High-precision linear polarimetry of magnetic massive stars

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Definition

The **magnetosphere** of an object is the region where charged particles interact and are affected by its magnetic field (and possibly vice-versa)

Magnetosphere around σ Ori E
Definition

**OB magnetosphere stars**: magnetosphere studied by circumstellar emission, absorption and scattering of stellar radiation

→ Evidence: Periodic modulation with rotational period

Hesser et al. (1977)
Dynamical Spectrum of \( \sigma \) Ori E

“Double cloud” picture quite obvious

Oksala et al., 2011
The RRM model

When B field is strong, plasma completely dominated by the strong B field

The wind plasma, flowing along fixed trajectories along the field lines, experiences an effective potential arising from a combination of the stellar gravitational field and the centrifugal force due to co-rotation.

Wind plasma settles around the local minima of the effective potential. The RRM formalism by Townsend et al. (2005) predicts quantitatively the relative circumstellar plasma distribution for arbitrary magnetic field configurations.
The RRM model

In particular, for an **oblique dipolar rotator such as σ Ori E**, accumulation happens at intersection of rotational and magnetic equators ➔ two co-rotating clouds.

- **Angle between rotational and magnetic axes**
  \[ \beta = 60° \]

- **Inclination angle**
  \[ i = 75° \]

RRM prediction for σ Ori E
The RRM model

“Quantitative” tests for σ Ori E

Townsend et al. 2005
The RRM model

“Quantitative” tests for σ Ori E

Townsend et al. 2005
Linear polarization

Kemp & Herman (1977) ➔ marginal P detection

Defined an useful upper limit, but accuracy not enough for modeling

total polarization ➔

intrinsic polarization ➔
Observations

Monitoring made at Pico dos Dias Observatory (Brazil)

IAGPOL: imaging polarimeter

→ Calcite prism
→ λ/2 retarder
→ Photon noise limited up to polarization levels of 0.005% or better

Single observation:

→ 16 positions of the retarder
→ Typically 100 frames/position
→ S/N ~ 5000
→ Temporal resolution ~ 20 min
Observations

Observed Polarization

Points: σ Ori E

Dashed lines: σ Ori AB

\[ Q_{AB} = -0.348 \pm 0.015\% \]
\[ U_{AB} = -0.040 \pm 0.015\% \]
Observations

**Intrinsic polarization**

- Double-peak $P$ curve
- Polarization curve roughly symmetric w.r.t. $\varphi \approx 0.6$, while photometry is not
- Polarization never zero!
- $<\text{PA}> = 150^\circ$

Carciofi et al. 2013
Observations

Intrinsic polarization rotated by 150°

- The $\langle PA \rangle = 150^\circ$ tells us the (average) direction of the minor axis of the asymmetric structure.

- The projected axis of symmetry of the magnetosphere varies little ($15^\circ$ max) as the star rotates.

- Quite important consequences for the RRM model.

Carciofi et al. 2013
RRM Model

All parameters taken from Townsend et al. (2005)

Calculations done with NLTE RT code HDUST (Carciofi & Bjorkman 2006)

1) High density model (solid lines)
Photometry OK
Polarization level not OK

2) Low density model (dashed lines)
Photometry not OK
Polarization level ~OK

Both models: PA variations way too large!
RRM Model
“Dumbbell + Disk” Model

Simple model, physically motivated by the RRM

Two components:

1) Pair of spherical blobs (Dumbbell)
2) Thin disk connecting them

Disk plane tilted with respect the stellar equator

Phase = $\delta$
Phase = $0.25 + \delta$
Phase = $0.50 + \delta$
Phase = $0.75 + \delta$

Carciofi et al. 2013
“Dumbbell + Disk” Model

Model Parameters

Since very optically thin, only the mass of each component (disk and blobs) is well constrained.

\( i < 90^\circ \rightarrow \text{counterclockwise rotation} \)

\( i > 90^\circ \rightarrow \text{clockwise rotation} \)

![Parameters of the Single-scattering Model](image)

Carciofi et al. 2013
Results

- Solid lines: $i = 70^\circ$
- Dashed lines: $i = 110^\circ$

**Counterclockwise rotation!**

- Mass of blob:
  \[ M_b = 6.0 \times 10^{-12} \, M_\odot \]

- Mass of disk
  \[ M_d = 1.0 \times 10^{-11} \, M_\odot \]

What is wrong with the RRM model? The “disk component” is about 3 times more massive than it should be...

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Carciofi et al. 2013
HR 7355

Discovery paper: Rivinius et al. (2013)

Magnetic field strength and configuration is similar to \( \sigma \) Ori E

**One key difference:** HR7355 rotates at 90% of the critical velocity, while \( \sigma \) Ori E only at 50%
HR 7355

Polarization results (preliminary)

Pretty much a non-detection...

Under investigation: can the high rotation rate be responsible for the low polarization levels?
HR 5907

Discovery paper: Grunhut et al. (2012). Central star very similar to HR 7355, as well as the field strength

One key difference: field obliquity is very small (~7°)
HR 5907

Polarization results (preliminary)

Positive detection!

Further observations needed to better constrain the variations
Conclusions

Magnetospheres of OB stars can be studied from linear polarization

Polarization levels are quite small, requiring high accuracy

For ω Ori E, the main results are:

1) The RRM, in its current formalism, cannot explain the polarization data, suggesting that the prediction of the plasma distribution in the magnetosphere is wrong

2) The “dumbbell + disk” model satisfactorily reproduces the polarization modulation. The measured masses of the two components indicates the path for future modifications of the RRM model

For HR 7355: non-detection. Why? High rotation rate of the star?

For HR 5907: positive detection.