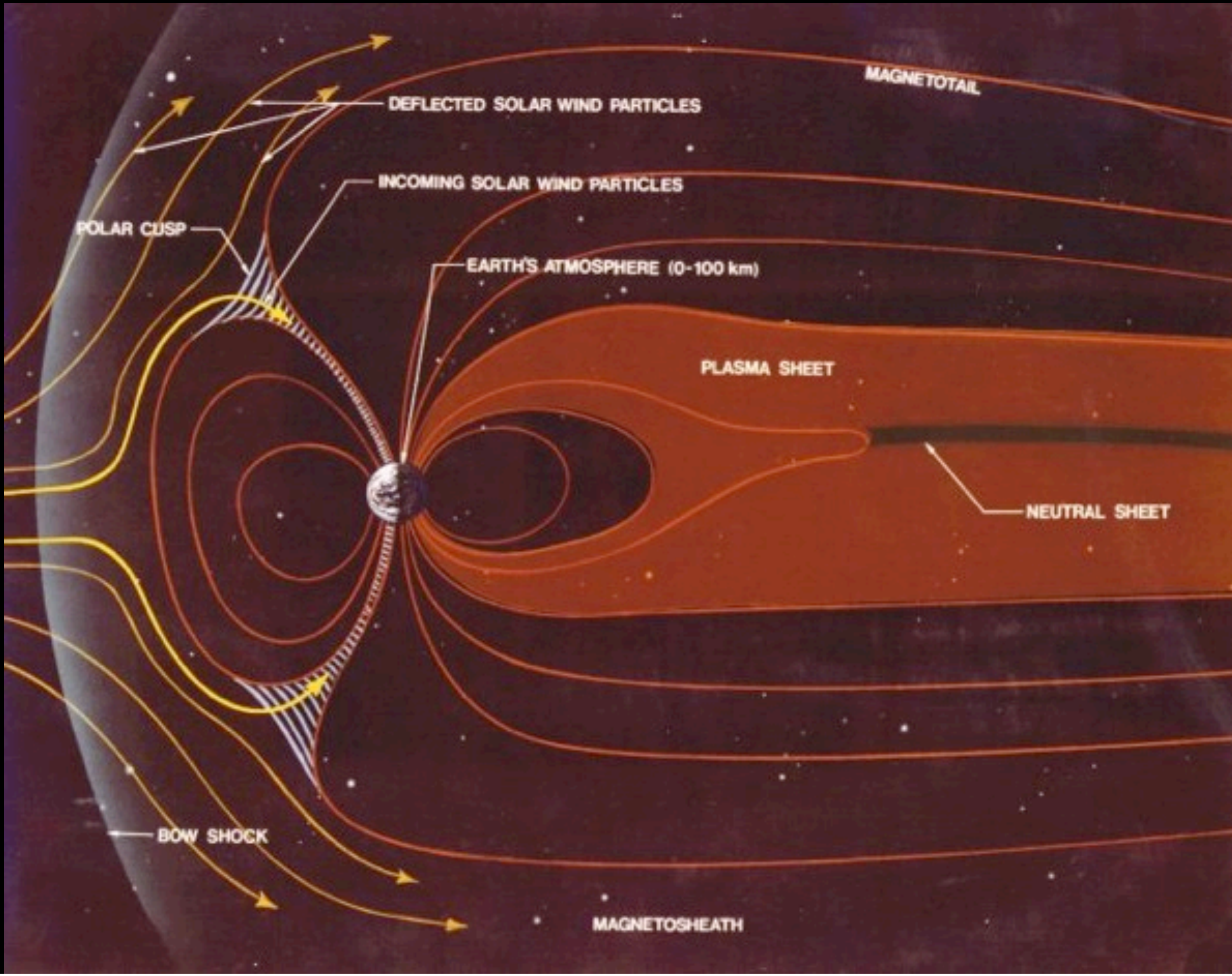
Mass Loss & Rotational Spindown of Magnetic Massive Stars

Stan Owocki
University of Delaware
Newark, Delaware USA

Collaborators

- Asif ud-Doula
- Rich Townsend

Earth's Magnetosphere



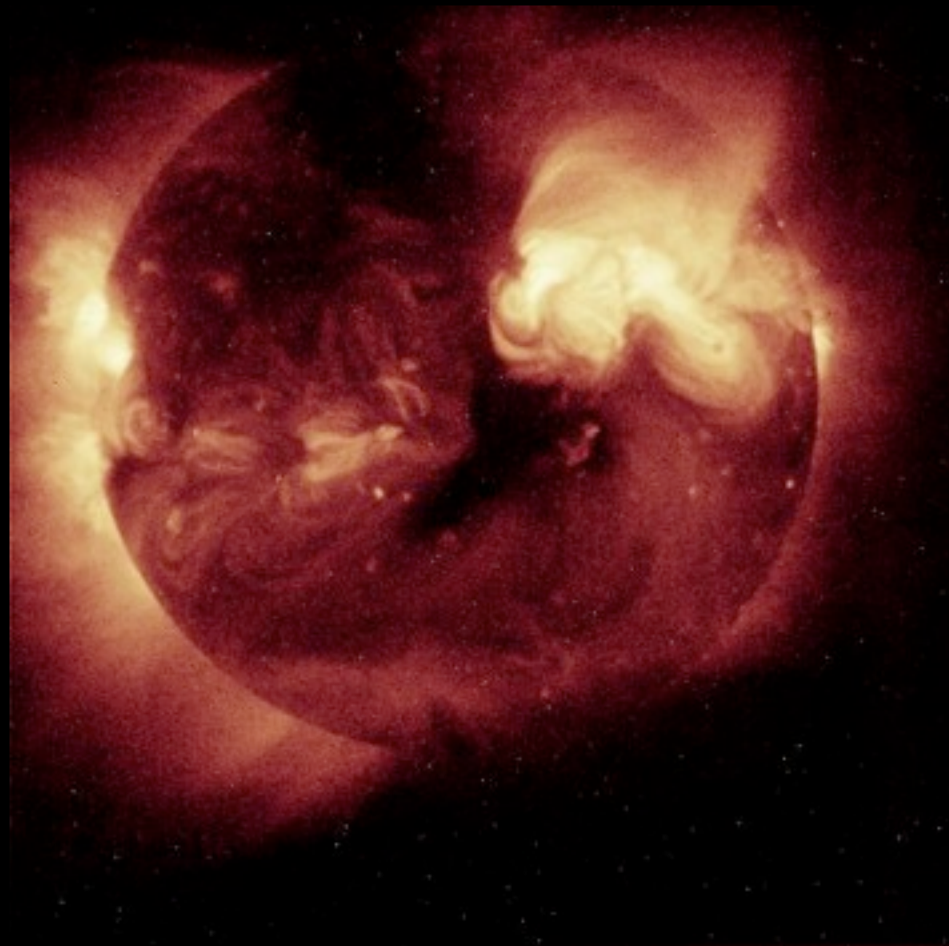
Solar Corona in EUV & X-rays

Composite EUV image from EIT/SOHO

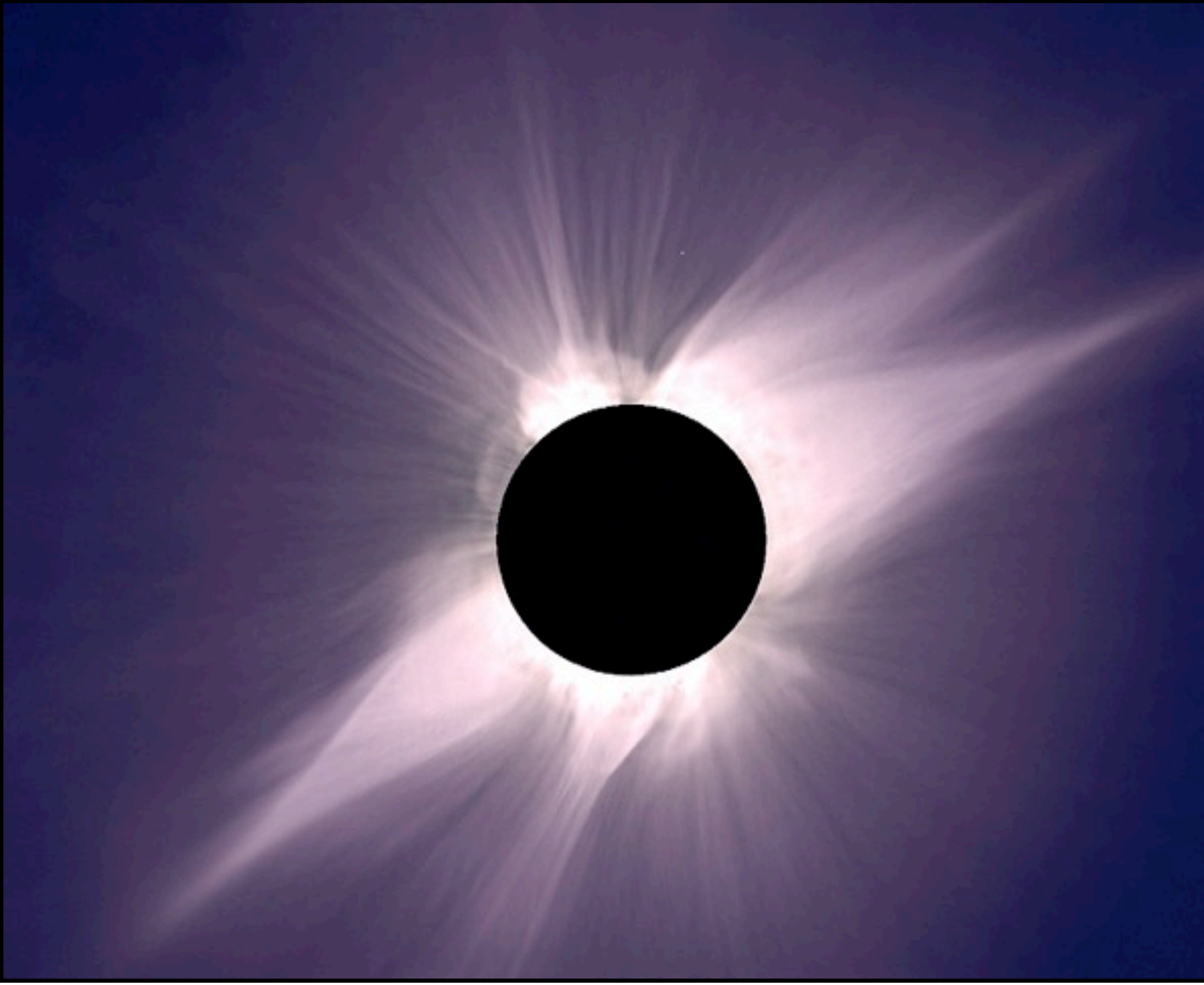
Solar Corona in EUV & X-rays

Composite EUV image from EIT/SOHO

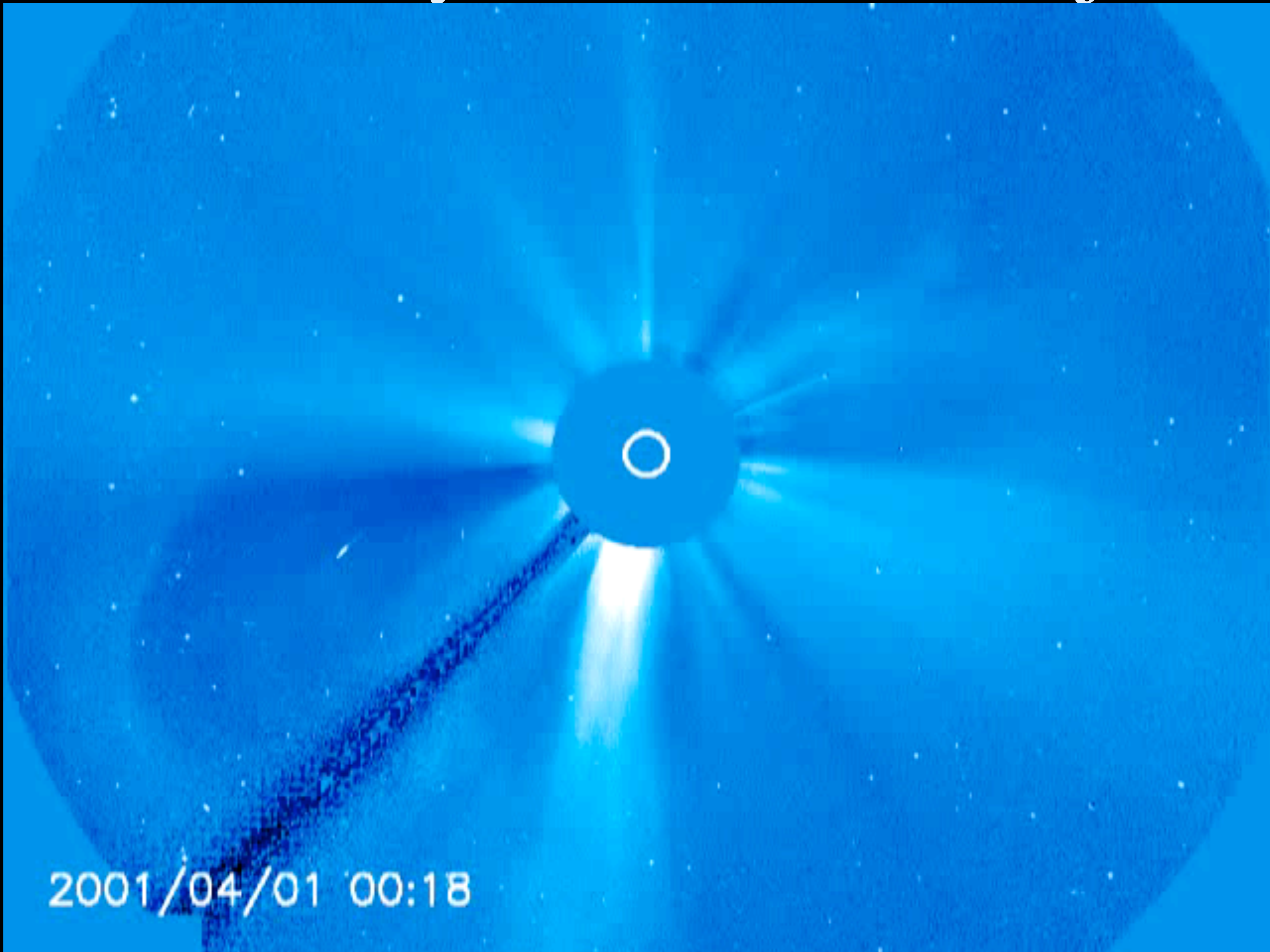
X-ray Corona from SOHO



Corona during Solar Eclipse



Solar Activity: Coronal Mass Ejections



Hot, Luminous, Massive Stars

- Strong, radiatively driven stellar wind
  - $M_{dot} \sim 10^{-9}$-10^{-5} M_O/yr; $V_\infty > 1000$ km/s >> V_{sound}

Hot, Luminous, Massive Stars

- Strong, radiatively driven stellar wind
  - $M_{dot} \sim 10^{-9}$-10^{-5} M_O/yr; $V_\infty > 1000$ km/s >> V_{sound}
- Some have observed dipole field $\sim 10^3$-10^4 G
  - stable; not from convective dynamo; fossil?
- Fast rotation with $V_{rot} \sim 250$ km/s $\sim V_{crit}/2$
  - $P_{rot} \sim$ few days

Questions

Questions

- How does a strong magnetic field affect radiatively driven wind outflow?
  - wind channeling
  - magnetically confined wind shocks
  - wind-fed rotational magnetospheres

Questions

- How does a strong magnetic field affect radiatively driven wind outflow?
  - wind channeling
  - magnetically confined wind shocks
  - wind-fed rotational magnetospheres

- How does angular momentum loss & spindown scale with B_*, Mdot, n-pole order, etc.?
  - can we explain slow rotators w/ magnetic spindown?
  - what are implications for stellar evolution

Wind Magnetic Confinement

Ratio of magnetic to kinetic energy density:

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2}$$

Wind Magnetic Confinement

Ratio of magnetic to kinetic energy density:

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2} = \frac{B_*^2 R_*^2}{\dot{M}\,\mathrm{v}_\infty} \frac{(r/R_*)^{-2n}}{(1 - R_*/r)^\beta}$$

Wind Magnetic Confinement

Ratio of magnetic to kinetic energy density:

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2} = \frac{B_*^2 R_*^2}{\dot{M}\,\mathrm{v}_\infty}\,\frac{(r/R_*)^{-2n}}{(1-R_*/r)^{\beta}}$$

for n-pole

B(r) ~ $1/r^{n+1}$

Wind Magnetic Confinement

Ratio of magnetic to kinetic energy density:

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2} = \underbrace{\frac{B_*^2 R_*^2}{\dot{M}\, v_\infty}}_{\eta_*} \frac{(r/R_*)^{-2n}}{(1 - R_*/r)^{\beta}}$$

for n-pole

$B(r) \sim 1/r^{n+1}$

Wind Magnetic Confinement

Ratio of magnetic to kinetic energy density:

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2} = \underbrace{\frac{B_*^2 R_*^2}{\dot{M}\, v_\infty}}_{\eta_*} \frac{(r/R_*)^{-2n}}{(1-R_*/r)^\beta}$$

for n-pole
$B(r) \sim 1/r^{n+1}$

Note also $\eta = \frac{V_A^2}{v^2}$ so **Alfven Radius,** where $v=V_A$, has $\eta(R_A) \equiv 1$

Wind Magnetic Confinement

Ratio of magnetic to kinetic energy density:

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2} = \underbrace{\frac{B_*^2 R_*^2}{\dot{M}\,\mathrm{v}_\infty}}_{\eta_*} \frac{(r/R_*)^{-2n}}{(1-R_*/r)^\beta}$$

for n-pole $B(r) \sim 1/r^{n+1}$

Note also $\eta = \frac{V_A^2}{v^2}$ so **Alfven Radius,** where $v=V_A$, has $\eta($ **R_A**$) \equiv$ **1**

For $\beta=0$: $R_A = \eta_*^{1/2n} R_*$

Wind Magnetic Confinement

Ratio of magnetic to kinetic energy density:

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2} = \underbrace{\frac{B_*^2 R_*^2}{\dot{M}\, v_\infty}}_{\eta_*} \frac{(r/R_*)^{-2n}}{(1-R_*/r)^\beta}$$

for n-pole
$B(r) \sim 1/r^{n+1}$

Note also $\eta = \frac{V_A^2}{v^2}$ so **Alfven Radius,** where v=V_A, has $\eta($ **R_A** $) \equiv$ **1**

For β=0: $R_A = \eta_*^{1/2n} R_*$

e.g., for dipole, n=2: $\mathbf{R_A = \eta_*^{1/4} R_*}$

Magnetic confinement vs. Wind + Rotation

Wind mag. confinement

$$\eta_* \equiv \frac{B_*^2 R_*^2}{\dot{M} V_\infty}$$

Rotation vs. critical

$$W \equiv \frac{V_{rot}}{\sqrt{GM / R_*}}$$

Alfven radius for n-pole

$$R_A = \eta_*^{1/2n} R_*$$

$$= \eta_*^{1/4} R_* \text{ for n=2 dipole}$$

Kepler radius

$$R_K = W^{-2/3} R_*$$

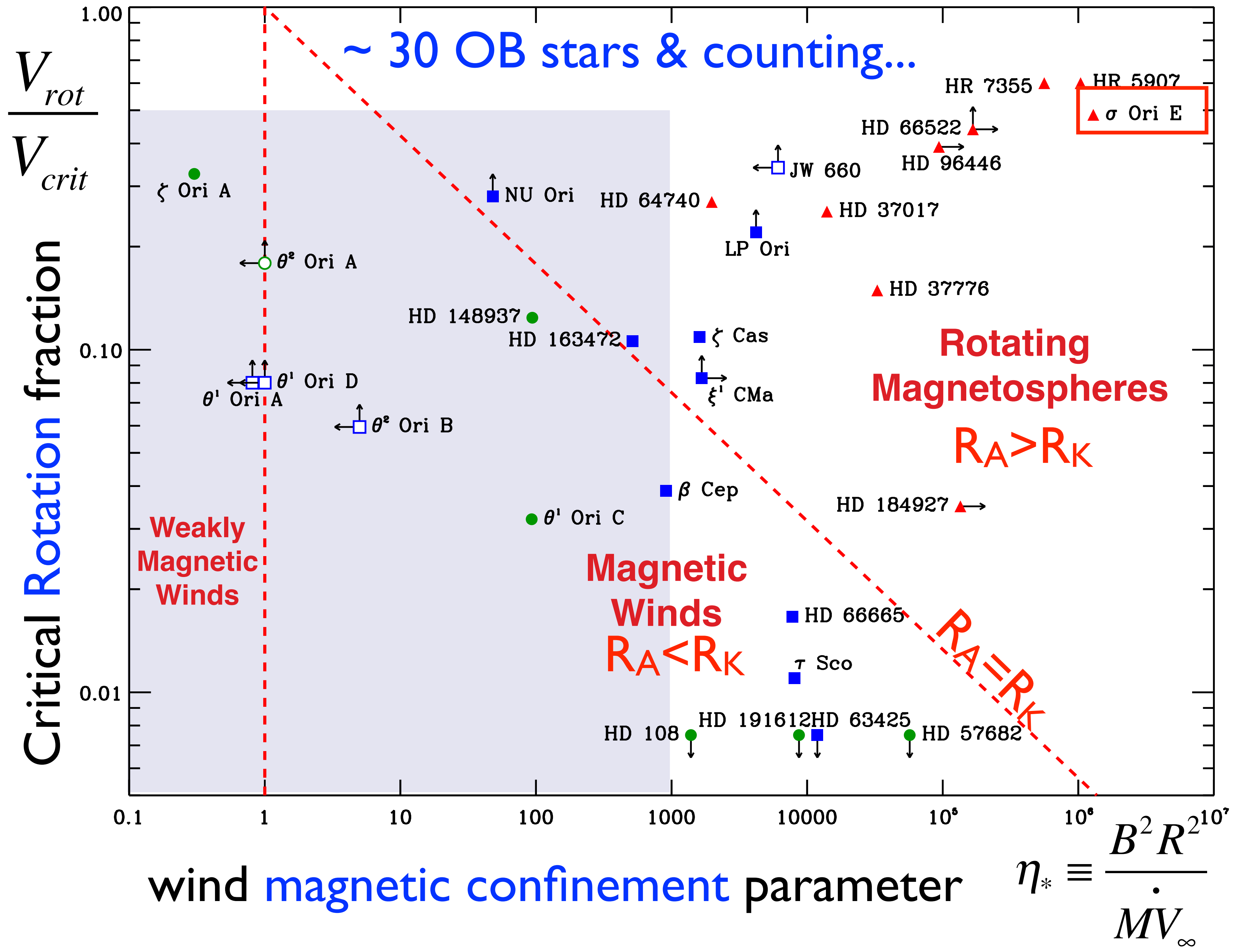
MiMeS

Magnetism in Massive Stars

P.I.: Gregg A. Wade, Royal Military College

50+ Co-Is, 2008-2012, CFHT Allocation: 640 hours

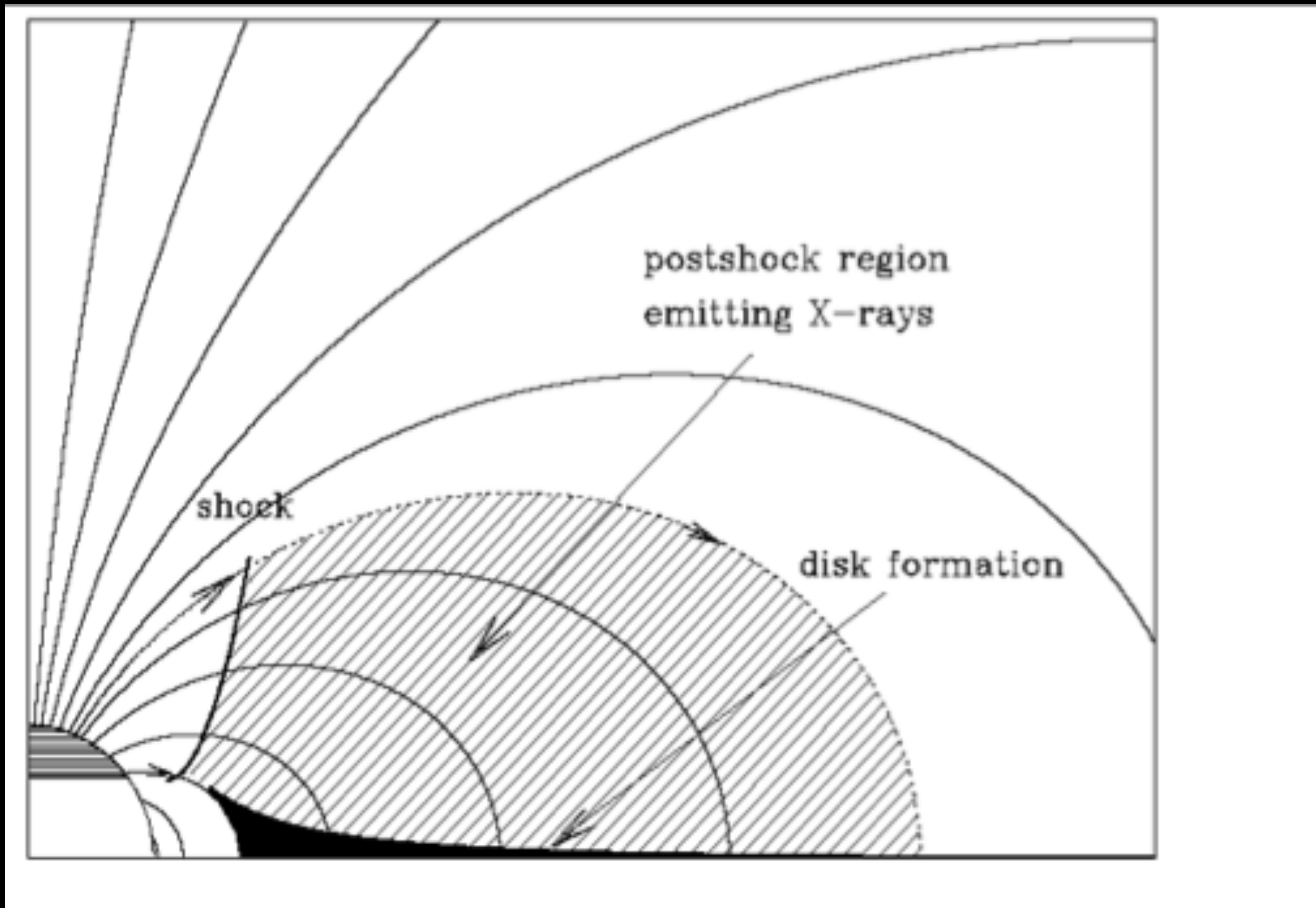
http://www.physics.queensu.ca/~wade/mimes/MiMeS__Magnetism_in_Massive_Stars.html


~ 30 OB stars & counting...
Critical Rotation fraction
V_{rot}/V_{crit}
1.00
0.10
0.01
0.1
1
10
100
1000
10000
10^5
10^6
10^7
wind magnetic confinement parameter
$\eta_* \equiv \frac{B^2 R^2}{\dot{M} V_\infty}$
Weakly Magnetic Winds
Magnetic Winds
$R_A < R_K$
Rotating Magnetospheres
$R_A > R_K$
$R_A = R_K$
ζ Ori A
θ² Ori A
θ¹ Ori D
θ¹ Ori A
θ² Ori B
θ¹ Ori C
NU Ori
HD 148937
HD 163472
HD 64740
LP Ori
JW 660
HD 37017
HD 37776
HD 66522
HD 96446
HR 7355
HR 5907
σ Ori E
ζ Cas
ξ¹ CMa
β Cep
HD 184927
HD 66665
τ Sco
HD 108
HD 191612
HD 63425
HD 57682

