

# X-WIND

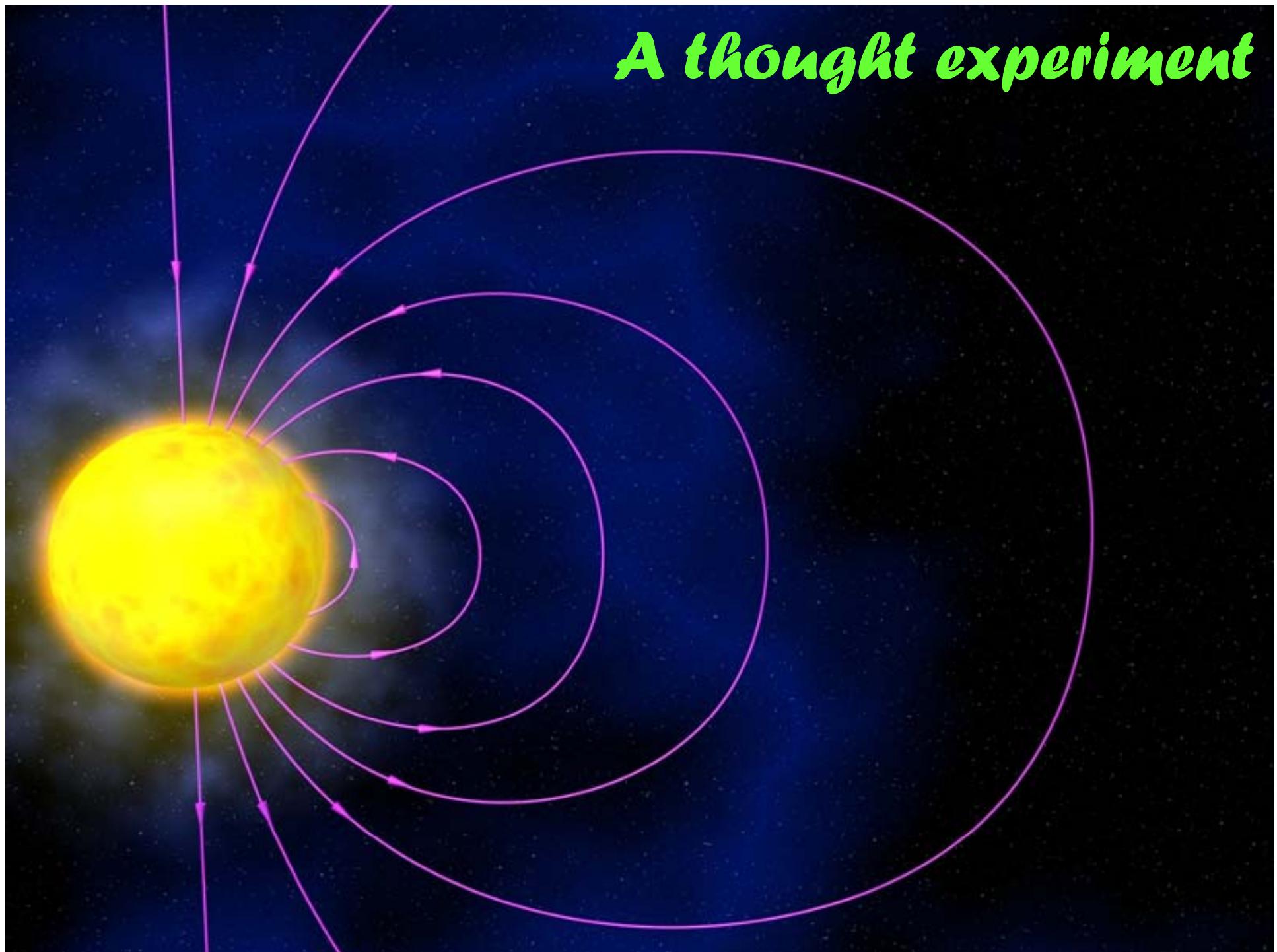
Mike J. Cai (ASIAA)

