# Massive-Star Magnetospheres: The Interplay between Outflows, Rotation and Magnetic Fields

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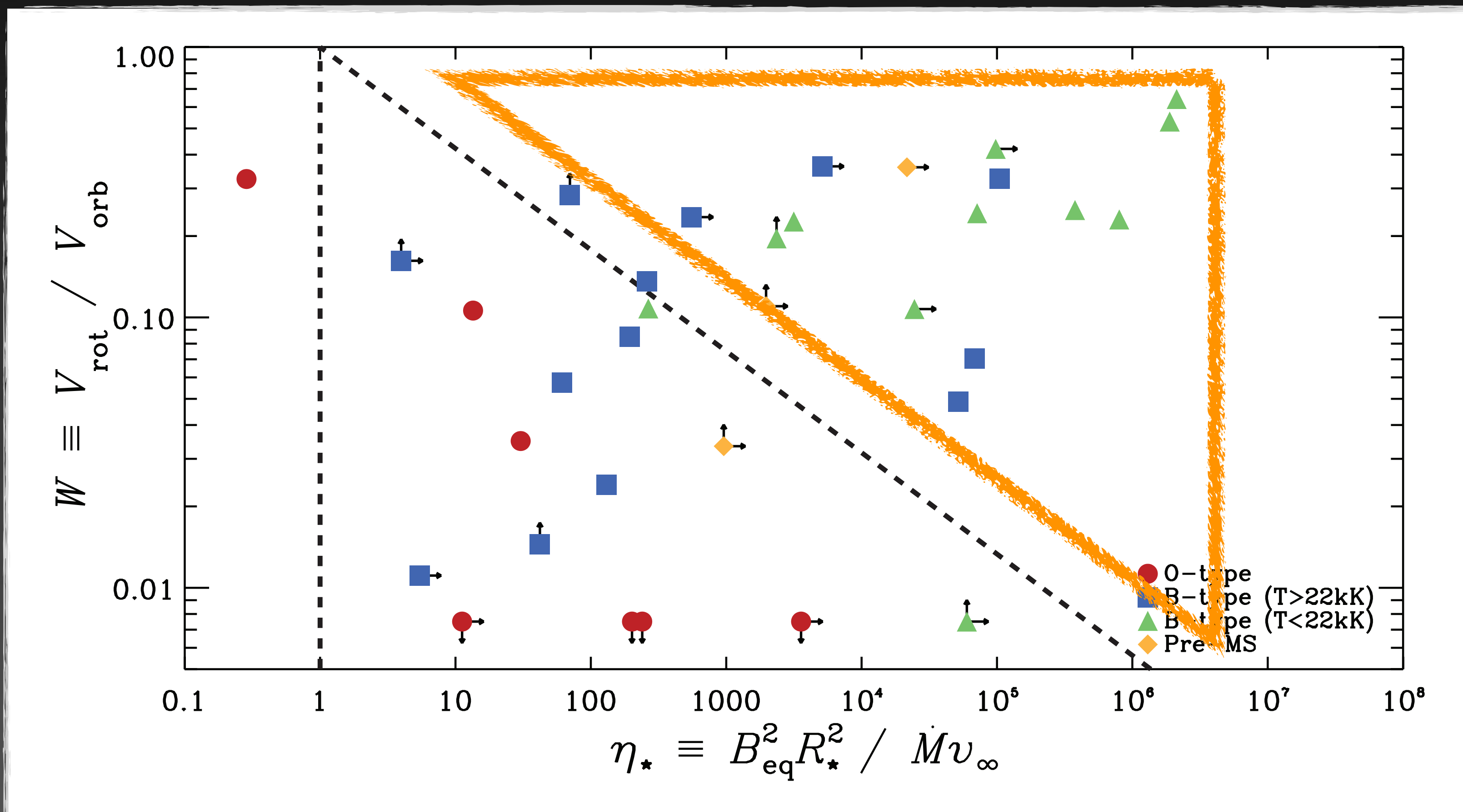
# Context:
# The $\eta_*$-W Diagram

# Strong Field + Rapid Rotation




Petit et al.