Magnetically Confined Wind-Shocks

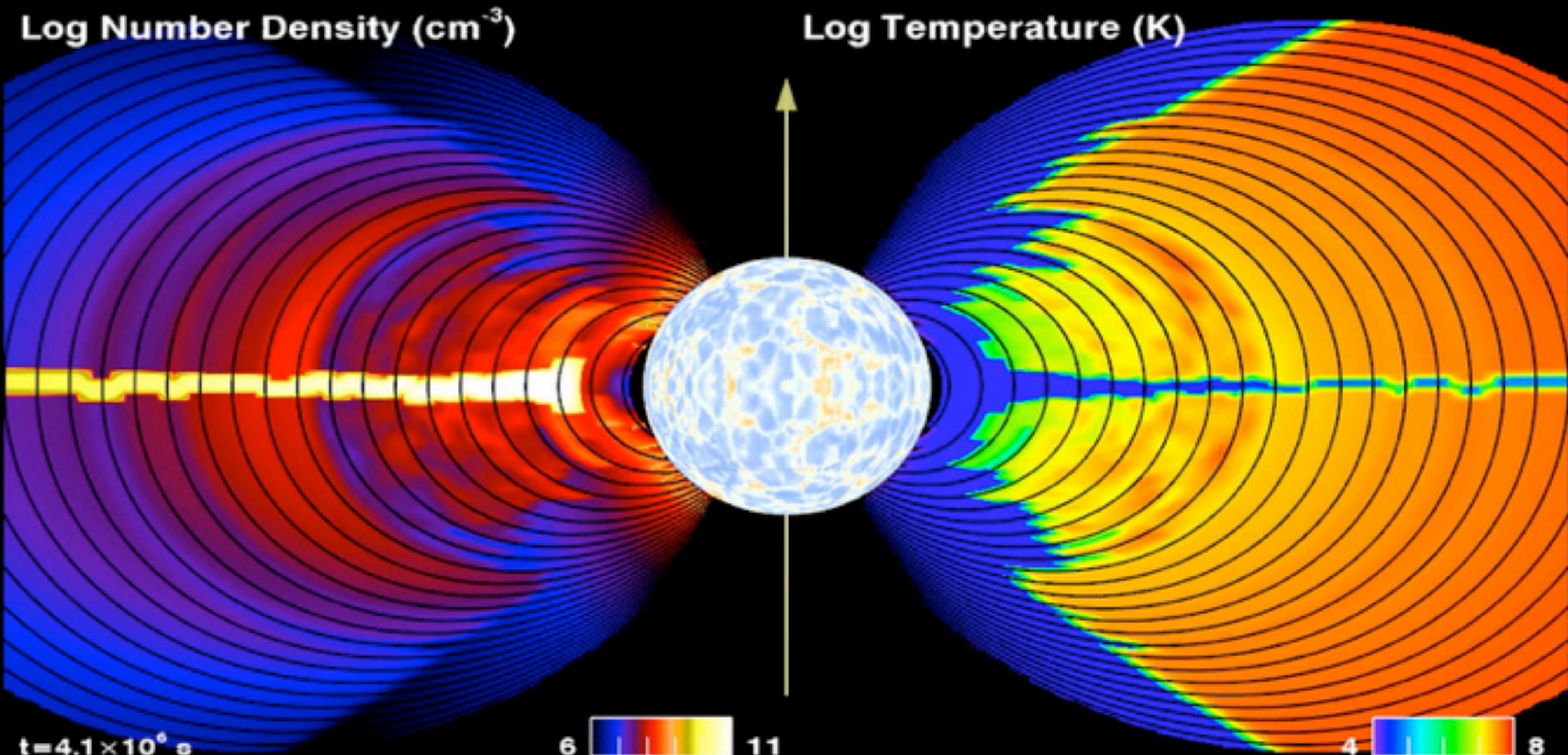
Babel & Montmerle 1997

Magnetic A_p-B_p stars



Rigid Field - Hydro Model

Rigid Field - Hydro Model



MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement parameter

$\eta_* = 1/3$

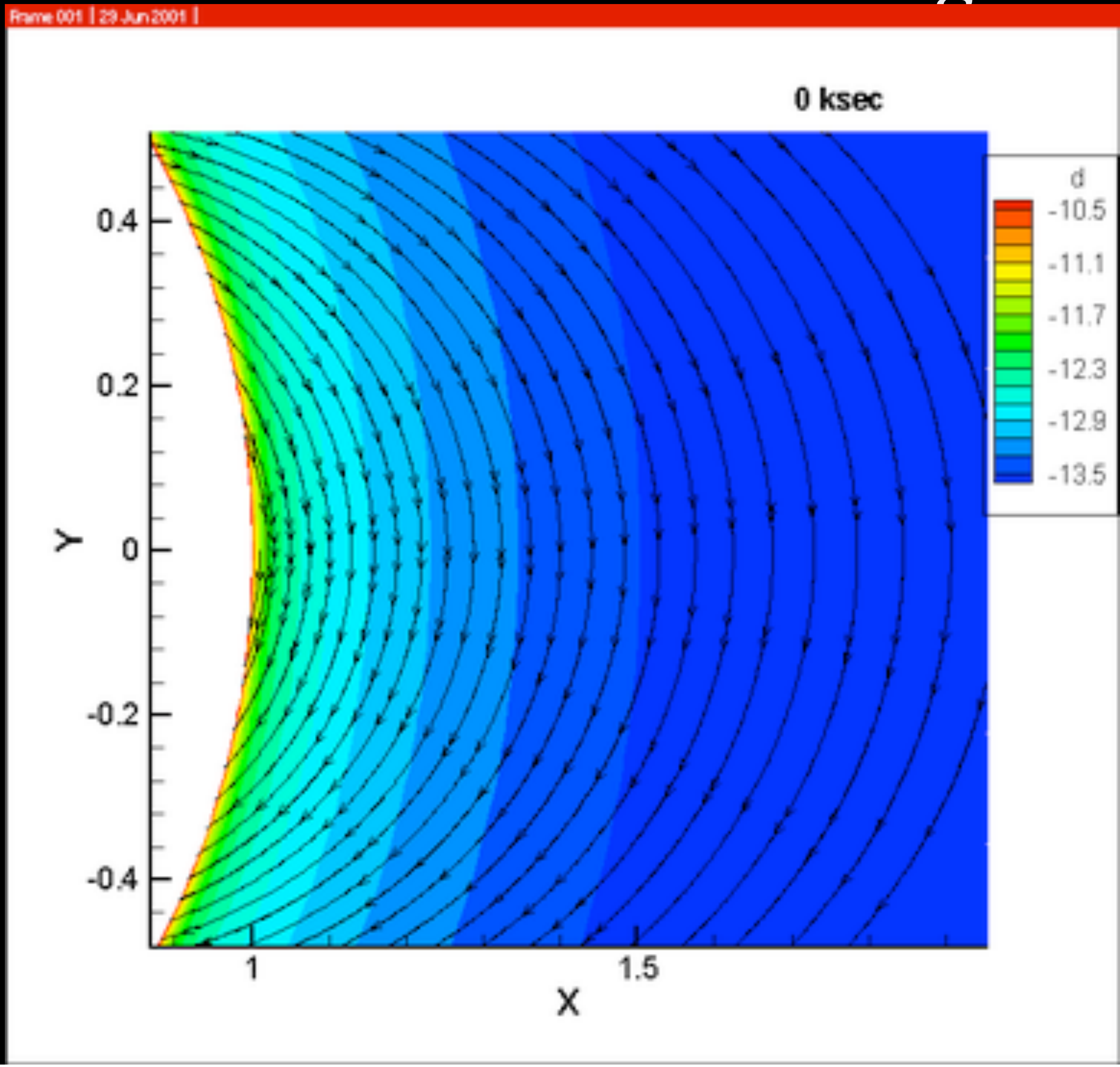
A. ud Doula
PhD thesis 2002

MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement parameter

$\eta_{*}=1/3$



A. ud Doula
PhD thesis 2002

MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement parameter

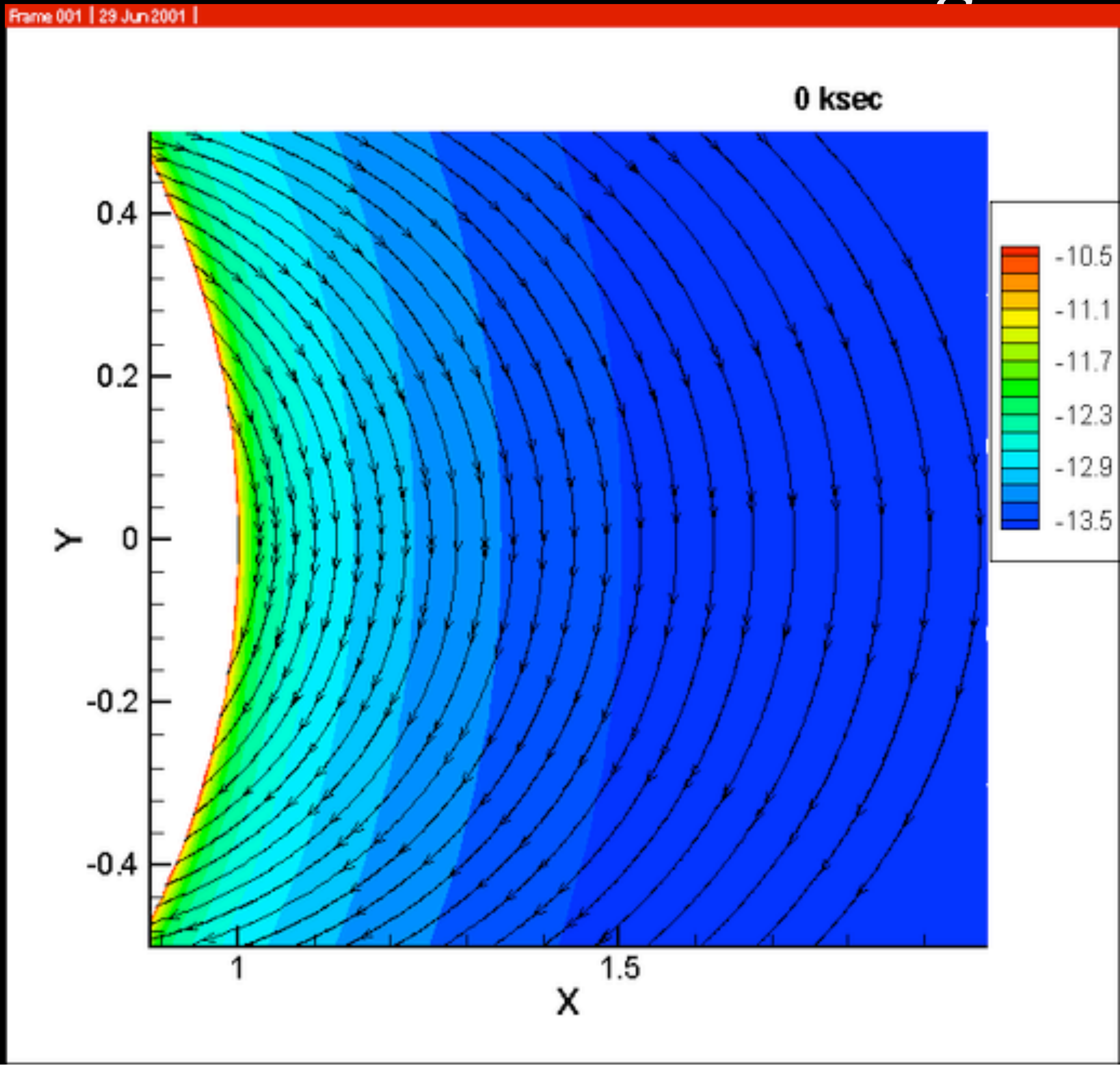
$\eta_{*}=1$

MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement parameter

$\eta_{*}=1$



MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement parameter

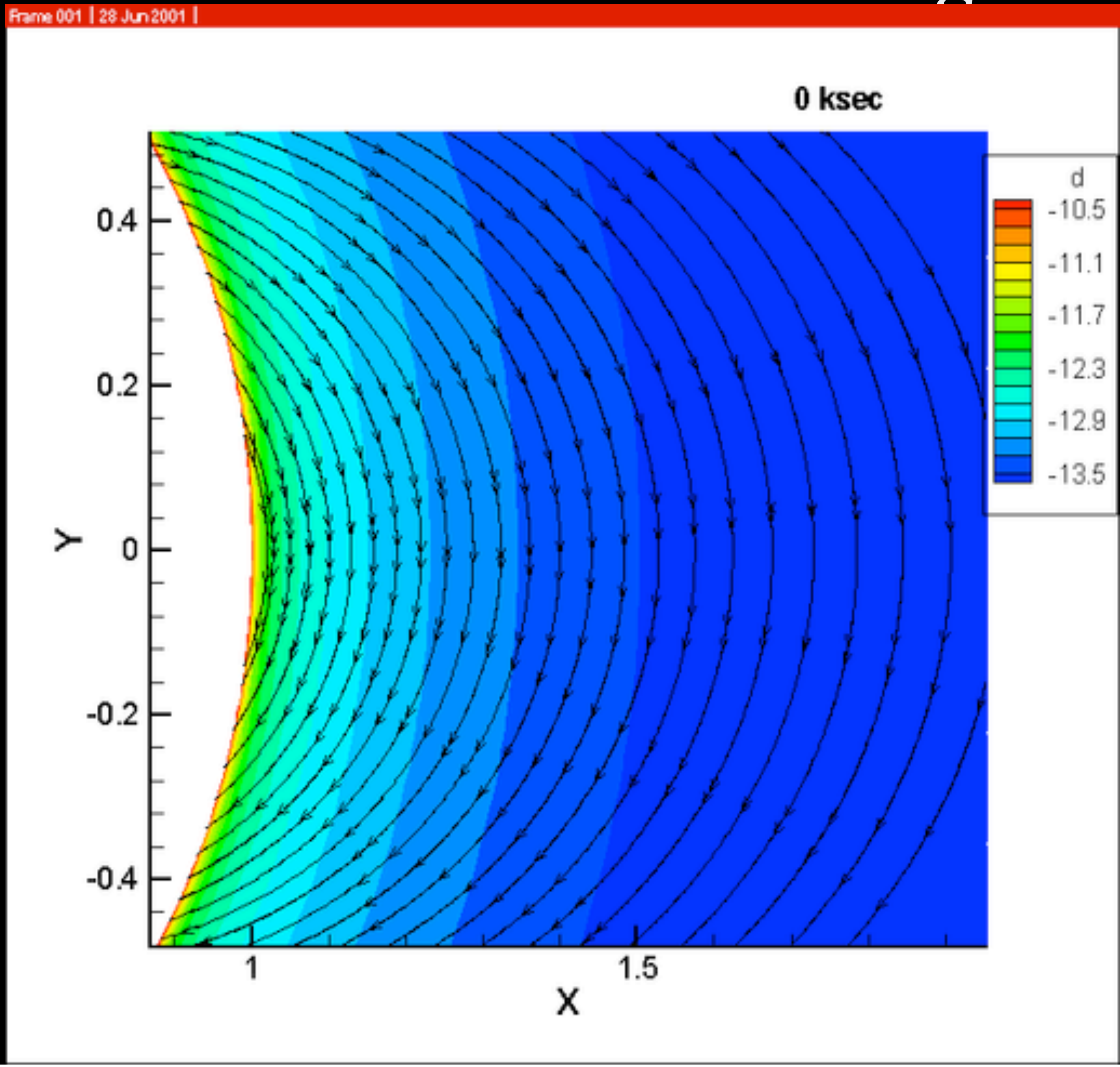
$\eta_* = 3$

MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement parameter

$\eta_* = 3$



MHD Simulation of Wind Channeling

Isothermal

No Rotation

Confinement parameter

$\eta_{*}=10$

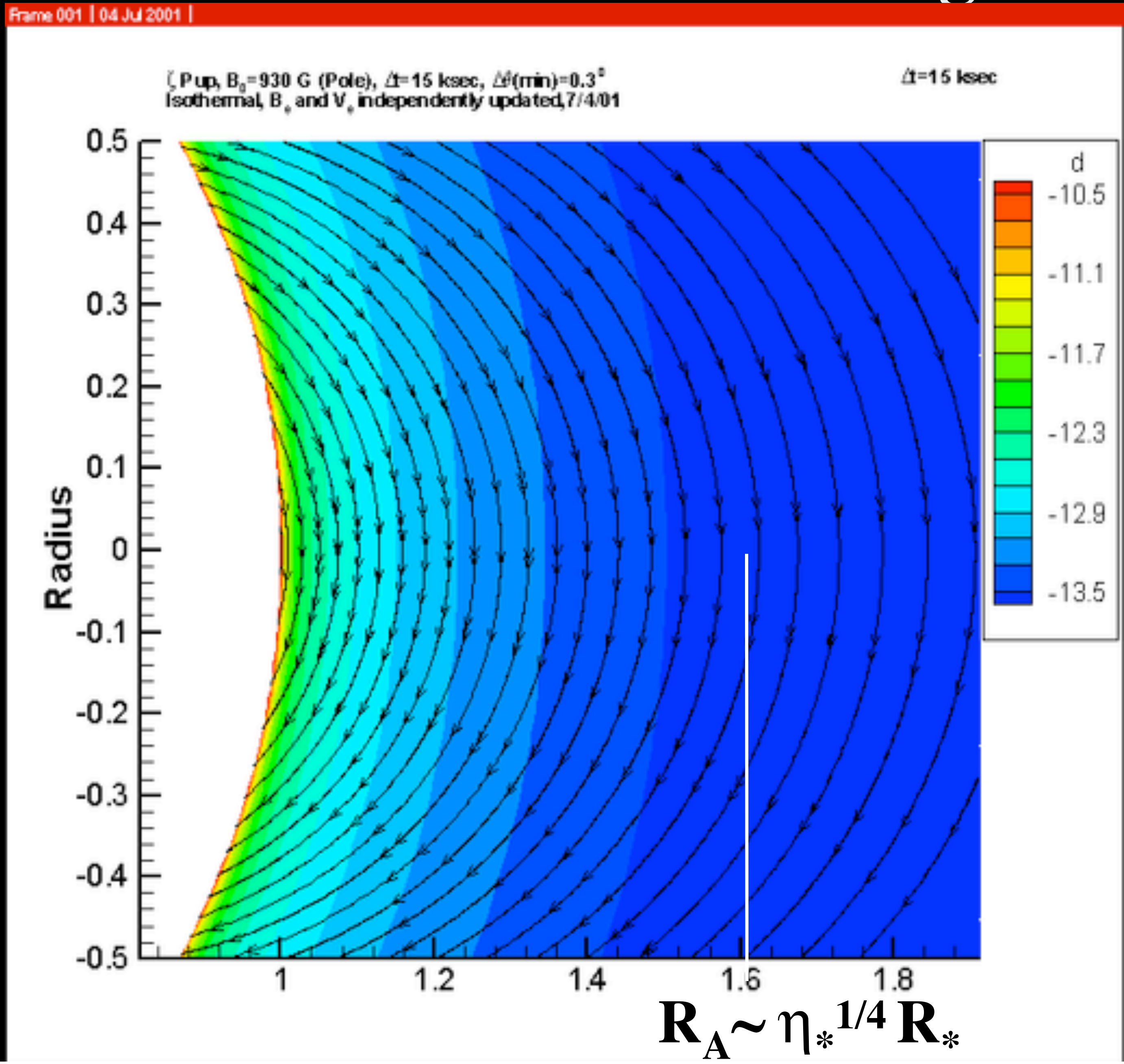
MHD Simulation of Wind Channeling

Isothermal

No Rotation

Confinement parameter

$\eta_* = 10$



$R_A \sim \eta_*^{1/4} R_*$

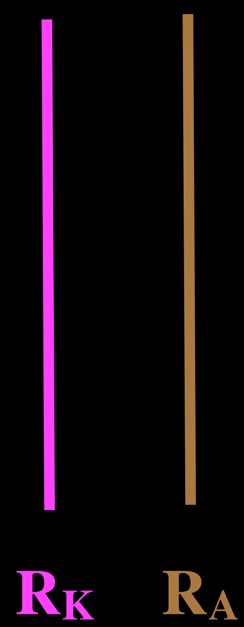
Field-aligned rotation

$\eta_* = 100$

$R_A = 3.2 R_*$

$W = 1/2$

$R_K = 1.6\ R_*$



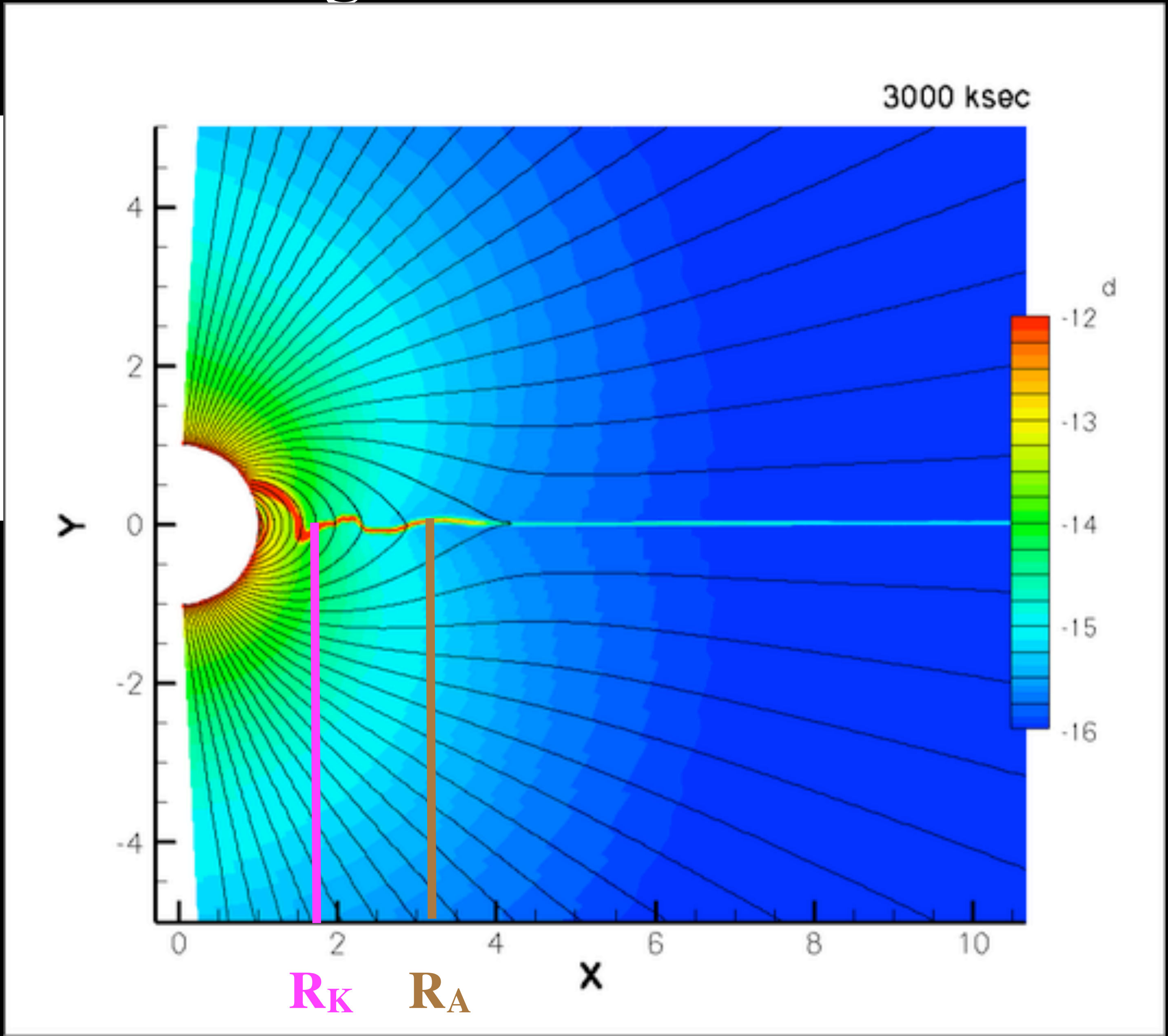
Field-aligned rotation

$\eta_* = 100$

$R_A = 3.2 R_*$

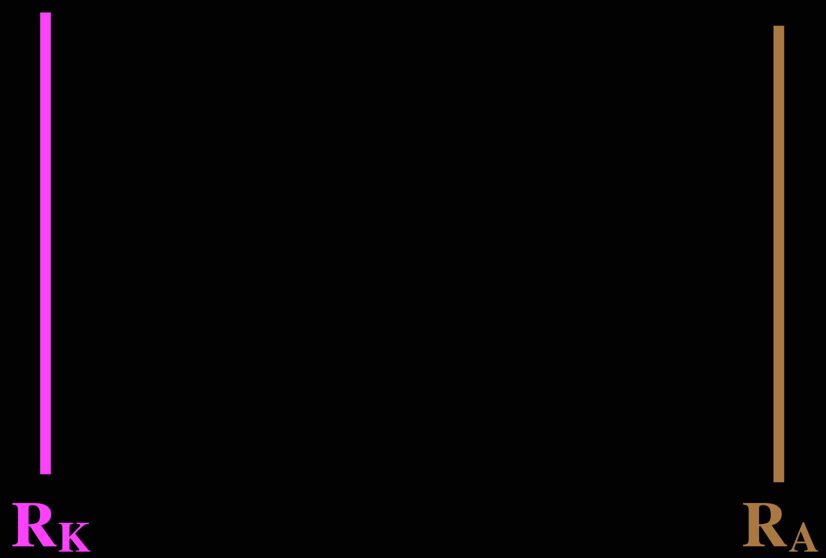
$W = 1/2$

$R_K = 1.6\ R_*$



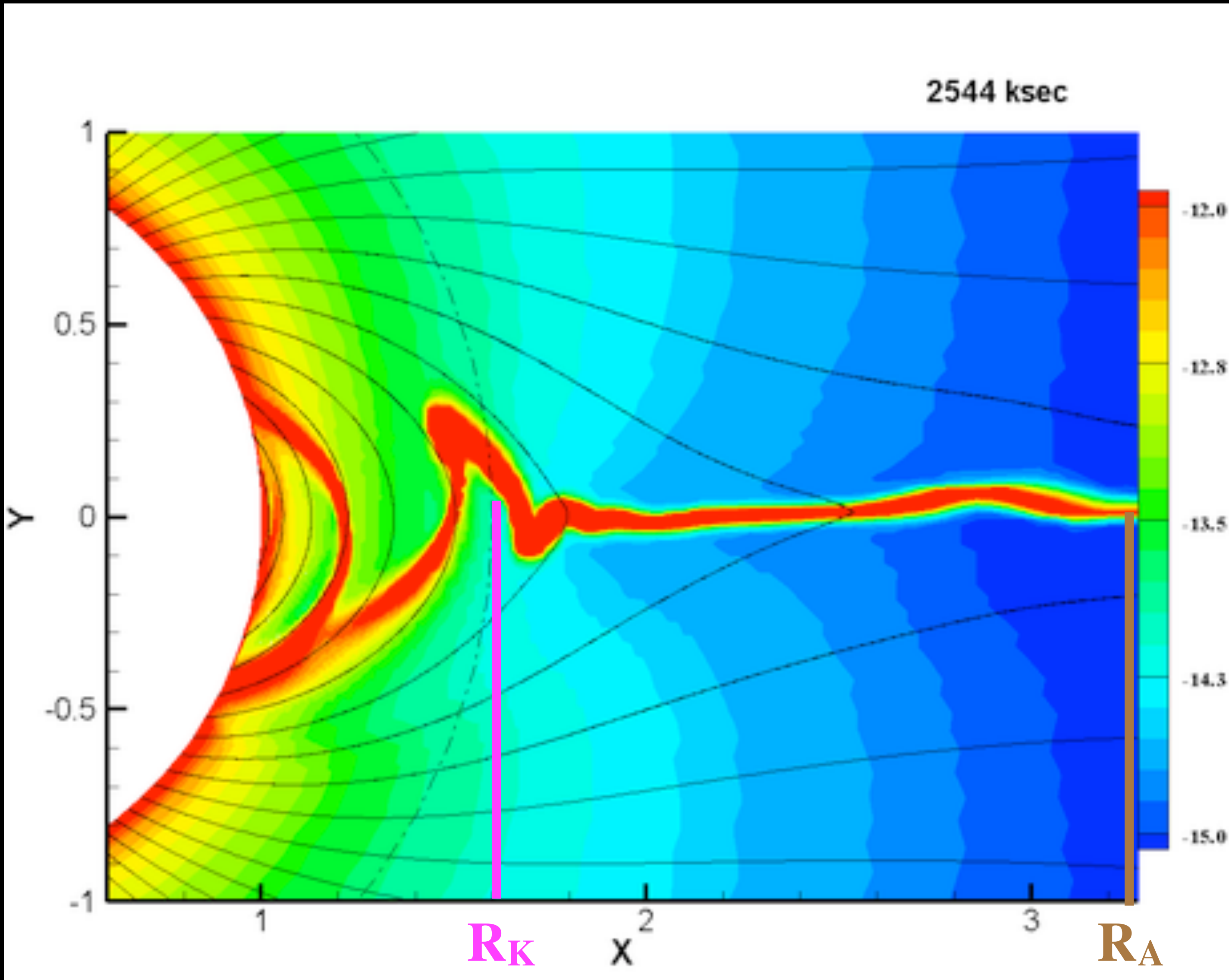
Strong Field + Rapid rotation

$\eta_* = 100$ $W = 1/2$

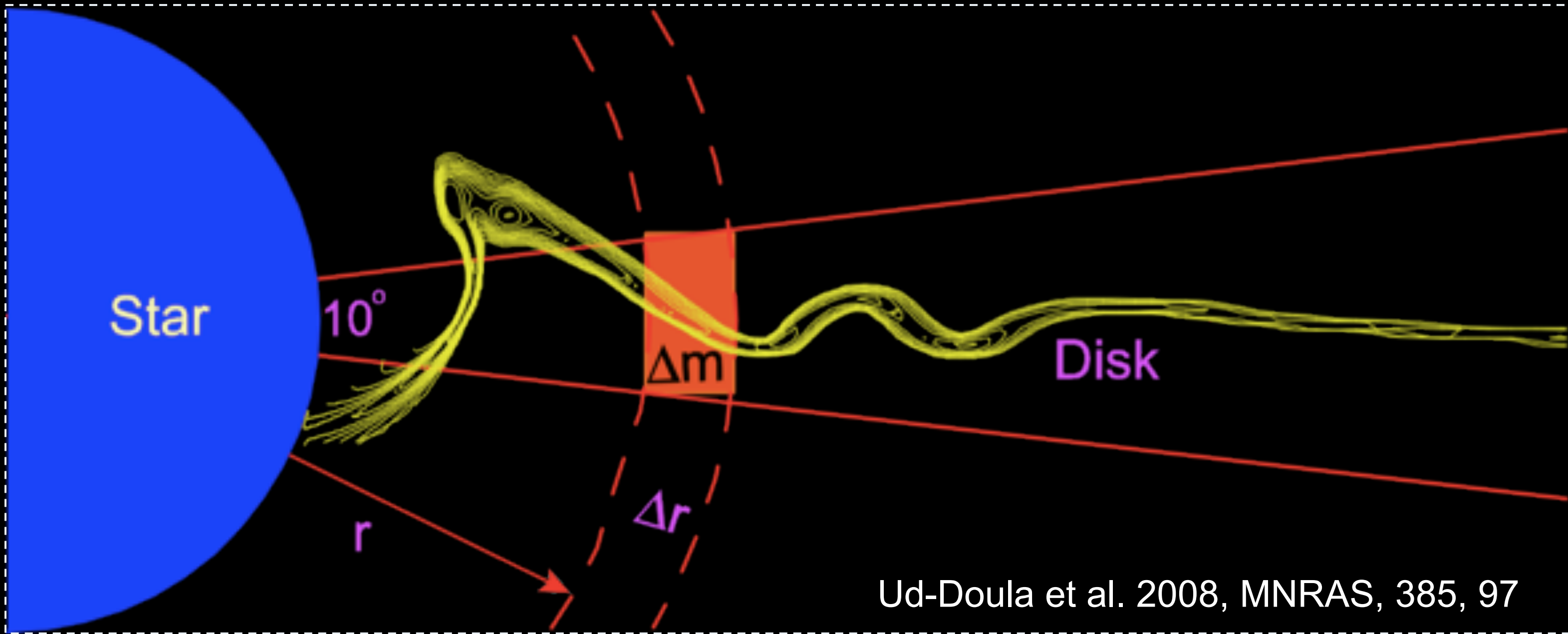


Strong Field + Rapid rotation

$\eta_*=100$ W=1/2



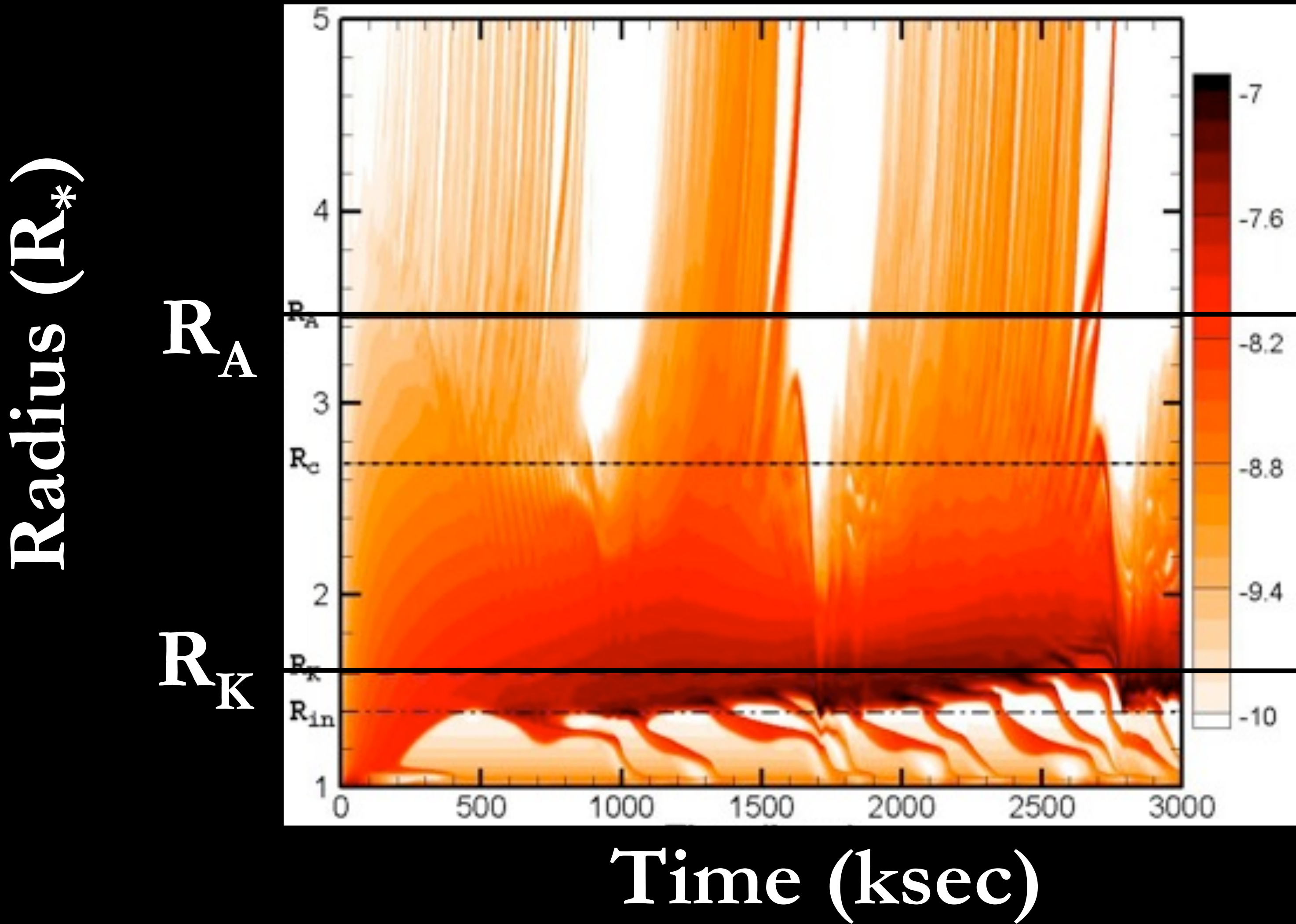
Radial Mass Distribution



$$\frac{dm_e(r,t)}{dr} \equiv 2\pi r^2 \int_{\pi/2-\Delta\theta/2}^{\pi/2+\Delta\theta/2} \rho(r,\theta,t)\sin\theta\, d\theta$$

