the spectroscopy, photometry and magnetic variability of the star along its 1.19 days period.

Carciofi et al. (2013) performed the first detection of a magnetosphere through linear polarization. The authors tried to reproduce the observed polarization modulation of σ Ori E by feeding the predicted density distribution of the RRM model to the HDUST radiative transfer code. They could not find a model that can reproduce both the photometry and polarimetry of σ Ori E simultaneously.

Based on the RRM model, Carciofi et al. (2013) developed a simple, parametric ad-hoc model that consists of a thin uniform disk tilted by an angle β from the rotational axis and a pair o spherical blobs situated at the intersection between the equatorial plane and the magnetic equator (Fig. 1) named *Dumbbell plus Disk* (hereafter, D+D model). The main conclusion of Carciofi et al. (2013) is that, although the RRM model of Townsend et al. (2005) does predict the structures present in σ Ori E's magnetosphere (namely a tilted disk and two blobs), the relative masses of these structures are incorrectly predicted by the model.

In this work, we present a new approach to the D+D model adopting a more robust statistical treatment than used before. We utilize Bayesian statistics via the Markov Chain Monte Carlo method, that will allow a much more precise fitting of the D+D model to the data. The minimization simultaneously determines all the selected physical parameters involved in the modeling. This method allows to evaluate the correlation between the parameters and the uncertainty in their determination, in a self-consistent analysis. The great advantage of using this method instead of obtaining just the best fit model, as we would from the frequentist approach, is that we find a distinct probability density function for each of the parameters, and the correlations between them.

The objective of this work is to study the CMs of OB stars through their linear polarization. More precisely, we intent to expand the list of centrifugal magnetosphere detected with linear polarization carrying out a survey at Observatorio Pico dos Dias (OPD). We will use the observational data of stars with a complete phase coverage to model the magnetospheres using the D+D model. This will provide important information on future attempts to expand the RRM model and make it more realistic.

2. Polarimetric Survey

Our survey consists of 27 magnetic OB stars, and we have data for 18 of them. In our observations at OPD, we gave priority for stars with shorter rotation period, that sustain centrifugal magnetospheres. The phase coverage of our observed targets are in Table 1.

We have five stars with a complete phase coverage: σ Ori E, HD 35502, HD 142990, HR 5907 and HR 7355. We applied the new routine of the D+D model to their data. The results are shown is Section 3. Six stars (HD 64740, HD 37017, δ Ori C, HD 148937, τ Sco, HD 191612, HD 96446) have a phase coverage higher than 50%, and we intend to complete their phase coverage as the OPD survey unfolds. The stars with a phase coverage of 50% or lower (HD 37776, θ^1 Ori C, HD 151018, σ Lup, HD 345439 and HD 57682) have a lower priority in our missions, but we also intend to obtain new data for them, given the opportunity.

3. Modeling Magnetospheres

3.1. σ Ori E

In order the verify the new routine of the D+D coupled with the emcee code, we did a reanalysis of the observational data of σ Ori E. Fig. 2 shows the intrinsic polarization (observational data subtracted by the interstellar polarization) with the best fit found by our model. The model fits very well both the Q and U Stokes parameters.

Table 2 compares the values of the best parameters of the magnetosphere found by our new model to the results of Carciofi et al. (2013). The best model we found was fixing. The parameters found by the new D+D for σ Ori E are compatible with the results of Carciofi et al. (2013). The new D+D model improved the previous results, providing parameters with lower errors and a more precise characterization of σ Ori E's magnetosphere.

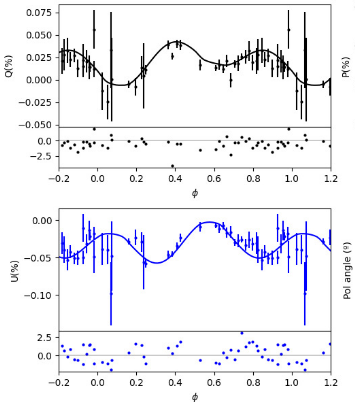

Figure 2. Intrinsic polarization of σ Ori E with the best fit found by the D+D model. Q and U Stokes parameters are in black and blue, respectively. Red is the polarization P and green the angle of polarization θ.

Table 2. Comparison of the best parameters found by the new routine of the D+D model with the values found by Carciofi et al. (2013) for σ Ori E.

