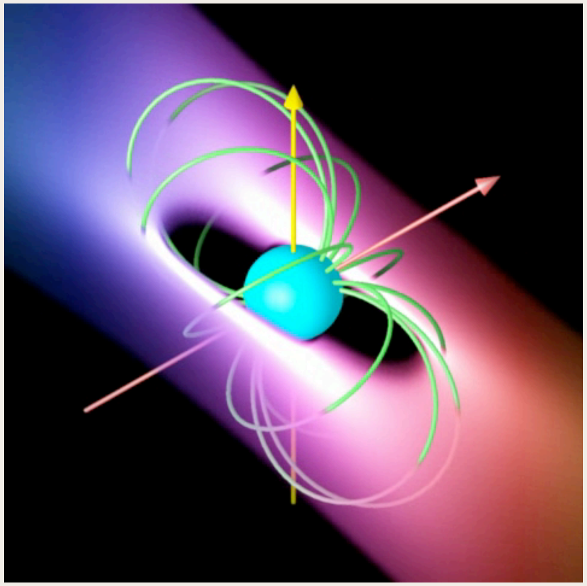
Modeling the Winds and Magnetospheres of Massive Stars

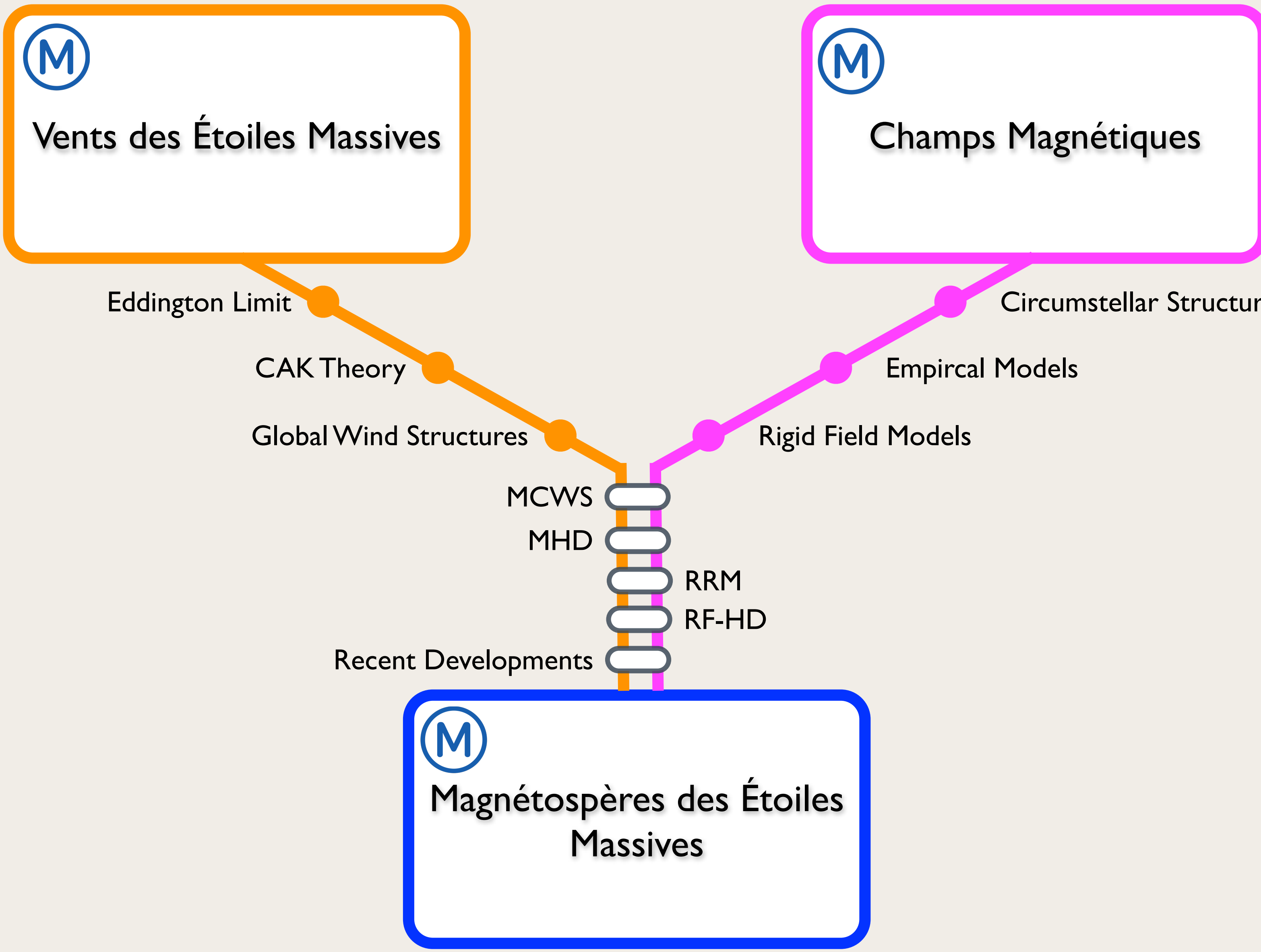
Rich Townsend

University of Wisconsin-Madison



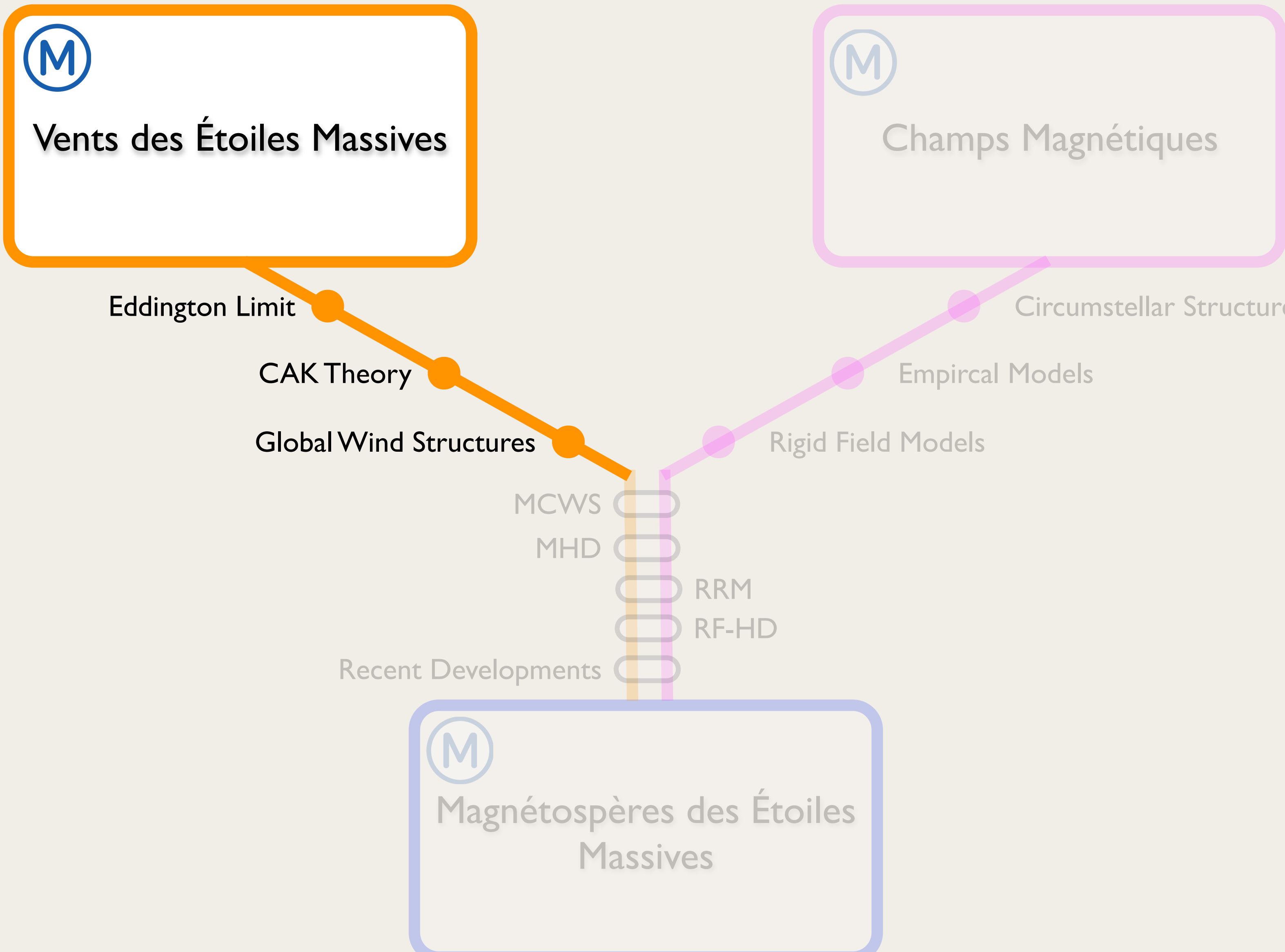
IAU 272 — July 2010

Overview



Vents des Étoiles Massives
Champs Magnétiques
Eddington Limit
CAK Theory
Global Wind Structures
Circumstellar Structure
Empircal Models
Rigid Field Models
MCWS
MHD
RRM
RF-HD
Recent Developments
Magnétospères des Étoiles Massives

Winds of Massive Stars



Why do Massive Stars have Winds?

- The Eddington limit:

$$\Gamma_{\rm e} = \frac{g_{\rm e}}{g} = \frac{\kappa_{\rm e} L}{4\pi G M c}$$

- Using line opacity:

$$\Gamma_{\rm thin} = \bar{Q}\Gamma_e$$

- Allowing for optical thickness:

$$\Gamma_{\rm thick} = \frac{\Gamma_{\rm thin}}{\tau} = \frac{\bar{Q}\Gamma_{\rm e}}{\tau}$$

Some Observations of Something

Lucy & Solomon (1970)

CAK Wind Theory

- Optical depth in an expanding wind:

$$\tau = \kappa\rho\,\mathrm{d}r = \frac{\kappa\rho v_{\mathrm{th}}}{\mathrm{d}v/\mathrm{d}r}$$

- For a power-law line distribution:

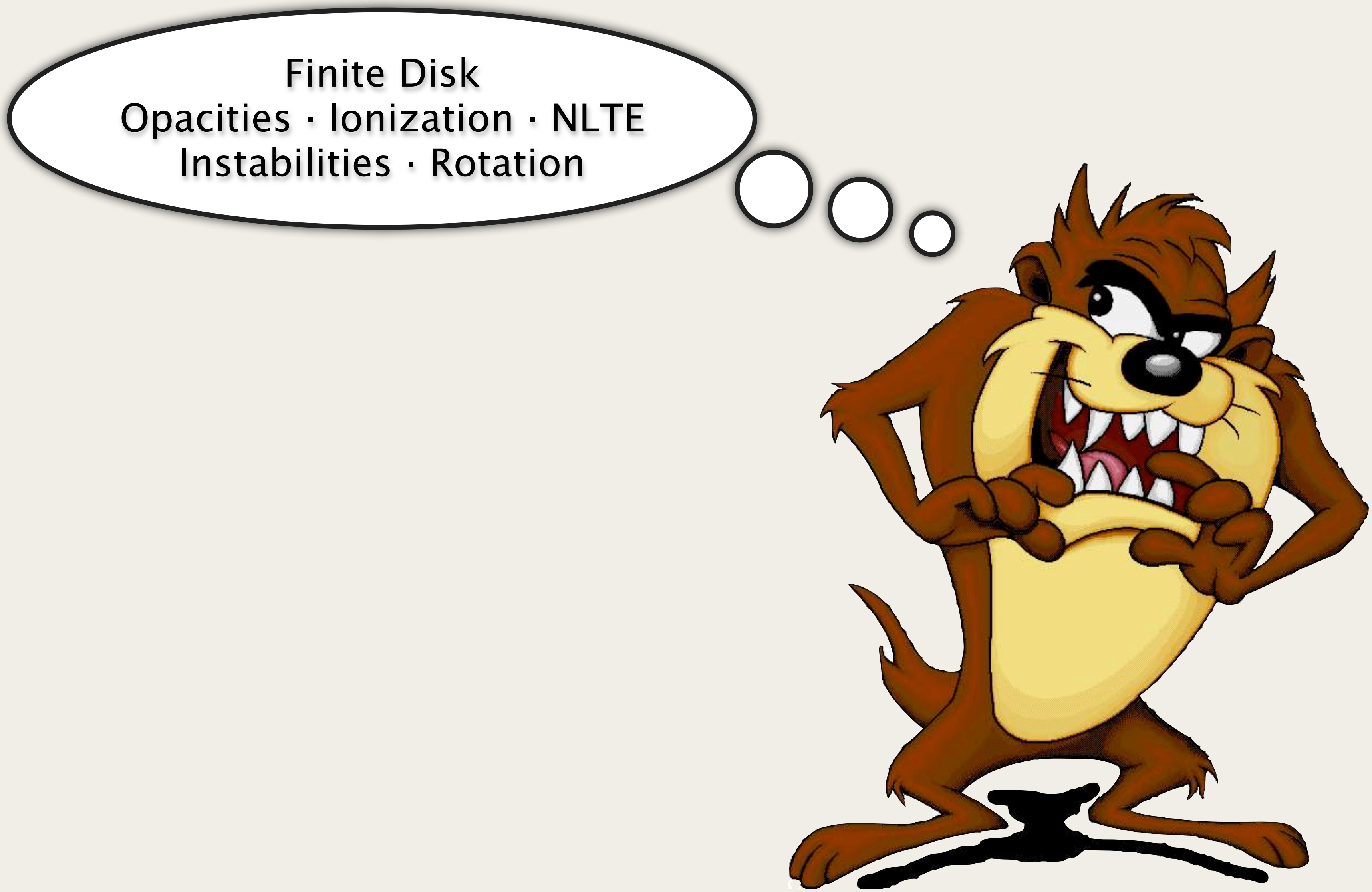
$$\Gamma_{\mathrm{thick}} = \frac{\bar{Q}\Gamma_{\mathrm{e}}}{1-\alpha}\frac{1}{\tau} = \frac{\bar{Q}\Gamma_{\mathrm{e}}}{1-\alpha}\left(\frac{\mathrm{d}v/\mathrm{d}r}{\rho c\bar{Q}\kappa_{\mathrm{e}}}\right)^{\alpha}$$

- Mass-loss rate and terminal velocity are *eigenvalues*:

$$\dot{M} = \frac{L}{c^2}\frac{\alpha}{\alpha-1}\left[\frac{\bar{Q}\Gamma_{\mathrm{e}}}{1-\Gamma_{\mathrm{e}}}\right]^{(1-\alpha)/\alpha} \qquad v_{\infty} = \sqrt{\frac{\alpha}{1-\alpha}}v_{\mathrm{esc}}$$

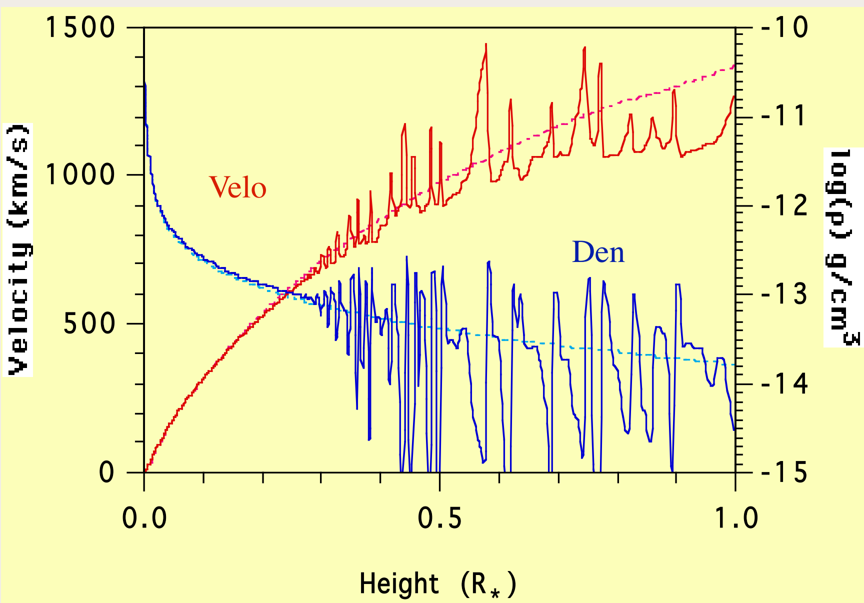
Castor, Abbott & Klein (1975)   (notation from Gayley 1995)

The Devil is in the Details



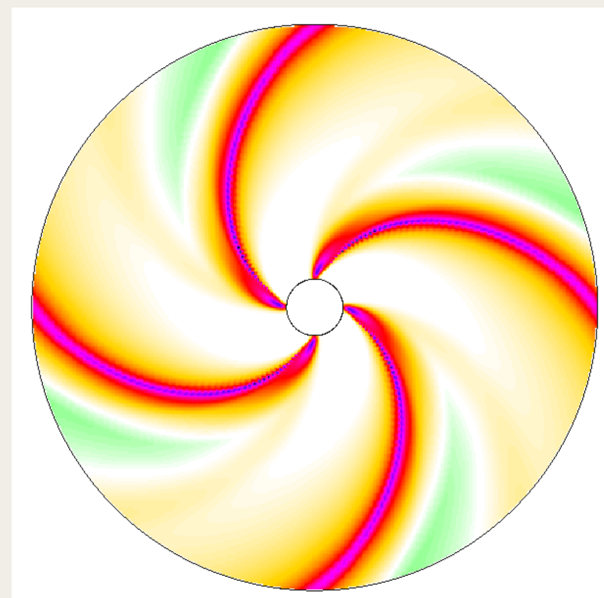
Wind Structure

- Line driving is unstable
- Spontaneous structure
- *Small* scales (clumping)



Feldmeier & Owocki (1998)

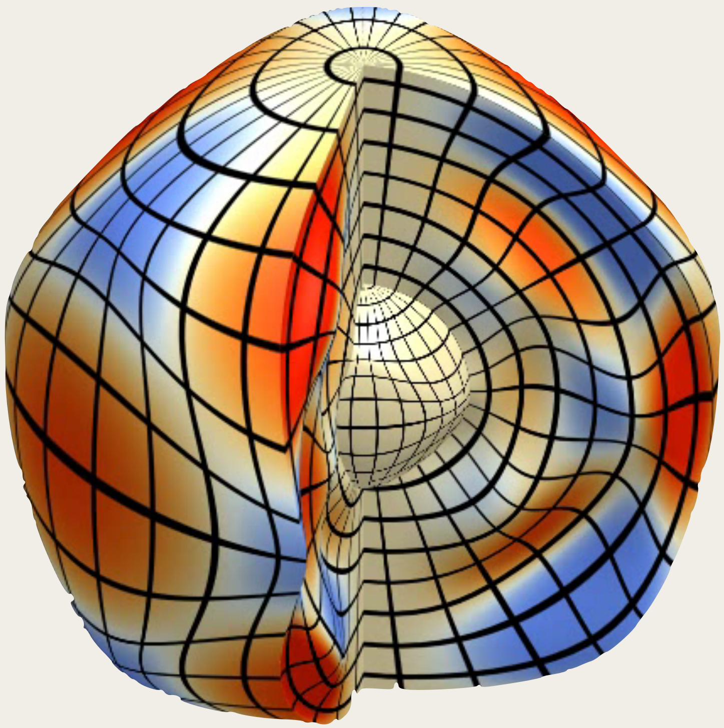
- Basal perturbations
- Imprinted structure
- *Large* scales (CIR, DAC, PAM)



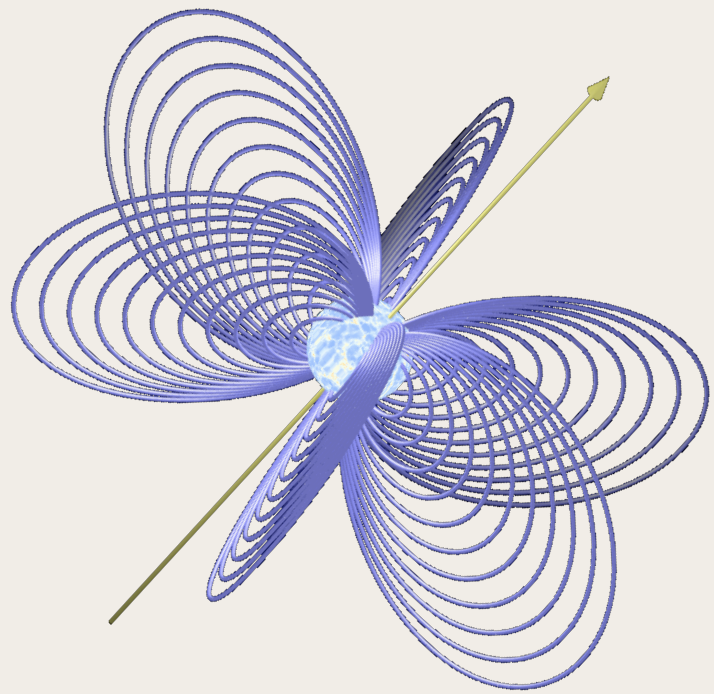
Cranmer & Owocki (1996)

What Perturbs the Wind?