Protostellar Jets in Context, July 8, 2008

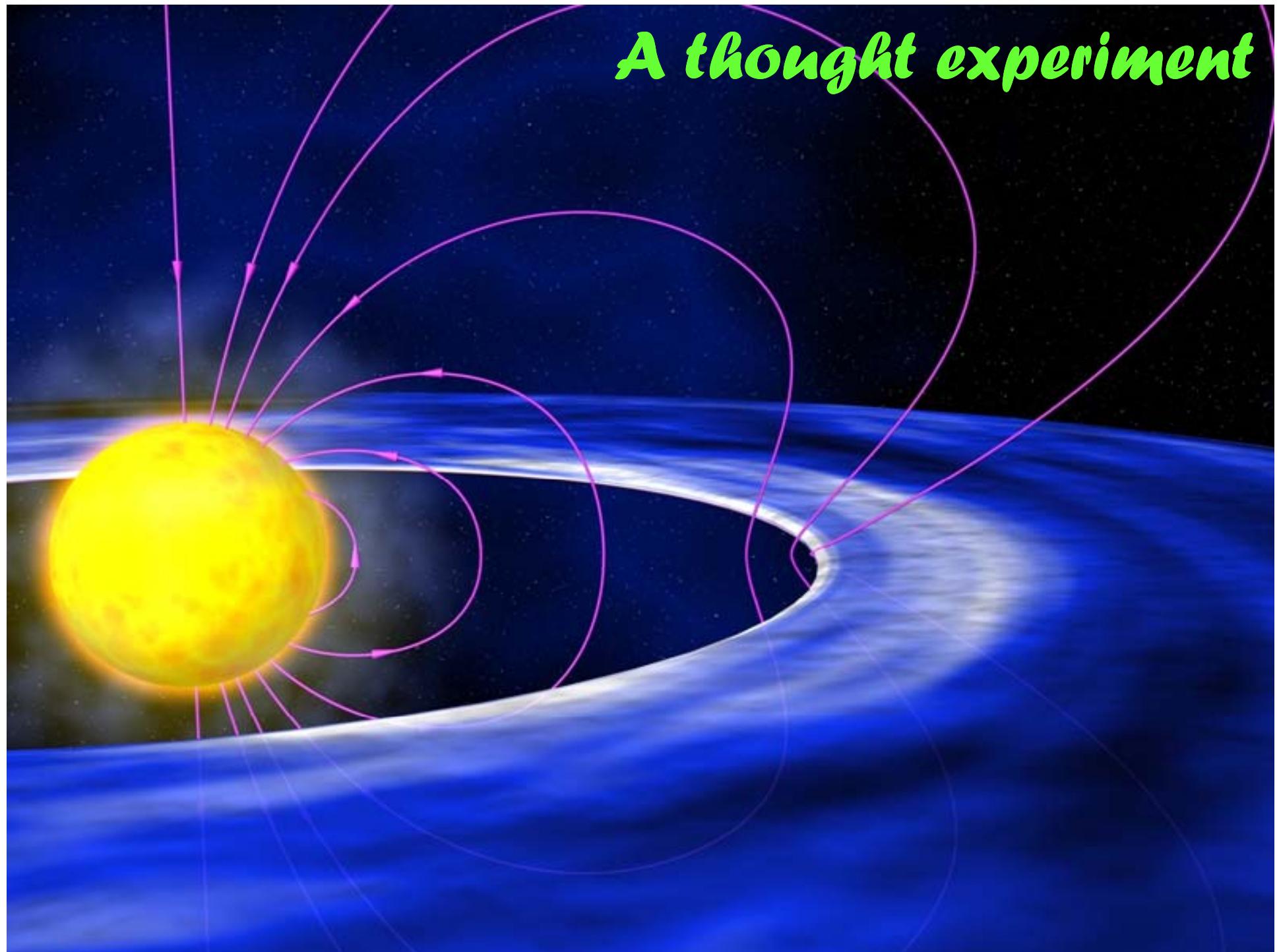
# Contributors

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- ◆ Hsien Shang
- ◆ Zhi-Yun Li
- ◆ Al Glassgold
- ◆ Subhanjoy Mohanty
- ◆ Mike J. Cai
- ◆ many more

