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A Rigidly Rotating Magnetosphere Model for the Circumstellar Environments of Magnetic OB Stars

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Abstract. We report on a new model for the circumstellar environments of rotating, magnetic hot stars. This model predicts the channeling of wind plasma into a corotating magnetosphere, where – supported against gravity by centrifugal forces – it can steadily accumulate over time. We apply the model to the B2p star σ Ori E, demonstrating that it can simultaneously reproduce the spectroscopic, photometric and magnetic variations exhibited by the star.

1. Introduction

Magnetohydrodynamical (MHD) simulations have provided the basis for much of the recent progress in understanding how magnetic fields can channel and confine wind plasma throughout the circumstellar environments of hot, OB-type stars (see, e.g., ud-Doula & Owocki 2002; Owocki & ud-Doula 2004). A key result of these simulations is that the influence of the field on the outflow may be quantified by the magnetic confinement parameter

$$\eta_* \equiv \frac{B_{\rm eq}^2 R_*^2}{\dot{M} v_\infty};$$

with equatorial surface field strength $B_{\rm eq}$, stellar radius R_*, mass-loss rate $\dot{M}$ and wind terminal speed v_∞, this parameter characterizes the ratio of magnetic-to-kinetic energy density in the wind, and indicates whether the flow is appreciably confined by the field ($\eta_* \gg 1$), or whether it remains to a large degree unaffected ($\eta_* \ll 1$).

Systems having very large η_* are of particular astrophysical interest, since the strong confinement of plasma promotes the incidence of energetic phenomena such as shocks and magnetic reconnection (see Oksala et al., these proceedings; ud-Doula, Townsend, & Owocki, *ibid*). However, these systems can be exceedingly expensive to model using MHD simulations, because the high Alfvén speeds require very short computational timesteps to preserve numerical stability.

Fortunately, there exists an alternative approach to modeling such systems, based on the idealized limit $\eta_* \to \infty$ in which the field lines may be regarded as completely rigid. The present paper outlines a new model built around this ansatz, that predicts the accumulation of channeled wind plasma into a corotating, centrifugally supported magnetosphere. In §2, we present a broad overview

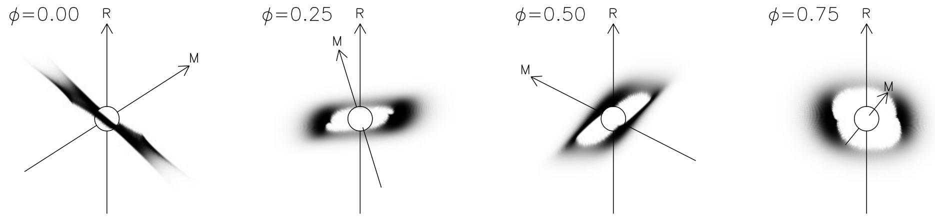

Figure 1. Maps of the Hα emission from circumstellar plasma in the RRM model for σ Ori E, plotted at four differing rotation phases. The arrows labeled 'M' and 'R' indicate the magnetic and rotation axes, respectively, while the star (whose emission is neglected in the plots) is shown by a circle.

of this *rigidly rotating magnetosphere* (RRM) model; in §3, we then go on to illustrate how the model can be applied to the chemically peculiar star σ Ori E. A more in-depth, rigorous description of the RRM model is given by Townsend & Owocki (2004).

2. The Rigidly Rotating Magnetosphere Model

In the idealized limit $\eta_* \to \infty$, wind plasma is constrained to flow along the fixed, rigid trajectories prescribed by the magnetic geometry of the system. For the simplest case of a dipole field[1], plasma streams from opposing footpoints are channeled into wind-wind collisions near the tops of closed magnetic loops, in the manner envisioned by Babel & Montmerle (1997) in their *magnetically confined wind shock* (MCWS) paradigm.

The fate of the dense, radiatively cooled post-shock plasma depends on whether or not the star is rotating. In the non-rotating case, this stagnated material has no means of support against the downward pull of gravity, and eventually falls back toward the star along one or the other arch of the magnetic loop that threads it (see ud-Doula & Owocki 2002). However, with the introduction of rotation, the plasma is torqued by the rigid field into strict corotation at the same angular velocity Ω as the star. At distances greater than the Kepler radius

$$r_{\rm K} \equiv \sqrt[3]{\frac{GM_*}{\Omega^2}}$$

(where G is the constant of gravitation, and M_* the stellar mass), the outward centrifugal force arising from the enforced rotation supports the plasma against gravity. This permits magneto*hydrostatic* configurations centered on the minima of the effective (gravitational plus centrifugal) potential along each field line.

With the steady feeding of wind material from the star, these effective potential wells should gradually fill with plasma, forming a quasi-steady magnetosphere that corotates with the star. Making certain simplifying assumptions

[1]We stress that the RRM model is not limited to such cases, and can in principle be applied to *any* conceivable magnetic geometry.