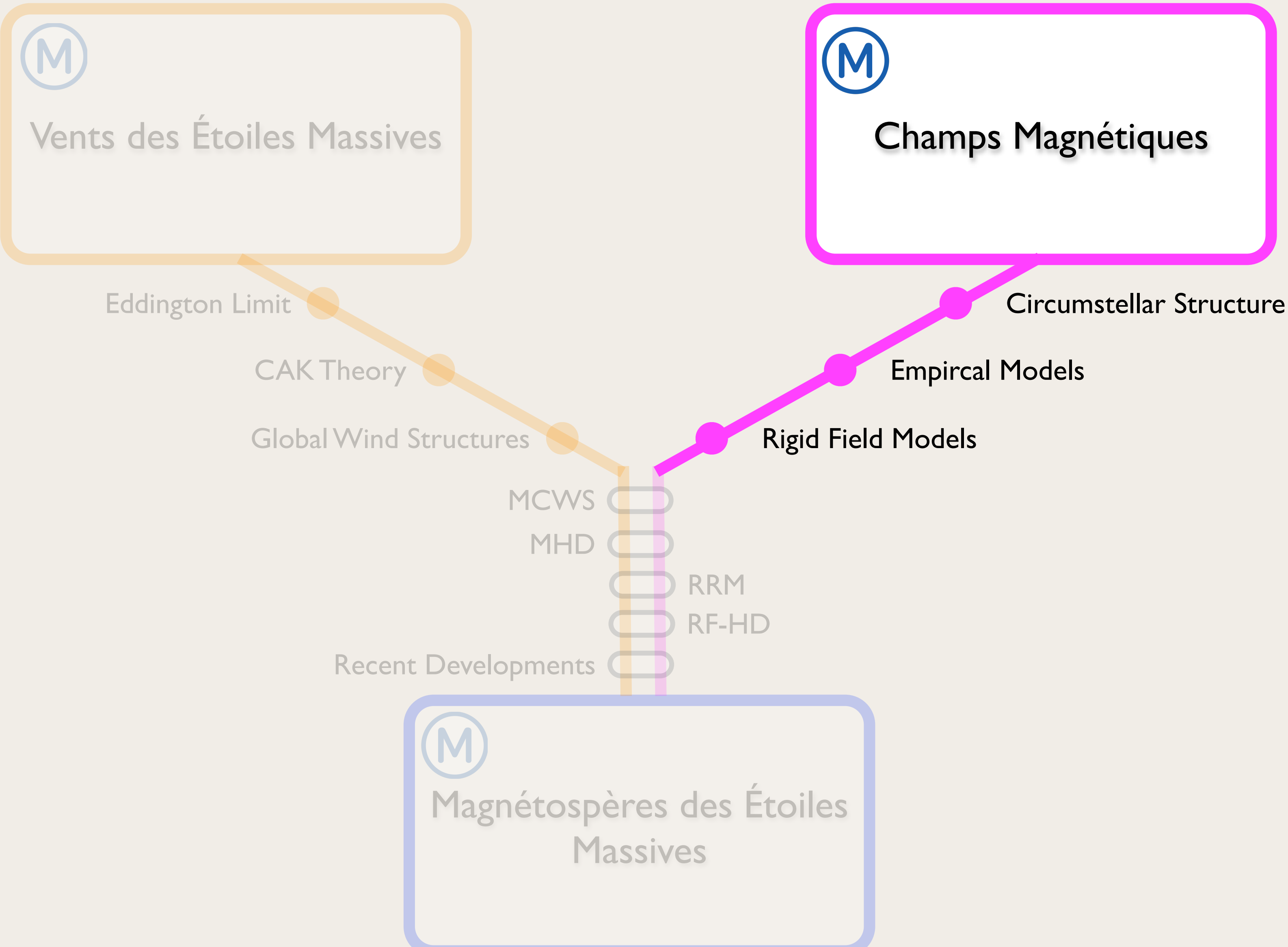
Pulsation?



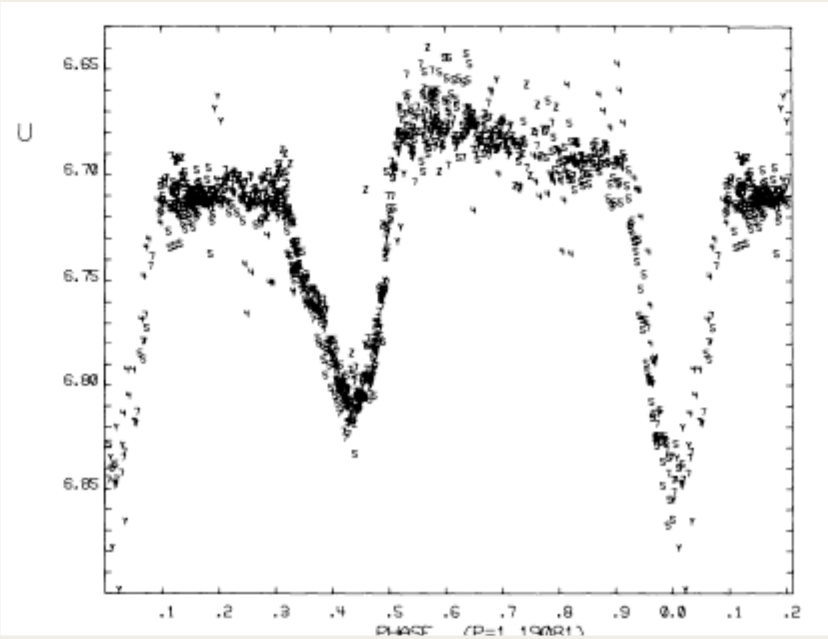
Magnetic Fields?



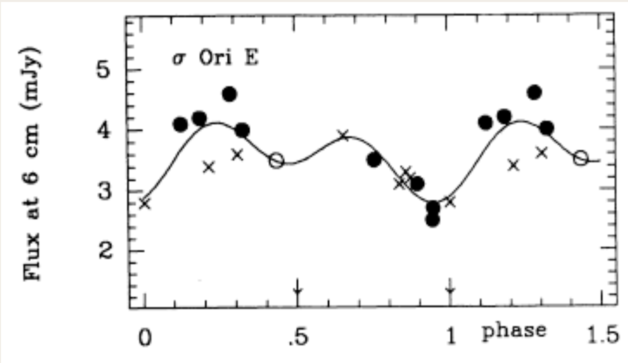
Magnetic Fields



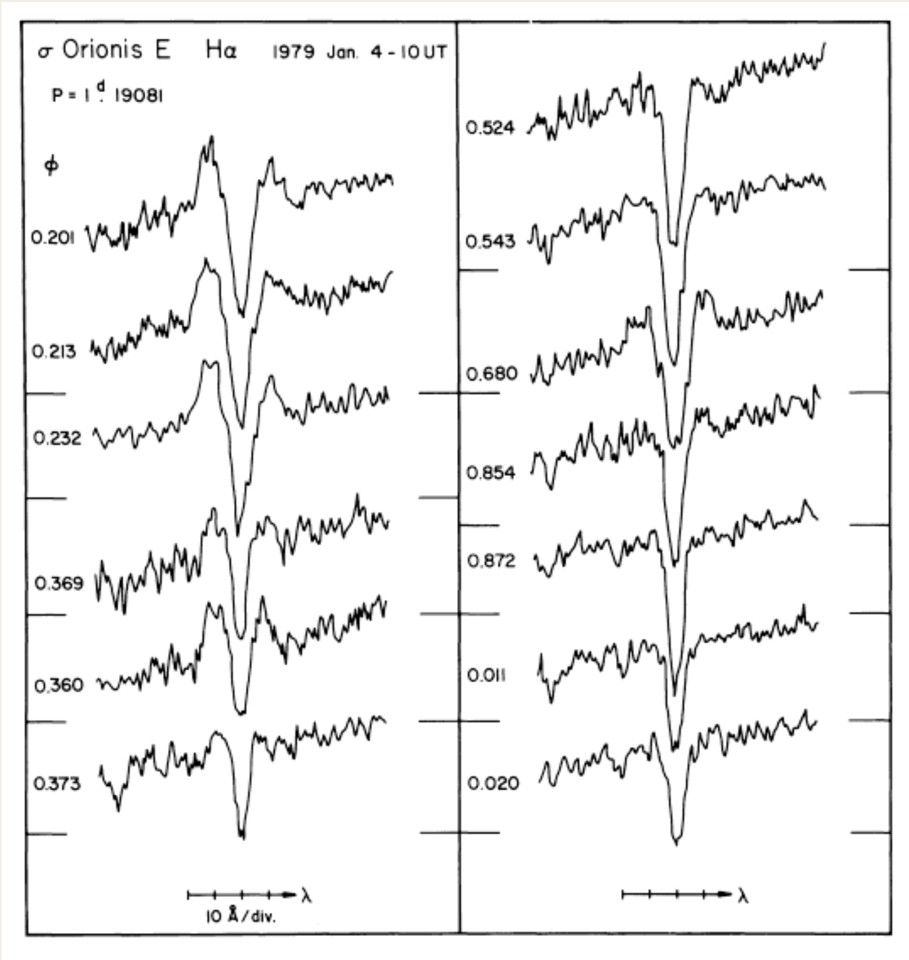
Evidence for Circumstellar Structure around Magnetic Massive Stars



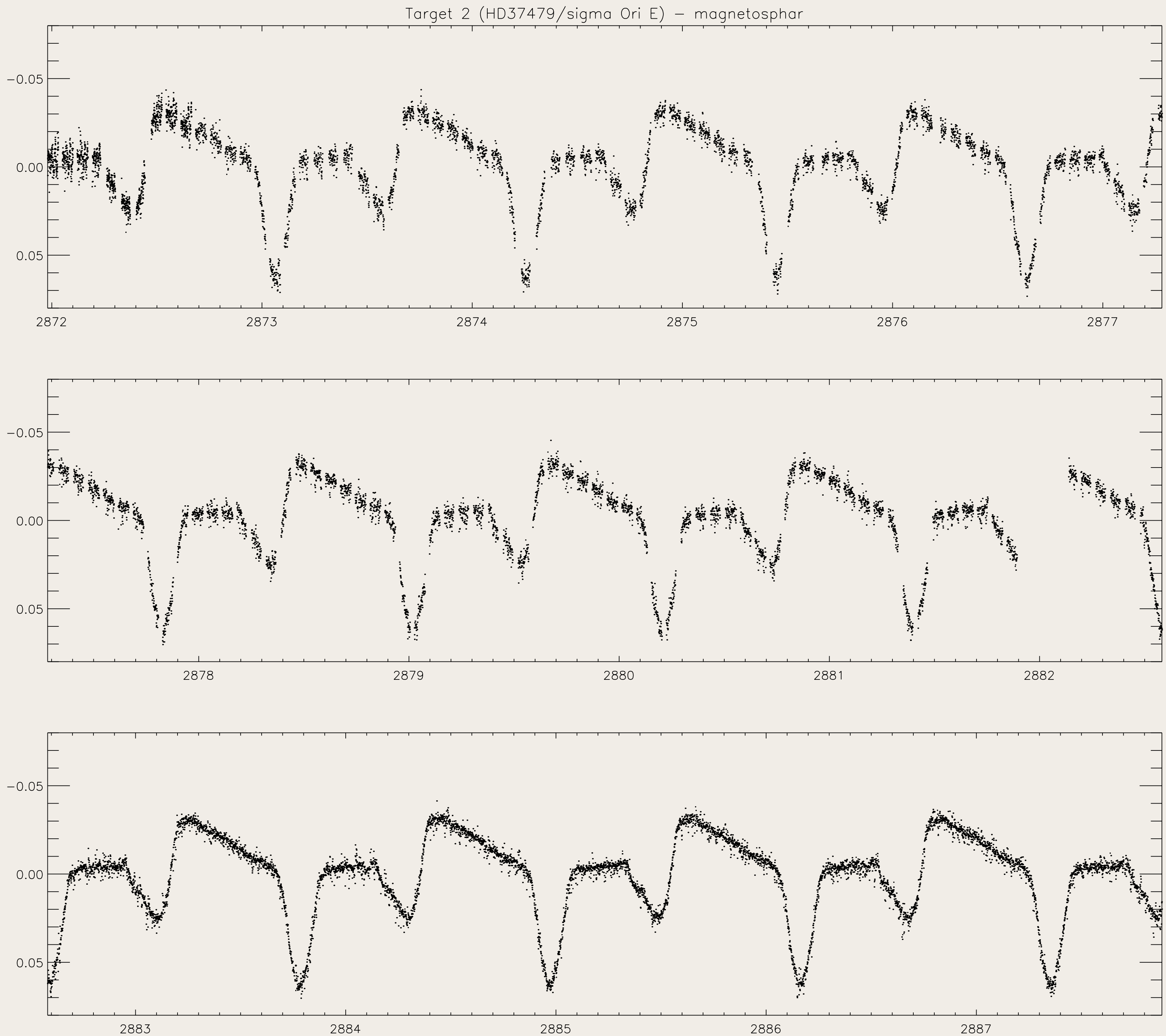
Hesser, Ugarte & Moreno (1977)



Leone & Umana (1993)



Walborn (1982)