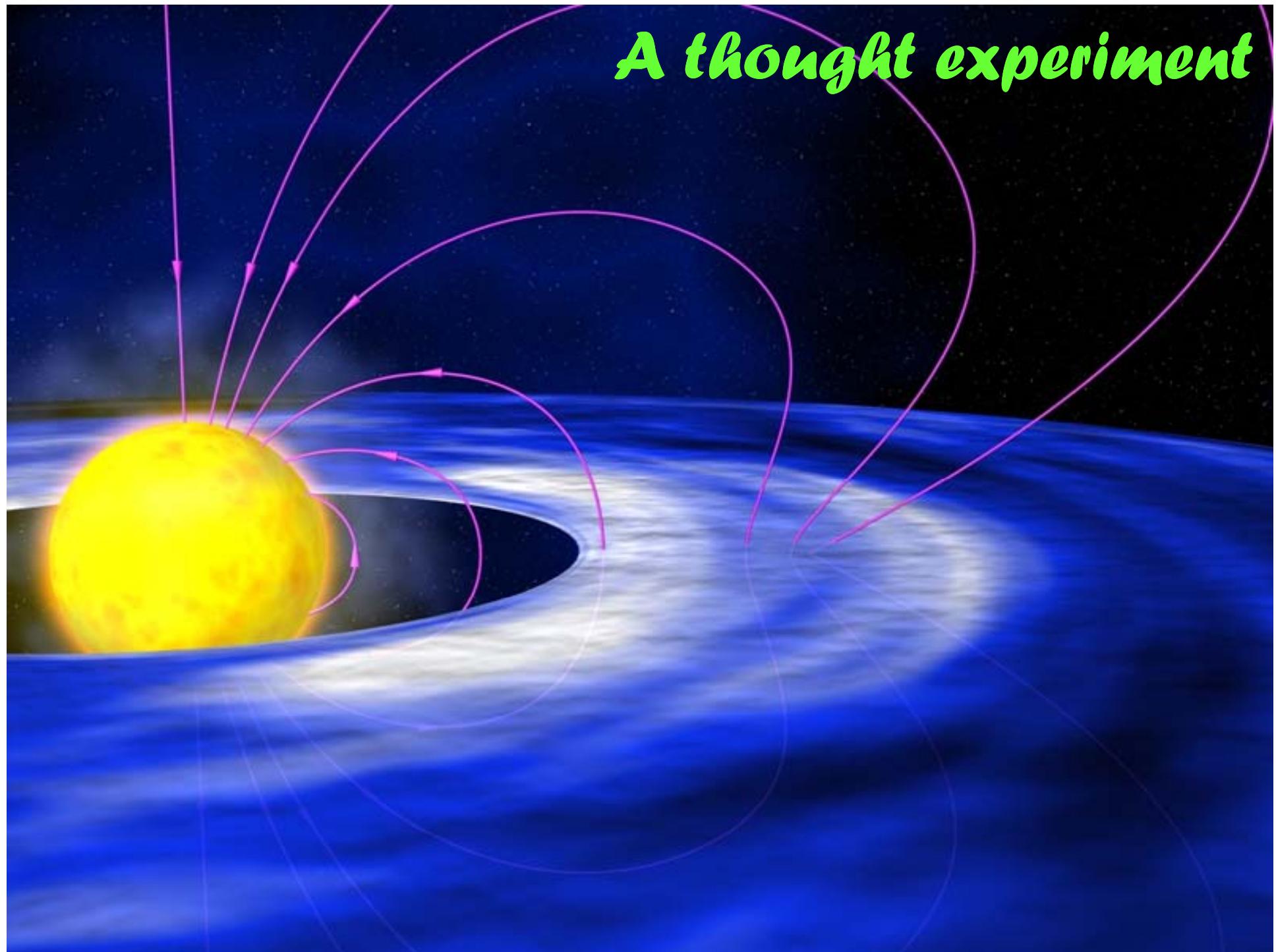
# *A thought experiment*

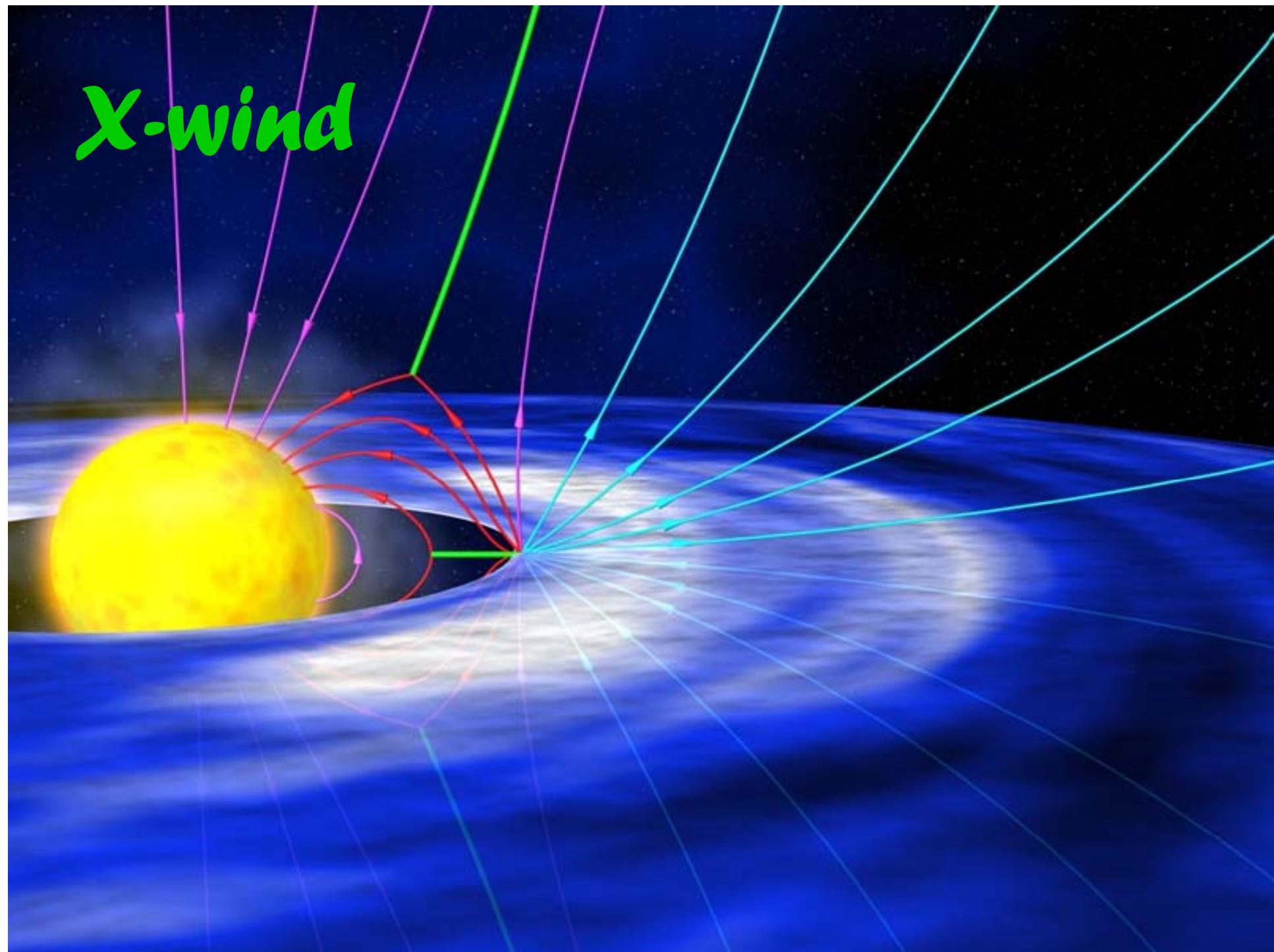


*A thought experiment*



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# General Properties

Shu, Najita, Ostriker, Wilkin, Ruden, Lizano (1994)

- ◆ Mass loss rate

$$\dot{M}_w = f \dot{M}_D \quad f = \frac{1 - \tau - 2b_{\text{eff}}}{\bar{J} - 2b_{\text{eff}}}$$

- ◆ Truncation radius

$$R_x = \Gamma_x R_* \quad \Gamma_x = \alpha_x \left( \frac{B_*^4 R_*^5}{G M_* \dot{M}_D^2} \right)^{1/7}$$

- ◆ Terminal velocity

$$\bar{v}_w \leq (2\bar{J} - 3)^{1/2} R_x \Omega_x$$

# Grad-Shafranov Formalism

Shu, Najita, Ruden, Lizano (1994)

- Stream function in the corotating frame  $\psi(\varpi, z)$ .
- Conserved quantities  
 $H = H(\psi)$ ,  $J = J(\psi)$ ,  $\beta = \beta(\psi)$
- Cold limit ( $a/v_K \rightarrow 0$ )
  - $H(\psi) = 0$ ,  $J(\psi) = \varpi_A^2$ ,  $\beta(\psi)$  specified by user
- Energy conservation along streamlines (BE)

$$|\nabla\psi|^2 + \frac{1}{A^2} \left( \frac{J}{\varpi^2} - 1 \right)^2 + \frac{2\varpi^2 V_{\text{eff}}}{(\beta^2 - \varpi^2 A)^2} = 0$$