Time evolution of Radial distribution of equatorial disk mass

$\eta_* = 100$ & Vrot/Vcrit =1/2

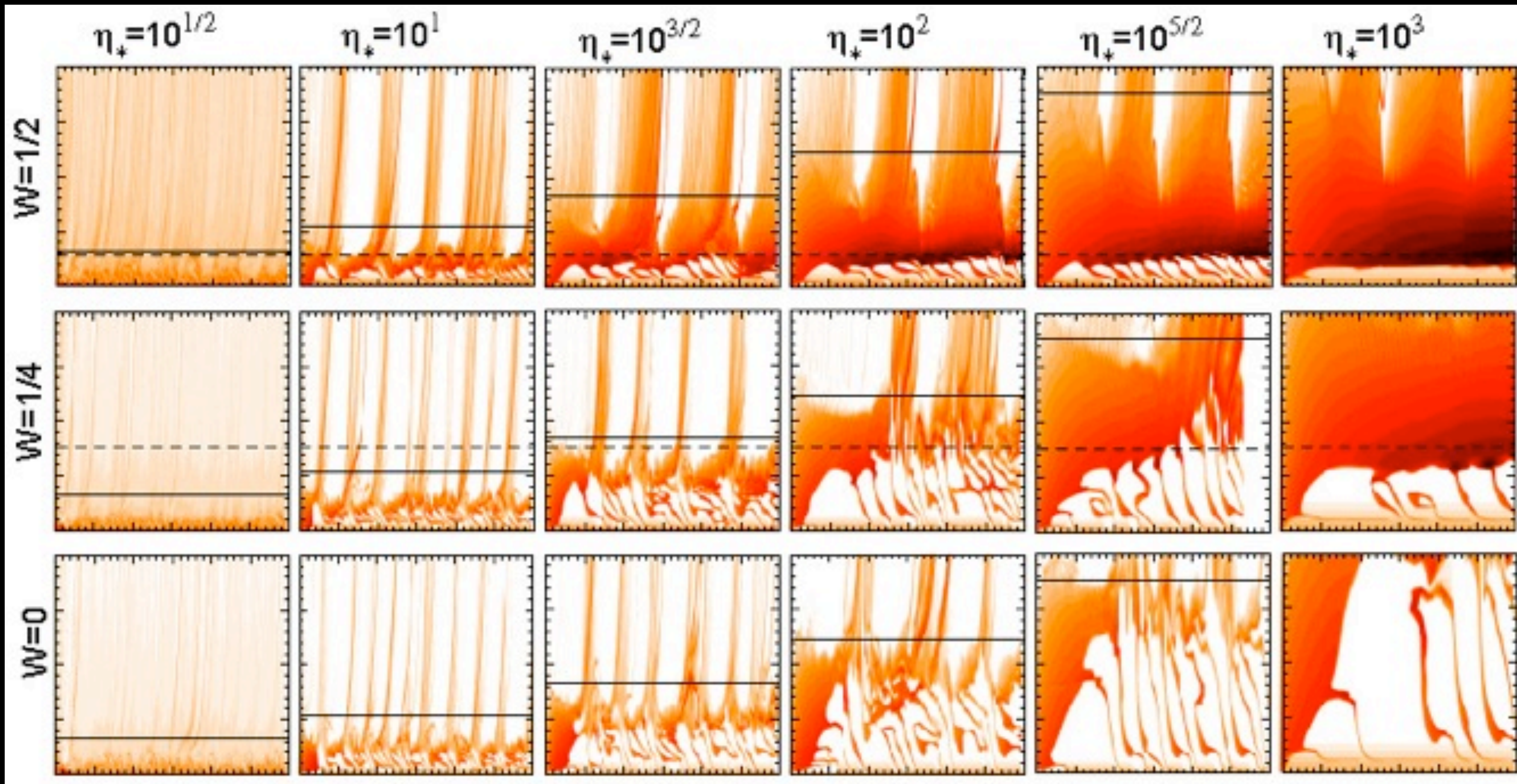


Ud-Doula et al. 2008, MNRAS, 385, 97

Temporal evolution of radial distribution of equatorial disk mass

r=1-5

More Rapid Rotation --->



t=0-3 Msec

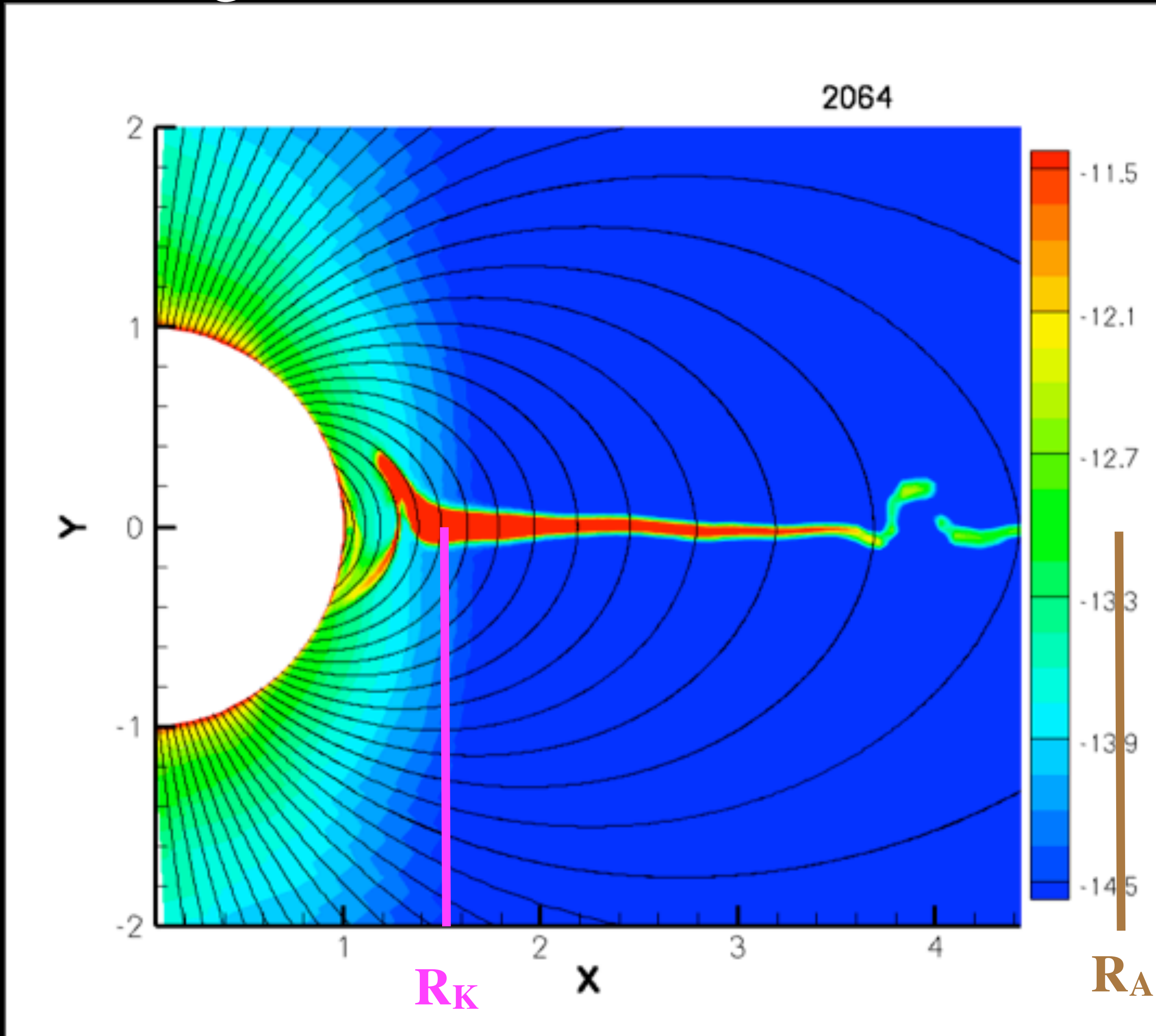
Stronger Magnetic Confinement --->

Ud-Doula et al. 2008, MNRAS, 385, 97

Strongest MHD sim

$\eta_* = 1000$

$W = 1/2$



Magnetic Bp Stars

Magnetic Bp Stars

- σ Ori E (B2p V)
  - P_{rot} = 1.2 days => $v_{rot}/v_{crit} \sim 1/2$
  - $B_{obs} \sim 10^4$ G => $\eta_* \sim 10^7$!
  - => V_{Alfven} very large => Courant time very small
  - => Direct MHD impractical

Magnetic Bp Stars

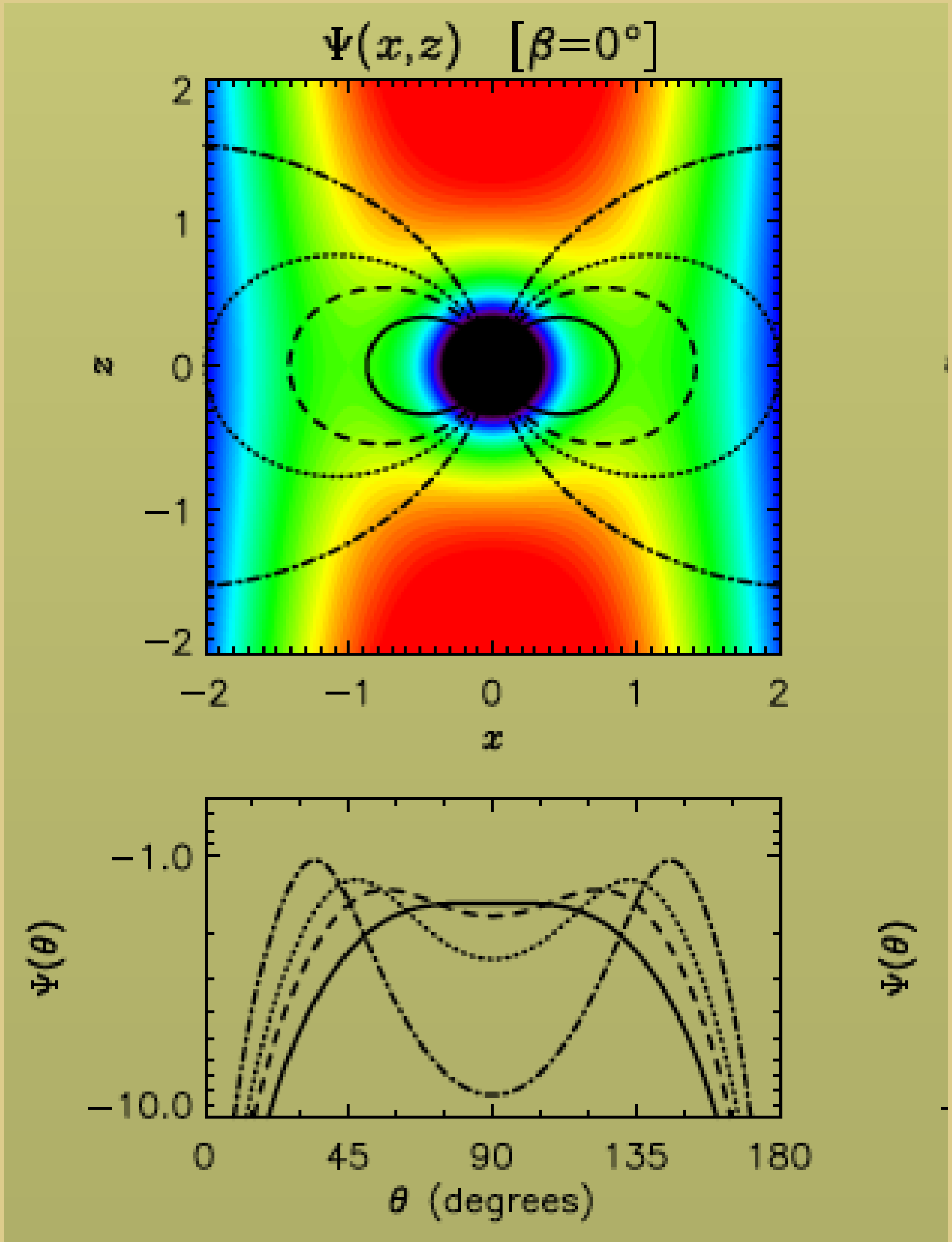
- σ Ori E (B2p V)
  - P_{rot} = 1.2 days => $v_{rot}/v_{crit} \sim 1/2$
  - $B_{obs} \sim 10^4$ G => $\eta_* \sim 10^7$!
  - => V_{Alfven} very large => Courant time very small
  - => Direct MHD impractical

Magnetic Bp Stars

- σ Ori E (B2p V)
  - P_{rot} = 1.2 days => $v_{rot}/v_{crit} \sim 1/2$
  - $B_{obs} \sim 10^4$ G => $\eta_* \sim 10^7$!
  - => V_{Alfven} very large => Courant time very small
  - => Direct MHD impractical

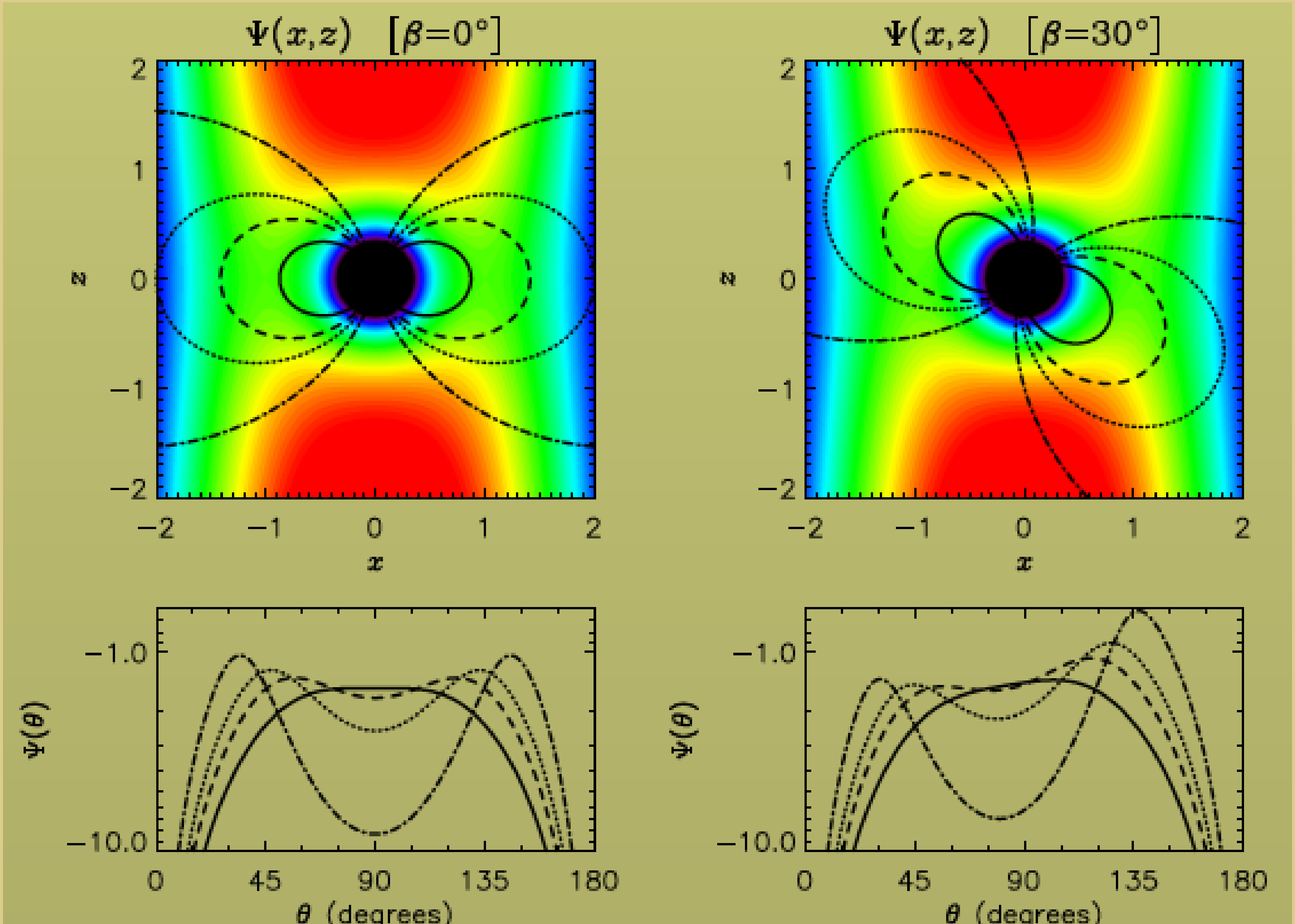
- Instead treat fields lines as Rigid guides
  - **Torque up** wind outflow
  - **Hold down** disk material vs. centrifugal force

Effective Gravitational+Centrifugal Potential



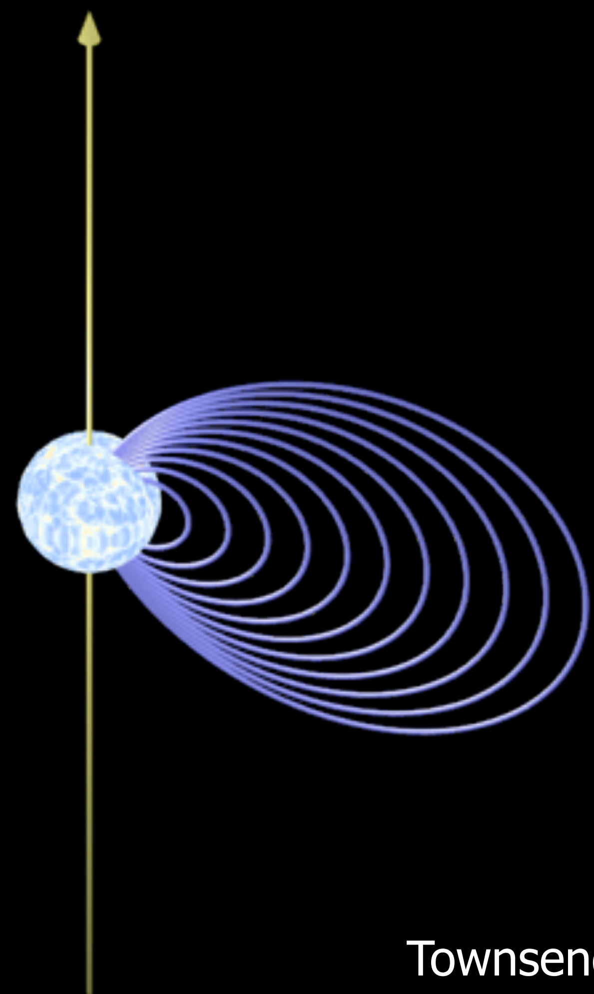
Townsend & Owocki 2005, MNRAS, 357, 251

Effective Gravitational+Centrifugal Potential



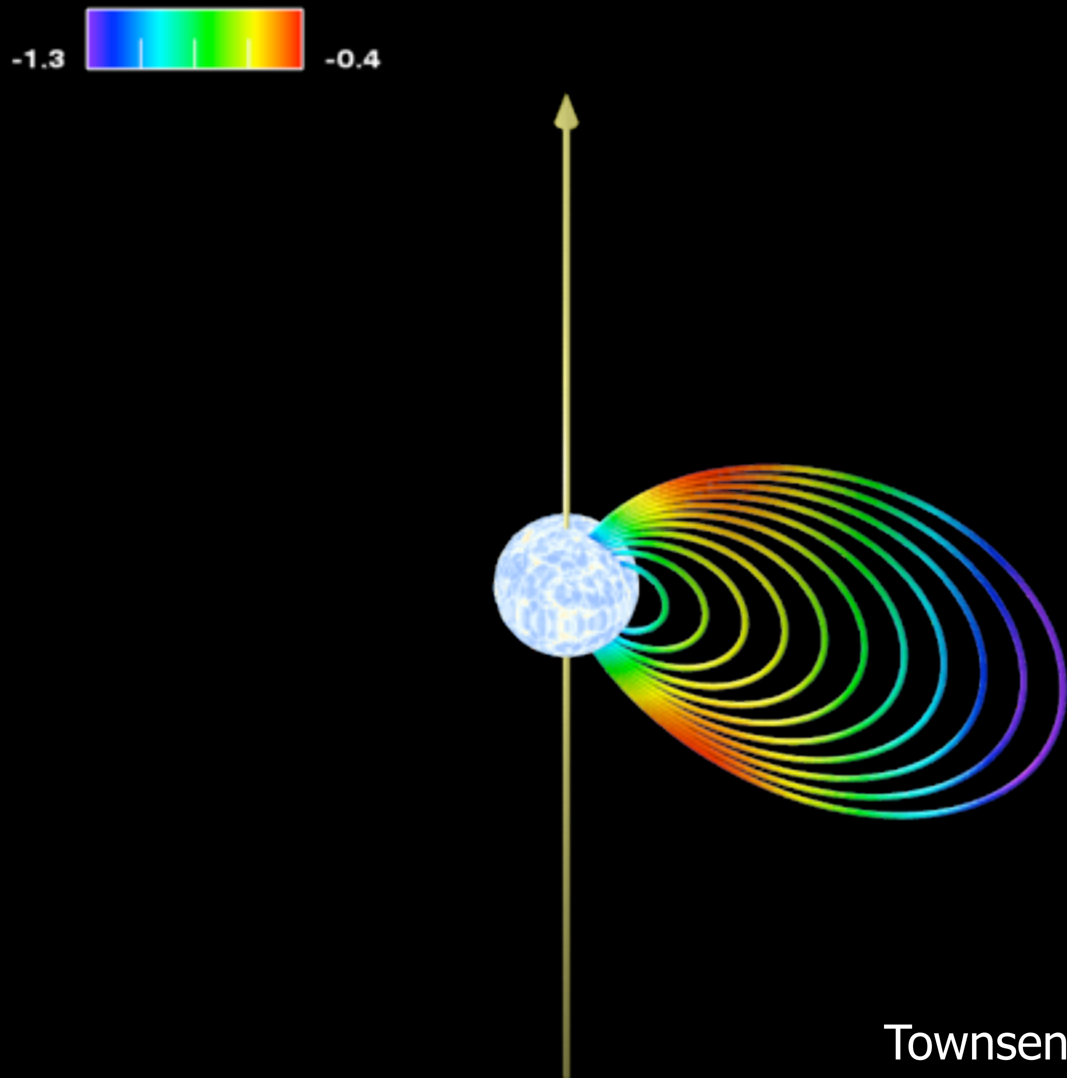
Townsend & Owocki 2005, MNRAS, 357, 251

Rigidly Rotating Magnetosphere



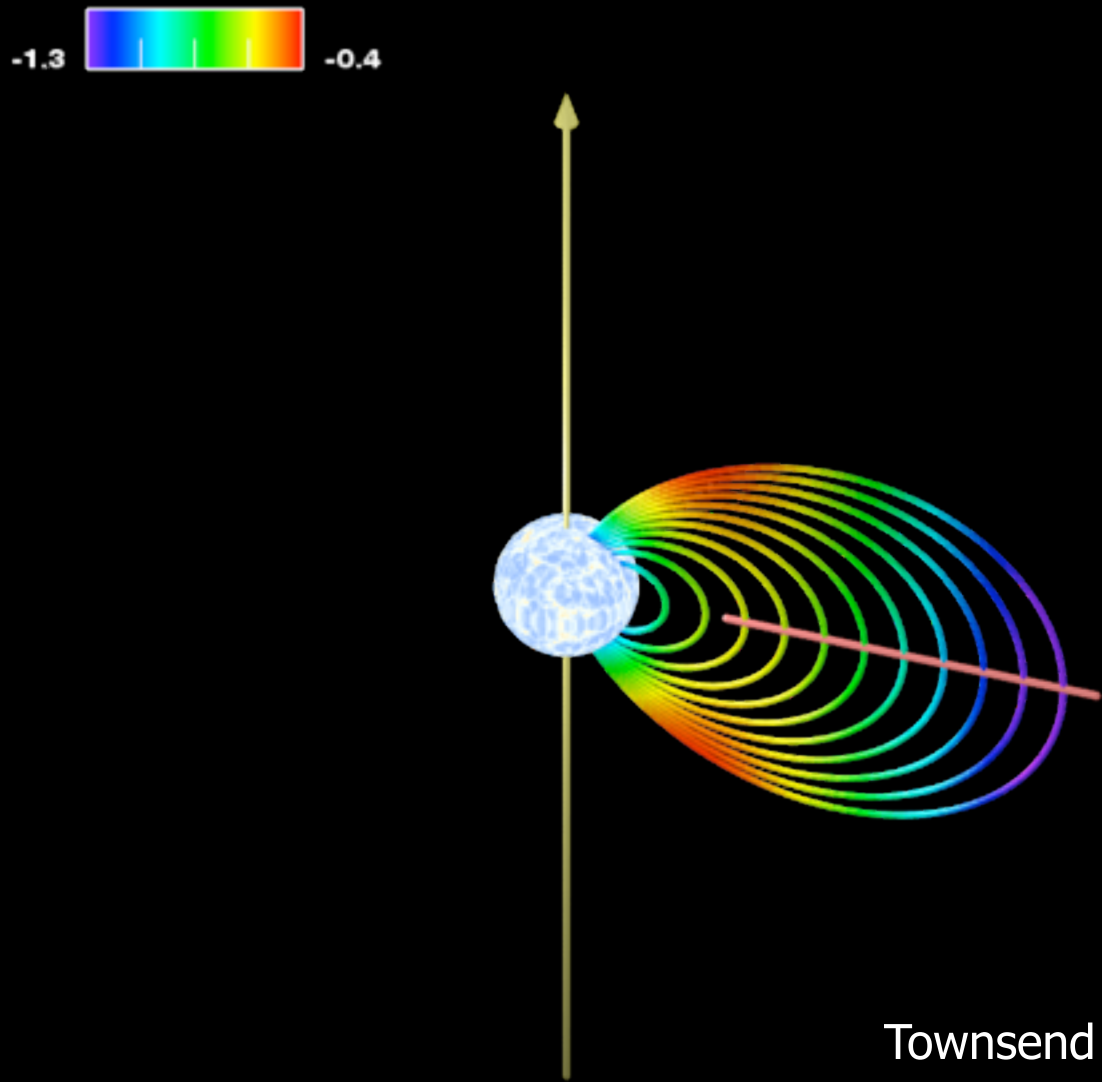
Townsend & Owocki (2005)