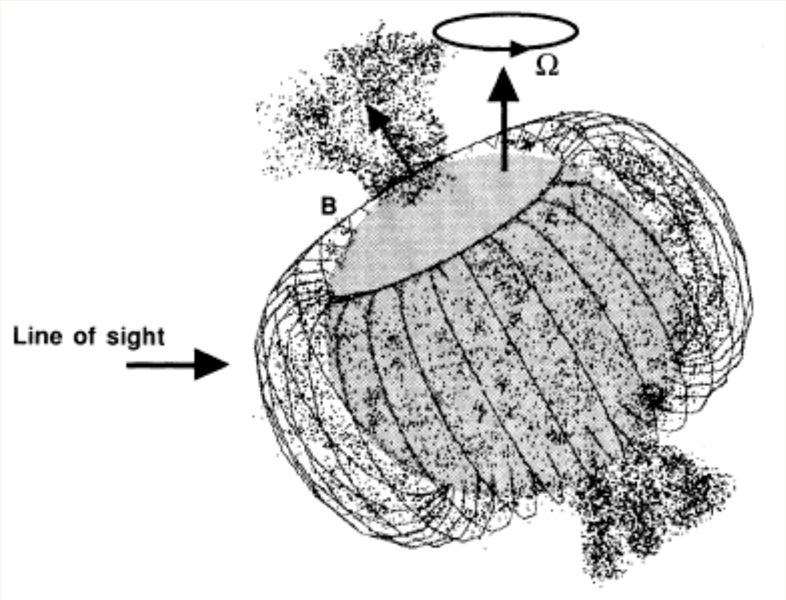


MOST — Townsend et al. (in prep)

Empirical Models

“…an oblique rotator model that has hot gas trapped in a magnetosphere above the magnetic equator”

Landstreet & Borra (1978)



Shore & Brown (1990)

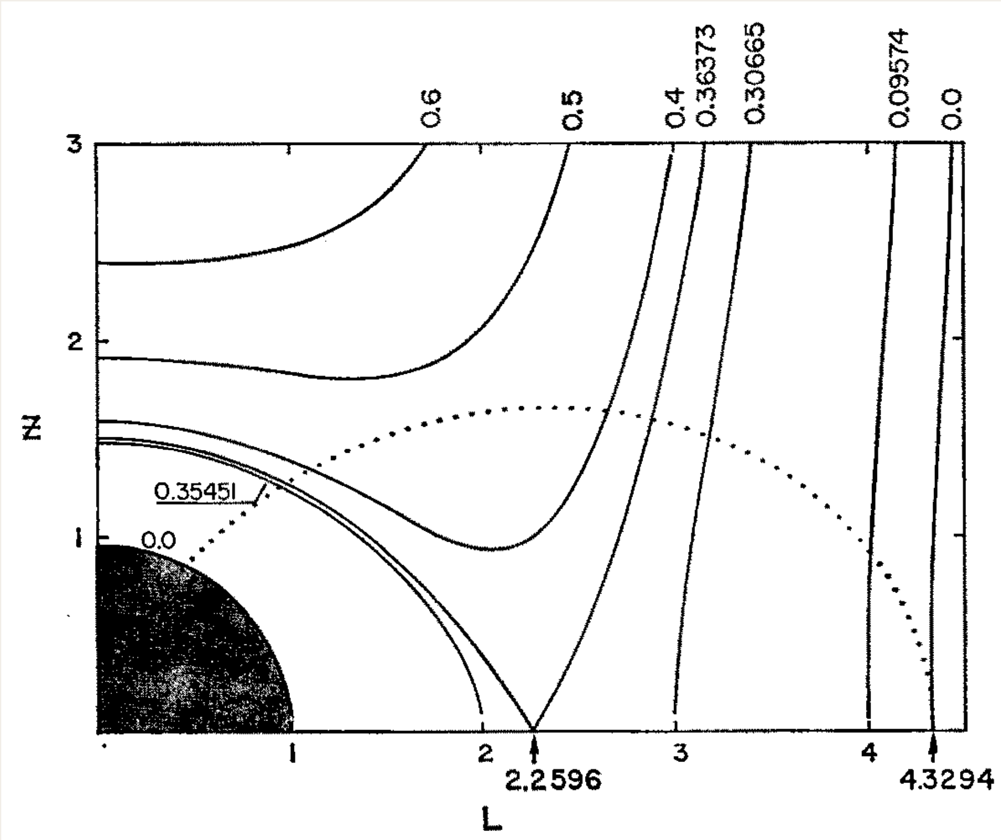
Rigid Field Models

- Circumstellar material moves along rigid field lines

- Gravity & centrifugal force represented by effective potential $\Phi_e(s)$

- Hydrostatic eqm. gives relative distribution of material:

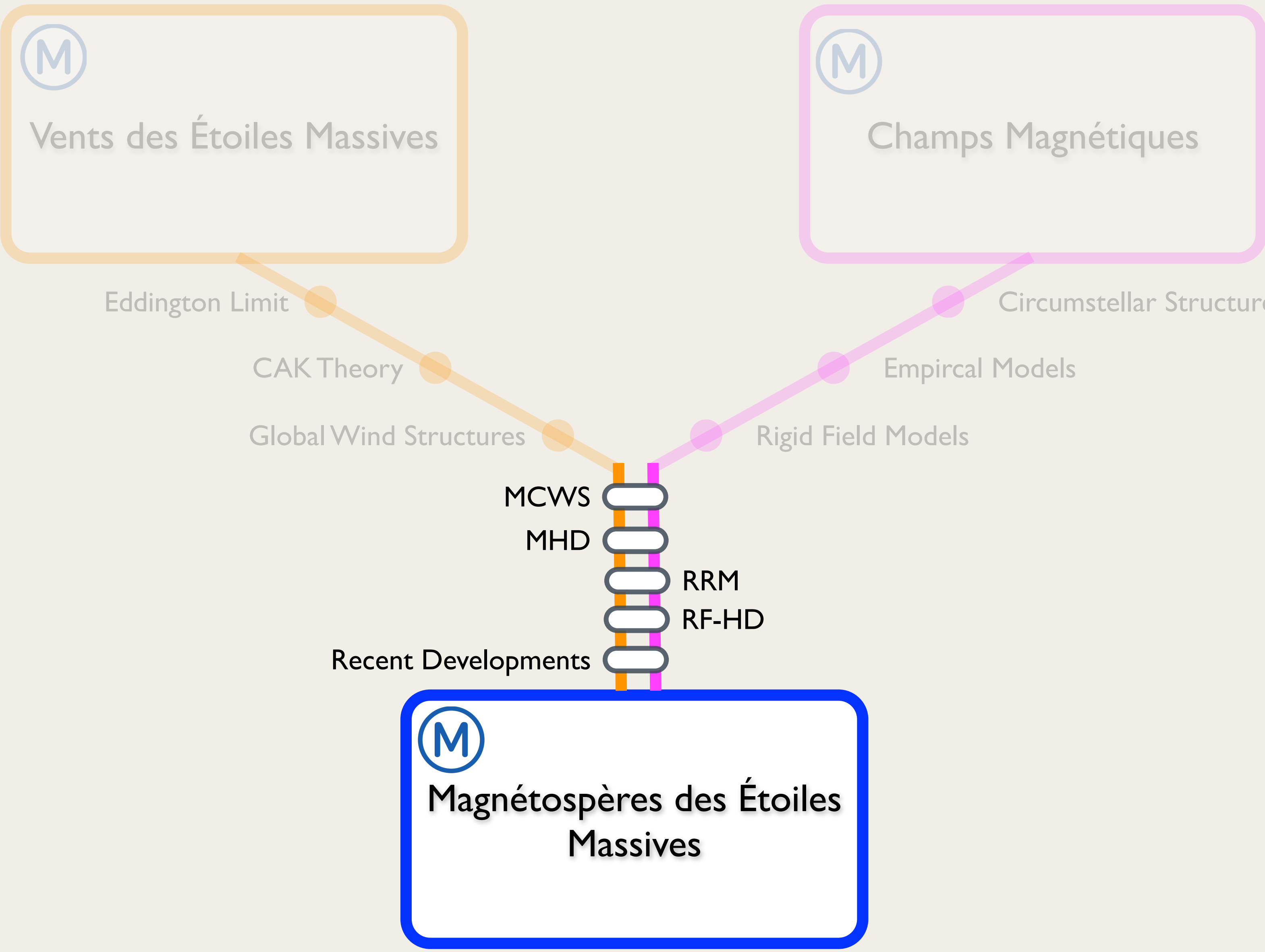
$$\rho(s) = \rho_0 \, \mathrm{e}^{-\Phi_{\mathrm{e}}(s)\, \mu m_{\mathrm{H}}/kT}$$



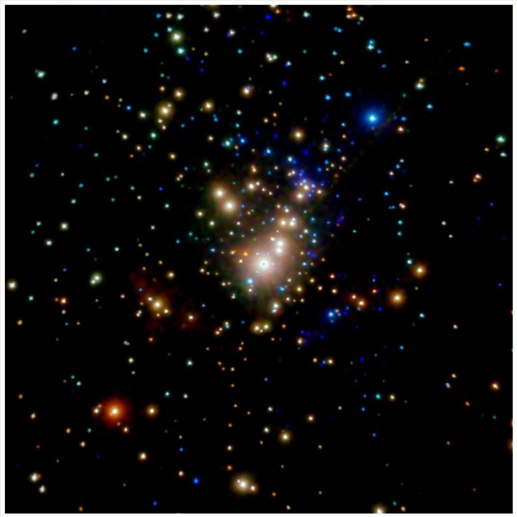
Michel & Sturrock (1974)

(also, Havnes & Goertz 1984, Nakajima 1985)

Massive-Star Magnetospheres

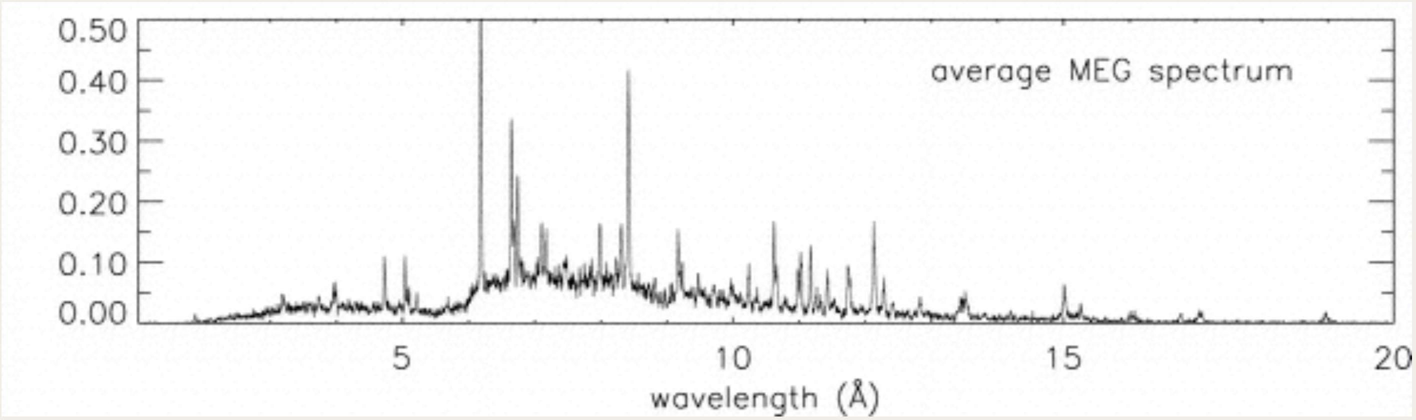


The Unusual X-rays of θ¹ Ori C



Getman et al. (2005)