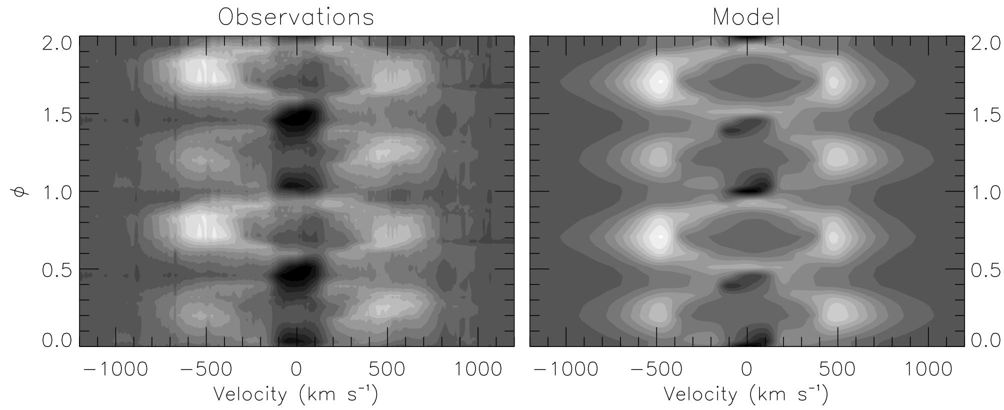

Figure 2. Time-series spectra of the varying Hα emission of σ Ori E, as observed (left) and as predicted by the RRM model (right); white indicates emission relative to the background photospheric profile (which has been subtracted away), and black denotes absorption. The observational data were obtained during commissioning of the FEROS spectrograph (see Reiners et al. 2000).

about the accumulation and stratification processes, Townsend & Owocki (2004) derive a semi-analytical formulation for the distribution of plasma throughout such rigidly rotating magnetospheres. For dipole field geometries, the predicted distribution has a disk-like morphology, becoming increasingly warped and inhomogeneous as the obliquity β between rotational and magnetic axes is increased from the aligned case ($\beta = 0°$) toward the perpendicular configuration ($\beta = 90°$).

3. Application to σ Ori E

The B2p star σ Ori E is characterized by distinctive modulations in its Balmer Hα emission, photometric indices and magnetic field, all of which vary on the star's 1.19 d rotation period. This object, the archetype of the He-strong chemically peculiar B stars, has a strong ($\sim 10\,\mathrm{kG}$) magnetic field and a relatively low ($\sim 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$) mass-loss rate. Such data imply a very large value ($\sim 10^7$) of the magnetic confinement parameter η_*, suggesting that the RRM paradigm should be applicable to the star.

Accordingly, we have constructed a preliminary RRM model for the circumstellar environment of σ Ori E. From a coarse exploration of parameter space, we find that a good fit to the observations can be achieved by assuming an oblique dipole magnetic field, tilted at $\beta = 60°$ to the rotation axis and decentered by $0.3\,R_*$ in a direction perpendicular to both magnetic and rotation axes. With the resulting RRM viewed from an inclination $i = 75°$ and at four differing rotation phases ϕ, Fig. 1 shows maps of the predicted Hα emission.

Of particular note is the concentration of plasma into two clouds, situated at the intersection between magnetic and rotational equators. These clouds, which corotate with the star, can explain the double S-wave modulations observed in the Hα line profile of σ Ori E. We show these modulations in Fig. 2, side-by-side with the corresponding predictions of the RRM model. The agreement between

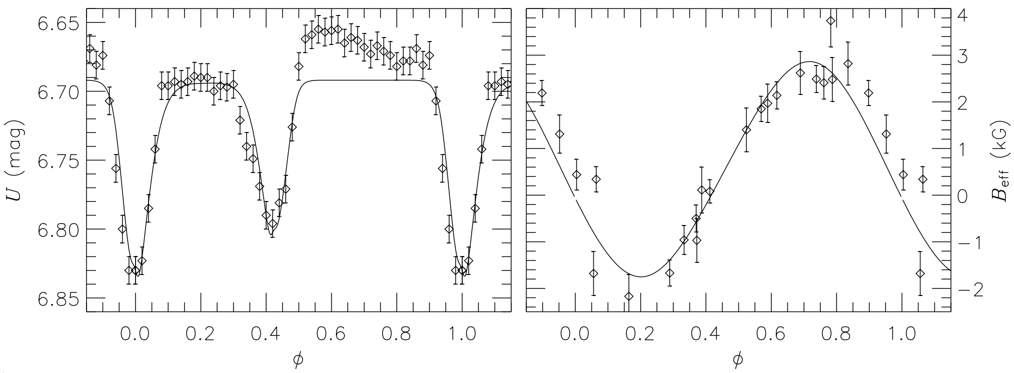

Figure 3. The time-varying U-band magnitude (left) and effective longitudinal field strength $B_{\rm eff}$ (right) of σ Ori E, as observed (diamonds) and as predicted by the RRM model (solid lines). The observed light curve is taken from Hesser et al. (1977), with the error bars estimated from the scatter in their data, while the magnetic field measurements are obtained from the tabulations by Bohlender et al. (1987).

the two is striking; note in particular the model's successful reproduction of the observed blue-red and temporal asymmetries in the line-profile variations.

In addition to reproducing the spectroscopic variability, the same RRM model furnishes a good match to the photometric and magnetic modulations exhibited by σ Ori E. In Fig. 3, superimposed over the observed U-band magnitude and effective longitudinal field strength $B_{\rm eff}$ of the star, we show the corresponding synthetic data predicted by the model. With the exception of the anomalous brightening of the star around phase $\phi \approx 0.6$, the light curve is reproduced well by the model. Likewise, the fit to the measured field, implying a polar strength $B_{\rm pole} = 12.2\,{\rm kG}$, reveals an encouraging degree of agreement.

We are therefore led to conclude that the observed variability of σ Ori E – spectroscopic, photometric and magnetic – can be well described by a rigidly rotating magnetosphere model for the star's circumstellar environment. In a forthcoming paper, we intend to refine this model further, and investigate whether it can be applied to other hot stars possessing strong magnetic fields.

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