# Context: The Magnetosphere of σ Ori E

A NEW PHENOMENON IN THE SPECTRUM OF SIGMA ORIONIS E

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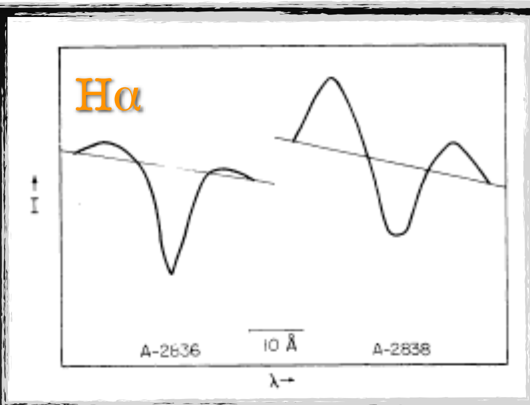
*Received 1974 March 4; revised 1974 May 15*




ON THE PERIOD AND LUMINOSITY STABILITY OF SIGMA ORIONIS E

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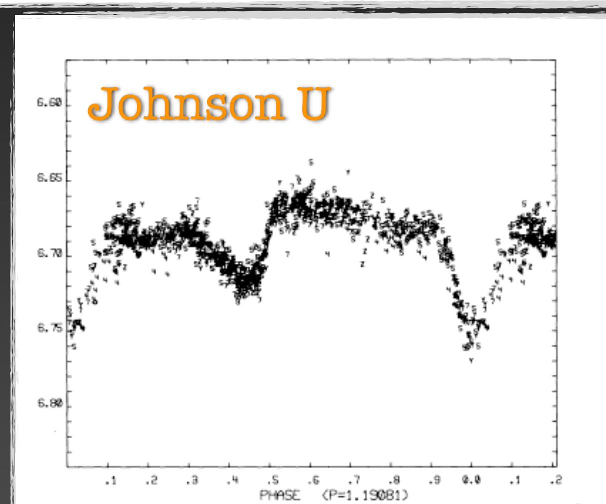