- Emission peak > 1keV
- Δv ~ 200 km/s
- T ~ 20-30 MK
- R_X ~ 2 R_*



Gagné et al. (2005)

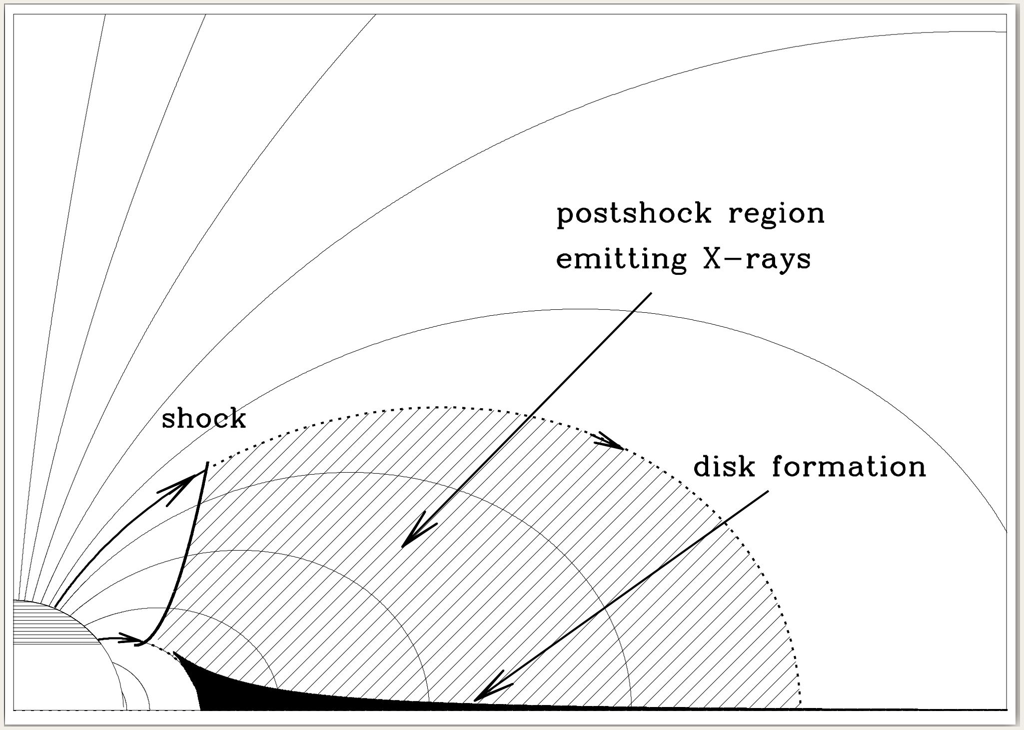
Magnetically Confined Wind Shocks

- Wind streams from opposing footpoints collide

- Shocks propagate back down field lines

- Equilibrium reached when pre/postshock pressures in balance

- Three regions:
  - wind upflow (cool, fast)
  - postshock (hot, slow)
  - disk (cool, stationary)



Babel & Montmerle (1997)
(also Usov & Melrose 1992)

Quantifying the Wind-Field Interaction

- Local ratio between magnetic and kinetic energy:

$$\eta = \frac{\mathcal{E}_{\rm mag}}{\mathcal{E}_{\rm kin}} = \frac{B^2}{4\pi\rho v^2}$$

- Dipole field & β-law wind:

$$\eta(r) = \boxed{\frac{B_*^2 R_*^2}{\dot{M} v_\infty}} \frac{r^{-4}}{(1 - R_*/r)^\beta}$$

$$\eta_*$$

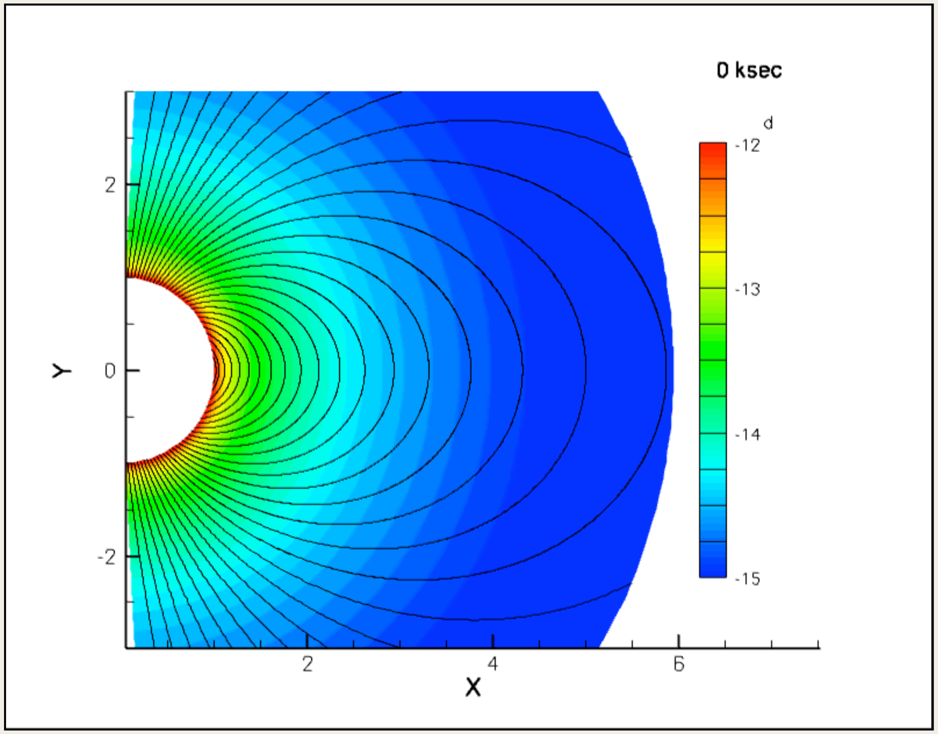
Star	η_*	$R_{\rm Alf}$
θ^1 Ori C	16	2
σ Ori E	10^7	30
ζ Ori	0.1	—

- Wind regimes bounded by $R_{\rm Alf} = \eta_*^{1/4}\ R_*$
  - Field dominated — $R_* \leq r \leq R_{\rm Alf}$
  - Wind dominated — $r > R_{\rm Alf}$

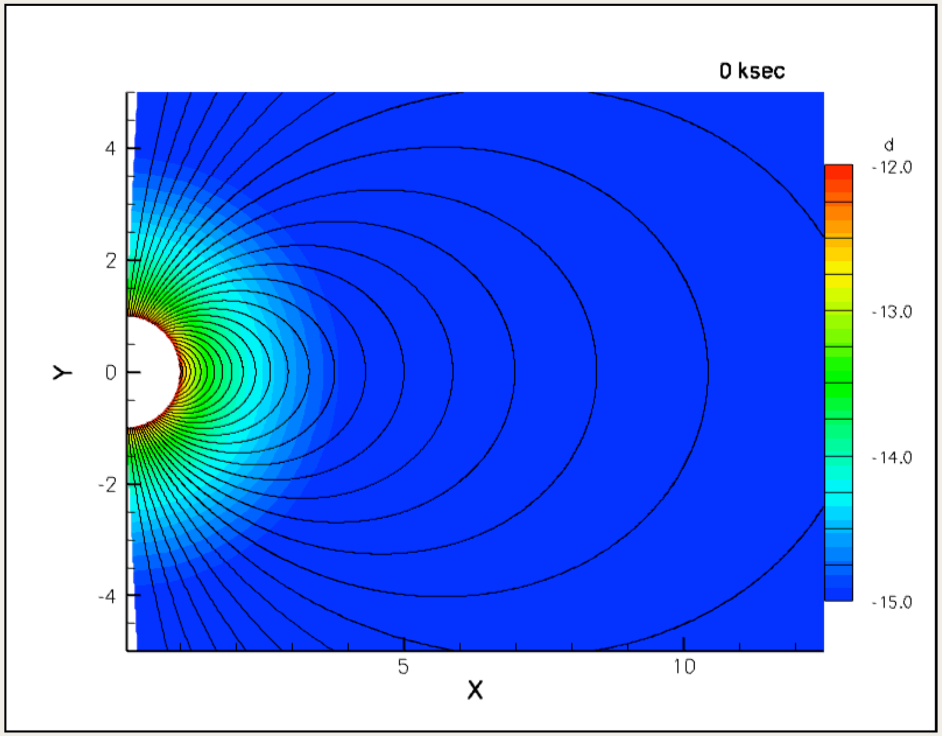
ud-Doula & Owocki (2002)
Owocki & ud-Doula (2004)