- Force balance across field lines (GSE)

$$\nabla \cdot (A \nabla \psi) + \frac{1}{A} \left( \frac{J}{\varpi^2} - 1 \right) \frac{J'}{\varpi^2} + \frac{\beta^{2'} V_{\text{eff}}}{(\beta^2 - \varpi^2 A)^2} = 0$$

# X-winds in Action

Najita, Shu (1994)

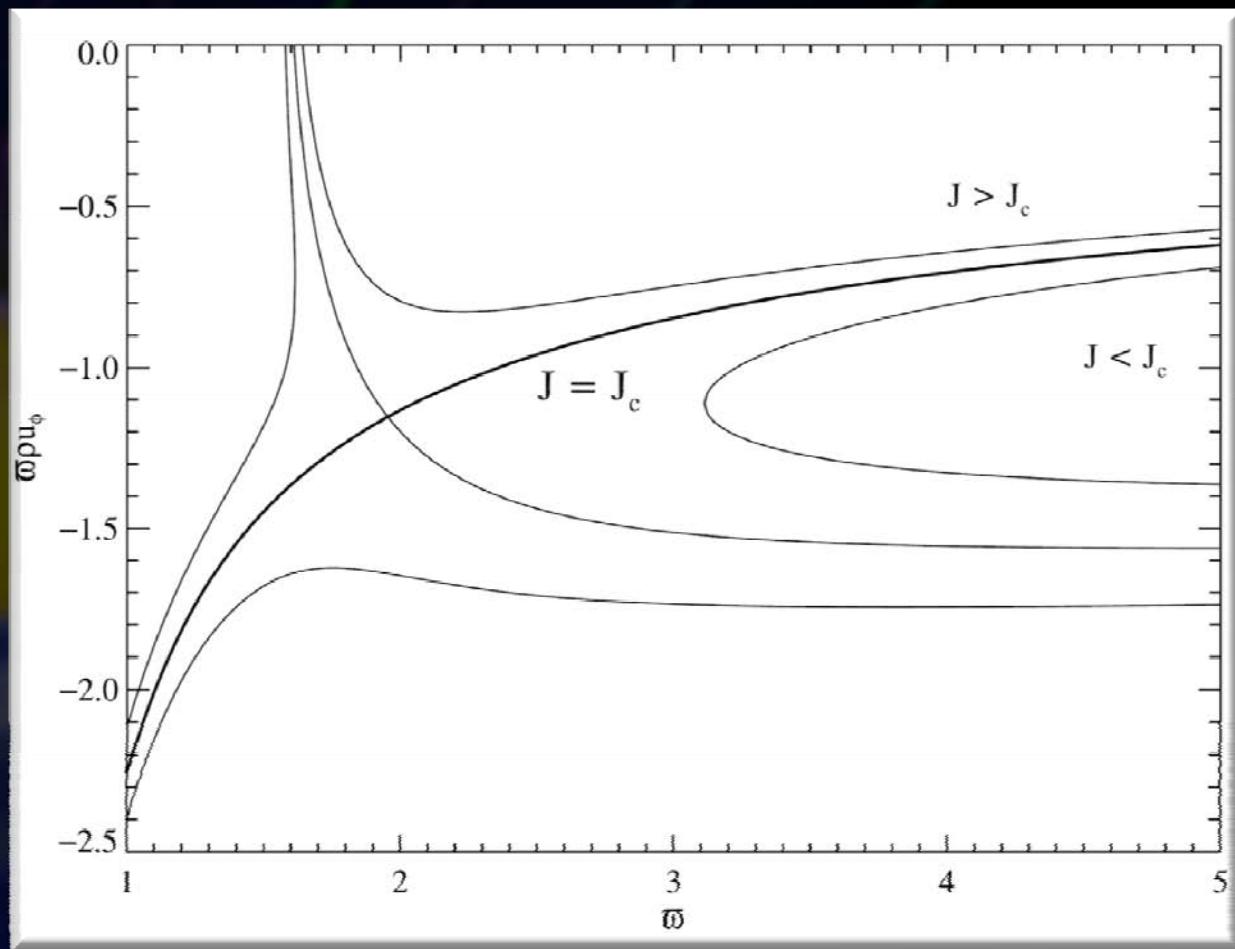
Shu, Najita, Ostriker, Shang (1995)

Cai, Shang, Lin, Shu (2008)