Parameters	New D+D	Old D+D
i (deg)	$77.5^{+1.9}_{-1.8}$	70 (Fixo)
n_e^b	$1.25^{+0.15}_{-0.18} \times 10^{12}$	$1.0^{+0.6}_{-0.9} \times 10^{12}$
n_e^d	$2.3^{+1.5}_{-0.7} \times 10^{12}$	$2.7 \pm 1.0 \times 10^{12}$
α (deg)	24^{+24}_{-12}	28
Q_{IS} (%)	$-0.350^{+0.008}_{-0.010}$	-0.35 ± 0.01
U_{IS} (%)	$0.028^{+0.015}_{-0.014}$	0.025 ± 0.010
Θ (deg)	150 (Fixed)	150 ± 7
δ	$0.086^{+0.03}_{-0.02}$	0.085 ± 0.02

Table 3. Parameters of the best fit of HD 35502.

Parameters	Value
i (deg)	$48.0^{+0.8}_{-0.7}$
n_e^b	$2.04^{+0.76}_{-0.83} \times 10^{11}$
n_e^d	$5.12^{+1.12}_{-0.80} \times 10^{12}$
α (deg)	$28.2^{+3.6}_{-2.6}$
Q_{IS} (%)	$-0.397^{+0.003}_{-0.003}$
U_{IS} (%)	$-0.121^{+0.003}_{-0.005}$
Θ (deg)	$88.2^{+6.8}_{-5.0}$
δ	$0.021^{+0.027}_{-0.014}$

3.2. HD 35502

HD 35502 is a He-weak star and the primary component of a triple system. Measurements of the Zeeman signatures in Stokes V parameter indicates a rotational period of 0.85 days and a magnetic field strength of 14kG. The variability of the strong Hα emission suggests two dense clouds magnetically confined that corotate with the star.

The best fit found by our model and the intrinsic polarization of HD 35502 are in Fig. 3 and the parameters of the magnetosphere in Table 3. The D+D model fits very well the observational data, and HD 35502 has the second clearest modulation of our sample, the modulation amplitude, 0.015%, is three times the average observational error (0.005%). One notable result is the difference of densities of the blobs and disk: the density of the disk is over ten times higher than the density of the blob. This is probably due to the strength and geometry of the magnetic field.

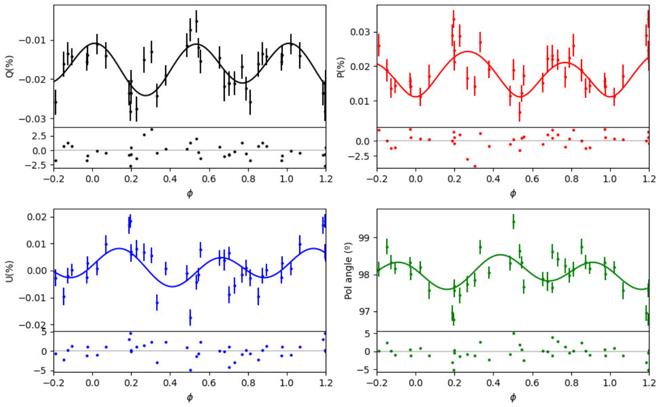

Figure 3. Same as Fig. 2 for HD 35502.

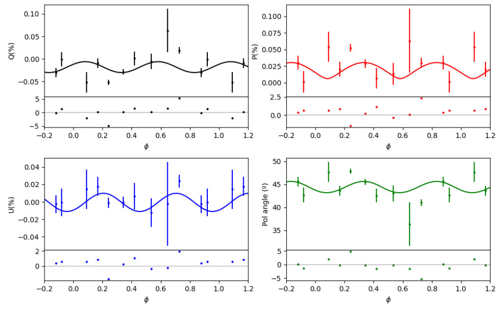

Figure 4. Same as Fig. 2 for HD 142990.

Table 4. Parameters of the best fit of HD 142990.

Parameters	Value
i (deg)	$54.7^{+1.5}_{-1.5}$
n_e^b	$1.25^{+0.25}_{-0.25} \times 10^{11}$
n_e^d	$5.12^{+1.12}_{-0.80} \times 10^{12}$
α (deg)	$0.160^{+0.016}_{-0.016}$
Q_{IS} (%)	$0.017^{+0.007}_{-0.019}$
U_{IS} (%)	$0.287^{+0.008}_{-0.01}$
Θ (deg)	101^{+49}_{-19}
δ	$-0.10^{+0.14}_{-0.05}$

3.3. HD 142990

HD 142990 has a magnetic field stregth of 4.3kG and period of 0.98 days. The star shows weak Hα lines, specially on the blue wing, and hints at the possible existence of a centrifugally driven wind originating a magnetosphere.

There is a clear variation of the observed data several times above σ. The model, however, is only capable to capture a borderline modulation, specially for the Stokes parameter Q. This borderline modulation is reflected in the larger errors of the parameters, comparing the results to other models. An obliquity of $\beta = 89.84°$ causes the effective potential to have two local minima, making the magnetosphere of HD 142990 to have a very peculiar shape.