Exploring η_* with MHD Simulations*

$\eta_* = 0.1$



$\eta_* = 100$

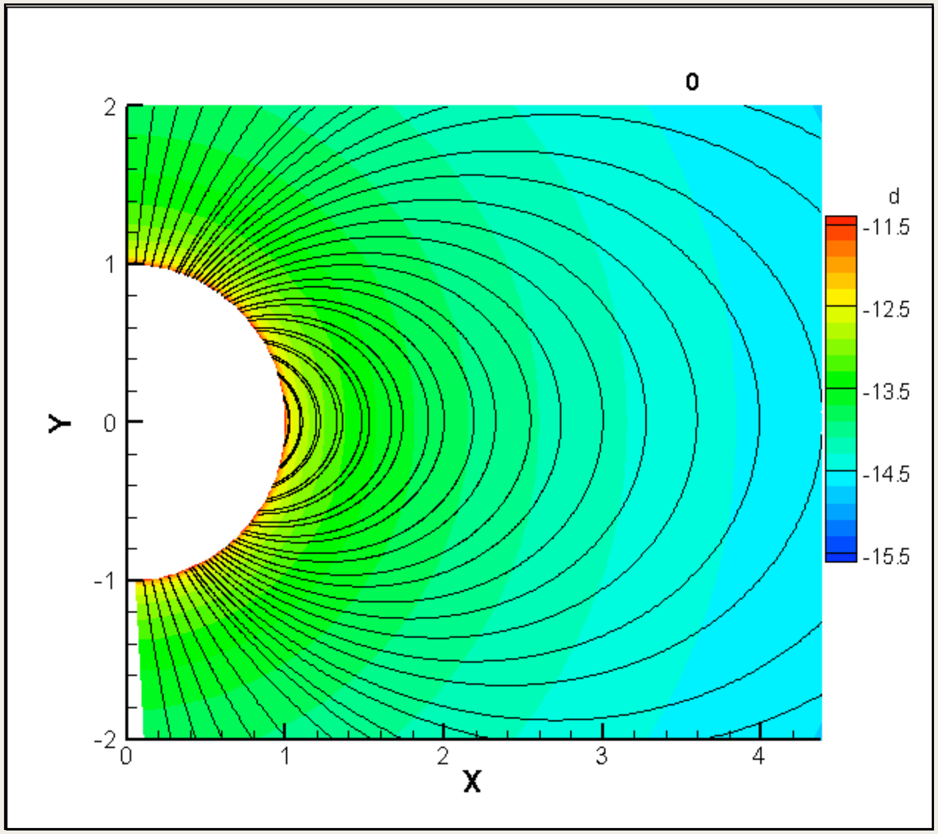


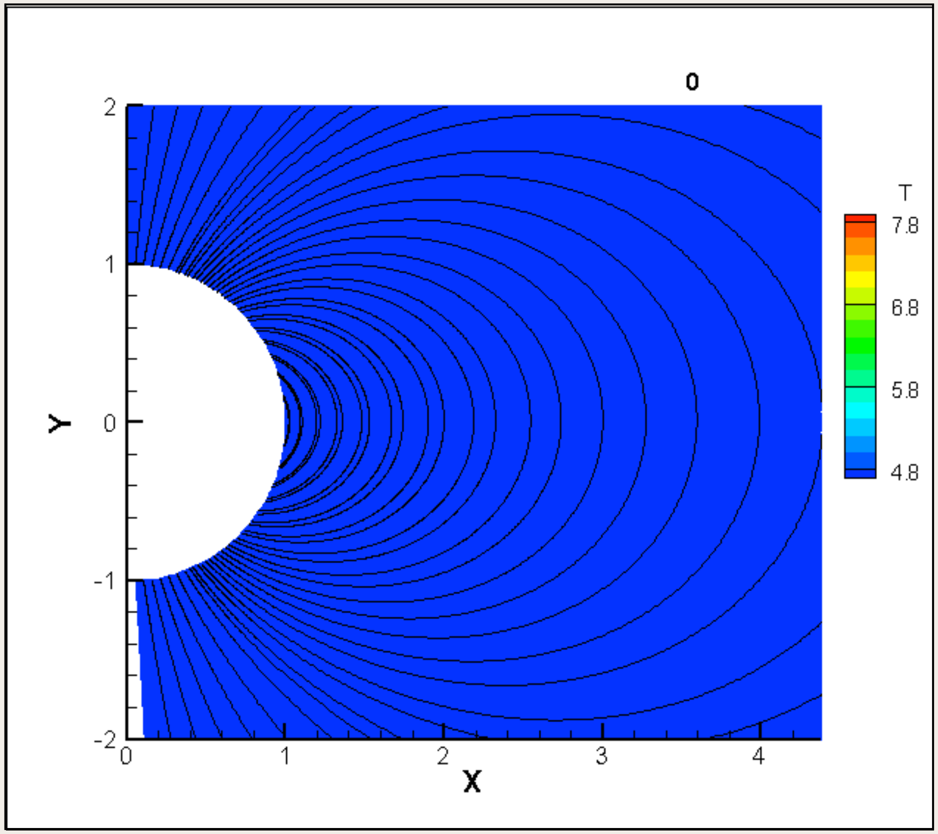
*ZEUS-2D; CAK line force; isothermal; no rotation

Asif ud-Doula

MHD Simulation* of θ^1 Ori C

$$\eta_* = 16$$





*ZEUS-2D; CAK line force; non-isothermal optically thin cooling; no rotation

Asif ud-Doula
(see also Gagné et al 2005)

Return to Rigid Field Models

- In the limit $\eta_* \gg 1$, field completely dominates wind

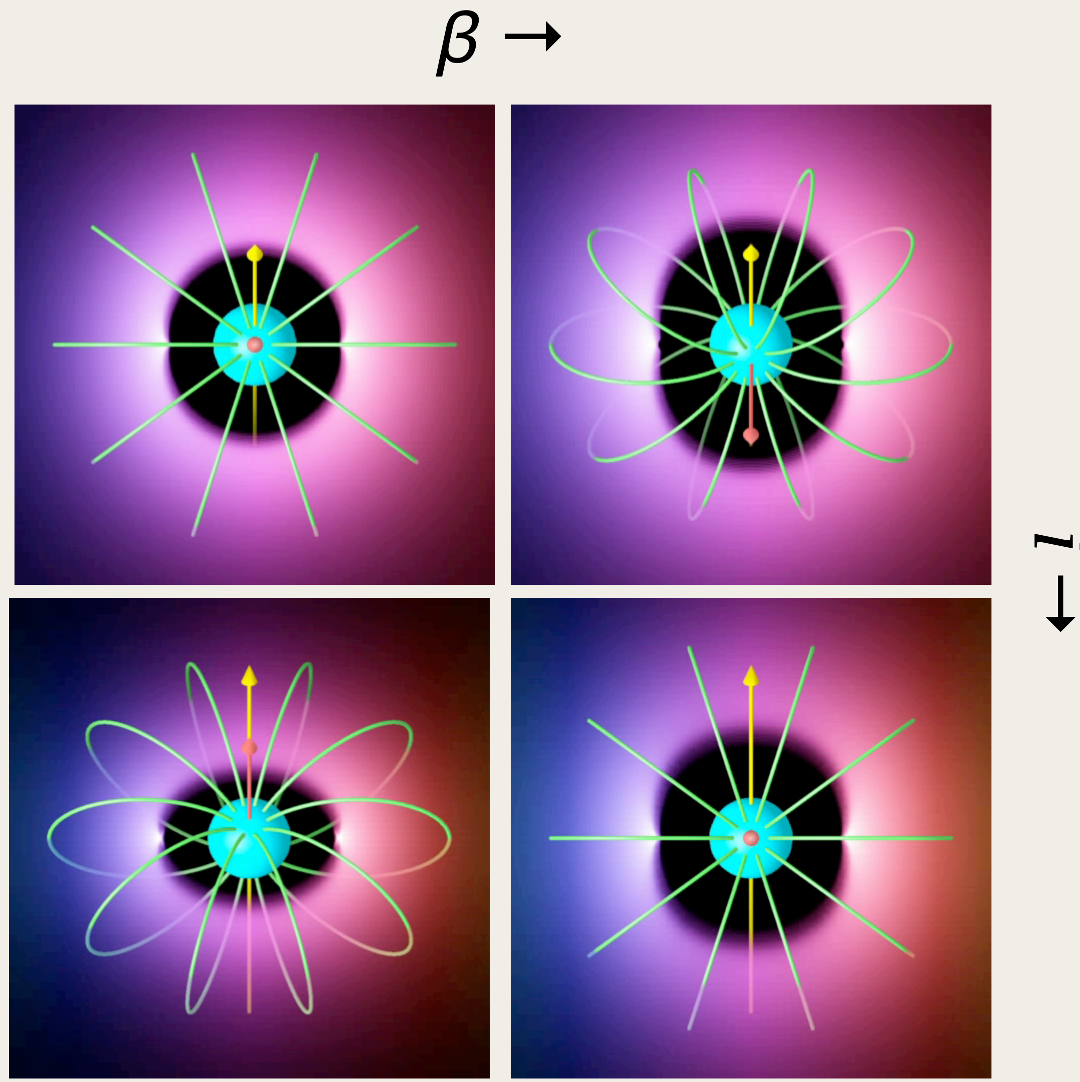
- Field lines behave as rigid pipes guiding the wind flow

- Resurrect rigid field models:

$$\rho(s) = \rho_0 \, \mathrm{e}^{-\Phi_\mathrm{e}(s)\, \mu m_\mathrm{H}/kT}$$

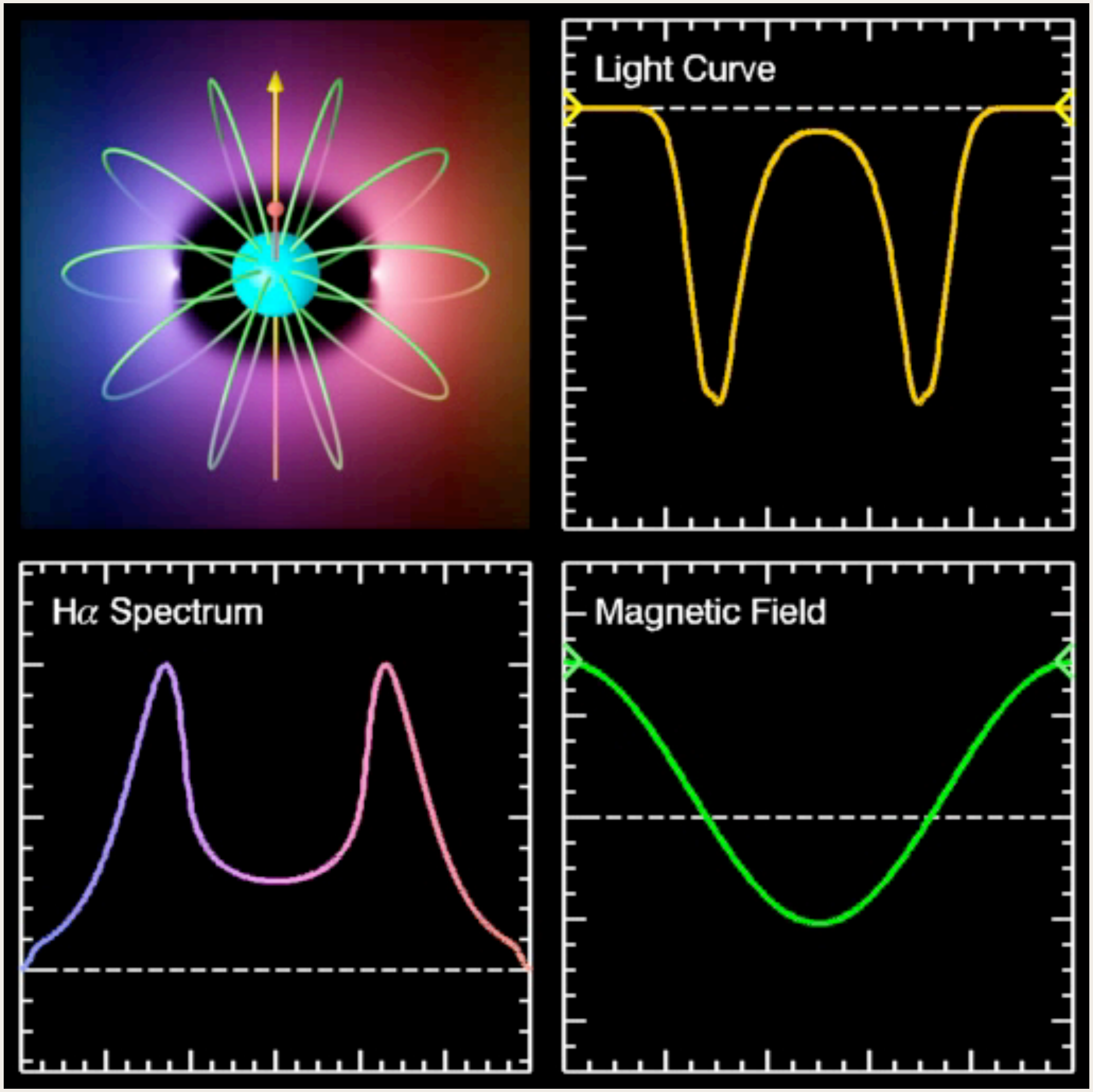
- **BUT:** we can now fix the normalizing density ρ_0 from the surface mass flux scalings found in MHD models