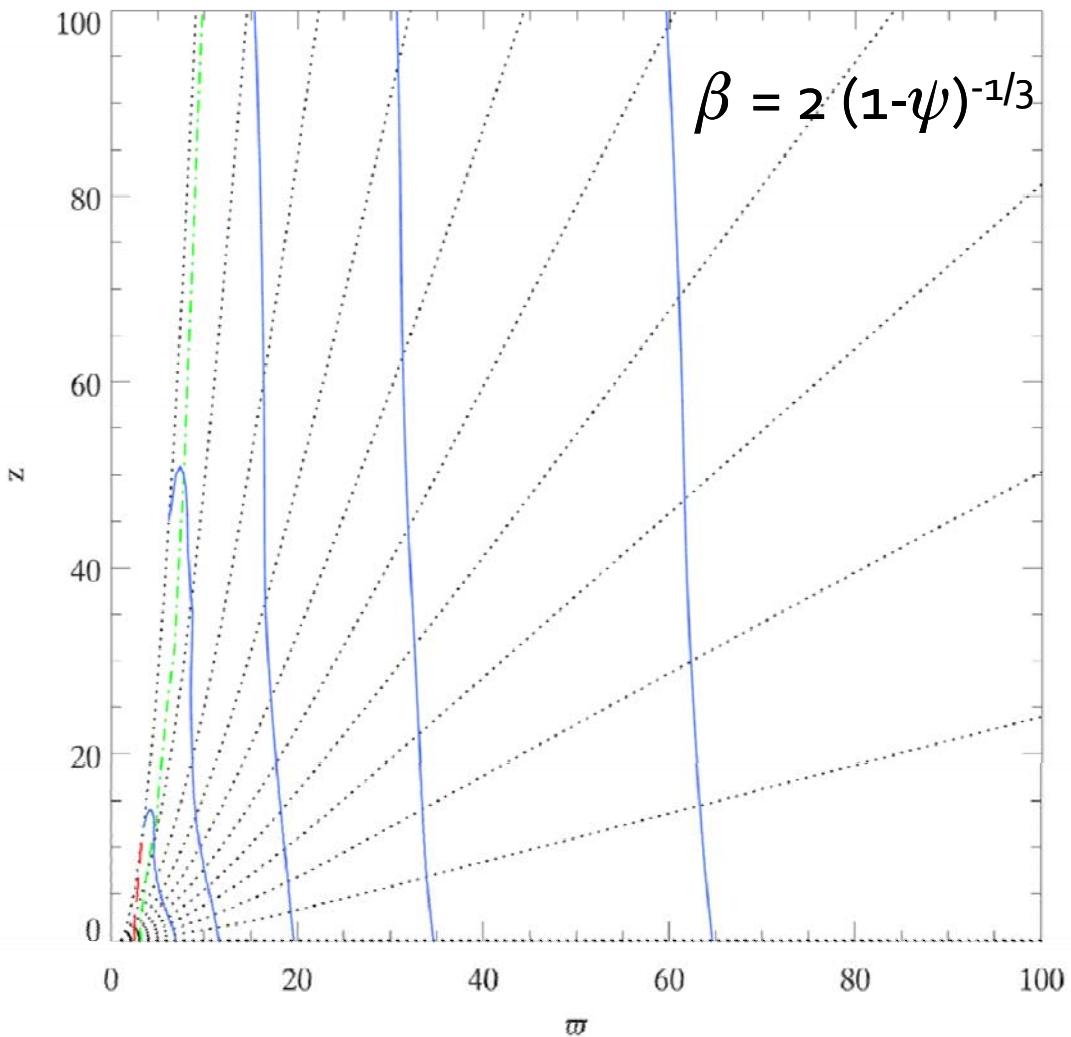
- ◆ The GSE is a PDE of mixed type
  - 💣 Elliptic from X-point to fast surface  $\Rightarrow$  Boundary conditions (but where?)
  - 💣 Hyperbolic after fast surface  $\Rightarrow$  Initial conditions (but characteristics are singular)
- ◆ Variational principle

$$S = \int \left[ \frac{1}{2} \mathcal{A} |\nabla \psi|^2 - \frac{1}{2\mathcal{A}} \left( \frac{J}{\varpi^2} - 1 \right)^2 + \frac{V_{\text{eff}}}{\beta^2 - \varpi^2 \mathcal{A}} \right] d^3x$$

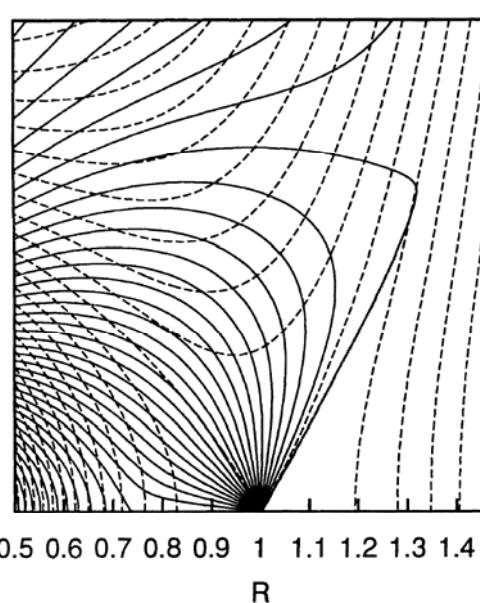
# X-winds in Action



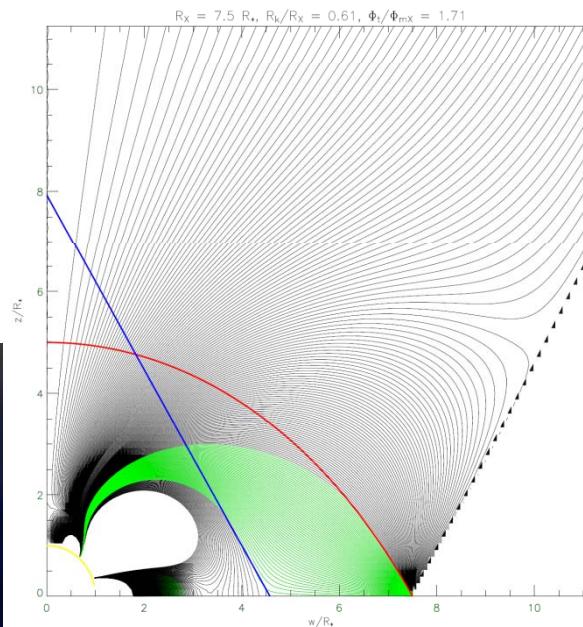
# X-winds in Action



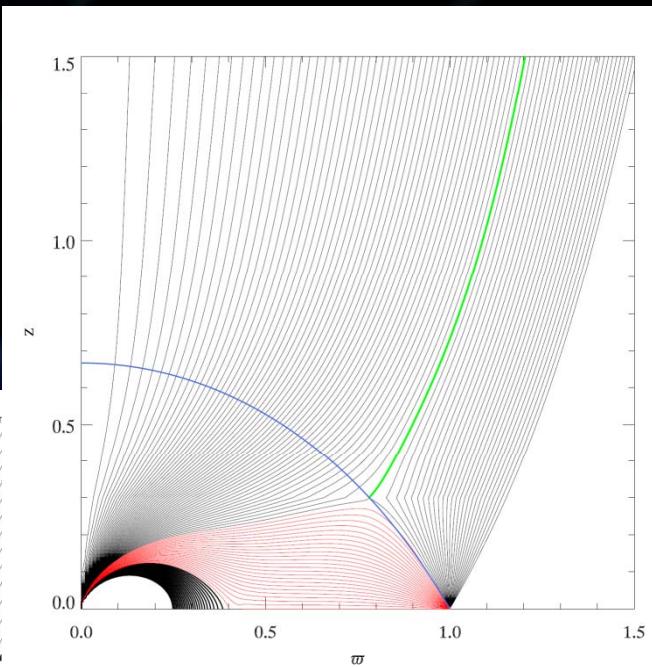
# Deadzone and Funnel Flow



Ostriker & Shu (1995)