THE MAGNETIC FIELD OF SIGMA ORIONIS E

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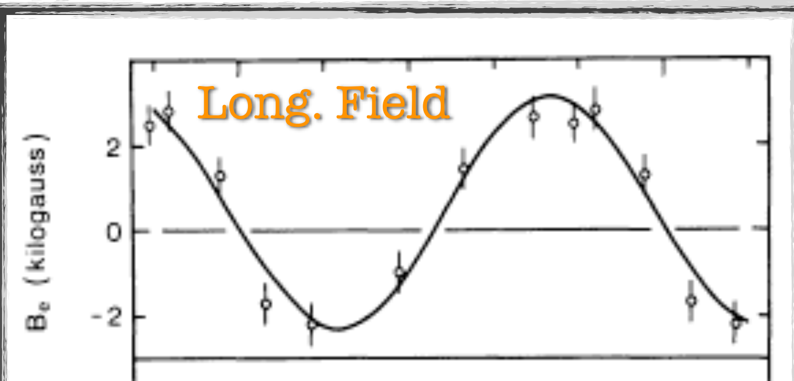
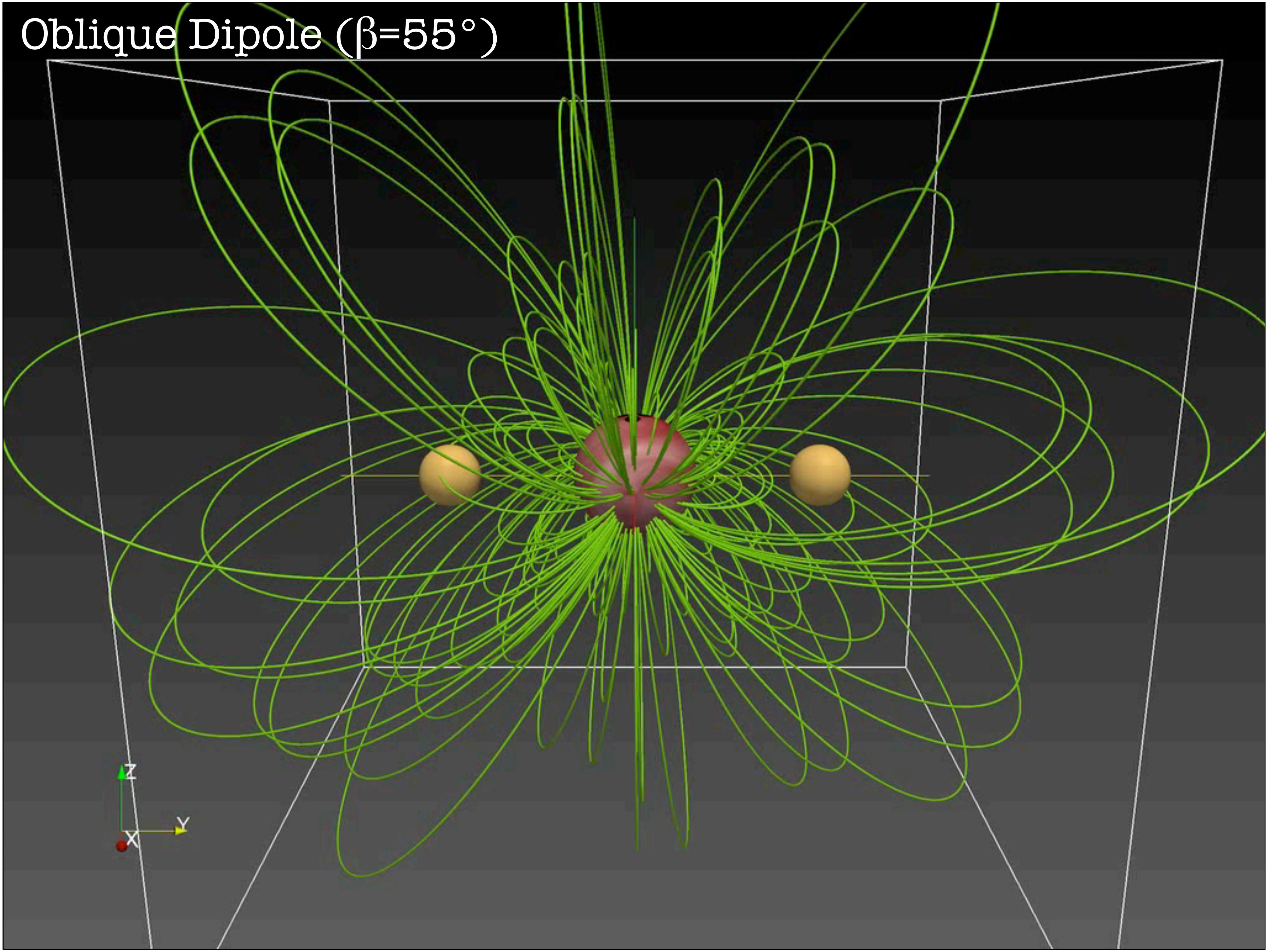
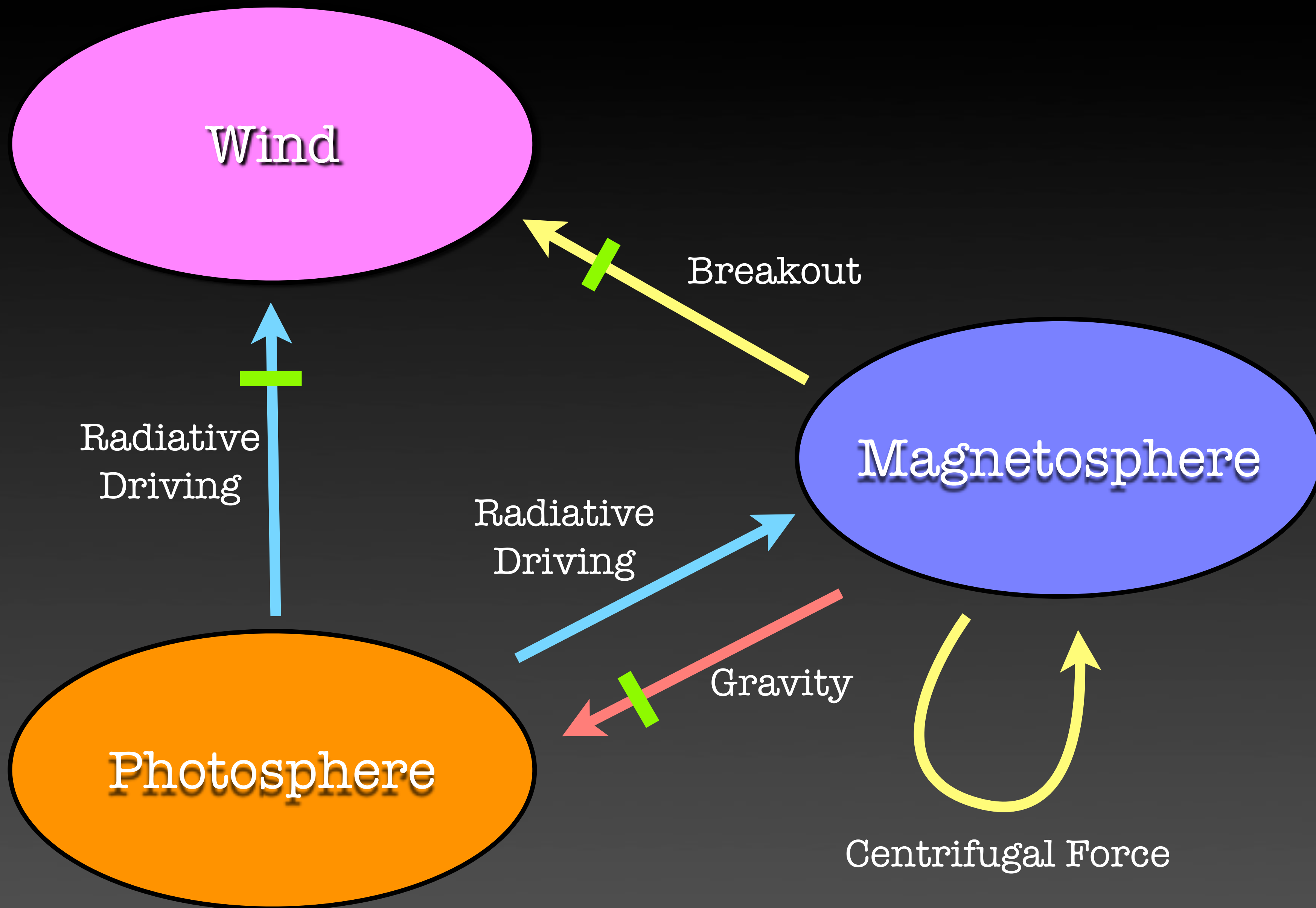
*Received 1977 December 5; accepted 1978 May 24*