Rigidly Rotating Magnetosphere Models

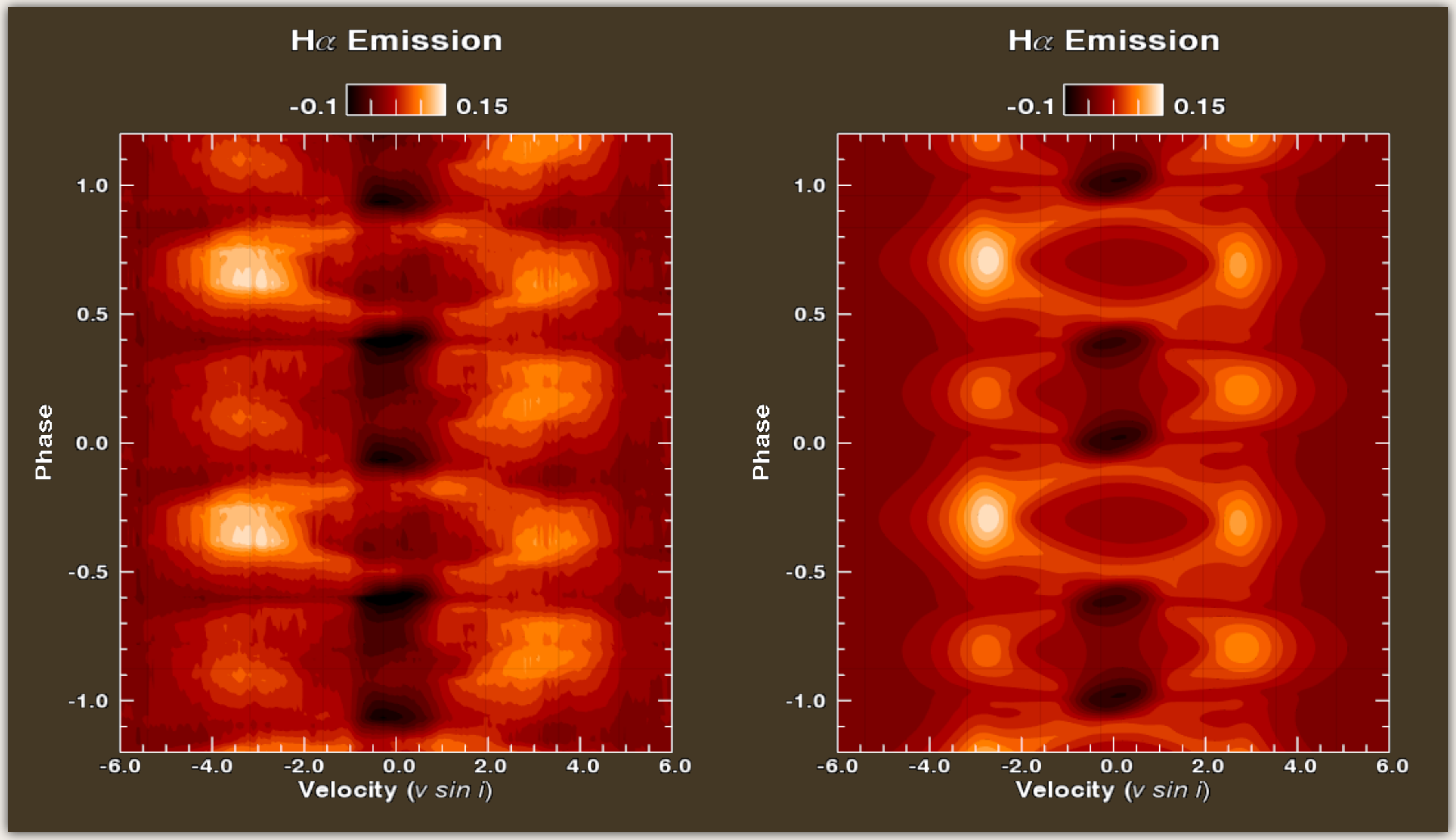


Townsend & Owocki (2005)

RRM Model of σ Ori E

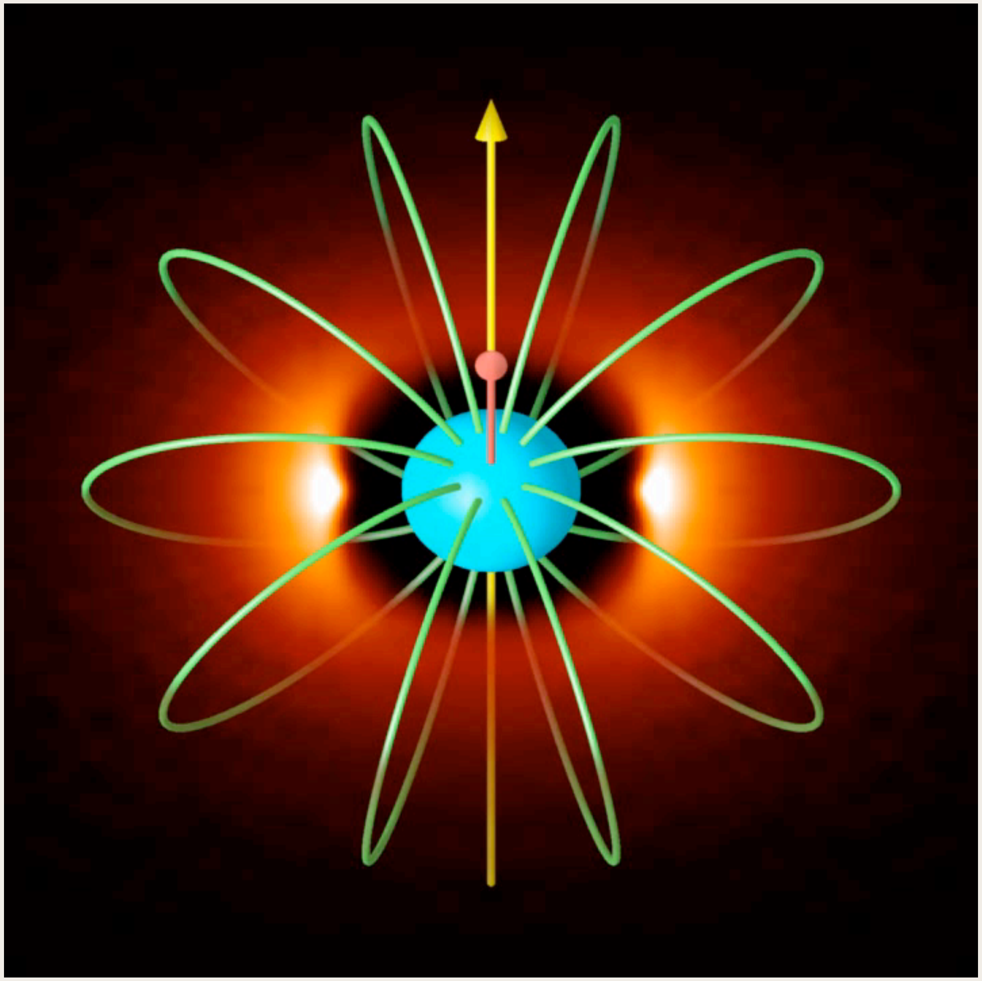


Models vs. Observations



Townsend, Owocki & Groote (2005)

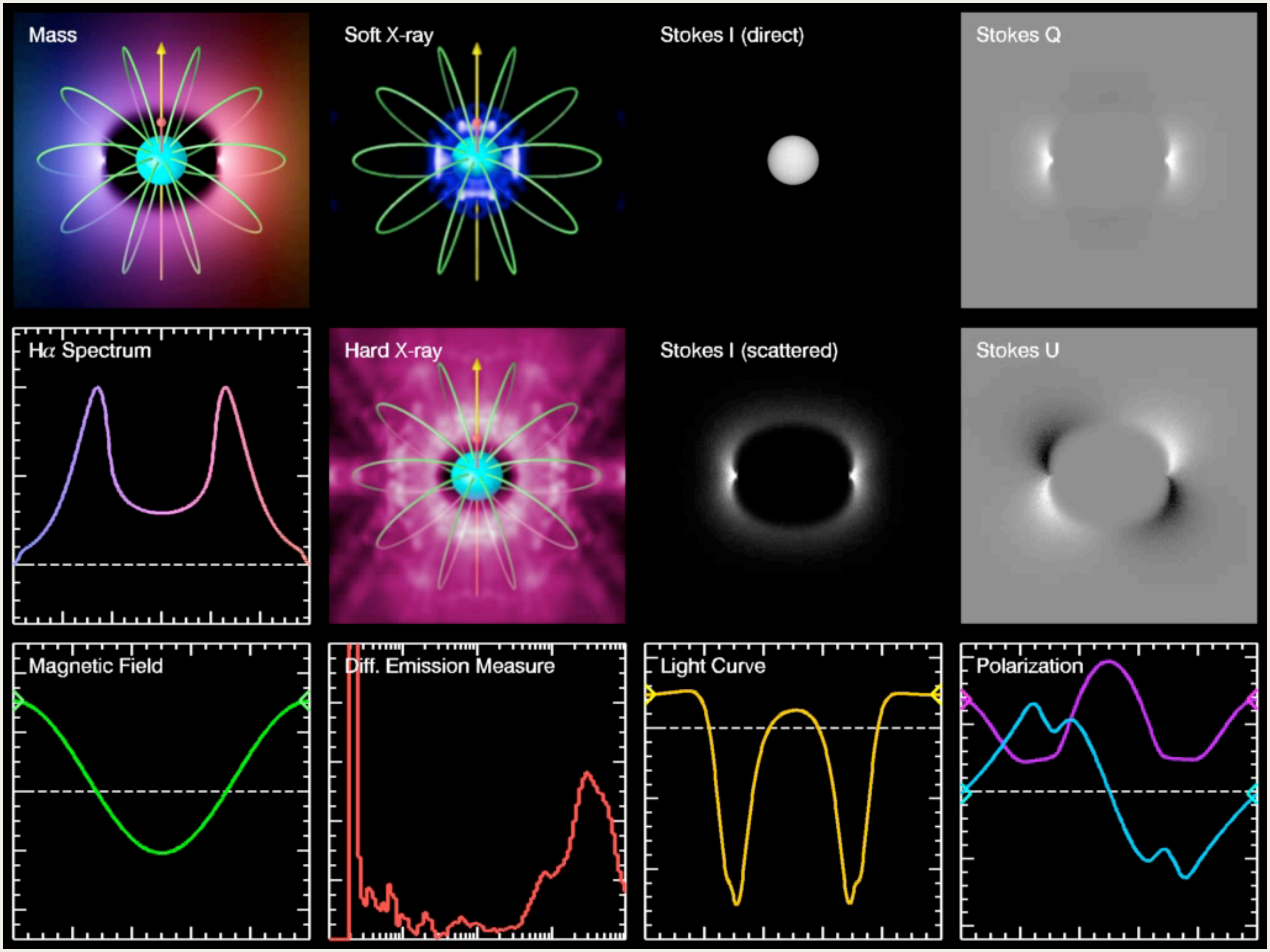
Beyond RRM: Rigid Field Hydrodynamics Simulation* of σ Ori E



*VH-1; rigid field; CAK line force; rotation; optically thin cooling; inverse Compton cooling; thermal conduction;

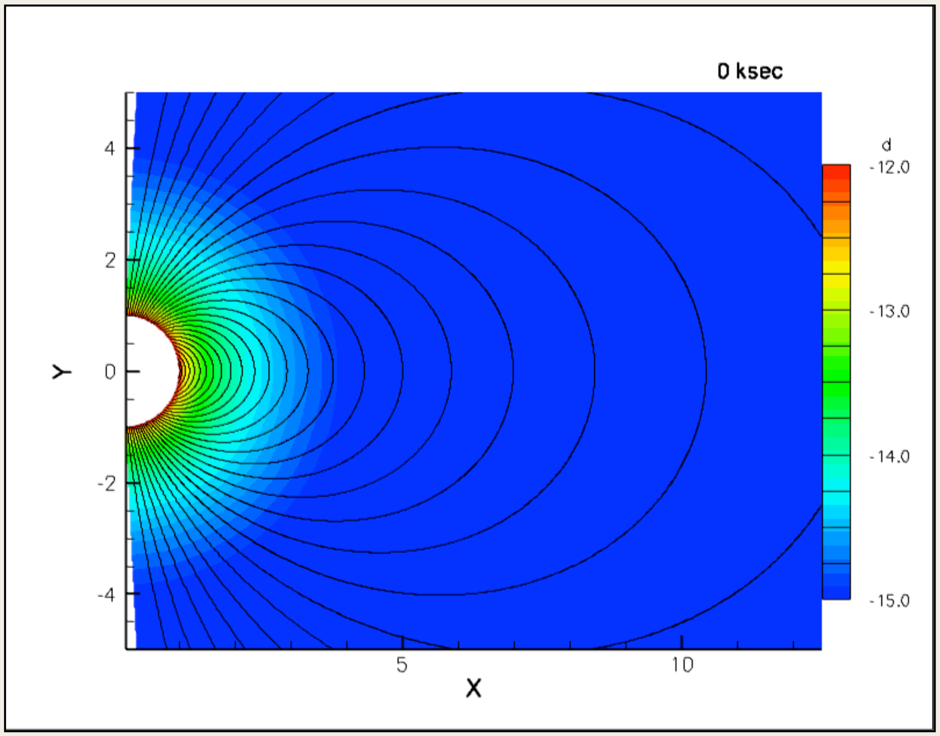
Townsend, Owocki & ud-Doula (2007)
Hill et al. (Poster S2-11)