Rigidly Rotating Magnetosphere



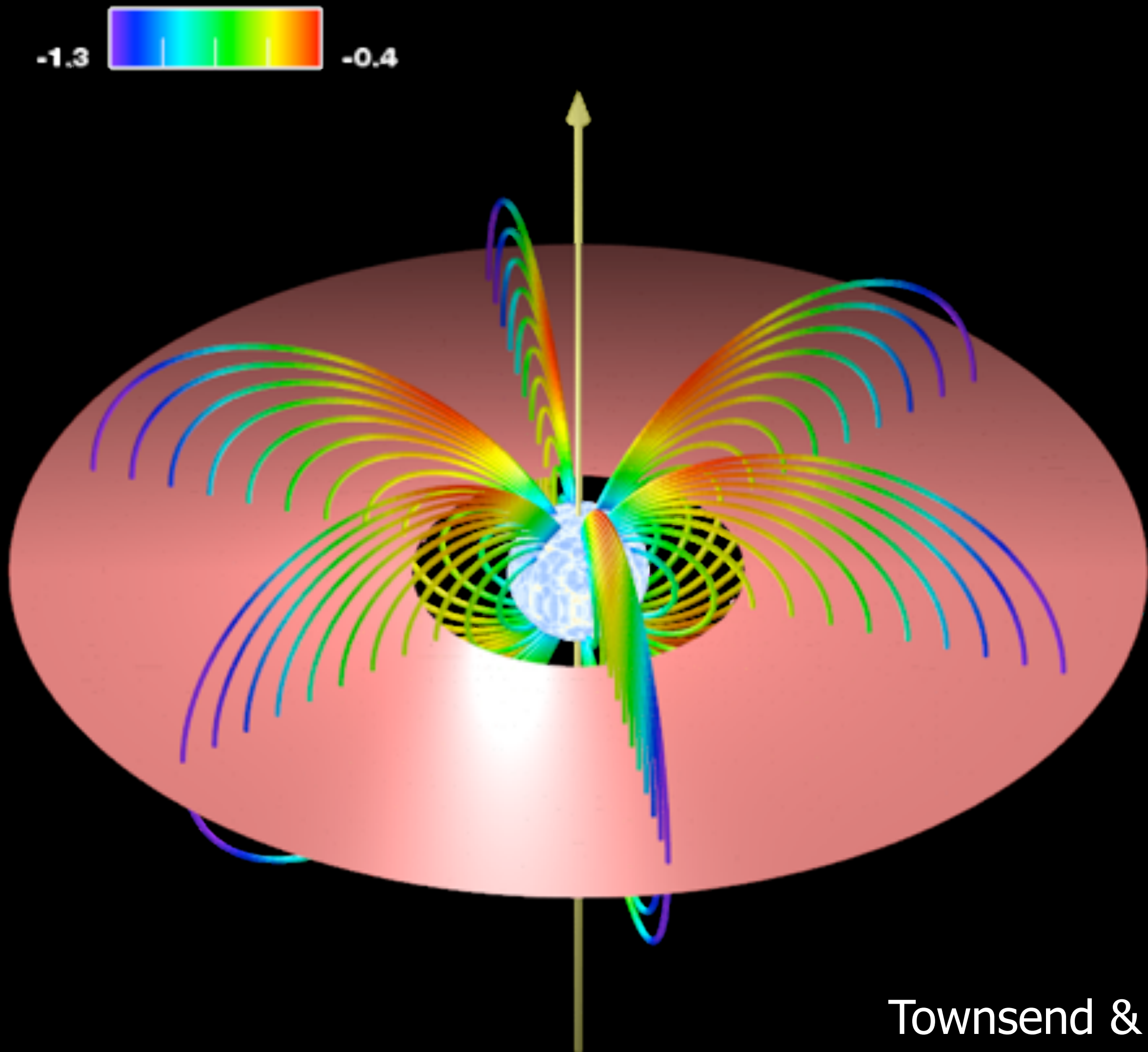
Townsend & Owocki (2005)

Rigidly Rotating Magnetosphere



Townsend & Owocki (2005)

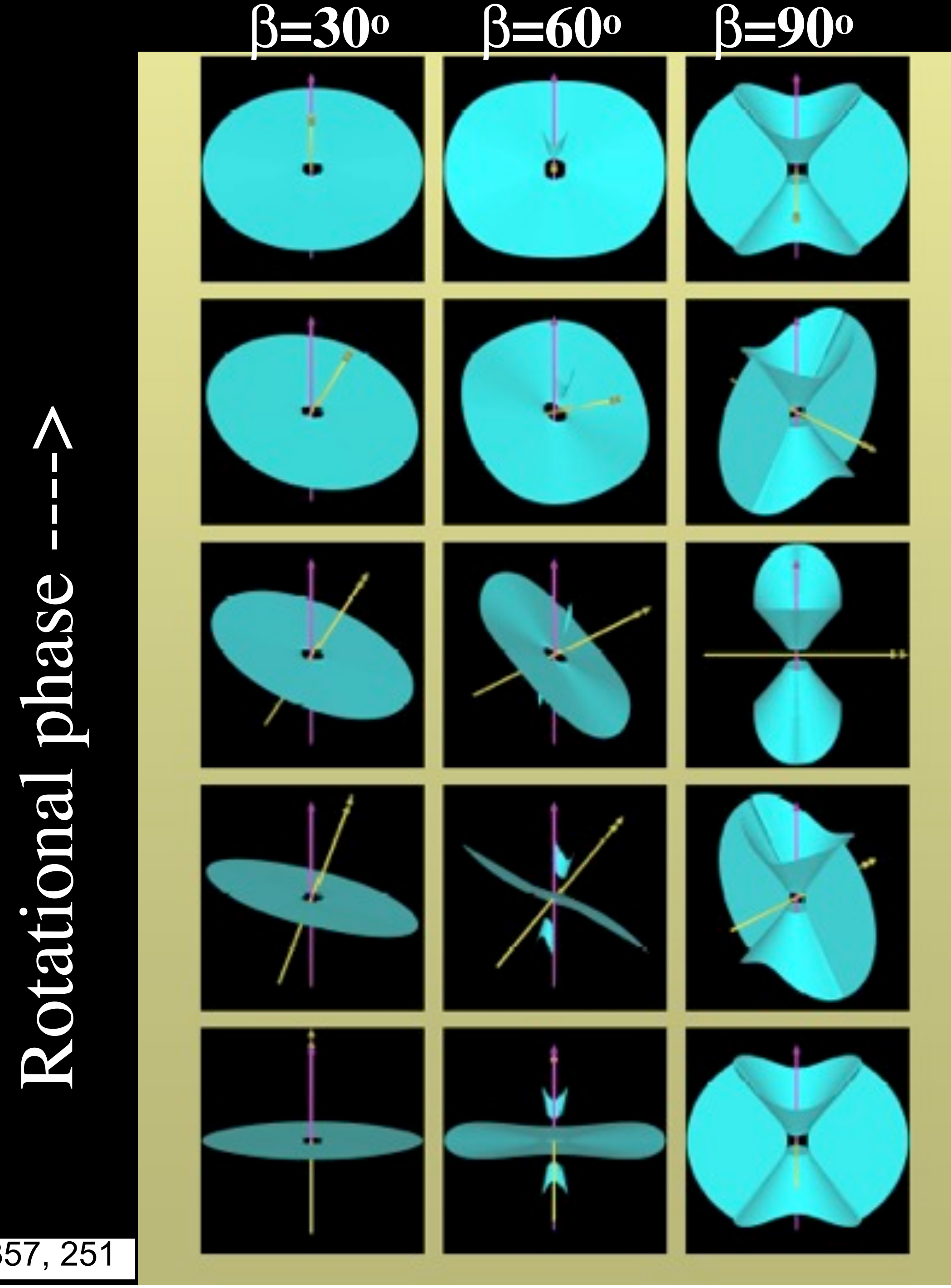
Rigidly Rotating Magnetosphere



Townsend & Owocki (2005)

Accumulation Surfaces

observed from **i=60°**



Townsend & Owocki 2005, MNRAS, 357, 251

RRM model
for σ Ori E

$B_* \sim 10^4$ G

$\eta_* \sim 10^6$!

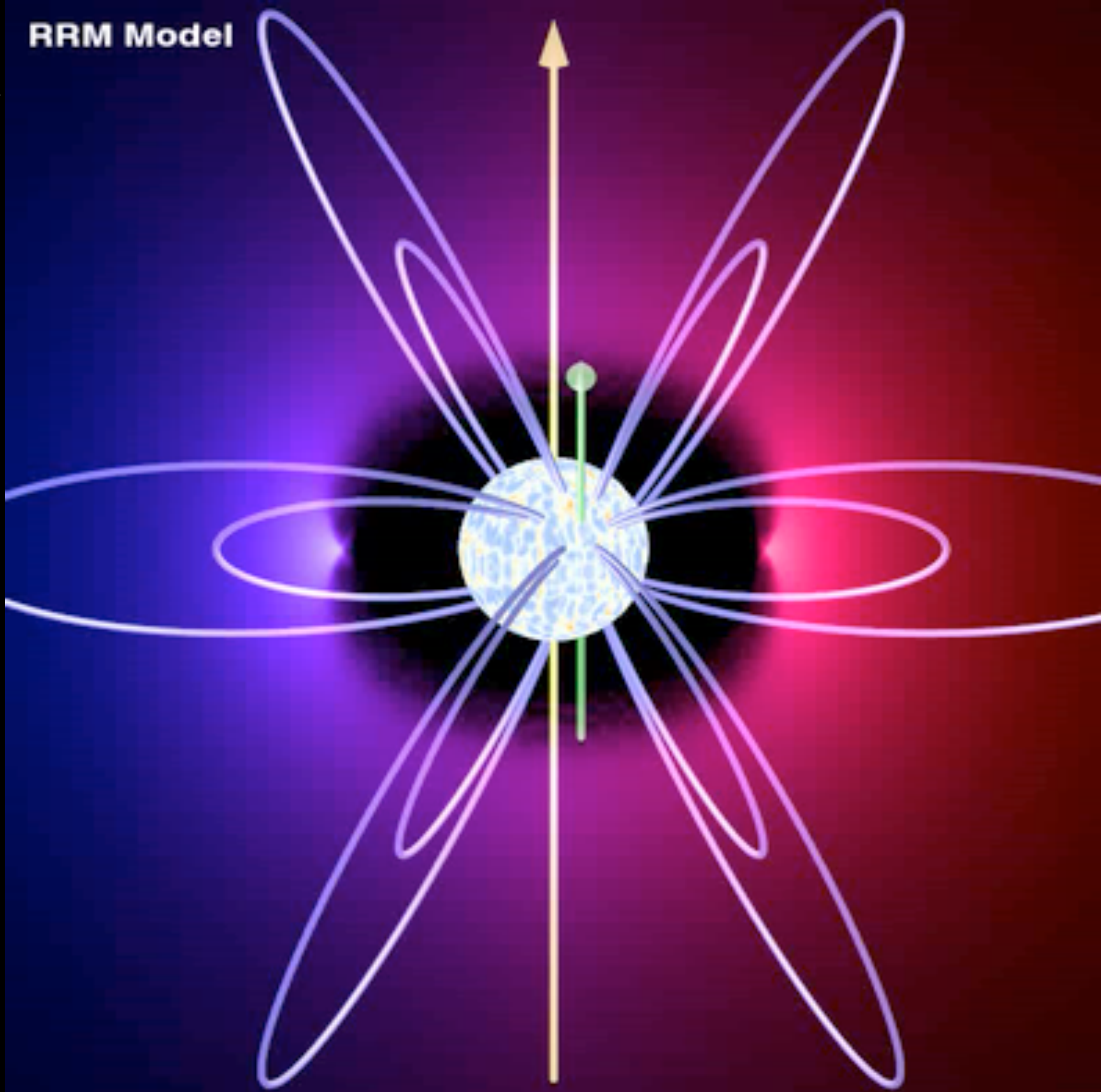
tilt $\sim 55^o$

RRM model for σ Ori E

$B_* \sim 10^4$ G

$\eta_* \sim 10^6$!

tilt ~ 55^o



RRM model for σ Ori E

EM +B-field

photometry

B_*~10^4 G

=> η_*~10^6 !

tilt ~ 55^o

Hα

polarimetry

RRM model for σ Ori E

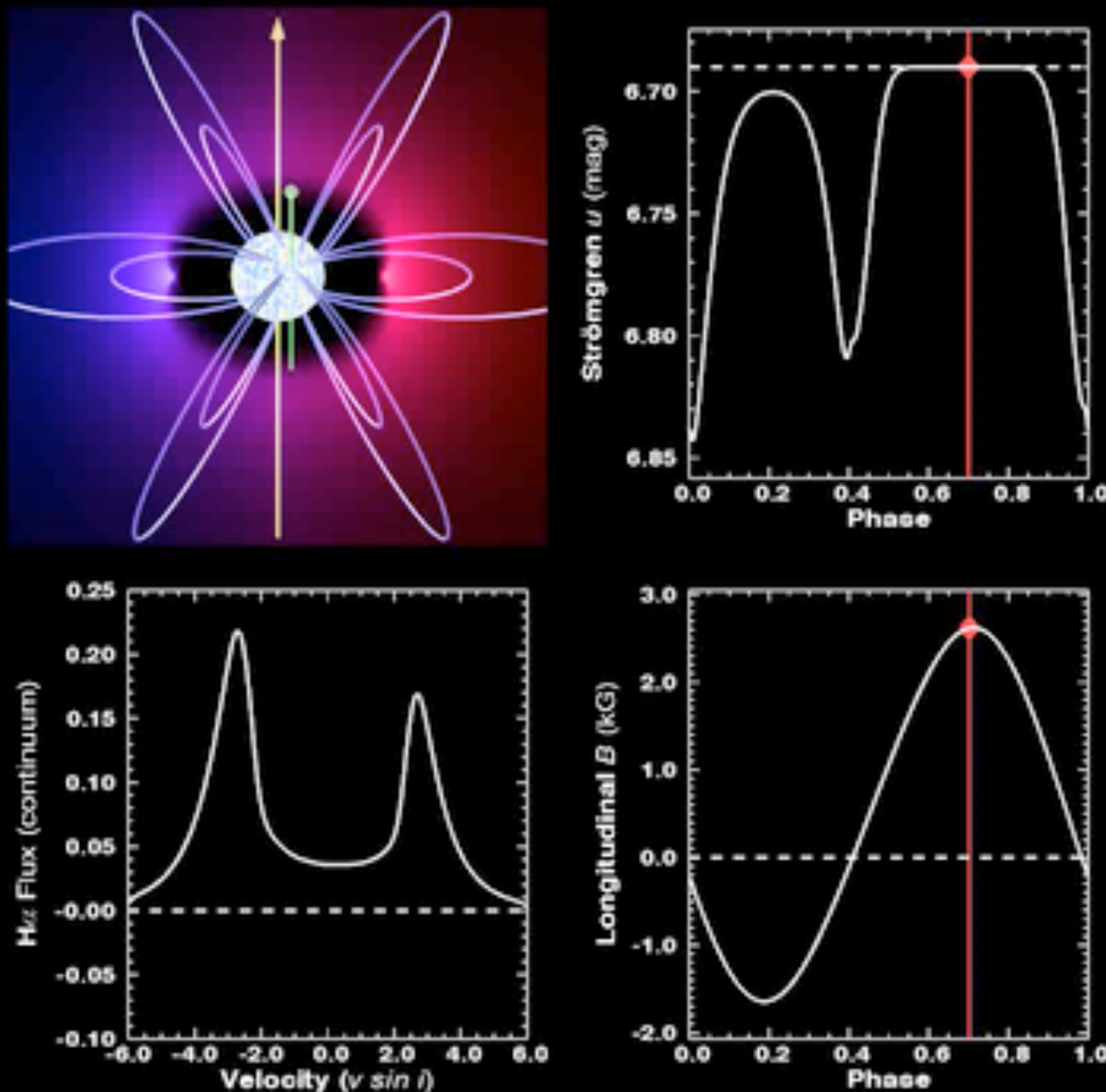
$B_* \sim 10^4$ G

$\Rightarrow \eta_* \sim 10^6$!