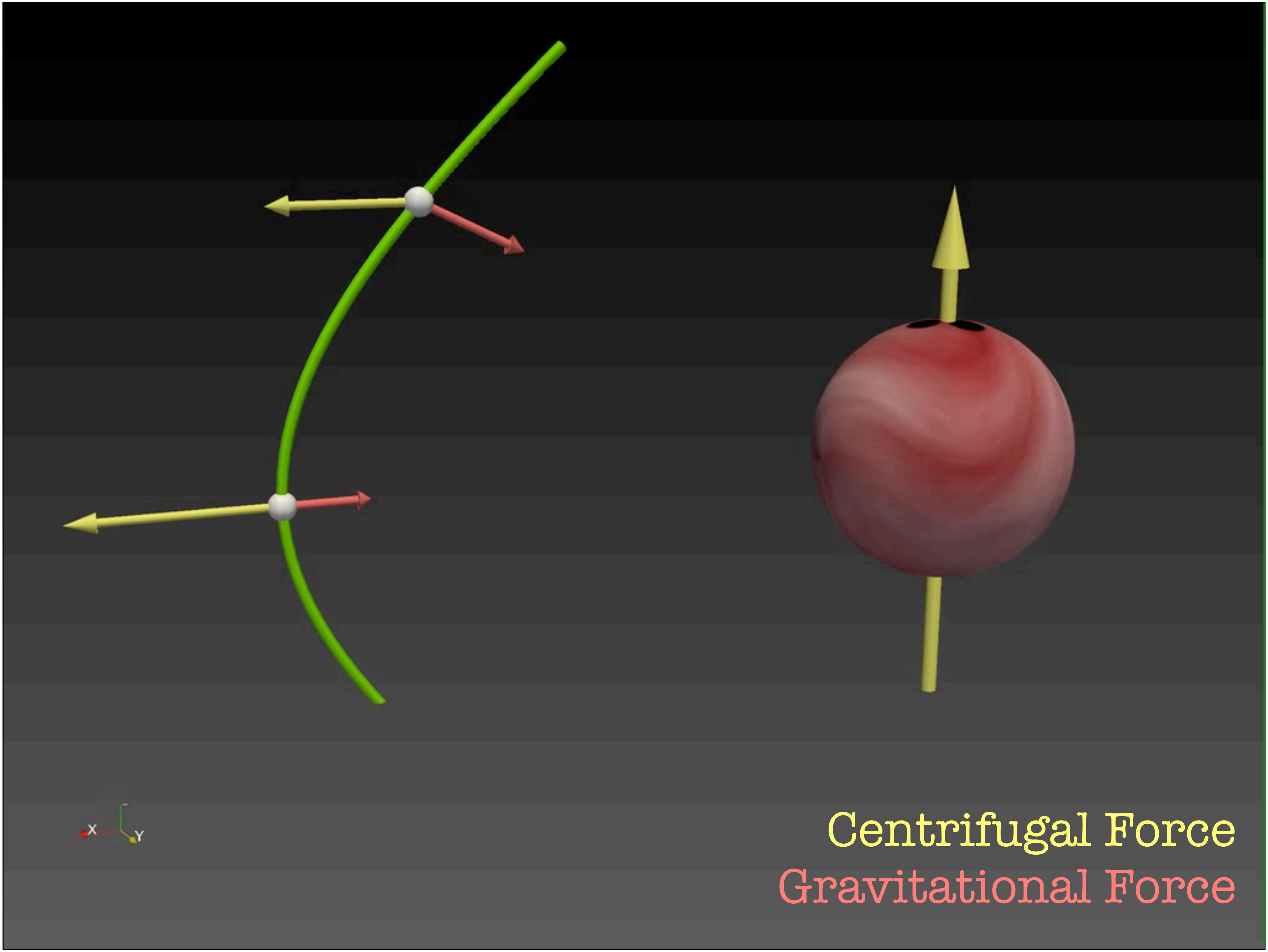


"…an oblique rotator model that has hot gas trapped in a magnetosphere above the magnetic equator."


Oblique Dipole (β=55°)
Z
Y
X

# The Magnetospheric Plasma Cycle


Wind
Breakout
Radiative
Driving
Radiative
Driving
Magnetosphere
Gravity
Photosphere
Centrifugal Force