Multi-wavelength Diagnostics from RF-HD

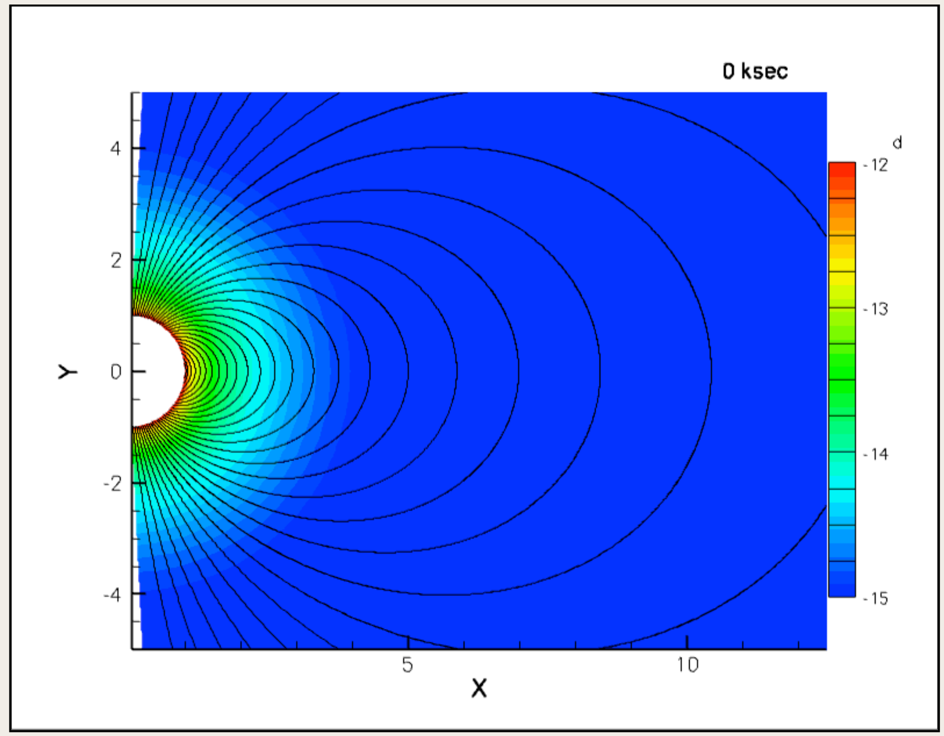


Recent Developments: MHD Simulations* with Rotation

v_{eq} = 0 km/s



v_{eq} = 125 km/s



*ZEUS-2D; CAK line force; isothermal; field-aligned rotation

Asif ud-Doula
(see also ud-Doula, Owocki & Townsend 2008)

Recent Developments: Angular Momentum Loss

- MHD simulations reproduce Weber & Davies (1967) result:

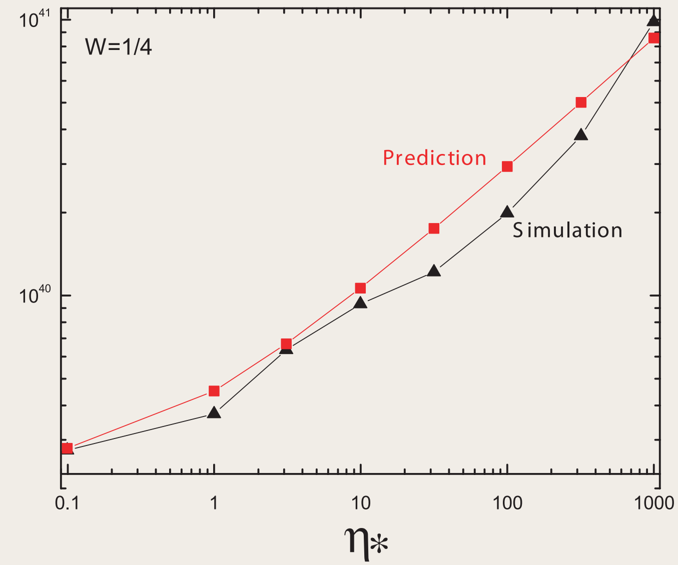
$$\dot{J} = \frac{2}{3}\dot{M}\,\Omega\,R_{\rm Alf}^2$$

- **However**, we must use $R_{\rm Alf}$ appropriate to a *dipole* field:

$$\dot{J} = \frac{2}{3}\dot{M}\,\Omega\,\eta_*^{1/2}$$

- Spin-down time:

$$t_{\rm spin} \approx \frac{3}{2}\,k\,\eta_*^{1/2}t_{\rm mass}$$

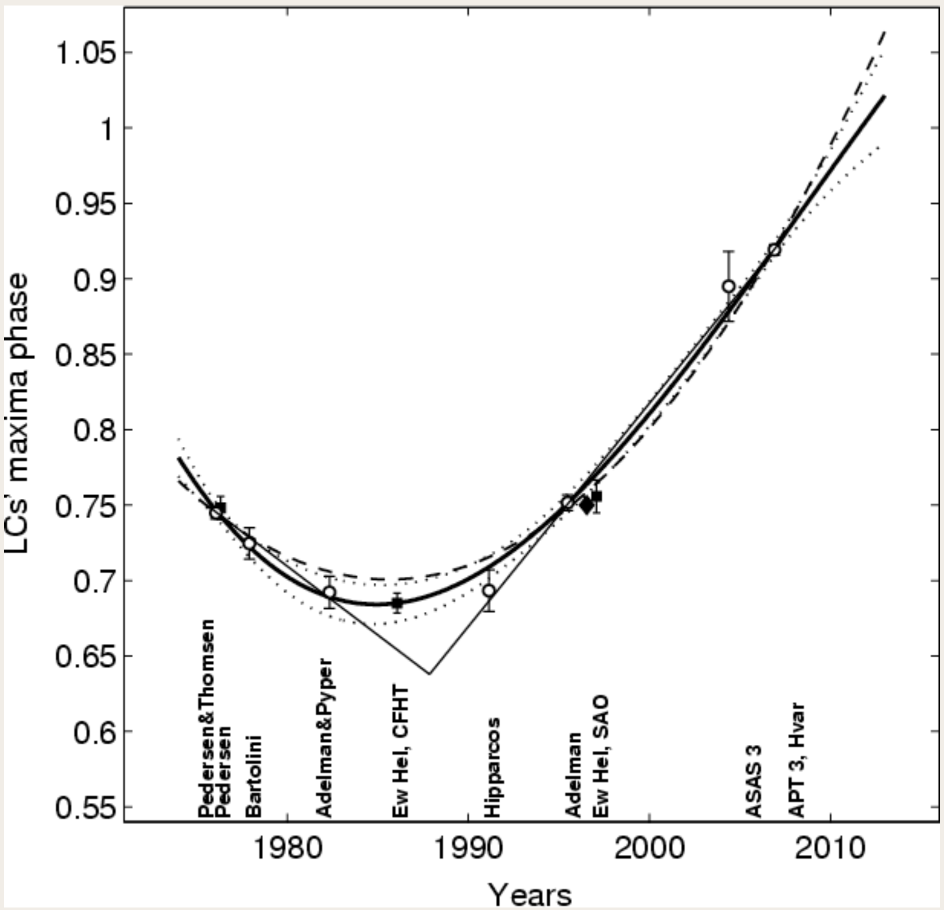


Star	η_*	$t_{\rm spin}$ (Myr)
θ^1 Ori C	16	8
σ Ori E	10^5	1.4
HD 191612	8	0.4

ud-Doula, Owocki & Townsend (2009)

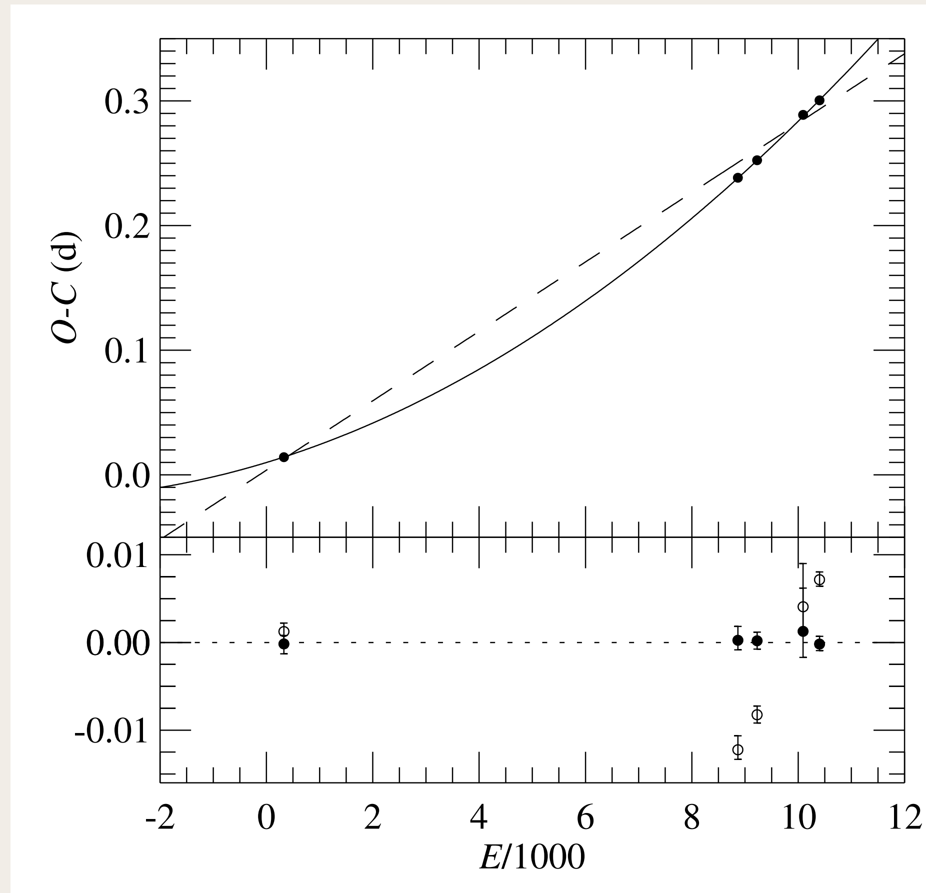
Recent Developments: Direct Measurements of Magnetic Braking

HD 37776 (t_{spin} ~ 200 kyr)



Mikulášek et al. (2008)

σ Ori E (t_{spin} ~ 1.3 Myr)



Townsend et al. (2010)

Key Concepts to Take Away...

$$\eta_* = \frac{B_*^2 R_*^2}{\dot{M} v_\infty}$$ — Magnetic confinement parameter

$$t_{\rm spin} \approx \frac{3}{2} k\, \eta_*^{1/2} t_{\rm mass}$$ — Spindown time