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MAGNETIC MODELS OF CIRCUMSTELLAR CLOUDS AROUND MASSIVE STARS

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This talk reviewed recent efforts to develop dynamical models for the effects of a surface dipole field on radiatively driven wind outflows. One particular project applies magnetohydrodynamic (MHD) simulations of a *Magnetically Confined Wind Shock* (MCWS) model (originally developed by Babel & Montmerle 1997) to explain X-ray emission observed by *Rosat* (Gagné et al. 1997) from the magnetic O7V star θ^1 Ori C.

Results are summarized in Figure 1. We also consider the role of magnetic fields in spinning up the wind outflow from a rotating star, emphasizing that this does *not* produce the *Magnetically Torqued Disk* (MTD) proposed by Cassinelli et al. (2002) as a mechanism for producing the orbiting, Keplerian disks inferred from the characteristic Balmer line emission in Be stars. Rather, as illustrated in Figure 2, material in the equatorial compression tends either to fall back on the star, or be ejected outward. However, the very strong magnetic fields of Bp stars can lead to a *Rigidly Rotating Magnetosphere* (RRM) (Townsend & Owocki 2004), with rigid-body disks or clouds (see Figure 3) that can explain quite well the observed emission in Bp stars like σ Ori E (Figure 4). Moreover, the eventual centrifugal breakout of such material can lead to strong heating from magnetic reconnection, which thus could explain the very hard X-ray flares seen from this star (ud-Doula et al. 2006) (Figure 5).

A more complete summary of these results will appear in Owocki et al. (2007). Further information, including animations of the simulations, can be accessed on the web at: `http://shayol.bartol.udel.edu/massivewiki/`

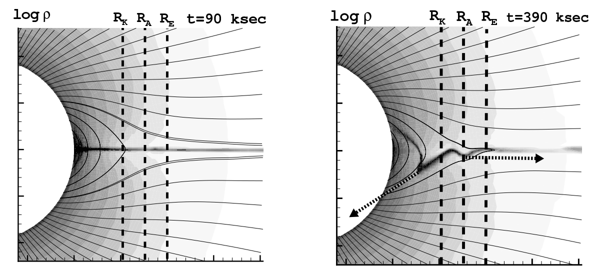

Fig. 2. Density of a 2D MHD simulation for a star rotating at half the critical with moderate magnetic confinement, shown at time snapshots of 90 ksec (left) and 390 ksec (right) after a dipole field is introduced into an initially steady-state, unmagnetized, line-driven stellar wind. The curves denote magnetic field lines, and the vertical dashed lines indicate the equatorial location of the Kepler, Alfv́en, and Escape radii. The arrows denote the upward and downward flow above and below the Kepler radius, emphasizing that the material never forms a stable, orbiting disk.

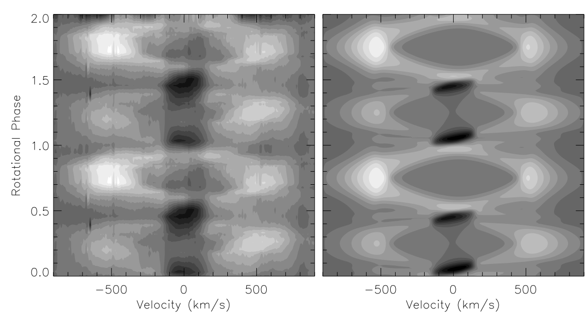

Fig. 4. Time-series spectra of the varying circumstellar H-α emission observed from σ Ori E (left; D. Groote, p.c.), phased on the 1.19-day rotation period of the star, compared against the corresponding synthetic data predicted by the RRM model (right; see Fig. 3); white indicates emission relative to the background photospheric H-α profile, and black indicates absorption. Note in particular the model's reproduction of the observed double S-wave variability, including the blue/red and temporal asymmetries, and the correct positioning of the eclipse-like absorptions at phases 0.05 and 0.45.

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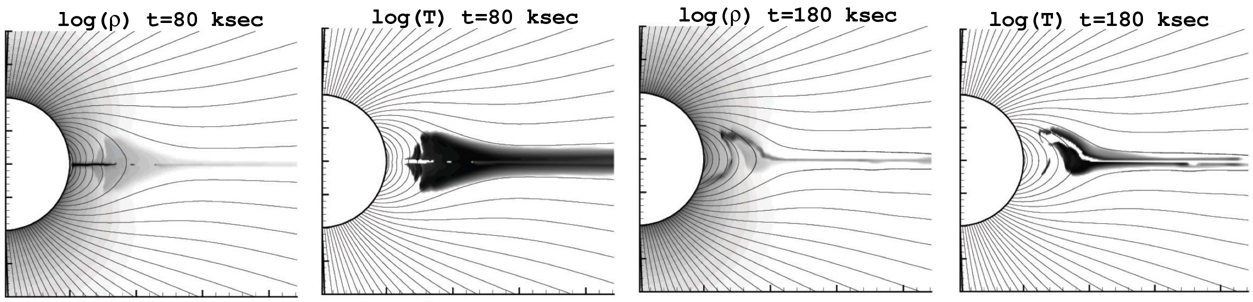