tilt ~ 55°

EM +B-field

photometry



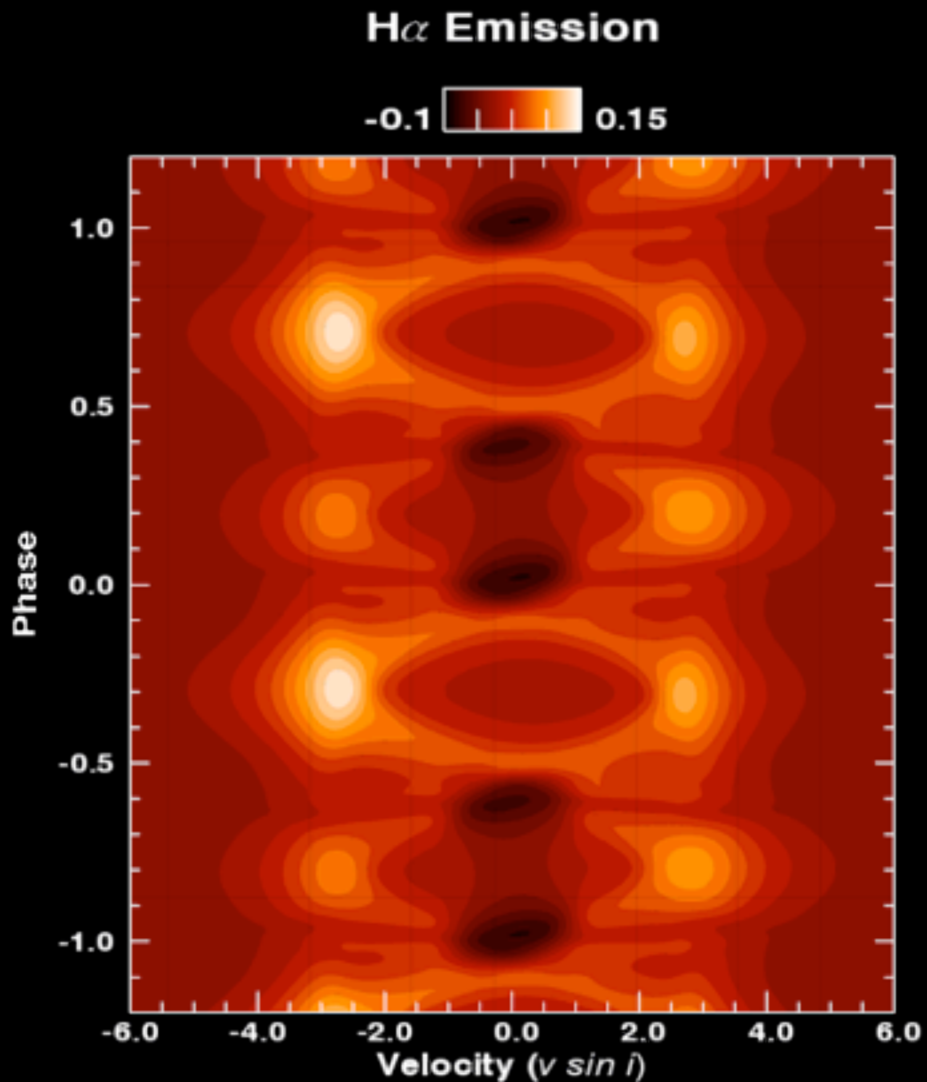
Hα

polarimetry

σ Ori E

Townsend et al. 2005, ApJ, 630, 81

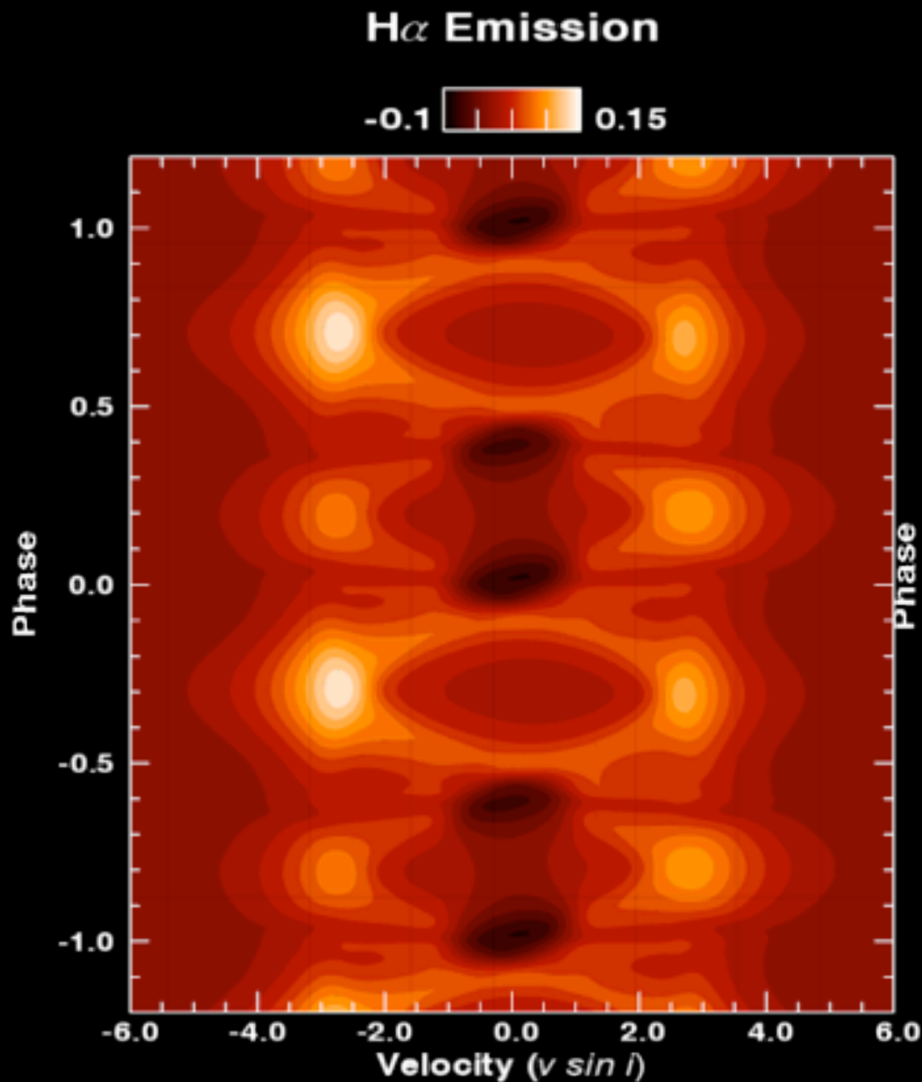
RRM Model



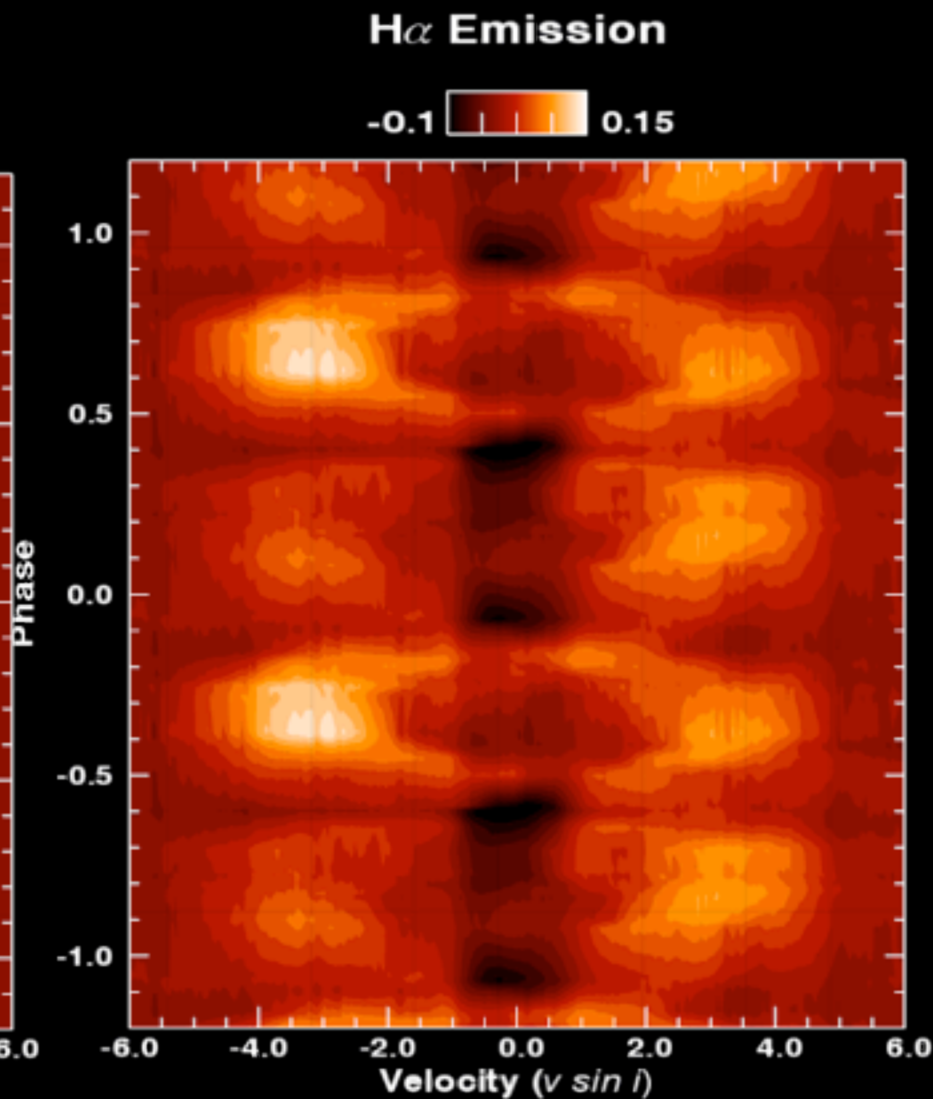
σ Ori E

Townsend et al. 2005, ApJ, 630, 81

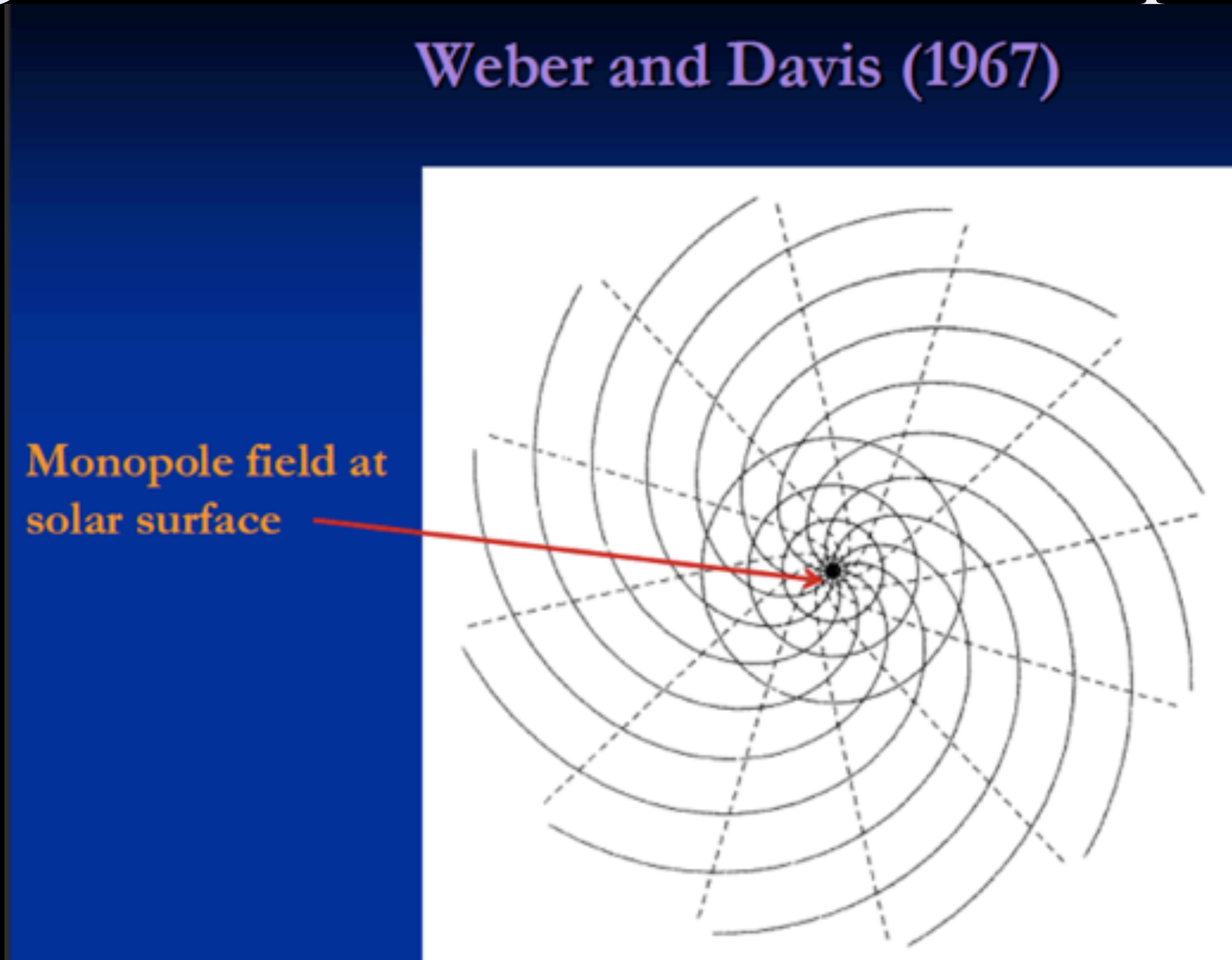
RRM Model



Hα Observations



Angular Momentum Loss & Spindown



$$\dot{J} = \frac{2}{3}\dot{M}\,\Omega R_A^2$$

Weber & Davis 1967

Spindown for n=1 monopole field

Total equatorial Ang. mom/mass

gas field

$$j = V_\phi r - \frac{B_\phi B_r r}{\rho V_r}$$

Weber & Davis 1967

Spindown for n=1 monopole field

Total equatorial Ang. mom/mass

gas field

$$j = V_\phi r - \frac{B_\phi B_r r}{\rho V_r}$$

Frozen flux

&

$$\frac{B_\phi}{B_r} = \frac{\Omega r - V_\phi}{V_r}$$

Weber & Davis 1967

Spindown for n=1 monopole field

Total equatorial Ang. mom/mass

Frozen flux

gas field

$$j = V_\phi r - \frac{B_\phi B_r r}{\rho V_r} \quad \& \quad \frac{B_\phi}{B_r} = \frac{\Omega r - V_\phi}{V_r}$$

=> $$j_{gas} \equiv V_\phi r = \frac{j M_A^2 - \Omega r^2}{M_A^2 - 1}$$

Weber & Davis 1967

Spindown for n=1 monopole field

Total equatorial Ang. mom/mass — Frozen flux

gas — field

$$j = V_\phi r - \frac{B_\phi B_r r}{\rho V_r} \quad \& \quad \frac{B_\phi}{B_r} = \frac{\Omega r - V_\phi}{V_r}$$

=> $$j_{gas} \equiv V_\phi r = \frac{j M_A^2 - \Omega r^2}{M_A^2 - 1}$$

At r= R_A,
M_A=1 implies

$$j = \Omega R_A^2$$

Spindown

$$\dot{J} = \frac{2}{3}\dot{M}\,\Omega R_A^2$$

contribution from both matter & field

$$\tau_{spin} \equiv \frac{J}{\dot{J}} \approx \frac{\frac{3}{2}I}{MR^2}\frac{M}{\dot{M}}\frac{1}{\eta_*^{1/n}} = \tau_{mass}\frac{\frac{3}{2}k}{\eta_*^{1/n}}$$

For dipole:

$$\frac{\tau_{spin}}{\tau_{mass}} \approx \frac{0.15}{\sqrt{\eta_*}}$$

Mon. Not. R. Astron. Soc. (2008) doi:10.1111/j.1365-2966.2008.14134.x

Dynamical simulations of magnetically channelled line-driven stellar winds – III. Angular momentum loss and rotational spin-down

Asif ud-Doula,[1★] Stanley P. Owocki[2] and Richard H. D. Townsend[3]
[1]Department of Physics, Morrisville State College, Morrisville, NY 13408, USA
[2]Bartol Research Institute, University of Delaware, Newark, DE 19716, USA
[3]Department of Astronomy, University of Wisconsin-Madison, 5534 Sterling Hall, 475 N Charter Street, Madison, WI 53706, USA

Accepted 2008 October 23. Received 2008 September 25; in original form 2008 August 4

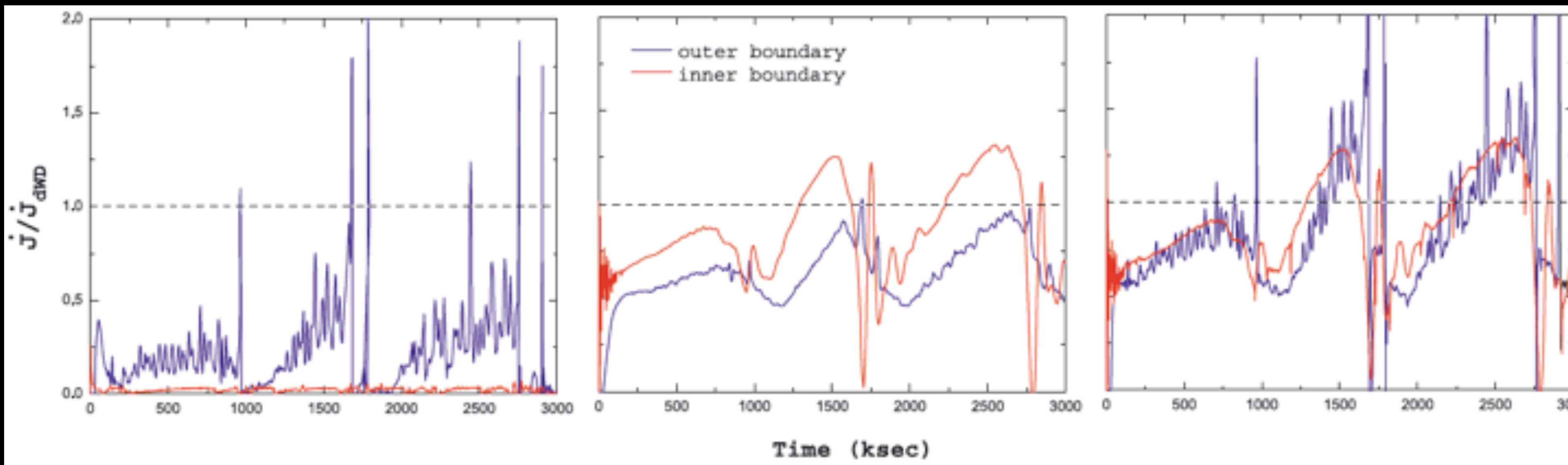
ABSTRACT

We examine the angular momentum loss and associated rotational spin-down for magnetic hot stars with a line-driven stellar wind and a rotation-aligned dipole magnetic field. Our analysis here is based on our previous two-dimensional numerical magnetohydrodynamics simulation study that examines the interplay among wind, field and rotation as a function of two dimensionless parameters: one characterizing the wind magnetic confinement ($\eta_* \equiv B_{\rm eq}^2 R_*^2/\dot{M} v_\infty$) and the other the ratio ($W \equiv V_{\rm rot}/V_{\rm orb}$) of stellar rotation to critical (orbital) speed. We compare and contrast the two-dimensional, time-variable angular momentum loss of this dipole model of a hot-star wind with the classical one-dimensional steady-state analysis by Weber and Davis (WD), who used an idealized monopole field to model the angular momentum loss in the solar wind. Despite the differences, we find that the total angular momentum loss $\dot{J}$ averaged over both solid angle and time closely follows the general WD scaling $\dot{J} = (2/3)\dot{M}\Omega R_{\rm A}^2$, where $\dot{M}$ is the mass-loss rate, Ω is the stellar angular velocity and $R_{\rm A}$ is a characteristic Alfvén radius. However, a key distinction here is that for a dipole field, this Alfvén radius has a strong-field scaling $R_{\rm A}/R_* \approx \eta_*^{1/4}$, instead of the scaling $R_{\rm A}/R_* \sim \sqrt{\eta_*}$ for a monopole field. This leads to a slower stellar spin-down time that in the dipole case scales as $\tau_{\rm spin} = \tau_{\rm mass}\, 1.5k/\sqrt{\eta_*}$, where $\tau_{\rm mass} \equiv M/\dot{M}$ is the characteristic mass loss time and k is the dimensionless factor for stellar moment of inertia. The full numerical scaling relation that we cite gives typical spin-down times of the order of 1 Myr for several known magnetic massive stars.

Key words: MHD – stars: early-type – stars: magnetic fields – stars: mass loss – stars: rotation – stars: winds, outflows.

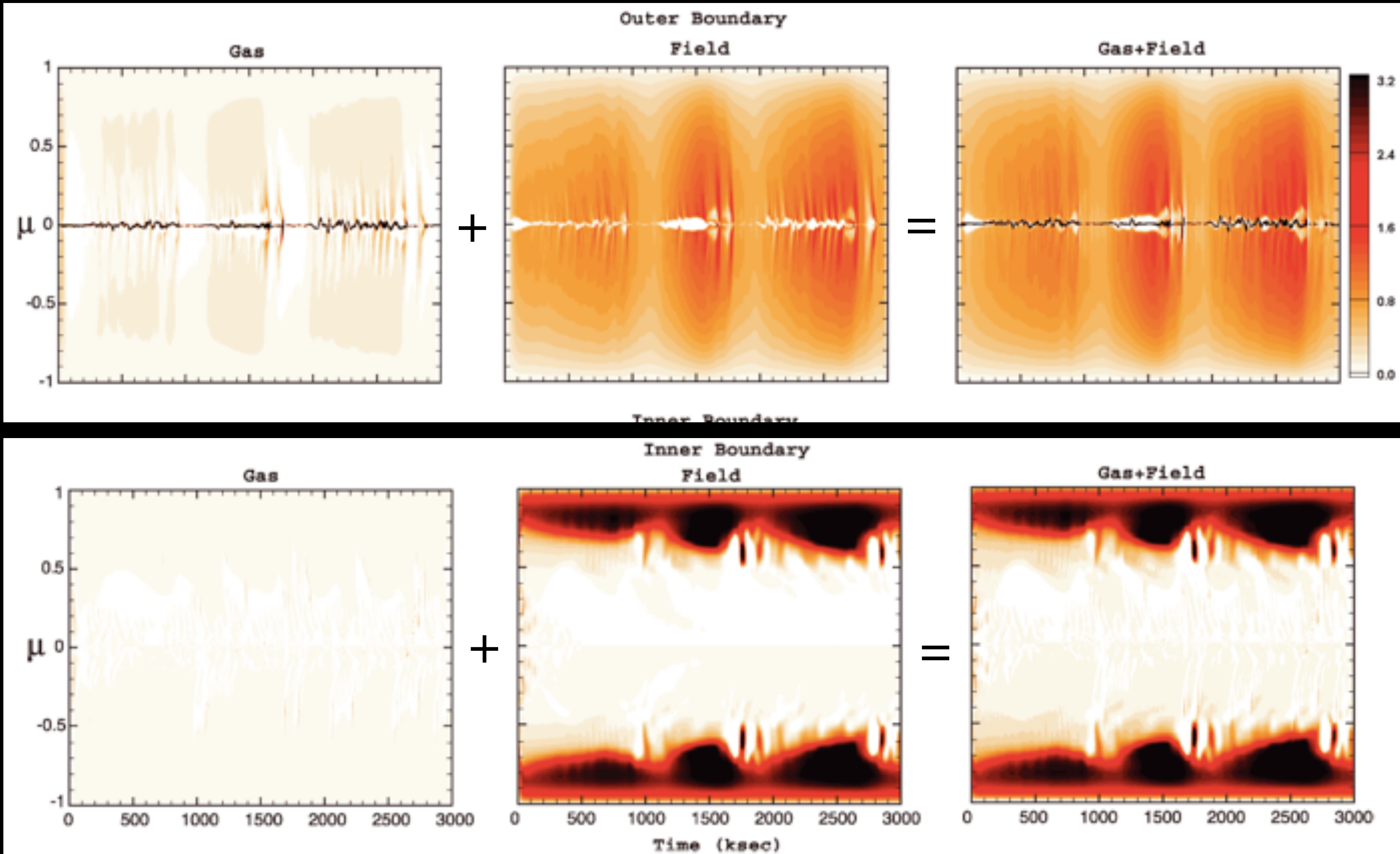
Time variation of total Angular Momentum Loss

Gas Field Total



Ud-Doula et al. 2009, MNRAS, 392, 1022

Angular Momentum Loss vs. latitude & time

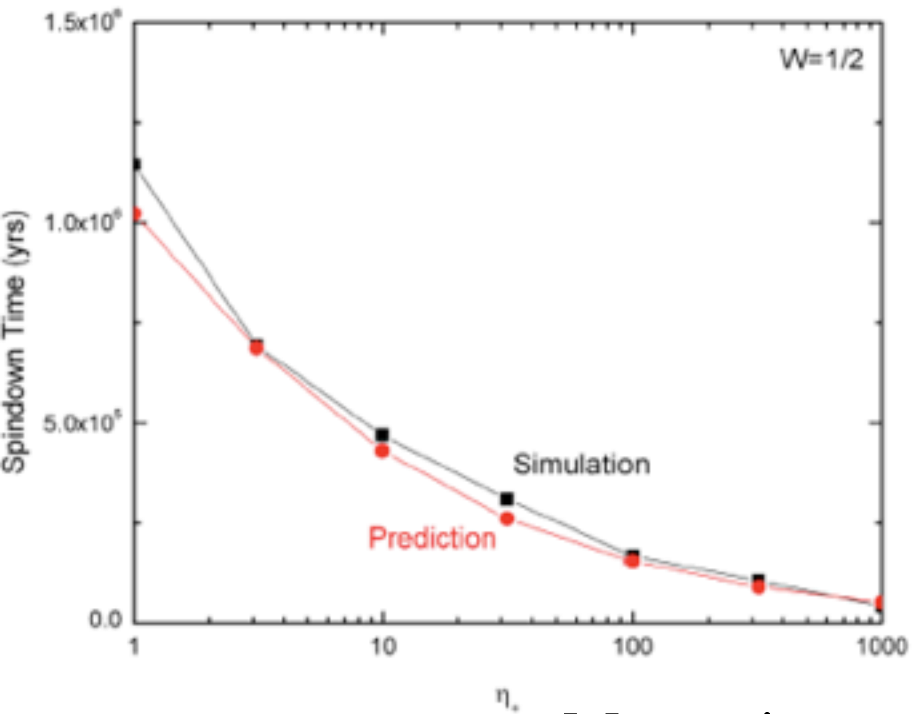


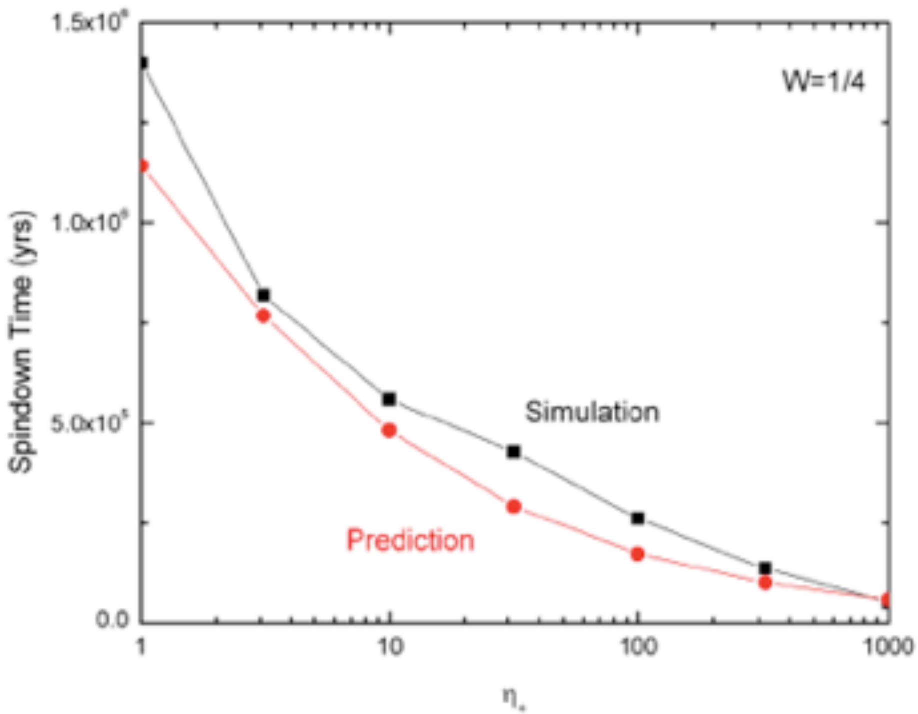
Ud-Doula et al. 2009, MNRAS, 392, 1022

Spindown Time

W=1/2 W=1/4

Ud-Doula et al. 2009, MNRAS, 392, 1022





Magnetic confinement parameter =>

Dipole spindown times

Table 1. Estimated spin-down time for selected known magnetic stars.

Star[a]	$M/M_\odot$	$R_*/R_\odot$	P (d)	k	$\dot{M}$ (10^{-9} $M_\odot$ yr^{-1})	v_∞(1000 km s^{-1})	B_p (kG)	η_*	τ_{spin} (Myr)
θ^1 Ori C[1]	40	8	15.4	0.28	400	2.5	1.1	15.7	8
HD191612[2]	40	18	538	0.17	6100	2.5	1.6	7.6	0.4
ζ Cas[3]	8	5.9	5.37	0.1	0.3	0.8	0.34	3200	65.2
σ Ori E[4]	8.9	5.3	1.2	0.1	2.4	1.46	9.6	1.4×10^5	1.4
ρ Leo[5]	22	35	7-47	0.12	630	1.1	0.24	20	1.1

Ud-Doula et al. 2009, MNRAS, 392, 1022

$$\tau_{spin} \approx \tau_{mass} \frac{\frac{3}{2} k}{\sqrt{\eta_*}}$$

$$\approx 11 Myr \; \frac{k_{-1}}{B_{kG}} \frac{M_*}{R_*} \sqrt{\frac{V_8}{\dot{M}_{-9}}}$$

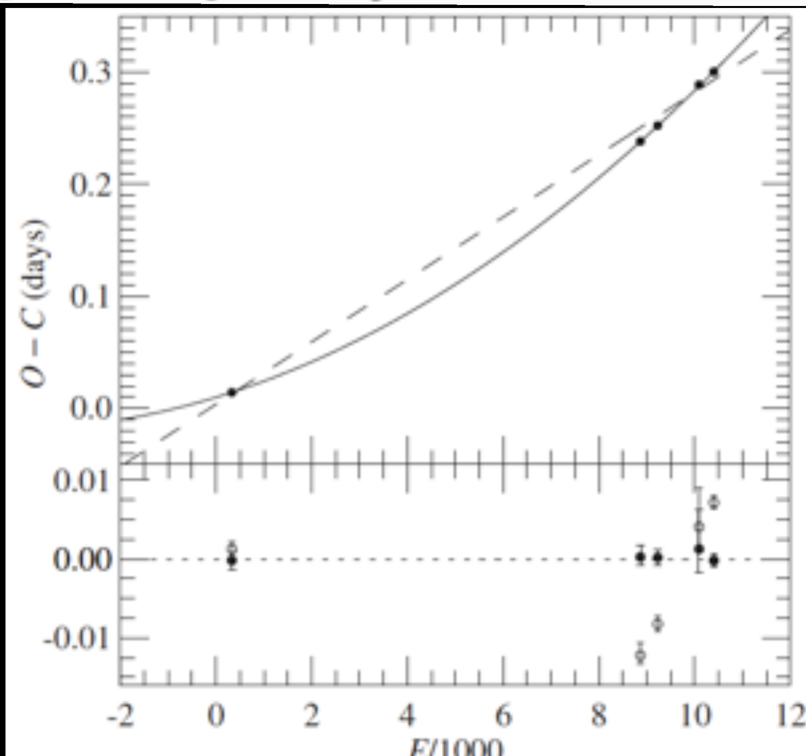
The Astrophysical Journal Letters, 714:L318–L322, 2010 May 10 doi:10.1088/2041-8205/714/2/L318

DISCOVERY OF ROTATIONAL BRAKING IN THE MAGNETIC HELIUM-STRONG STAR SIGMA ORIONIS E

R. H. D. Townsend[1], M. E. Oksala[2], D. H. Cohen[3], S. P. Owocki[2], and A. ud-Doula[4]
[1] Department of Astronomy, University of Wisconsin-Madison, Sterling Hall, 475 N. Charter Street, Madison, WI 53706, USA; townsend@astro.wisc.edu
[2] Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
[3] Department of Physics and Astronomy, Swarthmore College, Swarthmore, PA 19081, USA
[4] Penn State Worthington Scranton, 120 Ridge View Drive, Dunmore, PA 18512, USA
Received 2010 March 12; accepted 2010 April 14; published 2010 April 26

ABSTRACT

We present new *U*-band photometry of the magnetic helium-strong star σ Ori E, obtained over 2004–2009 using the SMARTS 0.9 m telescope at Cerro Tololo Inter-American Observatory. When combined with historical measurements, these data constrain the evolution of the star's 1.19 day rotation period over the past three decades. We are able to rule out a constant period at the $p_{null} = 0.05\%$ level, and instead find that the data are well described ($p_{null} = 99.3\%$) by a period increasing linearly at a rate of 77 ms per year. This corresponds to a characteristic spin-down time of 1.34 Myr, in good agreement with theoretical predictions based on magnetohydrodynamical simulations of angular momentum loss from magnetic massive stars. We therefore conclude that the observations are consistent with σ Ori E undergoing rotational braking due to its magnetized line-driven wind.



Spindown age

$$P = P_o e^{t/\tau_{spin}} \qquad\qquad P_o \approx f P_c$$

Spindown age

$$P = P_o e^{t/\tau_{spin}} \qquad P_o \approx f P_c$$

$$P_c = 0.21\, d\, R\sqrt{R/M} \qquad \Rightarrow\ P_o \sim day$$

Spindown age

$$P = P_o e^{t/\tau_{spin}} \qquad P_o \approx f P_c$$

$$P_c = 0.21\, d\, R\sqrt{R/M} \qquad \Rightarrow\; P_o \sim day$$

$$\tau_{age} = 2.3\,(\mathrm{Log}\,P_{day} - \mathrm{Log}\,P_{o,day})\,\tau_{spin}$$

Spindown age

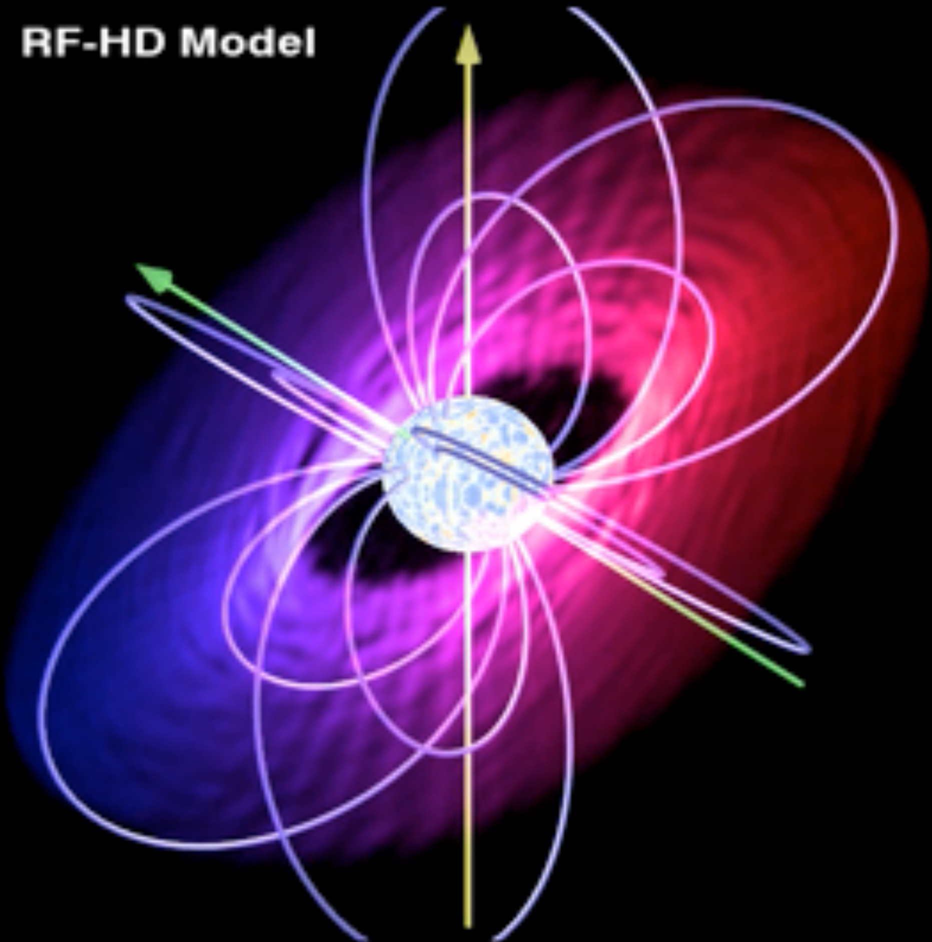
$$P = P_o e^{t/\tau_{spin}} \qquad P_o \approx f P_c$$

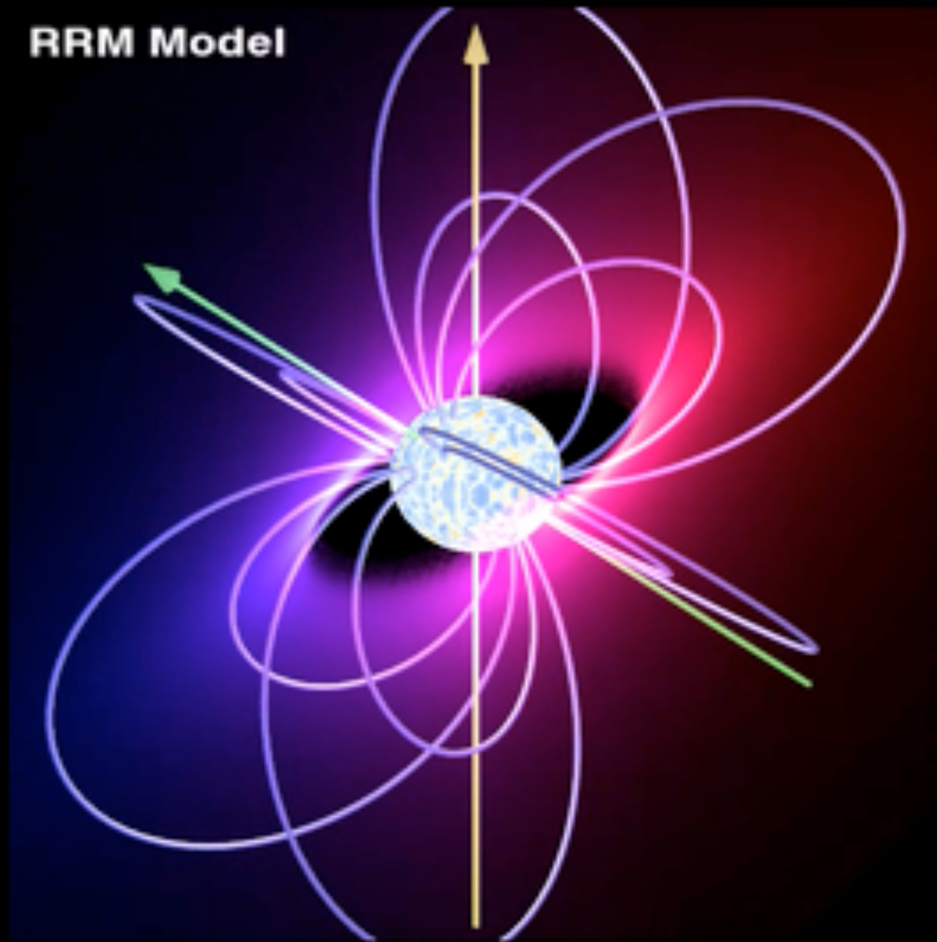
$$P_c = 0.21\, d\, R\sqrt{R/M} \qquad \Rightarrow\ P_o \sim day$$

$$\tau_{age} = 2.3\,(\mathrm{Log}\, P_{day} - \mathrm{Log}\, P_{o,day})\, \tau_{spin}$$

e.g. HD191612, with P_o = 0.5 to 1 day => now P=630 day:

$$\tau_{age} \approx 6.3 \rightarrow 6.9\ \tau_{spin} \approx 2.5 \rightarrow 2.9\ Myr$$


RF-HD Model


RRM Model

Extrapolated spindown law for higher order multipoles?

$$\frac{\tau_{spin}}{\tau_{mass}} = \frac{\frac{3}{2}k}{\eta_*^{1/n}}$$

n=1 monopole
=2 dipole
=3 quadrapole
... etc.