3.4. HR 7355

HR 7355 (HD 182180) is a He-rich star with a magnetic field strength of 11.6kG. Observations of the longitudinal magnetic field and of radio and X-ray emissions all oscillating in the same

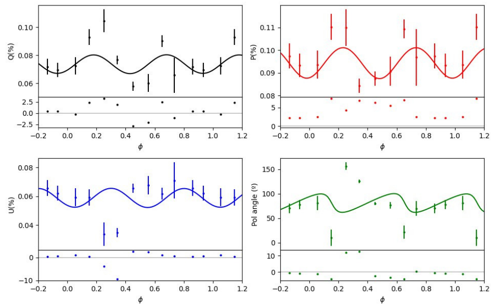

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Figure 5. Same as Fig. 2 for HR 7355.

Table 5. Parameters of the best fit of HR 7355.

Parameters	Value
i (deg)	$45.5^{+0.7}_{-0.6}$
n_e^b	$7.7^{+1.2}_{-1.2} \times 10^{11}$
n_e^d	$2.16^{+0.20}_{-0.19} \times 10^{13}$
α (deg)	$14.8^{+1.7}_{-1.6}$
Q_{IS} (%)	$-0.080^{+0.009}_{-0.009}$
U_{IS} (%)	$-0.058^{+0.007}_{-0.006}$
Θ (deg)	$19.9^{+2.4}_{-2.1}$
δ	$0.036^{+0.17}_{-0.014}$

period indicates that HR 7355 has a rotation period of 0.5214404 days.

There is a clear variation of the intrinsic polarization of HR 7355, but the model could not reproduce the details of the variation. The polarization angle (bottom right in Fig. 5) shows an acute disagreement between the observational data and the model between phases 0.1 and 0.4, this is a strong indication that the model does not reproduce the geometry of the magnetosphere correctly and need to be further improved. New tests with a model of only blobs or only disk are necessary in order to improve the results.

3.5. HR 5907

HR 5907 (HD 142184) is a He-strong main sequence star with a period of 0.508276 days. Among all the currently known non-degenerated magnetic OB stars, HR 5907 has the shortest rotation period known to date. Measurements of the longitudinal magnetic field phase coherently with the rotation period imply a surface dipole field strength of approximately 15.7kG. On the other hand, Bayesian analysis using the Least-Squares Deconvolution technique of the Stokes V profile indicates a dipolar field strength of approximately 10.4kG. This disagreement suggests a surface magnetic field configuration more complex with contributions from higher-order multipolar components or from the non-uniform Helium surface abundance distribution.

It is possible the see a small modulation in the data. However, this modulation is minimal (lower than 0.05%). The density of the blobs is the lowest of all models, while the disk density is similar. The fact that the blobs have such low density is a strong indication that the results of the modeling of HR 5907 are not reliable.

The fact that HR 5907 probably have a magnetic field topology more complex than a simple dipole can explain the failure of modeling with the D+D. The RRM model was created assuming a dipole magnetic field, where the material would settle where the potential undergoes a local minimum. A magnetic field with different topology would cause this potential to be completely different, and the magnetosphere of the star would have a complete distinct shape. In this case, a simple model with a disk and two blobs might fail completely to capture the essence of the magnetosphere's spatial configuration.

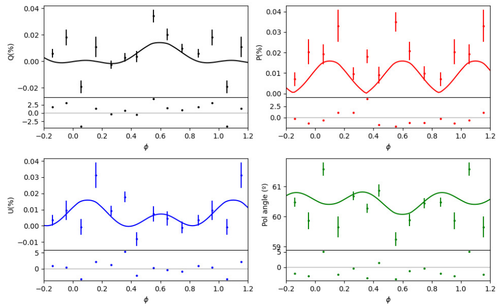

Figure 6. Same as Fig. 2 for HR 5907

Table 6. Parameters of the best fit of HR 5907.

Parameters	Value
i (deg)	$87.7^{+4.1}_{-4.5}$
n_e^b	$5^{+10}_{-1} \times 10^{8}$
n_e^d	$2.18^{+0.28}_{-0.41} \times 10^{12}$
α (deg)	$75.7^{+0.5}_{-1.1}$
Q_{IS} (%)	$-0.322^{+0.002}_{-0.002}$
U_{IS} (%)	$-0.525^{+0.002}_{-0.002}$
Θ (deg)	120^{+4}_{-5}
δ	$0.094^{+0.004}_{-0.009}$

Table 7. Average intrinsic polarizatin of the stars modelled by the D+D model and the total mass of their magnetospheres.