Fig. 1. MHD simulations of the MCWS model for θ^1 Ori C, showing the logarithmic density ρ and temperature T in a meridional plane. Left: at a time 80 ksecs after the initial condition, the magnetic field has channeled wind material into a compressed, hot disk at the magnetic equator. Right: at a time 180 ksecs, the cooled equatorial material is falling back toward the star along field lines, in a complex 'snake' pattern. The darkest areas of the temperature plots represent gas at $T \sim 10^7$ K, hot enough to produce relatively hard X-ray emission of a few keV.

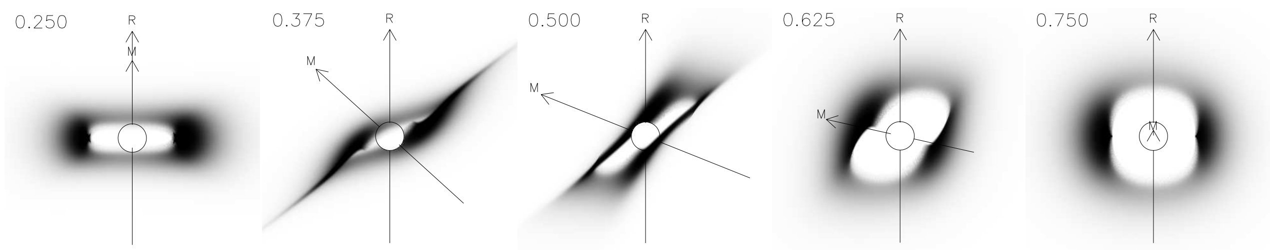

Fig. 3. Maps of the optically-thick H-α emission from circumstellar plasma in an RRM model for σ Ori E, plotted at five consecutive phases of the stellar rotation cycle (indicated at the top left of each panel). The field confining the plasma is a rigid dipole tilted by an angle $\beta = 67^\circ$ to the rotation axis, and then decentered by $0.3R_*$ in a direction perpendicular to both magnetic and rotation axes, the latter being shown by arrows labeled 'M' and 'R' respectively. The observer is situated at an inclination $i = 70^\circ$ to the rotation axis, and the disk of the star (whose emission is neglected in the plots) is shown by a circle. Note that the circumstellar emission is dominated by two clouds, edge-on at phase 0.25 and face-on at phase 0.75.

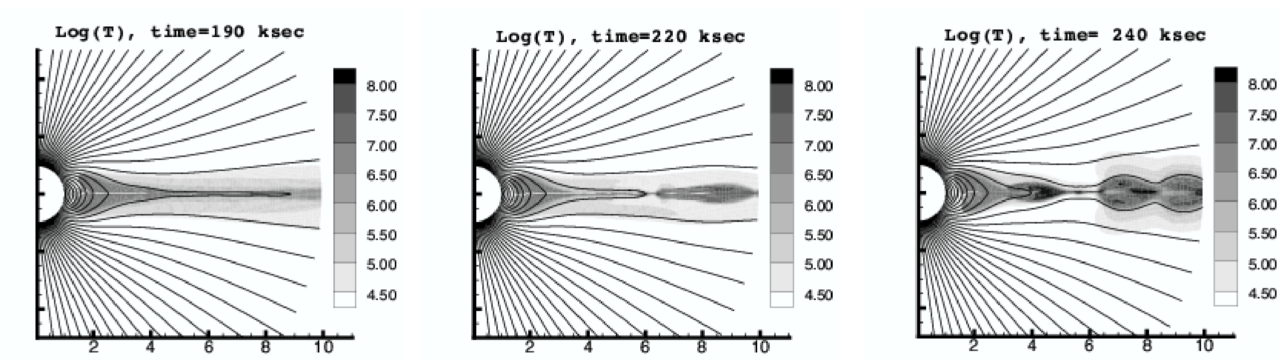

Fig. 5. MHD simulations of a Centrifugal Breakout model for X-ray flaring, showing the logarithmic temperature T in a meridional plane. Left: at a time 190 ksecs, the centrifugal force acting on dense material in the equatorial plane has drawn the magnetic field out into a long, narrow neck. Middle: at a time 220 ksecs, the stressed magnetic field has reconnected, heating material in the outer regions of the equatorial plane to $T \sim 10^8$ K. Right: at a time 240 ksecs, the reconnected field has snapped back toward the star, producing further heating.