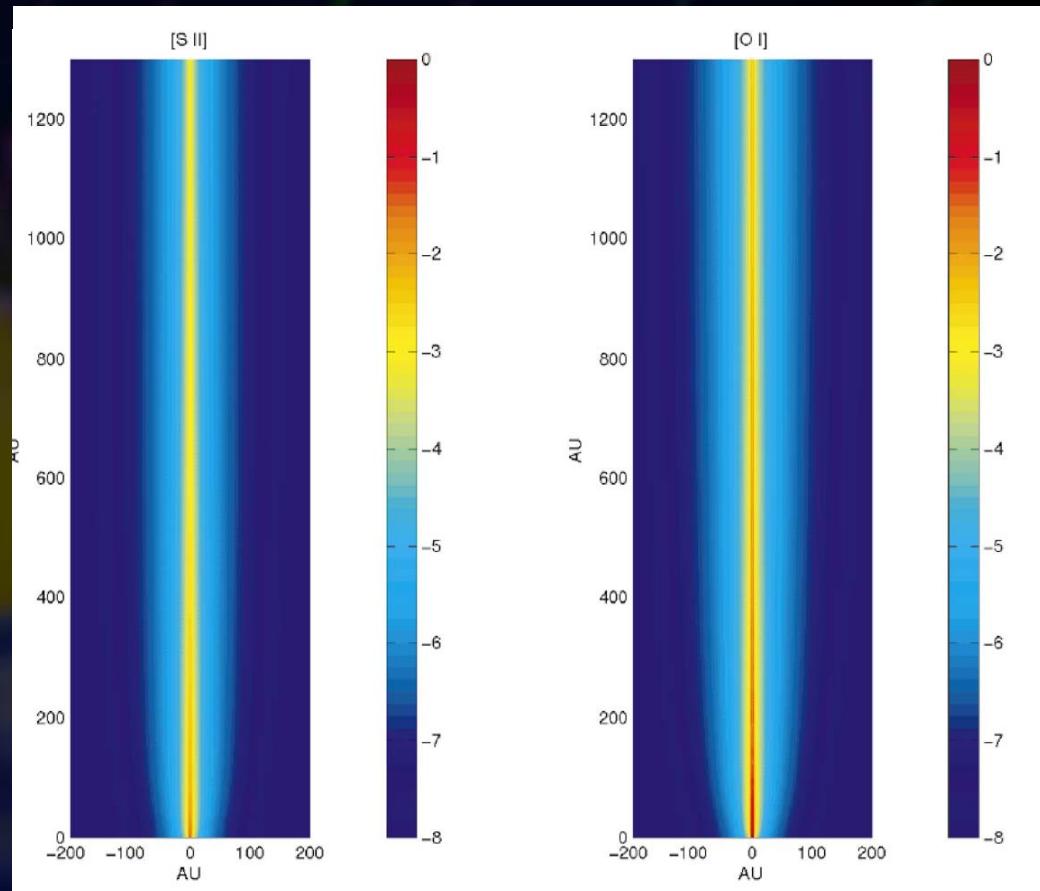
Cai, Shu, Shang, Liu (20??)



Mohanty & Shu (2008)