	$\langle P_{\rm int} \rangle$	Total Mass (Moon Mass)
σ Ori E	0.041 ± 0.018	5.6×10^{-4}
HD35502	0.048 ± 0.007	1×10^{-3}
HR5907	0.043 ± 0.026	2.2×10^{-4}
HR7355	0.103 ± 0.027	1.6×10^{-3}
HD142990	0.029 ± 0.019	2×10^{-4}

4. Analysis

The process of detection massive stars magnetospheres through their linear polarization is rather challenging. The observed polarization is very small, of order of 0.01%, and the variation of polarization over the period of rotation of the star can be even smaller. Since in the frame of the D+D model what controls the polarization of each of its components is the total mass of scatterers, the distinction of interstellar and intrinsic polarization is fundamental to determine the density of the magnetosphere. Table 7 shows the average intrinsic polarization of the magnetospheres and their total masses. The polarization is of the order 0.05%, except for HR 7355, that has a intrinsic polarization of 0.1%. Interestingly, HR 7355 was the star with the lowest polarization observed.

Another interesting aspect to study is how the total mass of the magnetosphere relates to the strength of the magnetic field of its host star. According the (ud-Doula, 2005), a star with stronger magnetic field should have a higher magnetic-confinement parameter η_*, and therefore should trap more material, increasing

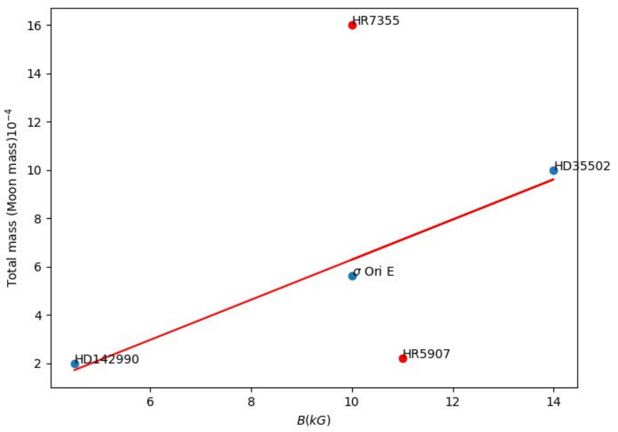

Figure 7. Total mass of the magnetosphere (moon mass) as function of the strength of the magnetic field of its host star.

the total mass of the magnetosphere. Fig 7 shows the total mass of the magnetosphere as a function of the strength of the magentic field of its host star. If we exclude HR 7355 and HR 5907, the two stars for which the D+D model failed, there is a clear correlation between the magnetosphere mass and magnetic field strength.

5. Conclusion

After carrying out a series of observations at Observatorio Pico dos Dias (OPD), we have data for 18 magnetic OB stars. We have completed the phase coverage for five of them, which we investigated further with the D+D model. Six of the stars have more than 50% of their rotational phases observed, and we plan to complete their observations in the near future.

We improved the statistical analysis of the Dumbbel plus Disk (D+D) model by coupling the routine to emcee, a Monte Carlo Markov Chain algorithm. The new D+D was capable to model the magnetosphere of σ Ori E, improving the results of Carciofi et al. (2013). We also applied the D+D to four new stars, HD 35502, HD 142990, HR 7355 and HR 5907, and reported new polarimetric detections of their magnetospheres through linear polarization.

The D+D fitted the observational data of HD 35502 very well, and made possible to estimate the mass of the components of the magnetosphere. After σ Ori E, it is the second best modeling done by the D+D model. In the case of HD 142990, a polarization modulation was clearly detected in the data; however, the D+D was not capable of reproducing all aspects of the observations. This is probably because of the geometry of the magnetic field, with such a high obliquity ($\beta = 89.86°$), the magnetosphere cannot be fully represented by the model. For HR 7355, thanks to the precise estimates of the interestellar polarization, we could also detect the magnetosphere polarization, which has only a rather weak modulation. The D+D model failed to capture the details of the observations for this star. A similar situation was found for HR 5907. We present a firm detection of the magnetosphere in polarization, with a small (but statistically significant) modulation. The D+D model was not successful for this star, which has the added complication of having a magnetic field more complex than a simple dipole.

Magnetospheres have a mass of about $10^{-3} M_{moon}$. We also study the relation of the mass of the magnetosphere with the strength of the magnetic field of its host star. As expected, there is a clear correlation between the mass and strength of the field.

The nexts steps are to continue the monitoring of magnetic stars at OPD. We will give priority to stars with near-complete phase coverage and apply their data to the D+D model.

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