Extrapolated spindown law for higher order multipoles?

$$\frac{\tau_{spin}}{\tau_{mass}} = \frac{\frac{3}{2}k}{\eta_*^{1/n}}$$

n=1 monopole
=2 dipole
=3 quadrapole
... etc.

=> Spindown weaker for more complex fields?

If so, hard to explain tau Sco by spindown??

Extrapolated spindown law for higher order multipoles?

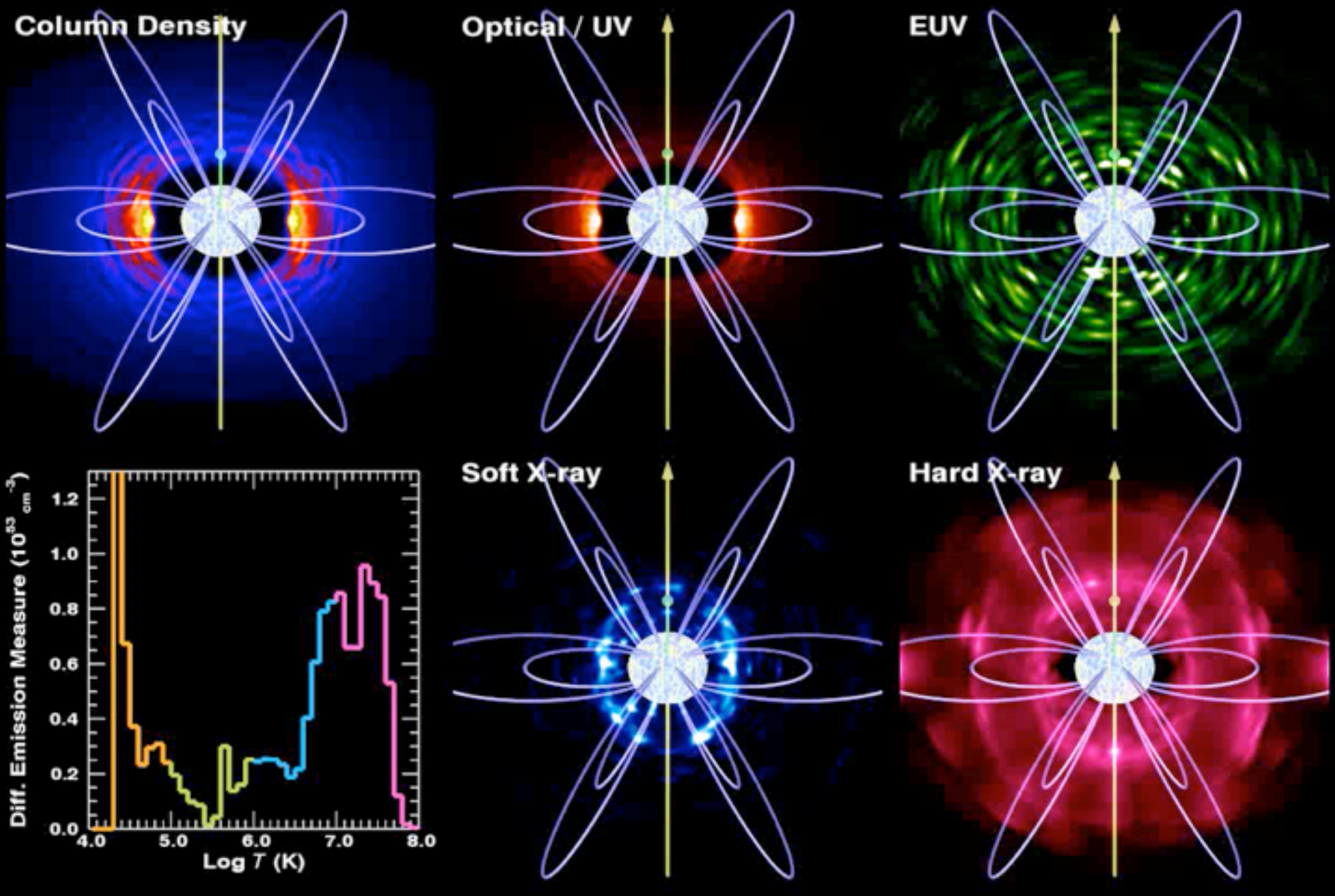
$$\frac{\tau_{spin}}{\tau_{mass}} = \frac{\frac{3}{2}k}{\eta_*^{1/n}}$$

n=1 monopole
=2 dipole
=3 quadrapole
... etc.

=> Spindown weaker for more complex fields?

If so, hard to explain tau Sco by spindown??

Need 3D MHD sims to test this!



Column Density
Optical / UV
EUV
Soft X-ray
Hard X-ray
Diff. Emission Measure (10^{53} cm^{-3})
Log T (K)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
4.0
5.0
6.0
7.0
8.0

Summary

- Wind feeding of magnetosphere
  - balanced by inner & outer “leakage”?
  - observations should estimate M_{tot}
  - breakout analysis predicts M_{tot} indep of M_{dot}!

- Wind Magnetic Spindown
  - $t_{spin} \sim t_{mass}$/Sqrt[eta$_*$] for aligned dipole
  - complex field => slower spindown?
  - need 3D sims to confirm!

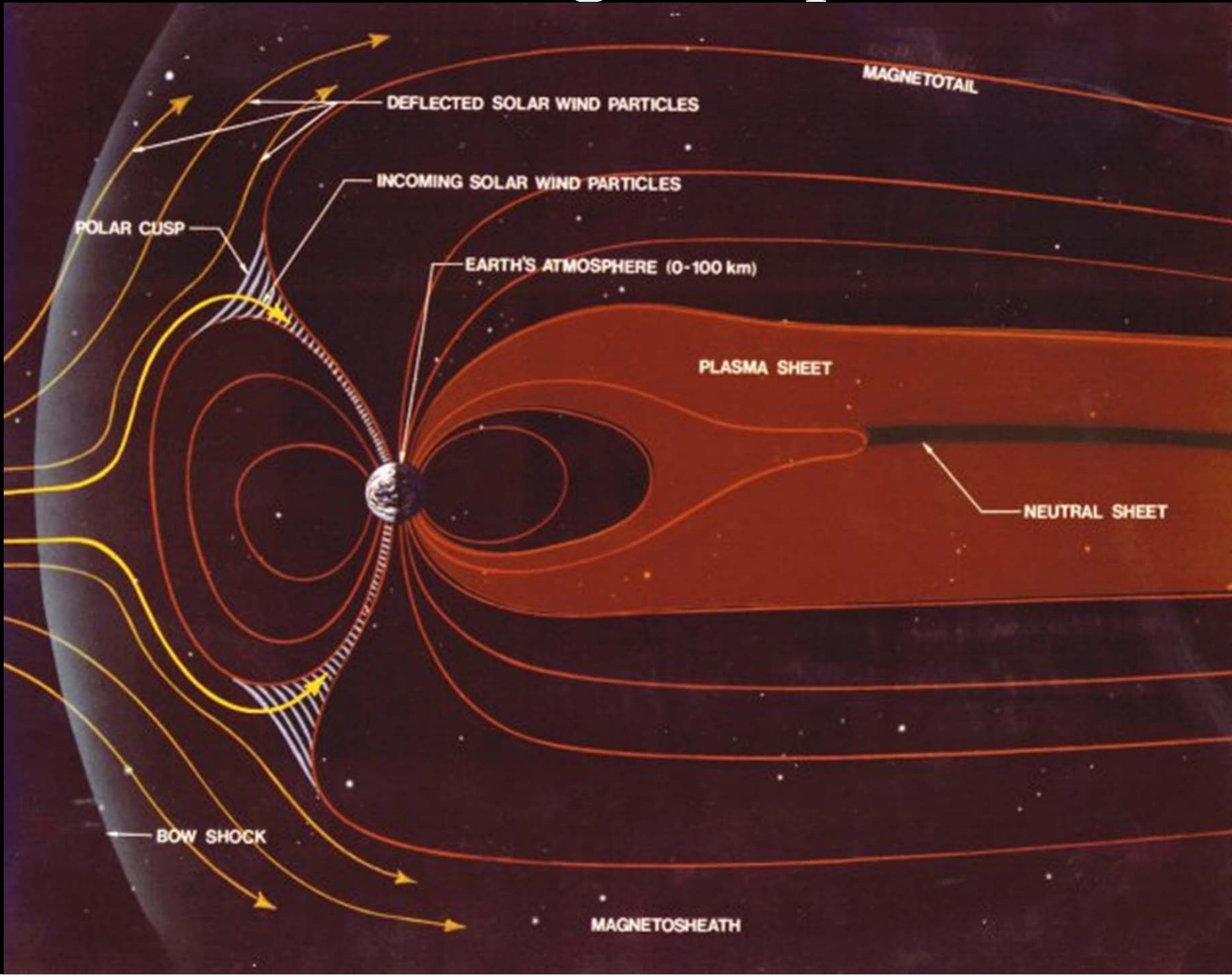
Mass Loss & Rotational Spindown of Magnetic Massive Stars

Stan Owocki
University of Delaware
Newark, Delaware USA

Collaborators

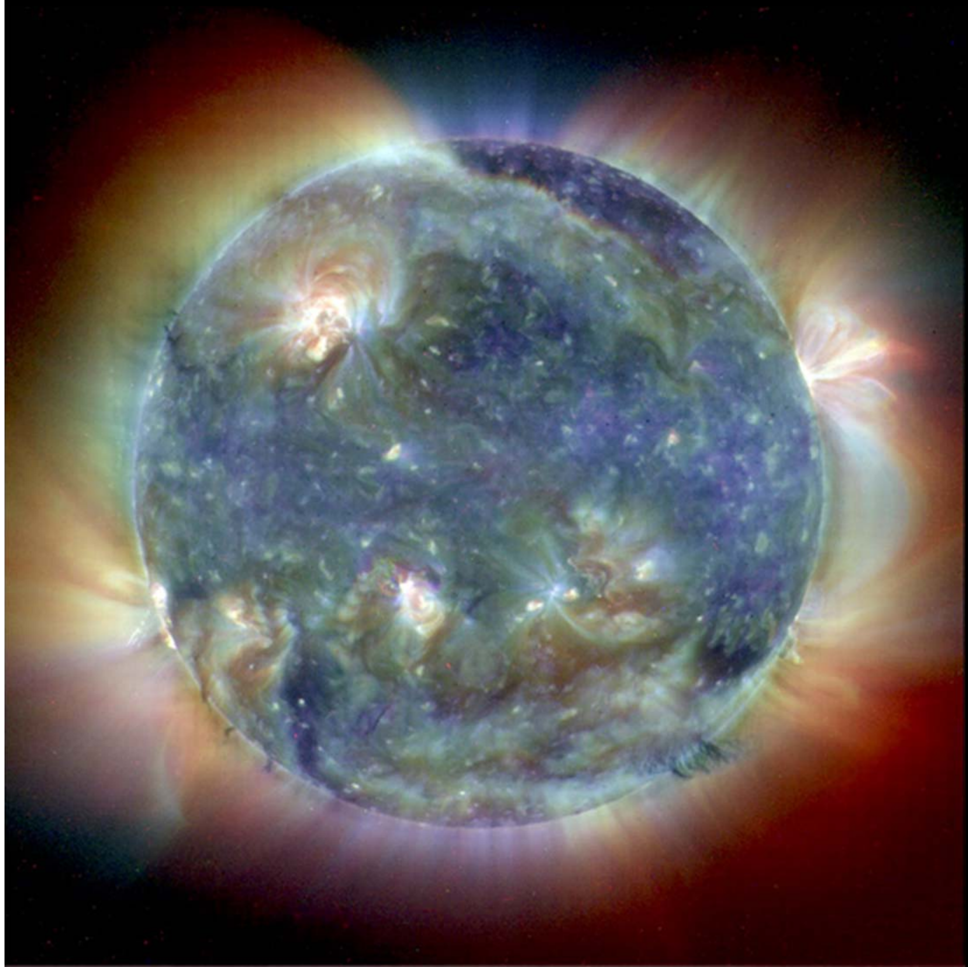
- Asif ud-Doula
- Rich Townsend

Earth's Magnetosphere

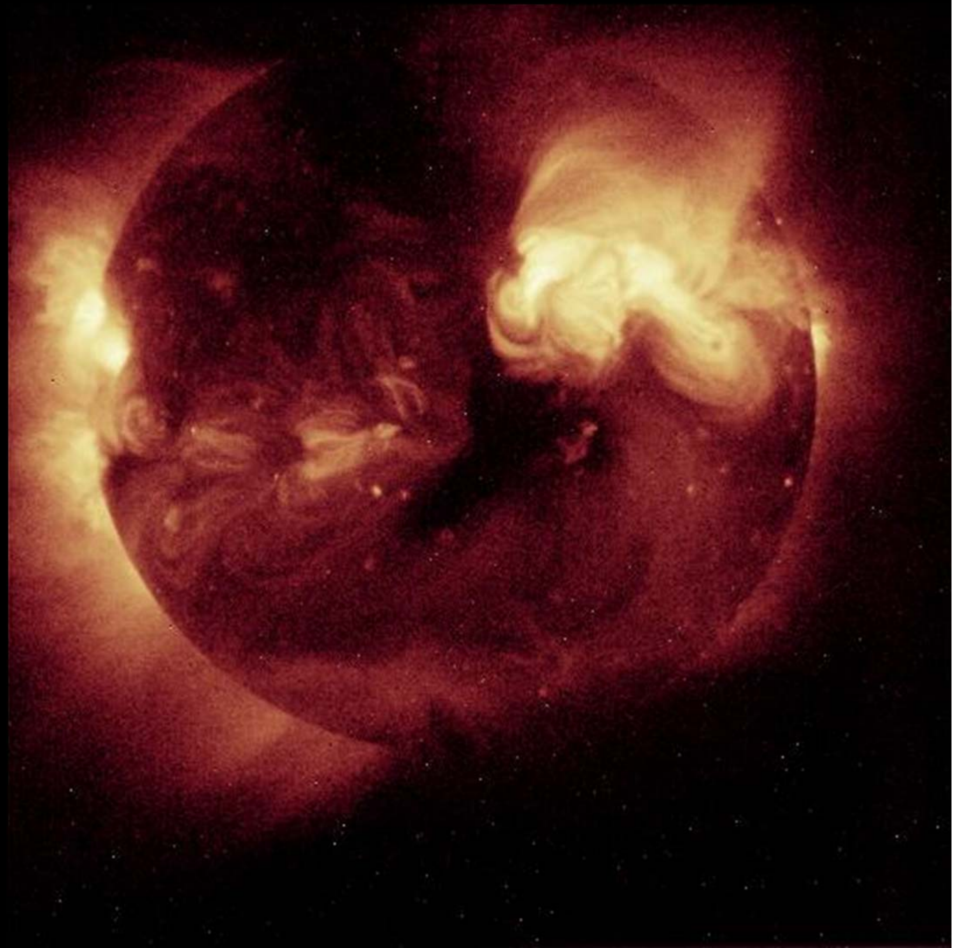


Solar Corona in EUV & X-rays

Composite EUV image from EIT/SOHO



X-ray Corona from SOHO



Corona during Solar Eclipse

Solar Activity: Coronal Mass Ejections

Hot, Luminous, Massive Stars

- Strong, radiatively driven stellar wind
  - $M_{dot} \sim 10^{-9}$-10^{-5} M_O/yr; $V_{\square}$ > 1000 km/s >> V_{sound}
- Some have observed dipole field ~10^3-10^4 G
  - stable; not from convective dynamo; fossil?
- Fast rotation with V_{rot} ~ 250 km/s ~ $V_{crit}/2$
  - P_{rot} ~ few days

Questions

- How does a strong magnetic field affect radiatively driven wind outflow?
  - wind channeling
  - magnetically confined wind shocks
  - wind-fed rotational magnetospheres

- How does angular momentum loss & spindown scale with B_*, Mdot, n-pole order, etc.?
  - can we explain slow rotators w/ magnetic spindown?
  - what are implications for stellar evolution

Wind Magnetic Confinement

Ratio of magnetic to kinetic energy density:

| *

for n-pole
$B(r) \sim 1/r^{n+1}$

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2} = \boxed{\frac{B_*^2 R_*^2}{\dot{M}\, v_\infty}} \frac{(r/R_*)^{-2\boxed{n}}}{(1 - R_*/r)^{\beta}}$$

Note also $\eta = \frac{V_A^2}{v^2}$ so **Alfven Radius,** where v=V_A, has | **(R_A) α 1**

For ®=0: $R_A = |_*^{1/2n} R_*$

e.g., for dipole, n=2: $\boxed{R_A = |_*^{1/4} R_*}$

Magnetic confinement vs. Wind + Rotation

Wind mag. confinement

$$\eta_* \equiv \frac{B_*^2 R_*^2}{\dot{M} V_\infty}$$

Rotation vs. critical

$$W \equiv \frac{V_{rot}}{\sqrt{GM / R_*}}$$

Alfven radius for n-pole

$$R_A = \eta_*^{1/2n} R_*$$

$$= \eta_*^{1/4} R_*$$ for n=2 dipole

Kepler radius

$$R_K = W^{-2/3} R_*$$

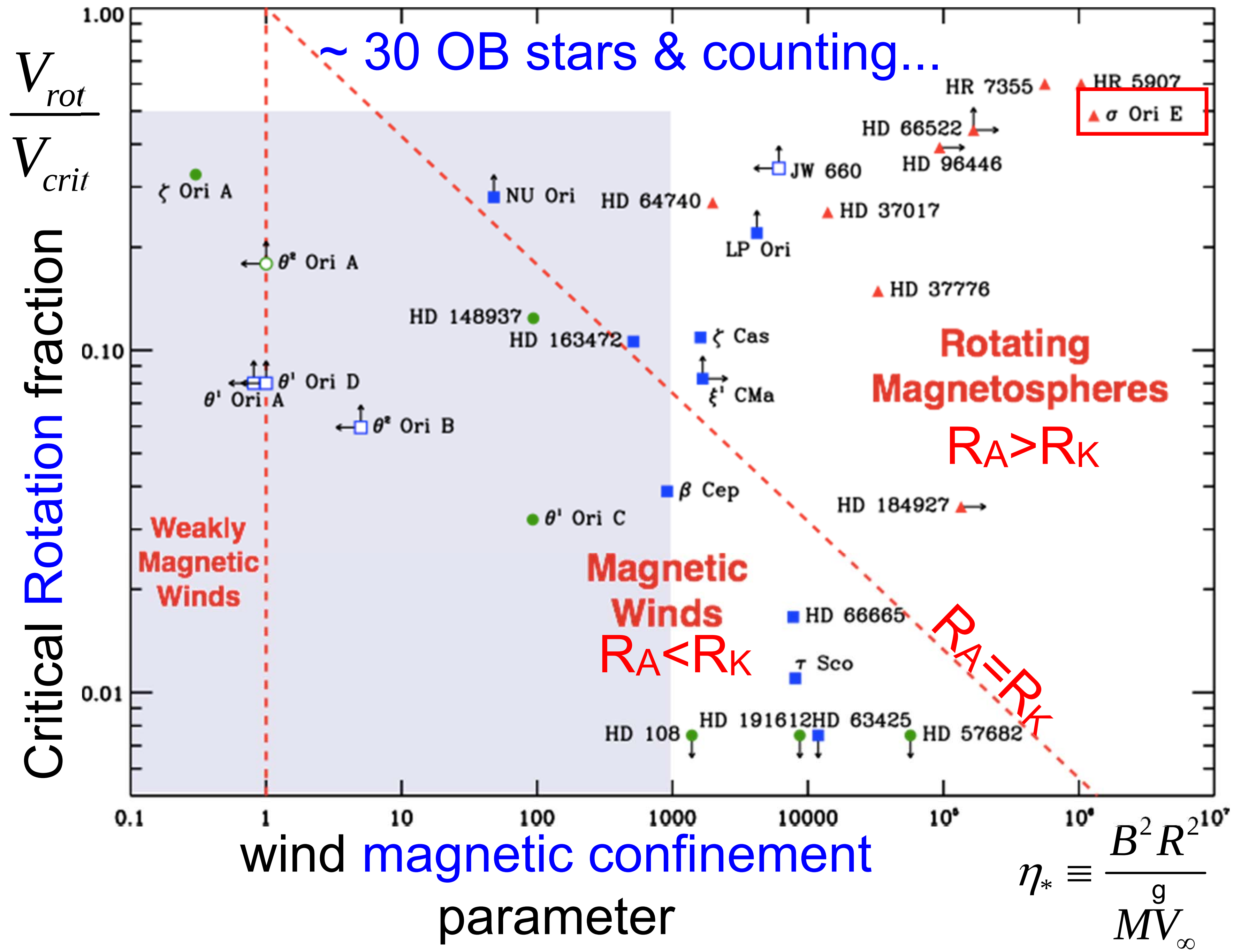
MiMeS

Magnetism in Massive Stars

P.I.: Gregg A. Wade, Royal Military College

50+ Co-Is, 2008-2012, CFHT Allocation: 640 hours

http://www.physics.queensu.ca/~wade/mimes/MiMeS___Magnetism_
Massive_Stars.html

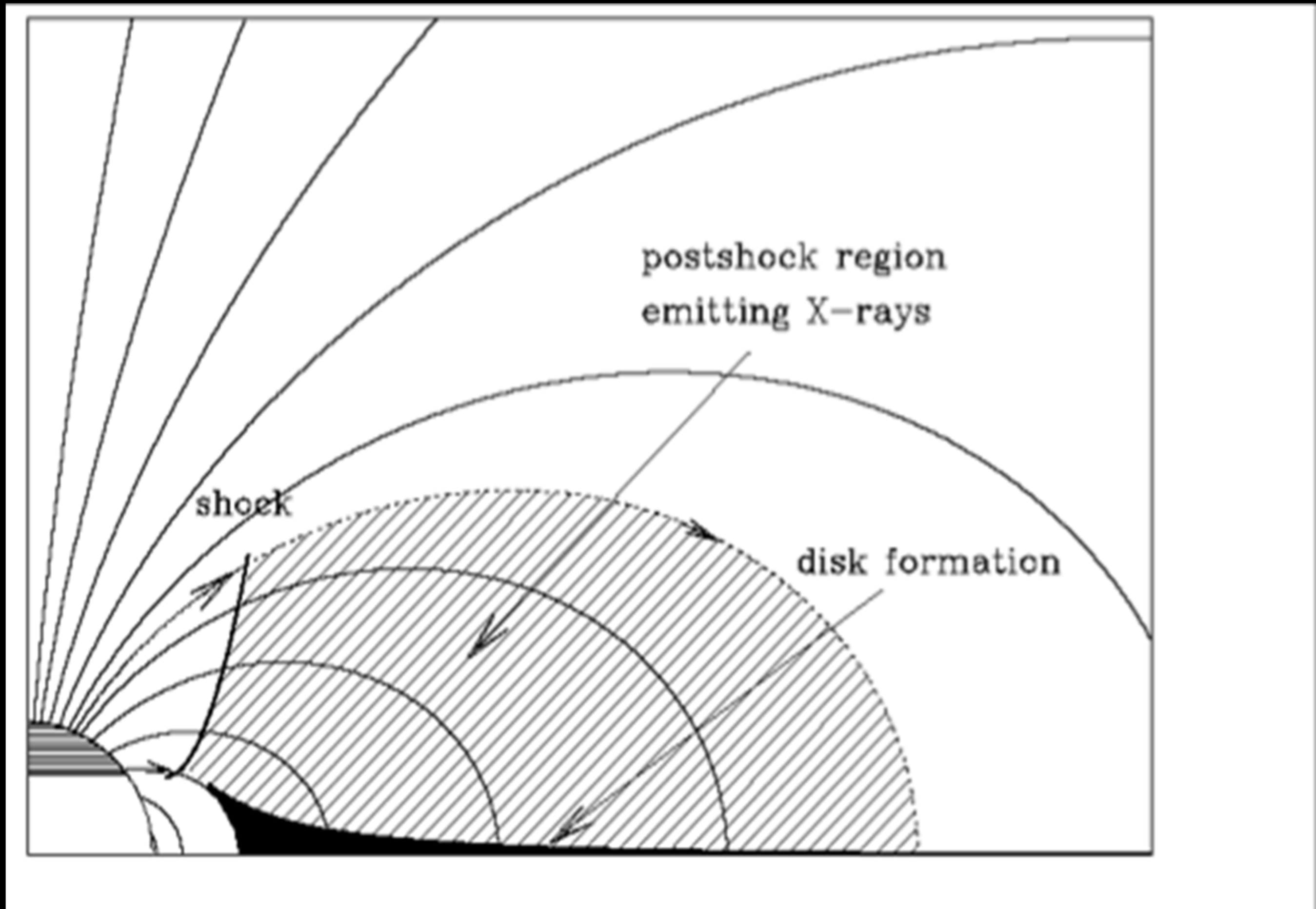


~ 30 OB stars & counting...
Critical Rotation fraction
$\frac{V_{rot}}{V_{crit}}$
1.00
0.10
0.01
0.1
1
10
100
1000
10000
10^5
10^6
10^7
HR 7355
HR 5907
σ Ori E
HD 66522
HD 96446
JW 660
NU Ori
HD 64740
HD 37017
ζ Ori A
LP Ori
θ² Ori A
HD 37776
HD 148937
HD 163472
ζ Cas
Rotating Magnetospheres
θ¹ Ori D
θ¹ Ori A
ξ¹ CMa
θ² Ori B
$R_A > R_K$
β Cep
HD 184927
θ¹ Ori C
Weakly Magnetic Winds
Magnetic Winds
HD 66665
$R_A < R_K$
$R_A = R_K$
τ Sco
HD 108
HD 191612
HD 63425
HD 57682
wind magnetic confinement parameter
$\eta_* \equiv \frac{B^2 R^2}{\dot{M} V_\infty}$