$R_X = 7.5 R_*$ ,  $R_b/R_X = 0.61$ ,  $\Phi_t/\Phi_{\text{max}} = 1.71$

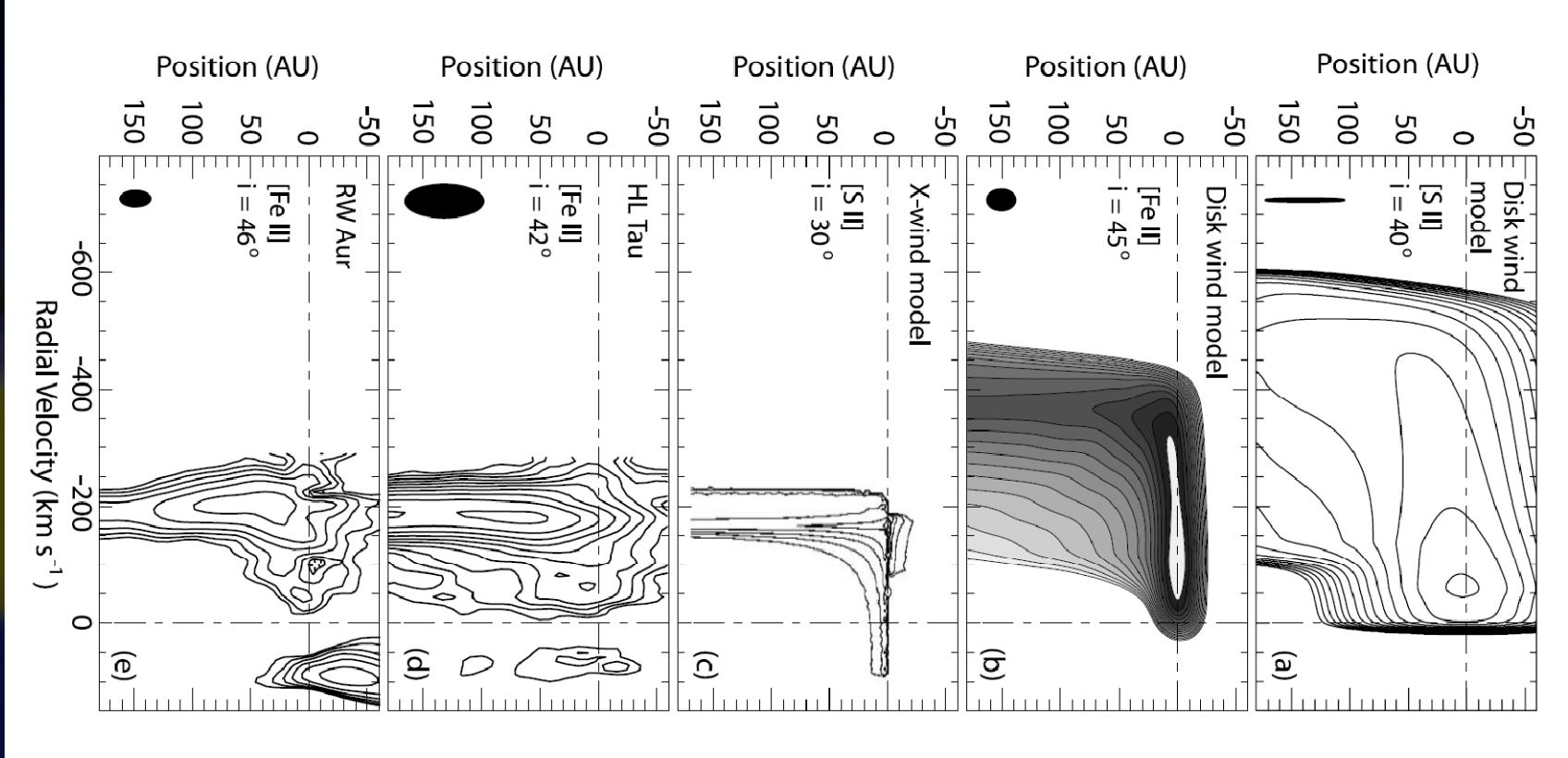
# Synthetic Images



$$\Gamma_{\text{mech}} = \alpha \rho \frac{v^3}{s}$$
$$\alpha \sim 10^{-3}$$

Shang, Glassgold, Shu (2002)

# PVD



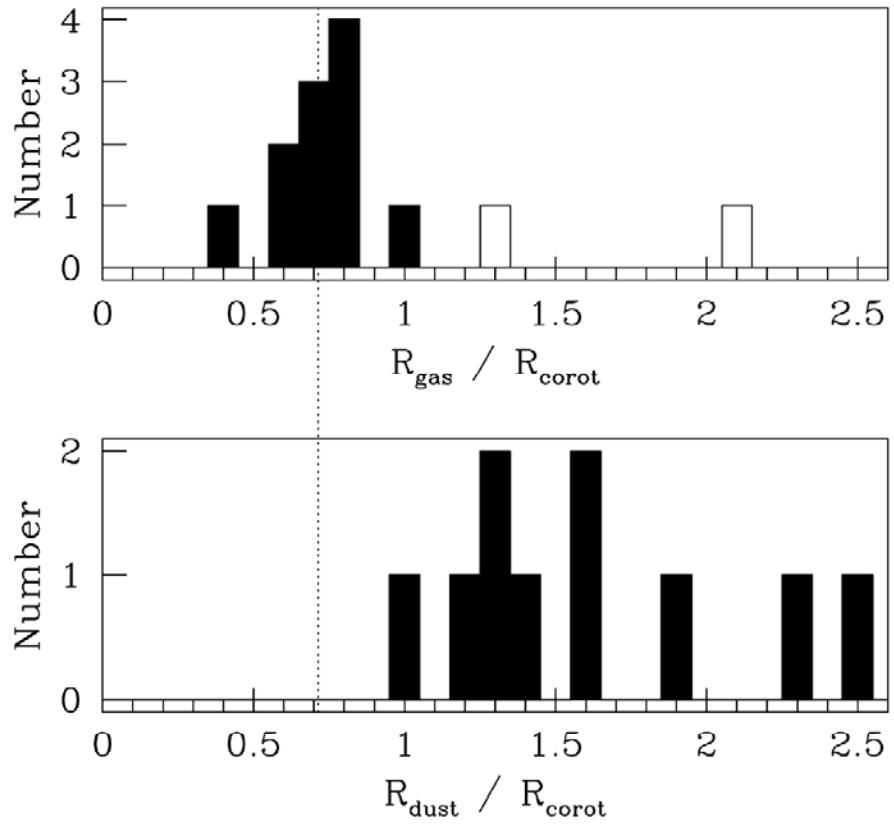
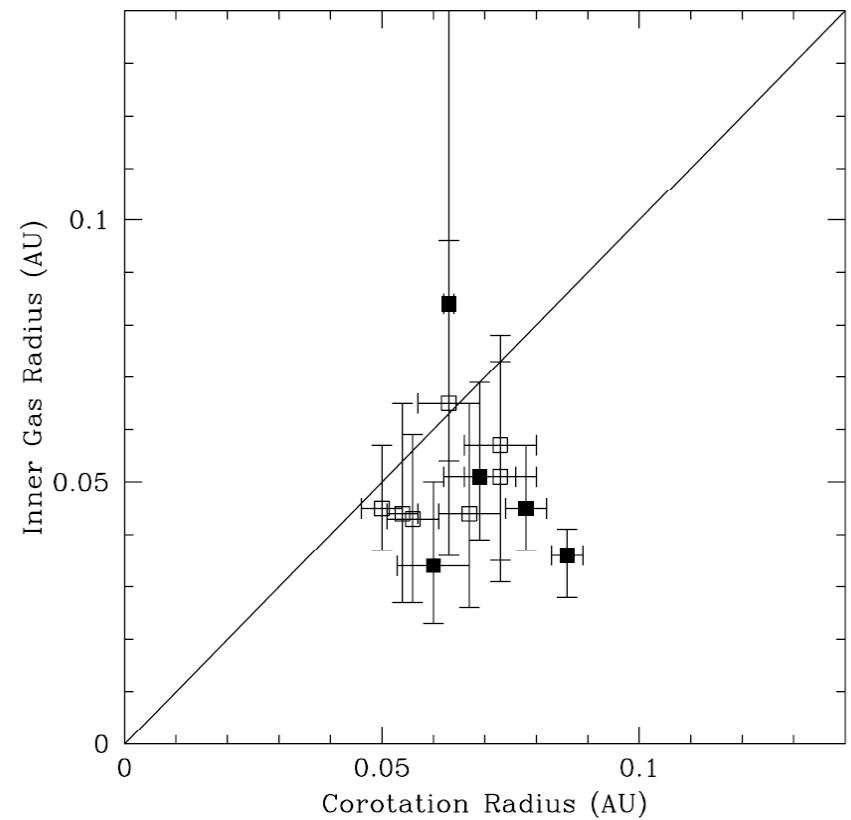
Shang et al (1998)

Cabrit et al (1999)

Pyo et al (2006)

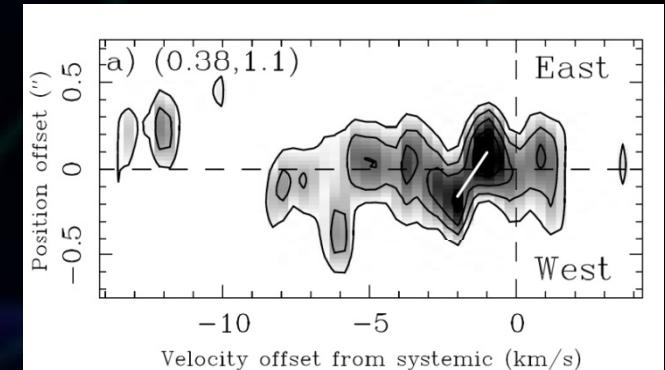
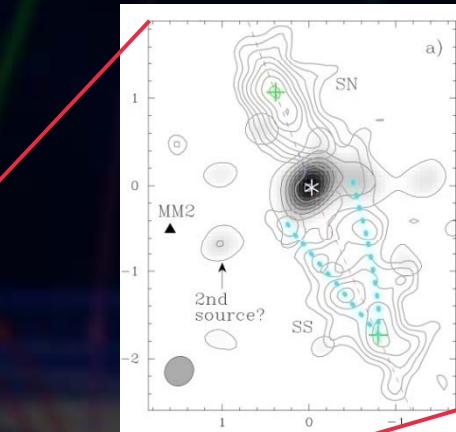
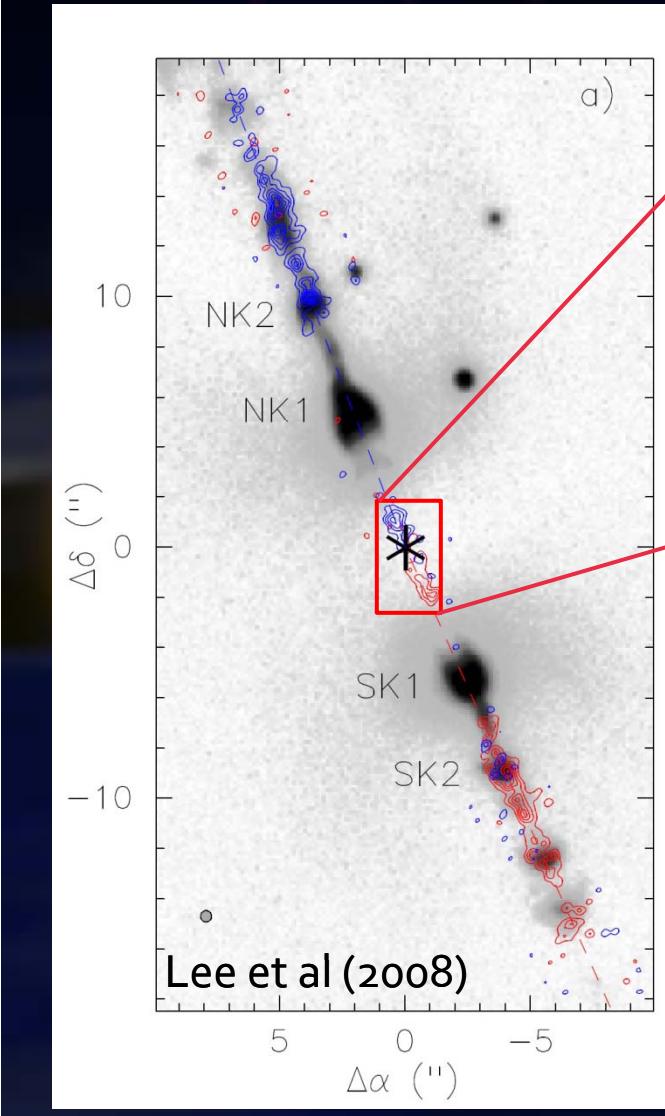
Pesenti et al (2003)

# Disk Locking?



Carr (2007)

# Jet Rotation?



$$v_w = \sqrt{2J_w - 3} \varpi_b \Omega_b \gtrsim 200 \text{ km/s}$$

$$j_w = J_w \varpi_b^2 \Omega_b \lesssim 25 \text{ AU km/s}$$

$$\Rightarrow \varpi_b = \frac{j_w}{v_w} \frac{\sqrt{2J_w - 3}}{J_w} \lesssim 0.125 \text{ AU} \times \frac{\sqrt{2J_w - 3}}{J_w}$$

$J_w$	6	20	400
$\varpi_b(\text{AU})$	0.06	0.04	0.009

# Summary

- ◆ The interaction between accretion disks and stellar magnetospheres naturally gives rise to X-winds and funnel flows.
- ◆ Predictions of the X-wind theory are being tested observationally.
- ◆ X-type outflows and funnel flows start to appear in numerical simulations (e.g. Romanova et al 2008).