Magnetically Confined Wind-Shocks

Babel & Montmerle 1997

Magnetic A_p-B_p stars



Rigid Field - Hydro Model

MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement
parameter

$|_{*}=1/3$

A. ud Doula
PhD thesis 2002

MHD Simulation of Wind Channeling

Isothermal

No Rotation

Confinement parameter

$| _{*} = 1$

MHD Simulation of Wind Channeling

Isothermal

No Rotation

Confinement parameter

$$|\ _{*}= 3$$

MHD Simulation of Wind Channeling

Isothermal

No Rotation

Confinement parameter

$|_{*}=10$

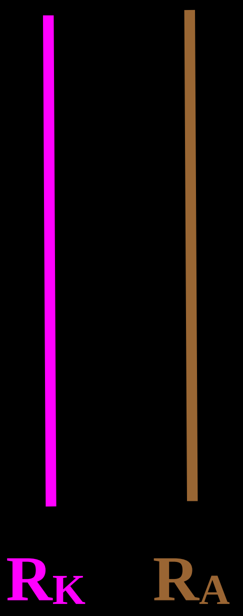
Field-aligned rotation

$|_{*}=100$

$R_A=3.2R_*$

$W=1/2$

$R_K=1.6\ R_*$

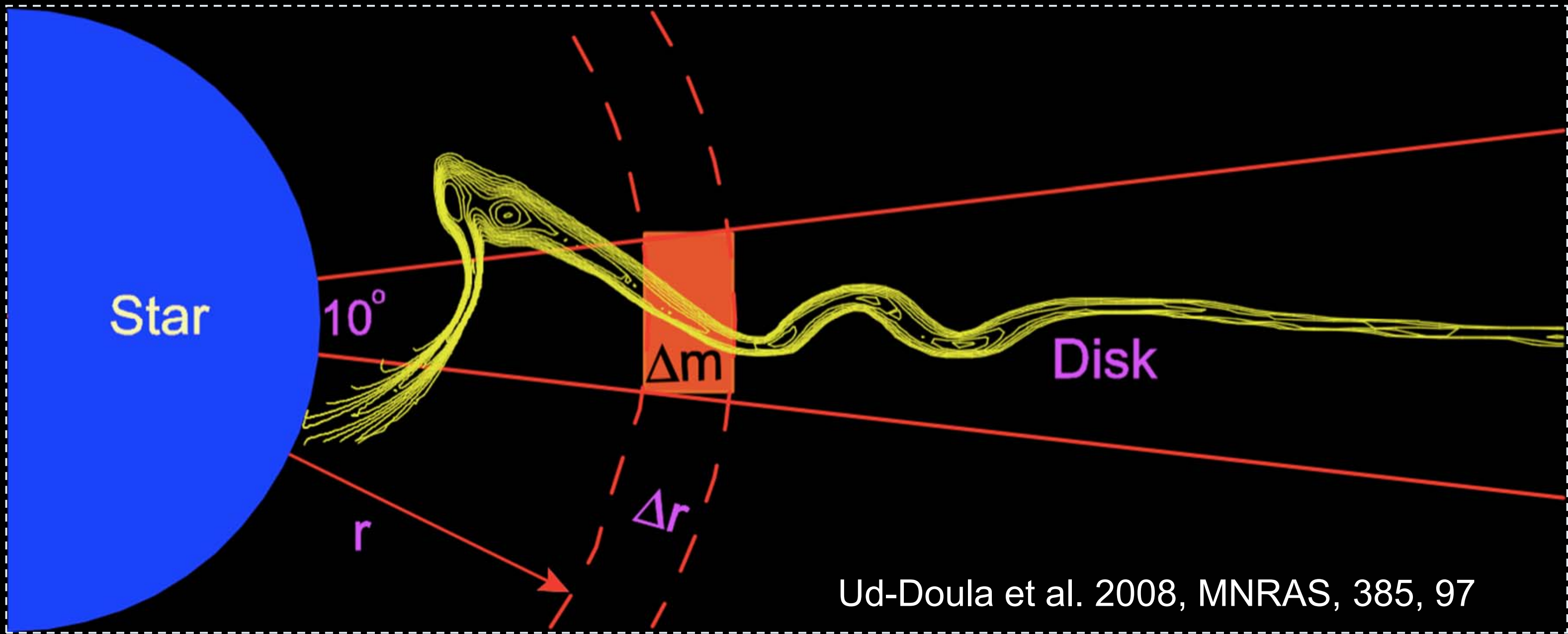


Strong Field + Rapid rotation

$|_*$=100 W=1/2

R_K R_A

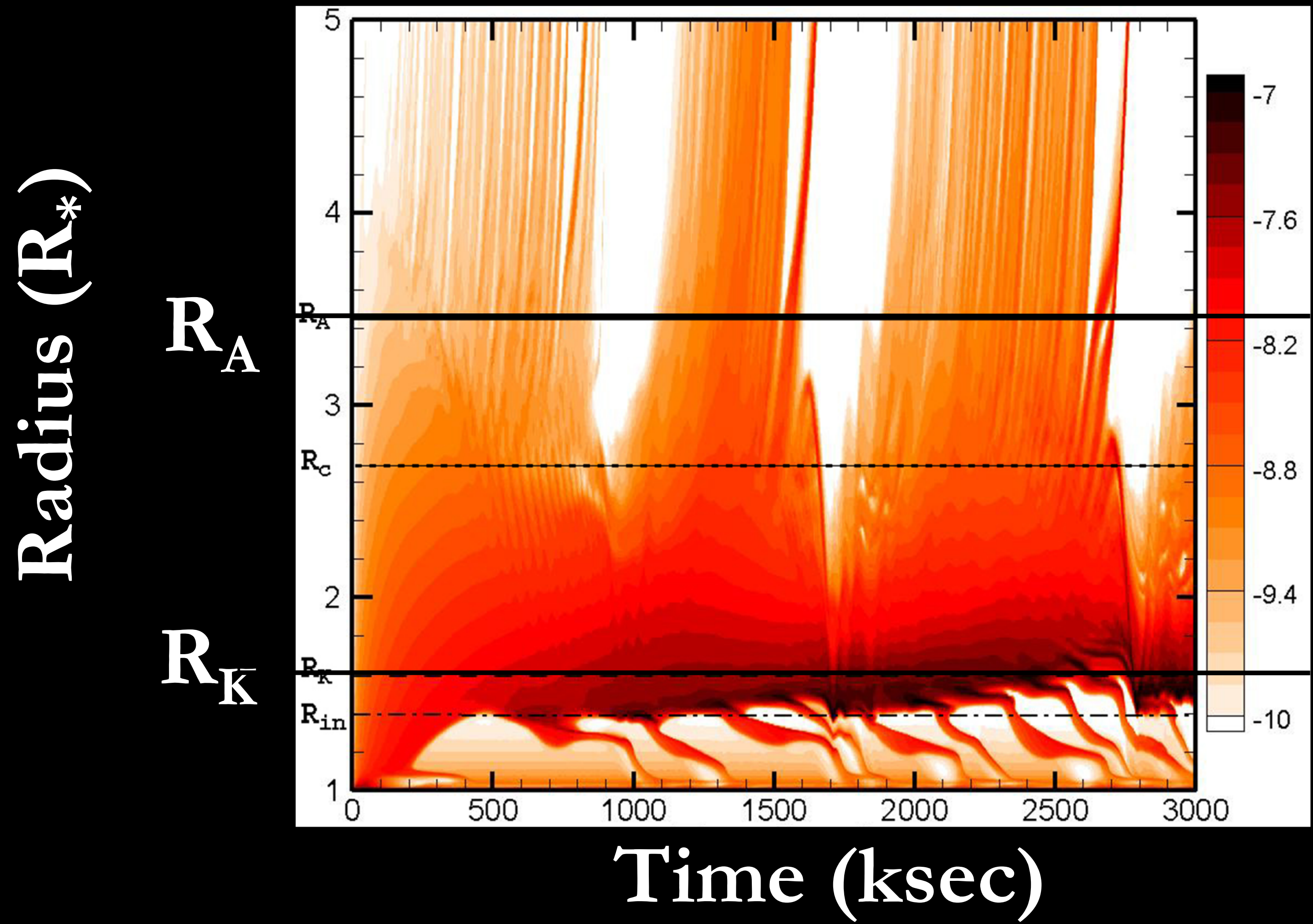
Radial Mass Distribution



$$\frac{dm_e(r,t)}{dr} \equiv 2\pi r^2 \int_{\pi/2-\Delta\theta/2}^{\pi/2+\Delta\theta/2} \rho(r,\theta,t)\sin\theta\, d\theta$$

Time evolution of Radial distribution of equatorial disk mass

η_* = 100 & Vrot/Vcrit =1/2

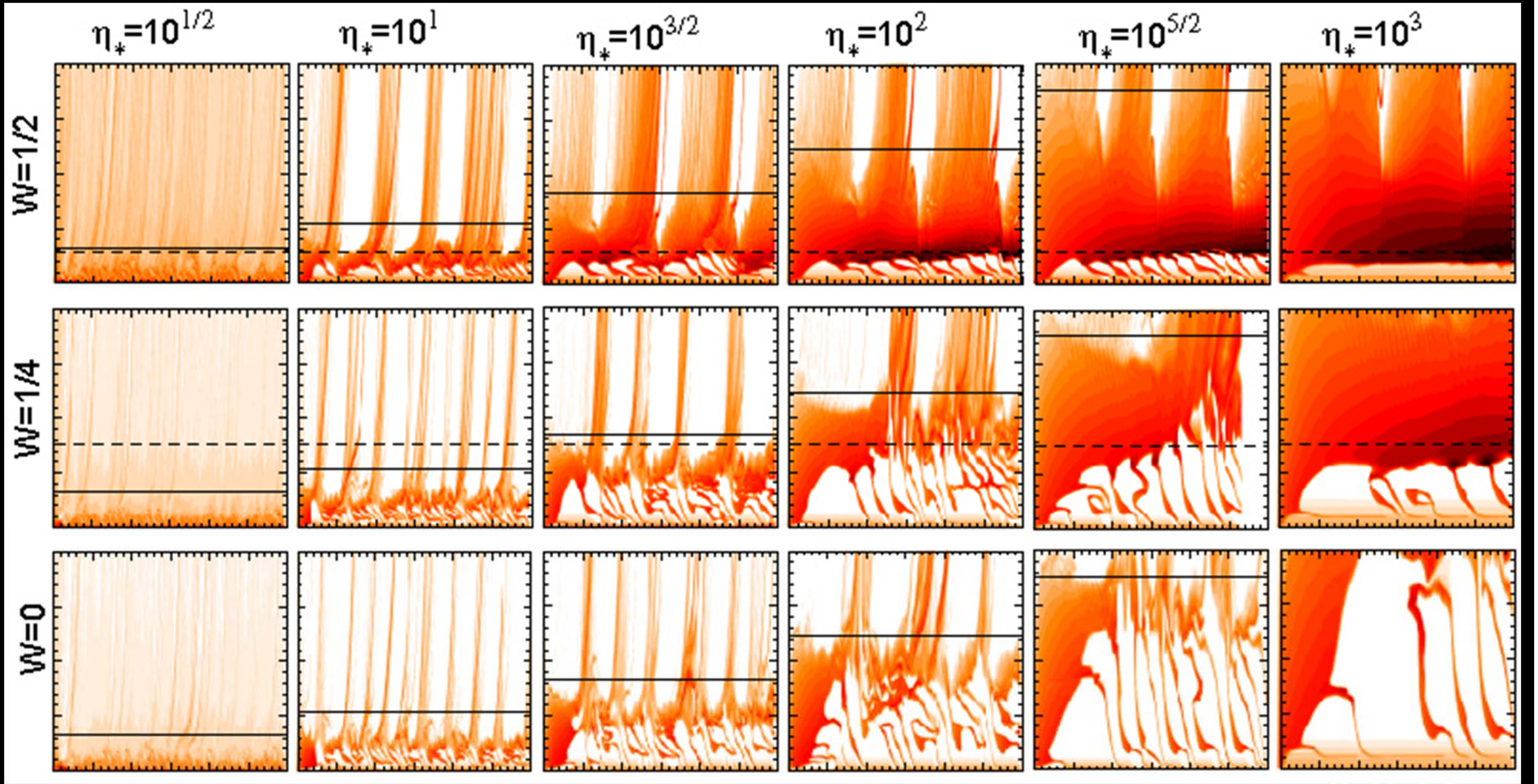


Ud-Doula et al. 2008, MNRAS, 385, 97

Temporal evolution of radial distribution of equatorial disk mass

r=1-5

More Rapid Rotation --->



t=0-3 Msec

Stronger Magnetic Confinement --->

Ud-Doula et al. 2008, MNRAS, 385, 97

Strongest MHD sim

$|_{*}$=1000

W=1/2

R_K

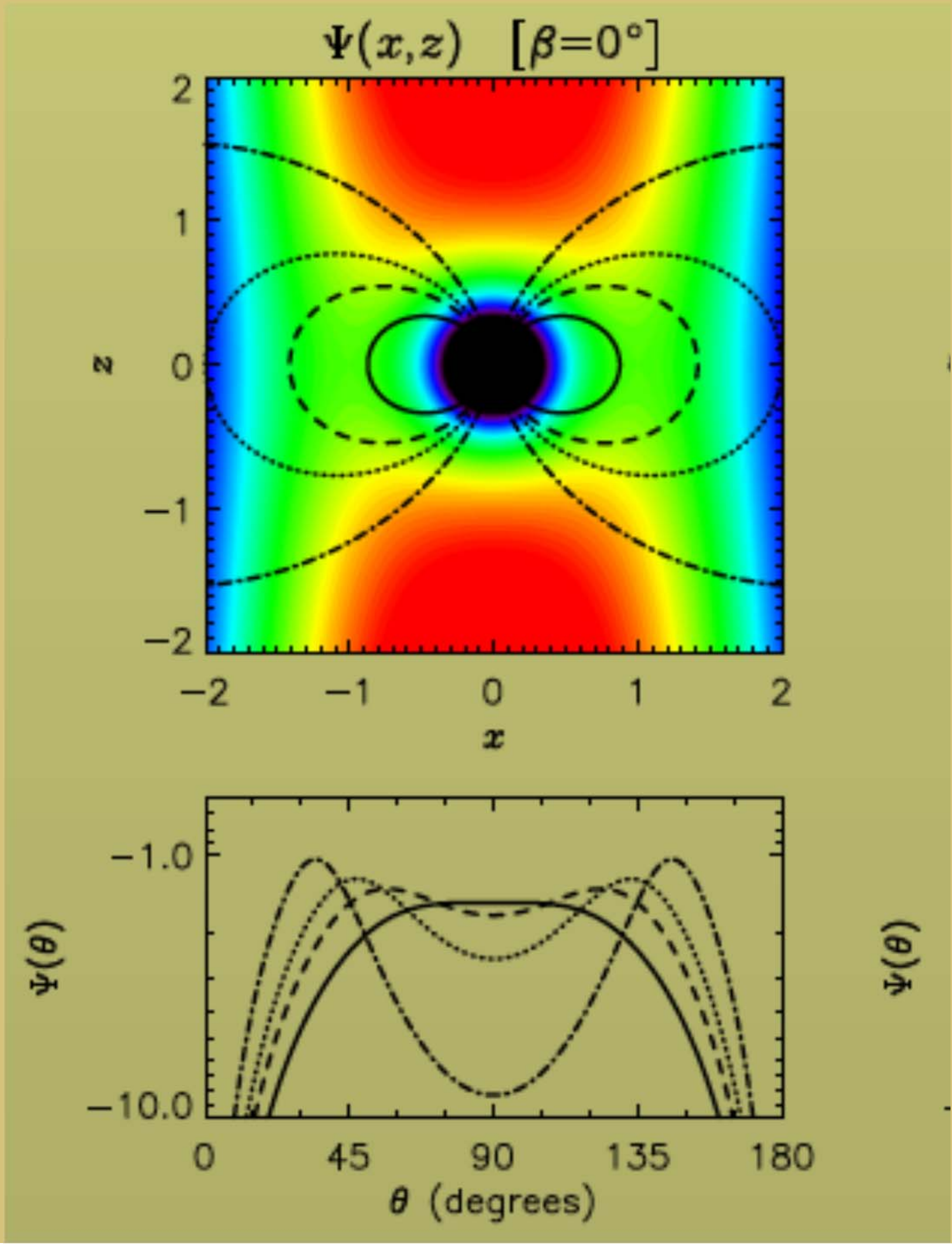
R_A

Magnetic Bp Stars

- σ Ori E (B2p V)
  - $P_{rot} = 1.2$ days => $v_{rot}/v_{crit} \sim 1/2$
  - $B_{obs} \sim 10^4$ G => **$\eta_* \sim 10^7$** !
  - => V_{Alfven} very large => Courant time very small
  - => Direct MHD impractical

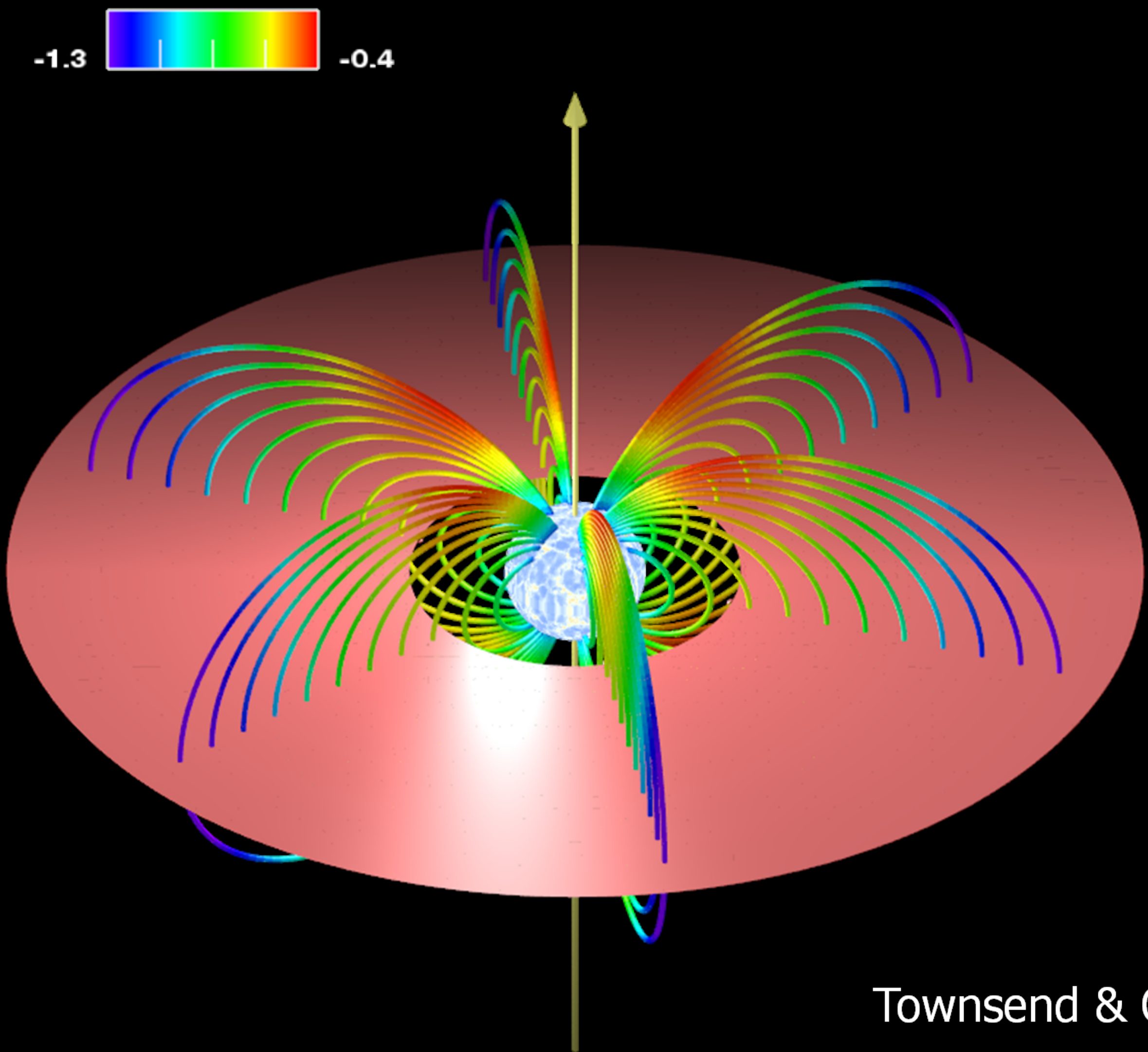
- Instead treat fields lines as Rigid guides
  - **Torque up** wind outflow
  - **Hold down** disk material vs. centrifugal force

Effective Gravitational+Centrifugal Potential



Townsend & Owocki 2005, MNRAS, 357, 251

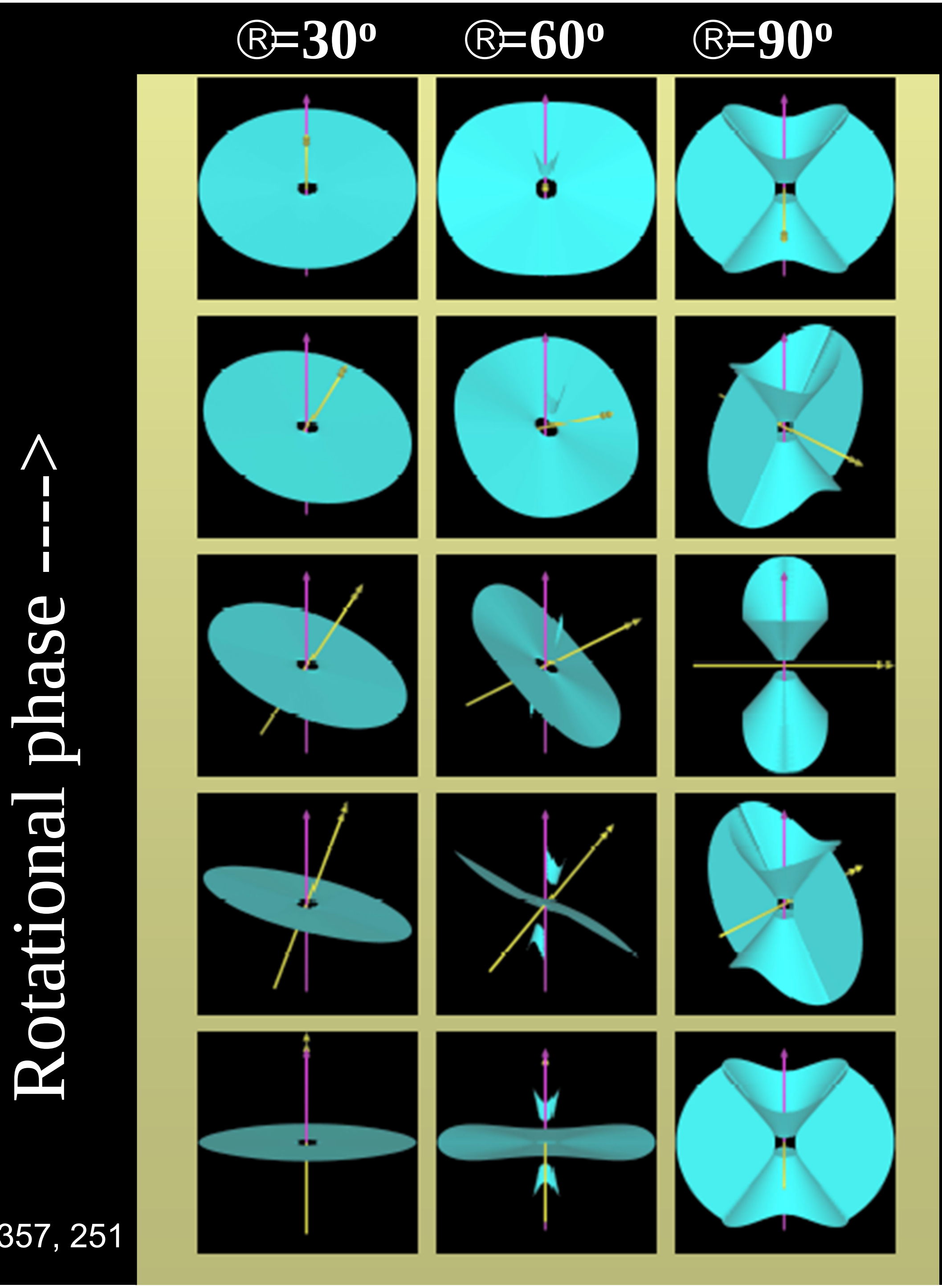
Rigidly Rotating Magnetosphere



Townsend & Owocki (2005)

Accumulation Surfaces

observed from **i=60º**



Townsend & Owocki 2005, MNRAS, 357, 251

RRM model
for ⌠Ori E

$B_* \sim 10^4$ G

| $_* \sim 10^6$!

tilt ~ 55^o

RRM model for σ Ori E

EM +B-field

photometry

B_{*}~10^{4} G

=> | $_{*}$~10^{6} !

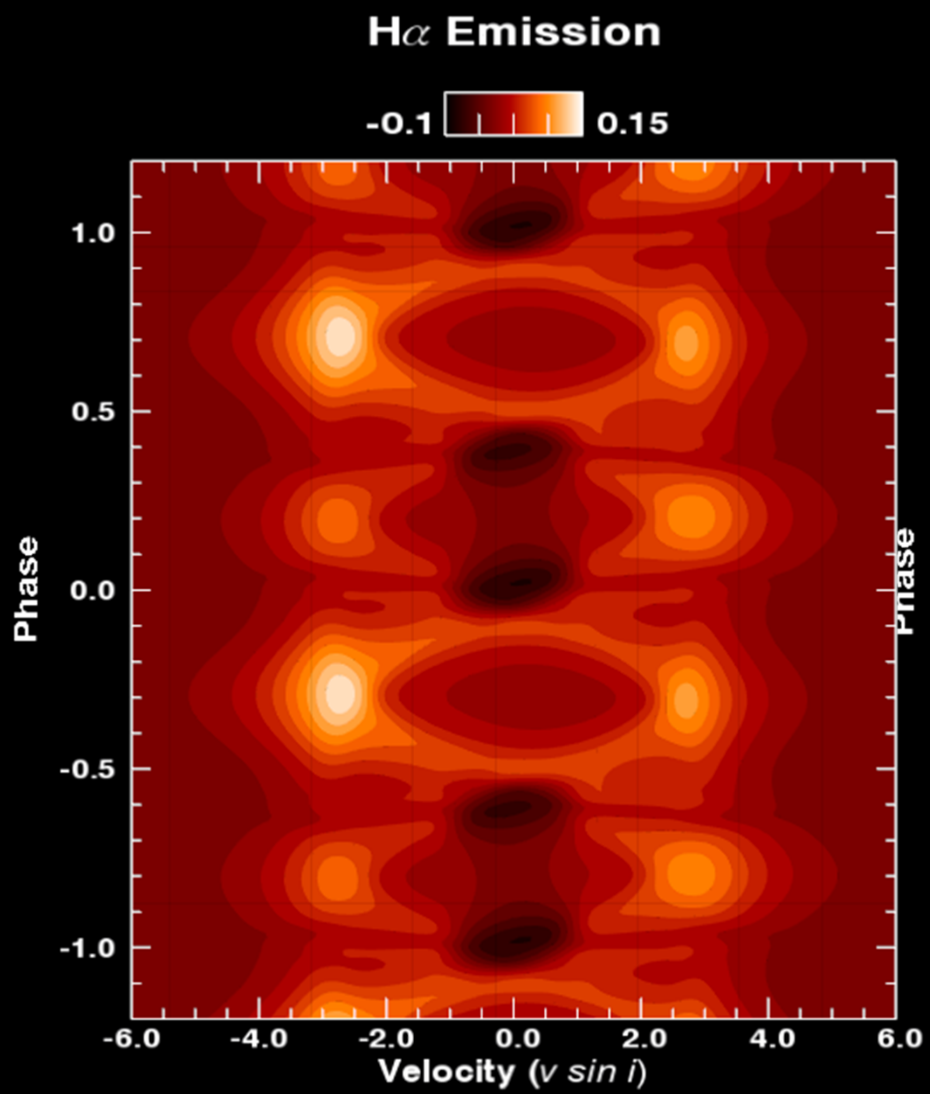
tilt ~ 55^{o}

polarimetry

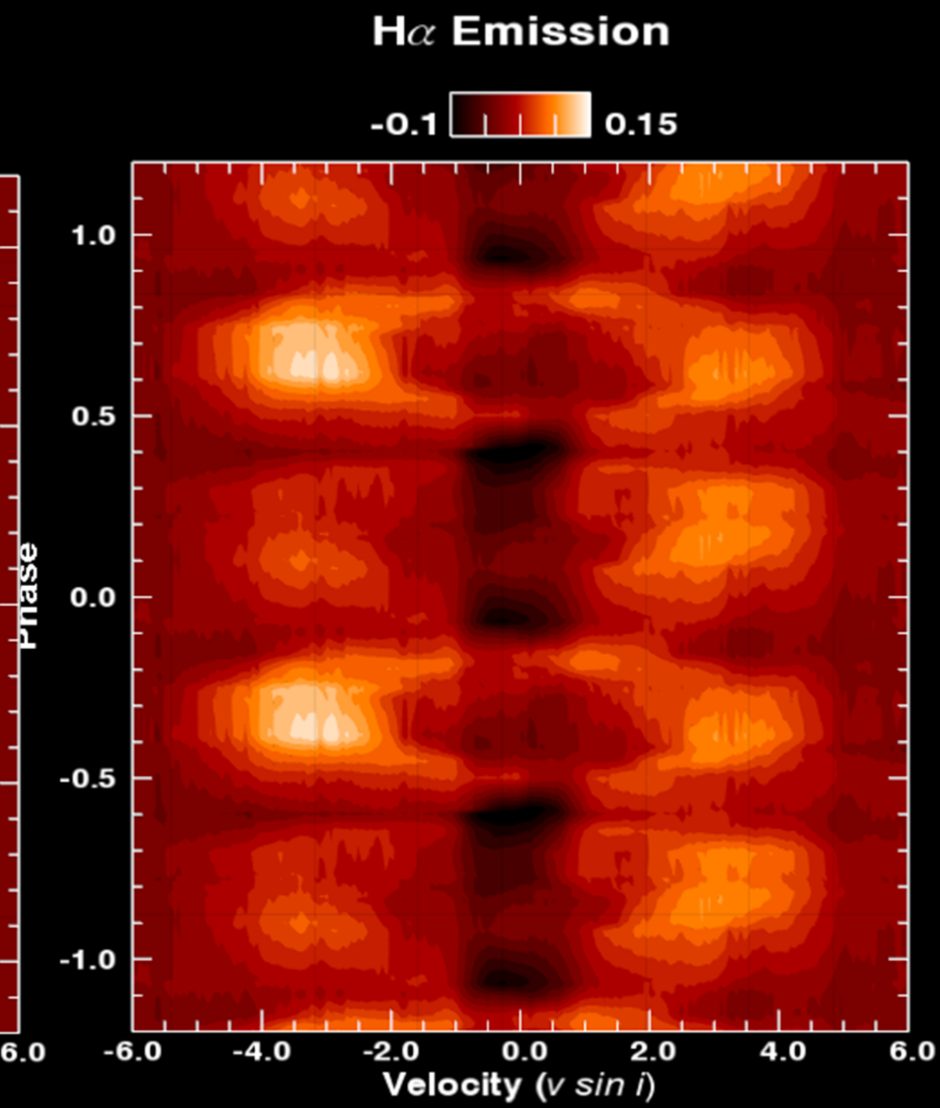
⌠Ori E

Townsend et al. 2005, ApJ, 630, 81

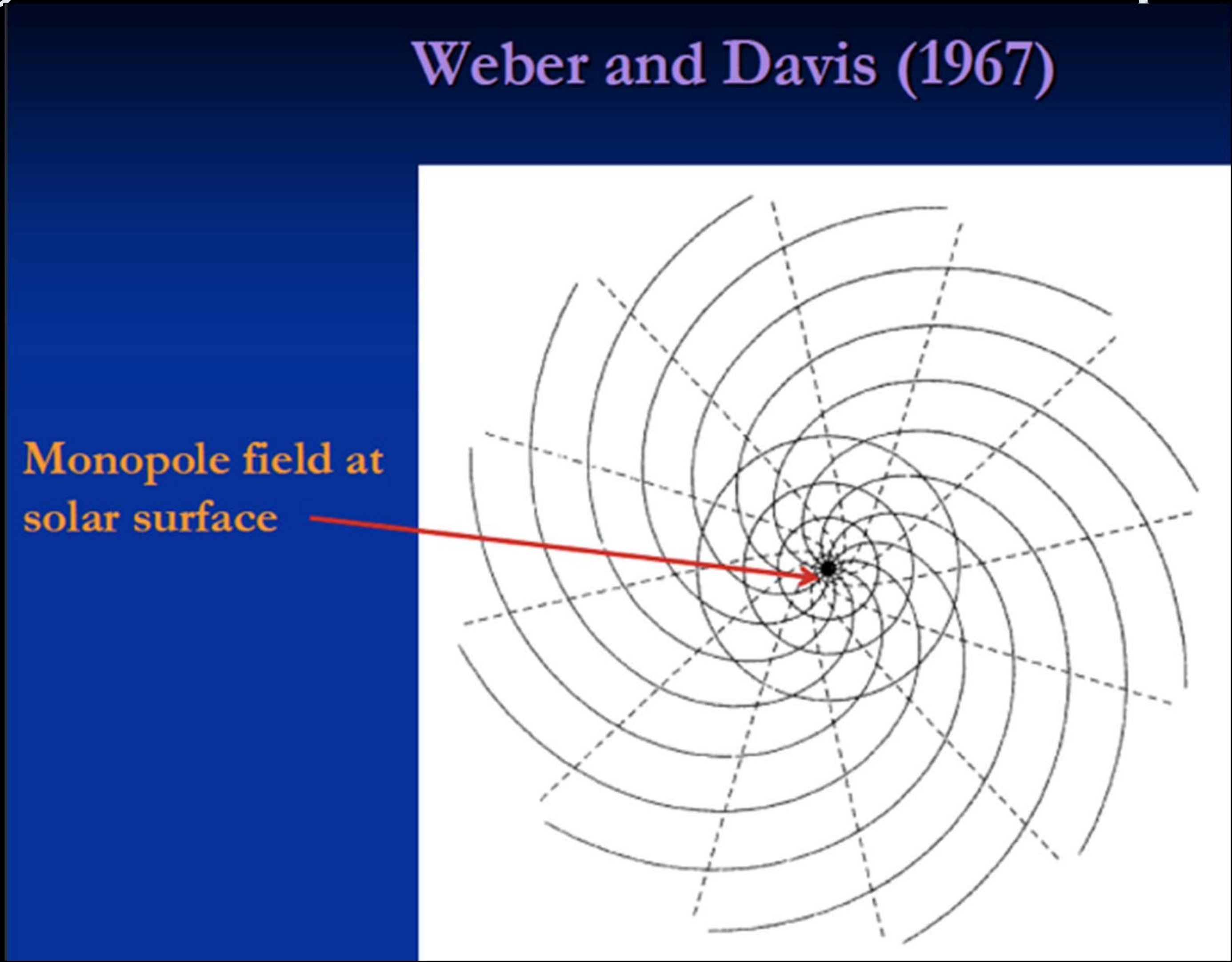
RRM Model



H⟨ Observations



Angular Momentum Loss & Spindown



$$\dot{J} = \tfrac{2}{3}\dot{M}\,\Omega R_A^2$$

Weber & Davis 1967

Spindown for n=1 monopole field

Total equatorial Ang. mom/mass

gas field

Frozen flux

$$j = V_\phi r - \frac{B_\phi B_r r}{\rho V_r} \quad \& \quad \frac{B_\phi}{B_r} = \frac{\Omega r - V_\phi}{V_r}$$

=> $$j_{gas} \equiv V_\phi r = \frac{j M_A^2 - \Omega r^2}{M_A^2 - 1}$$

At r= R_A,
M_A=1 implies

$$j = \Omega R_A^2$$

Spindown

$$\dot J = \frac{2}{3}\dot M \,\Omega R_A^2$$

contribution from both matter & field

$$\tau_{spin} \equiv \frac{J}{\dot J} \approx \frac{\frac{3}{2} I}{MR^2}\frac{M}{\dot M}\frac{1}{\eta_*^{1/n}} = \tau_{mass}\frac{\frac{3}{2} k}{\eta_*^{1/n}}$$

For dipole:

$$\frac{\tau_{spin}}{\tau_{mass}} \approx \frac{0.15}{\sqrt{\eta_*}}$$

Mon. Not. R. Astron. Soc. (2008) doi:10.1111/j.1365-2966.2008.14134.x

Dynamical simulations of magnetically channelled line-driven stellar winds – III. Angular momentum loss and rotational spin-down

Asif ud-Doula,[1★] Stanley P. Owocki[2] and Richard H. D. Townsend[3]
[1]*Department of Physics, Morrisville State College, Morrisville, NY 13408, USA*
[2]*Bartol Research Institute, University of Delaware, Newark, DE 19716, USA*
[3]*Department of Astronomy, University of Wisconsin-Madison, 5534 Sterling Hall, 475 N Charter Street, Madison, WI 53706, USA*

Accepted 2008 October 23. Received 2008 September 25; in original form 2008 August 4

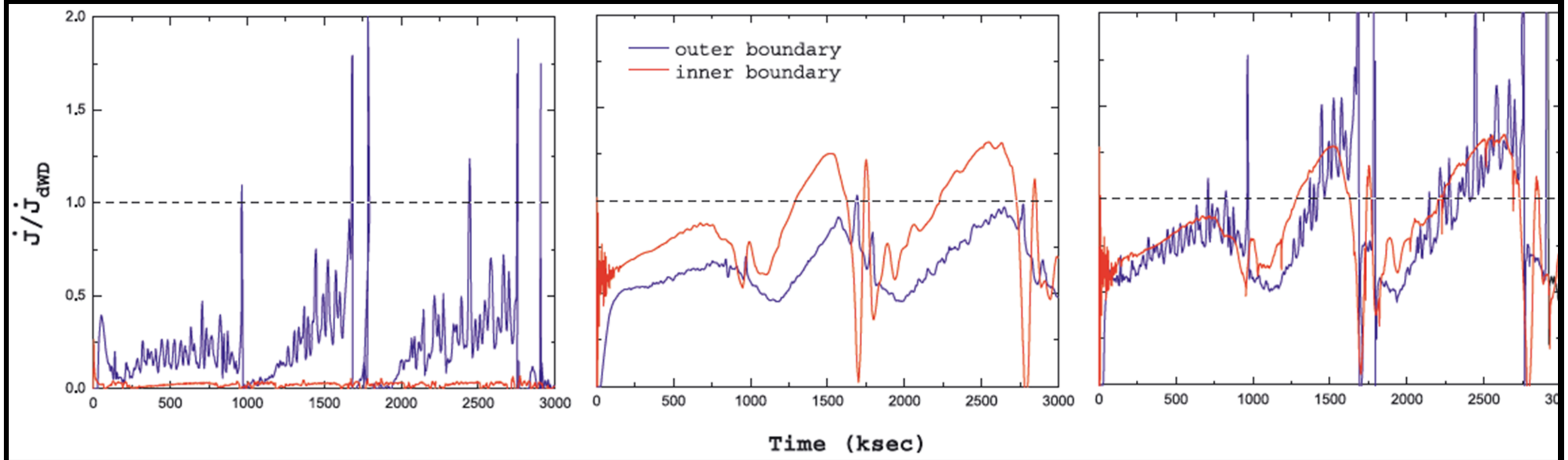
ABSTRACT

We examine the angular momentum loss and associated rotational spin-down for magnetic hot stars with a line-driven stellar wind and a rotation-aligned dipole magnetic field. Our analysis here is based on our previous two-dimensional numerical magnetohydrodynamics simulation study that examines the interplay among wind, field and rotation as a function of two dimensionless parameters: one characterizing the wind magnetic confinement ($\eta_* \equiv B_{\rm eq}^2 R_*^2/\dot{M} v_\infty$) and the other the ratio ($W \equiv V_{\rm rot}/V_{\rm orb}$) of stellar rotation to critical (orbital) speed. We compare and contrast the two-dimensional, time-variable angular momentum loss of this dipole model of a hot-star wind with the classical one-dimensional steady-state analysis by Weber and Davis (WD), who used an idealized monopole field to model the angular momentum loss in the solar wind. Despite the differences, we find that the total angular momentum loss $\dot{J}$ averaged over both solid angle and time closely follows the general WD scaling $\dot{J} = (2/3)\dot{M}\Omega R_{\rm A}^2$, where $\dot{M}$ is the mass-loss rate, Ω is the stellar angular velocity and $R_{\rm A}$ is a characteristic Alfvén radius. However, a key distinction here is that for a dipole field, this Alfvén radius has a strong-field scaling $R_{\rm A}/R_* \approx \eta_*^{1/4}$, instead of the scaling $R_{\rm A}/R_* \sim \sqrt{\eta_*}$ for a monopole field. This leads to a slower stellar spin-down time that in the dipole case scales as $\tau_{\rm spin} = \tau_{\rm mass}\, 1.5k/\sqrt{\eta_*}$, where $\tau_{\rm mass} \equiv M/\dot{M}$ is the characteristic mass loss time and k is the dimensionless factor for stellar moment of inertia. The full numerical scaling relation that we cite gives typical spin-down times of the order of 1 Myr for several known magnetic massive stars.

Key words: MHD – stars: early-type – stars: magnetic fields – stars: mass loss – stars: rotation – stars: winds, outflows.

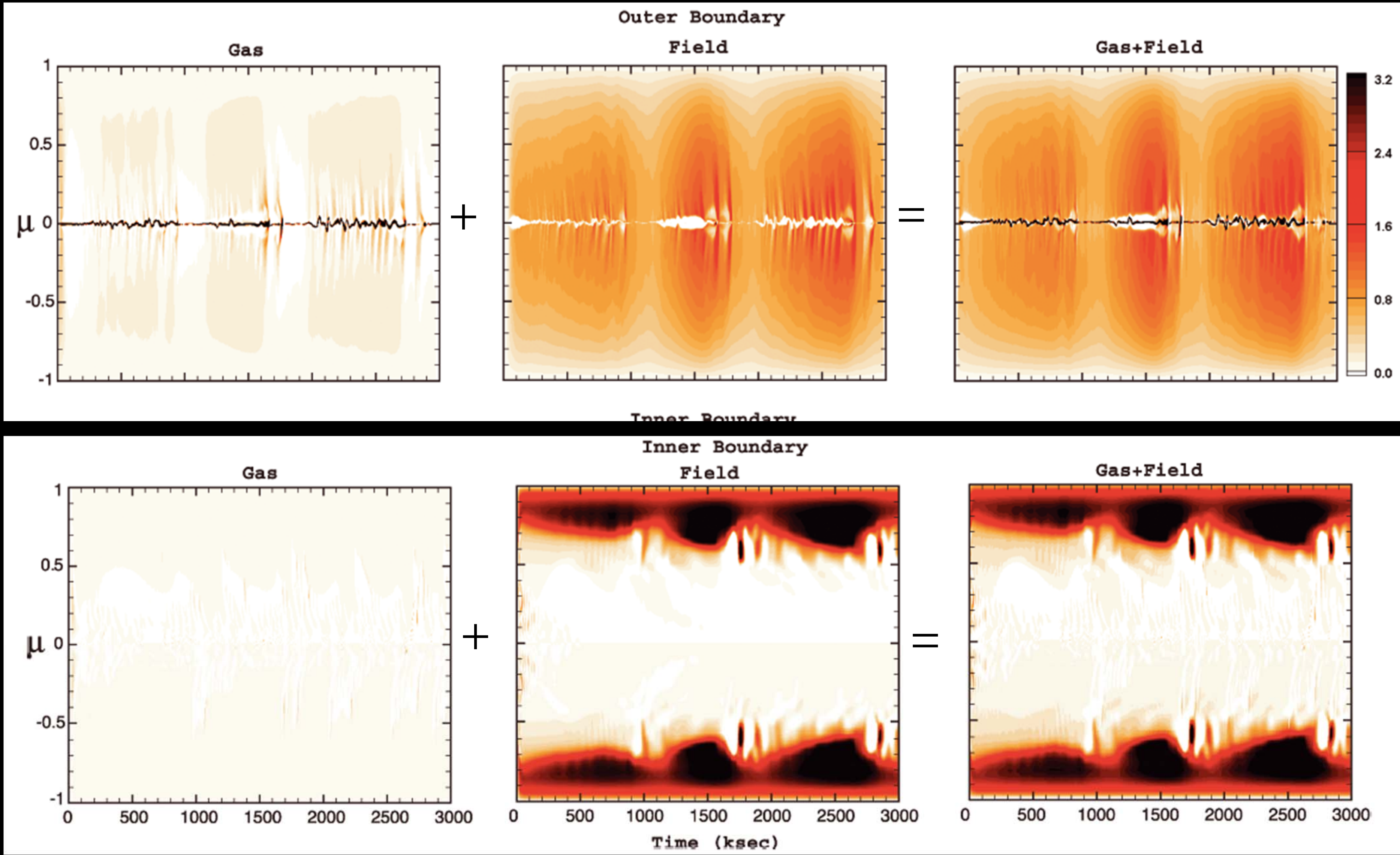
Time variation of total Angular Momentum Loss

Gas | Field | Total



Ud-Doula et al. 2009, MNRAS, 392, 1022

Angular Momentum Loss vs. latitude & time

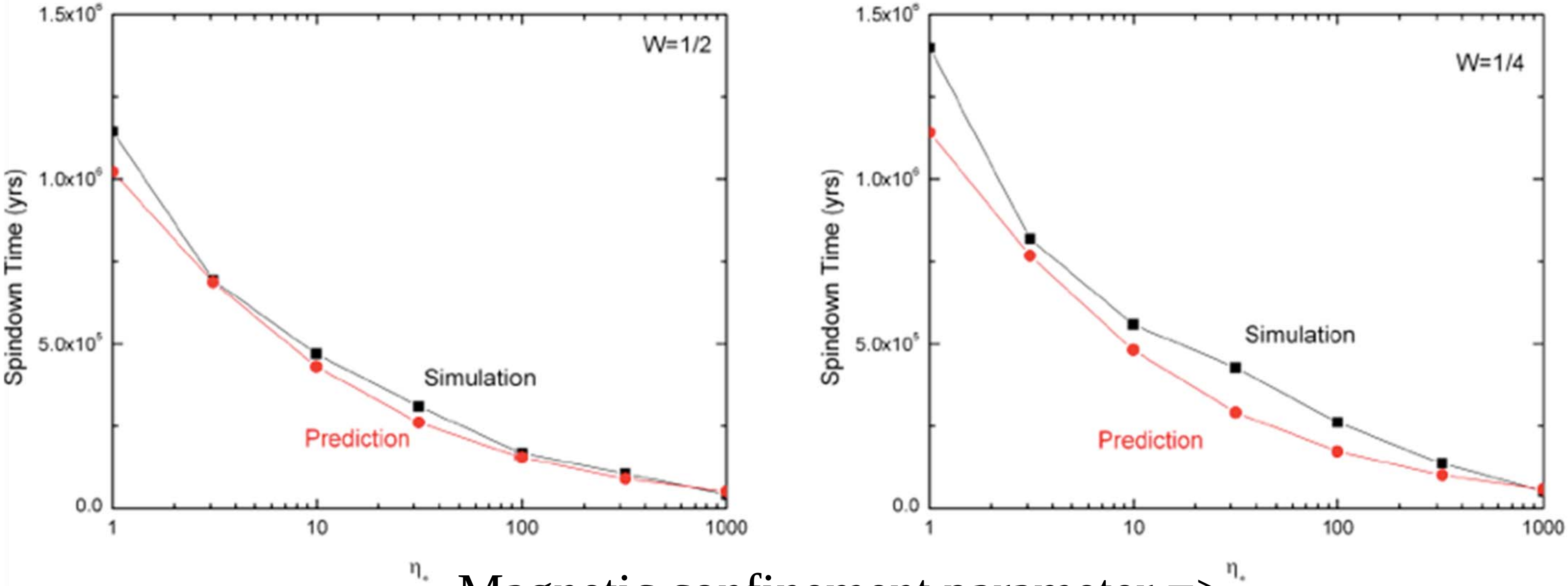


Ud-Doula et al. 2009, MNRAS, 392, 1022

Spindown Time

W=1/2 **W=1/4**

Ud-Doula et al. 2009, MNRAS, 392, 1022



Magnetic confinement parameter =>

Dipole spindown times

Table 1. Estimated spin-down time for selected known magnetic stars.

Star[a]	$M/M_\odot$	$R_*/R_\odot$	P (d)	k	$\dot{M}$ (10^{-9} $M_\odot$ yr^{-1})	v_∞(1000 km s^{-1})	B_p (kG)	η_*	τ_{spin} (Myr)
θ^1 Ori C[1]	40	8	15.4	0.28	400	2.5	1.1	15.7	8
HD191612[2]	40	18	538	0.17	6100	2.5	1.6	7.6	0.4
ζ Cas[3]	8	5.9	5.37	0.1	0.3	0.8	0.34	3200	65.2
σ Ori E[4]	8.9	5.3	1.2	0.1	2.4	1.46	9.6	1.4×10^5	1.4
ρ Leo[5]	22	35	7-47	0.12	630	1.1	0.24	20	1.1

Ud-Doula et al. 2009, MNRAS, 392, 1022

$$\tau_{spin} \approx \tau_{mass} \frac{\frac{3}{2} k}{\sqrt{\eta_*}}$$

$$\approx 11 Myr \ \frac{k_{-1}}{B_{kG}} \frac{M_*}{R_*} \sqrt{\frac{V_8}{\dot{M}_{-9}}}$$

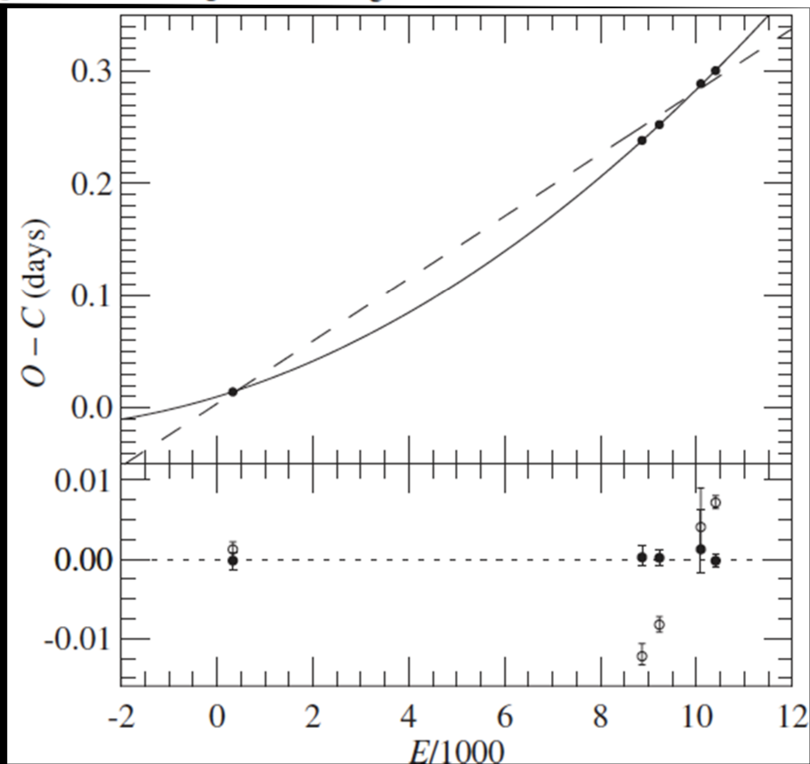
The Astrophysical Journal Letters, 714:L318–L322, 2010 May 10
doi:10.1088/2041-8205/714/2/L318

DISCOVERY OF ROTATIONAL BRAKING IN THE MAGNETIC HELIUM-STRONG STAR SIGMA ORIONIS E

R. H. D. Townsend[1], M. E. Oksala[2], D. H. Cohen[3], S. P. Owocki[2], and A. ud-Doula[4]
[1] Department of Astronomy, University of Wisconsin-Madison, Sterling Hall, 475 N. Charter Street, Madison, WI 53706, USA; townsend@astro.wisc.edu
[2] Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
[3] Department of Physics and Astronomy, Swarthmore College, Swarthmore, PA 19081, USA
[4] Penn State Worthington Scranton, 120 Ridge View Drive, Dunmore, PA 18512, USA
Received 2010 March 12; accepted 2010 April 14; published 2010 April 26

ABSTRACT

We present new *U*-band photometry of the magnetic helium-strong star σ Ori E, obtained over 2004–2009 using the SMARTS 0.9 m telescope at Cerro Tololo Inter-American Observatory. When combined with historical measurements, these data constrain the evolution of the star's 1.19 day rotation period over the past three decades. We are able to rule out a constant period at the $p_{\rm null} = 0.05\%$ level, and instead find that the data are well described ($p_{\rm null} = 99.3\%$) by a period increasing linearly at a rate of 77 ms per year. This corresponds to a characteristic spin-down time of 1.34 Myr, in good agreement with theoretical predictions based on magnetohydrodynamical simulations of angular momentum loss from magnetic massive stars. We therefore conclude that the observations are consistent with σ Ori E undergoing rotational braking due to its magnetized line-driven wind.



Spindown age

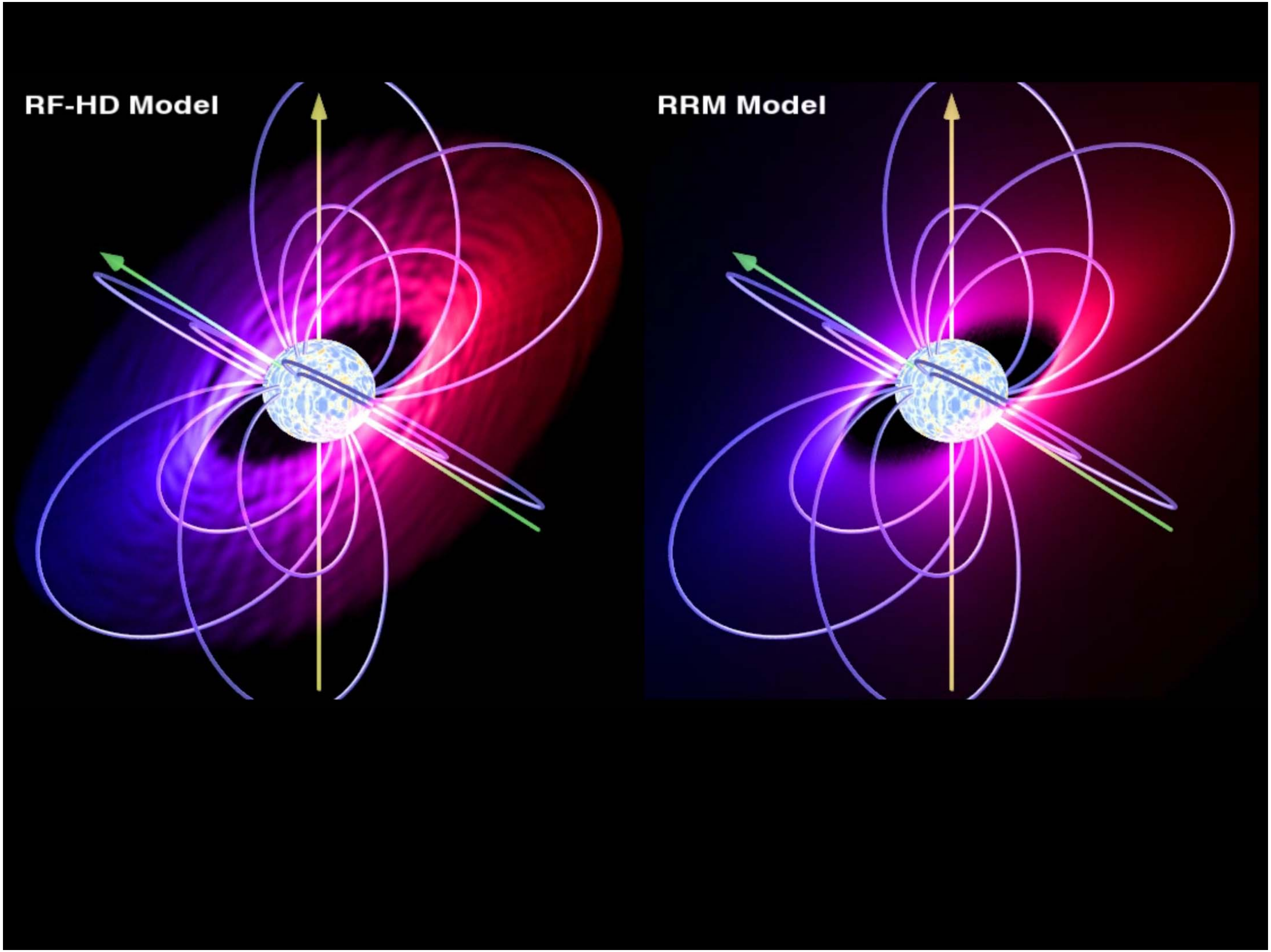
$$P = P_o e^{t/\tau_{spin}} \qquad P_o \approx f P_c$$

$$P_c = 0.21\, d\, R\sqrt{R/M} \qquad \Rightarrow\ P_o \sim day$$

$$\tau_{age} = 2.3\,(\mathrm{Log}P_{day} - \mathrm{Log}P_{o,day})\,\tau_{spin}$$

e.g. HD191612, with P_o = 0.5 to 1 day => now P=630 day:

$$\tau_{age} \approx 6.3 \rightarrow 6.9\ \tau_{spin} \approx 2.5 \rightarrow 2.9\ Myr$$


RF-HD Model
RRM Model

Extrapolated spindown law for higher order multipoles?

$$\frac{\tau_{spin}}{\tau_{mass}} = \frac{\frac{3}{2}k}{\eta_*^{1/n}}$$

n=1 monopole
=2 dipole
=3 quadrapole
... etc.

=> Spindown weaker for more complex fields?

If so, hard to explain tau Sco by spindown??

Need 3D MHD sims to test this!

[redacted]

Summary

- Wind feeding of magnetosphere
  - balanced by inner & outer “leakage”?
  - observations should estimate M_{tot}
  - breakout analysis predicts M_{tot} indep of M_{dot}!

- Wind Magnetic Spindown
  - t_{spin} ~ t_{mass}/Sqrt[eta$_*$] for aligned dipole
  - complex field => slower spindown?
  - need 3D sims to confirm!

References

- Babel, J. & Montmerle, T. 1997, X-ray emission from Ap-Bp stars: a magnetically confined wind-shock model for IQ Aur., A&A, 323, 121
- Ud-Doula, A. et al. 2008, Dynamical simulations of magnetically channelled line-driven stellar winds - II. The effects of field-aligned rotation, MNRAS, 385, 97
- Townsend, R.-H.-D. & Owocki, S.-P. 2005, A rigidly rotating magnetosphere model for circumstellar emission from magnetic OB stars, MNRAS, 357, 251
- Townsend, R.-H.-D. et al. 2005, The Rigidly Rotating Magnetosphere of Ïƒ Orionis E, ApJ, 630, 81
- Weber, E.-J. & Davis, L.-J. 1967, The Angular Momentum of the Solar Wind, ApJ, 148, 217
- Ud-Doula, A. et al. 2009, Dynamical simulations of magnetically channelled line-driven stellar winds - III. Angular momentum loss and rotational spin-down, MNRAS, 392, 1022
- Townsend, R.-H.-D. et al. 2010, Discovery of Rotational Braking in the Magnetic Helium-strong Star Sigma Orionis E, ApJ, 714, 318