X
Y
Centrifugal Force
Gravitational Force

# Rigidly Rotating Magnetospheres

Foz do Iguaçu — March 2012

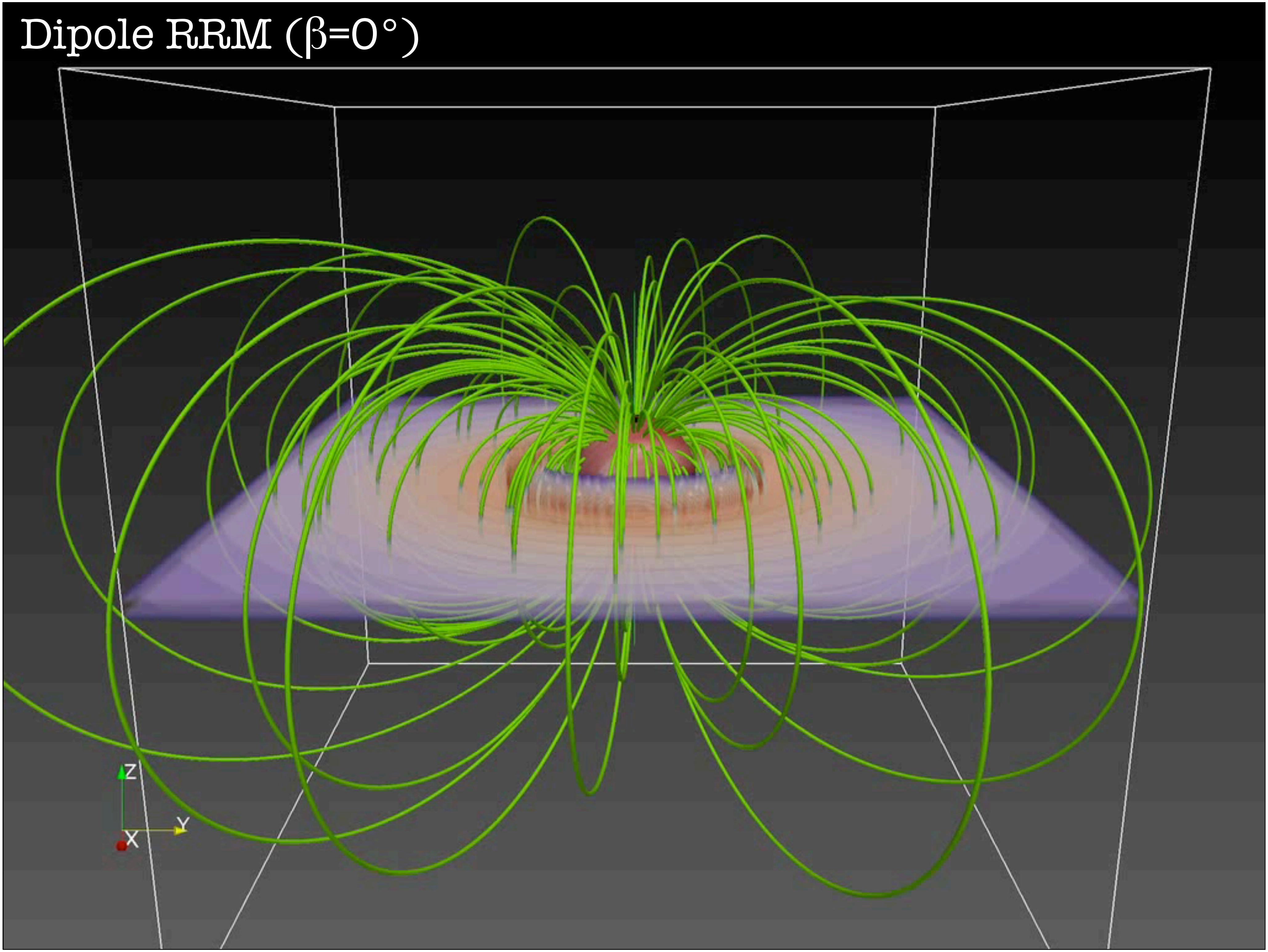
# The Formalism

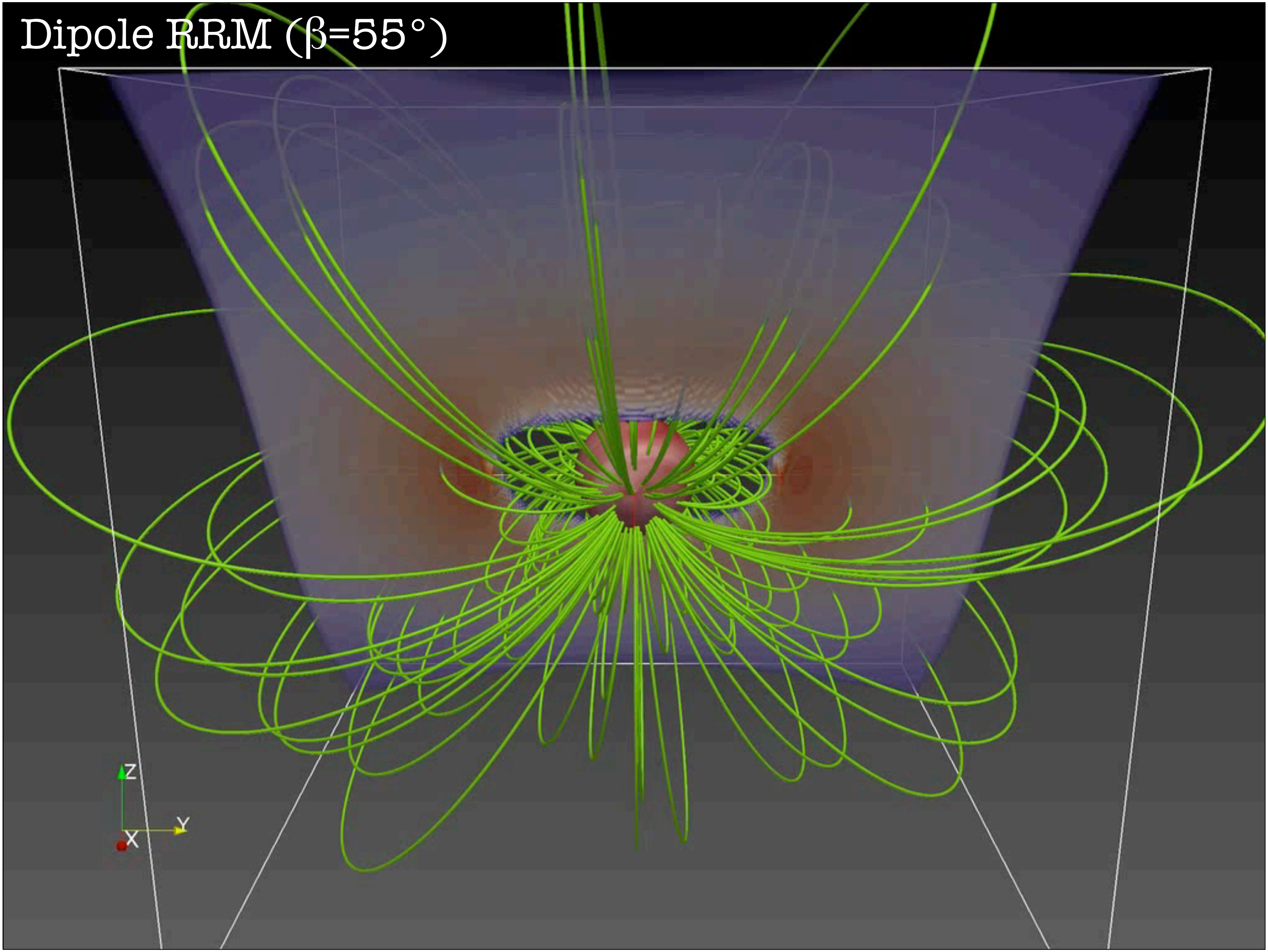
$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + \frac{1}{\rho} \nabla p = \mathbf{g}_{\mathrm{grav}} + \mathbf{g}_{\mathrm{cen}}$$

$$\frac{1}{\rho} \nabla p \cdot \hat{\mathbf{s}} = \mathbf{g}_{\mathrm{grav}} \cdot \hat{\mathbf{s}} + \mathbf{g}_{\mathrm{cen}} \cdot \hat{\mathbf{s}}$$

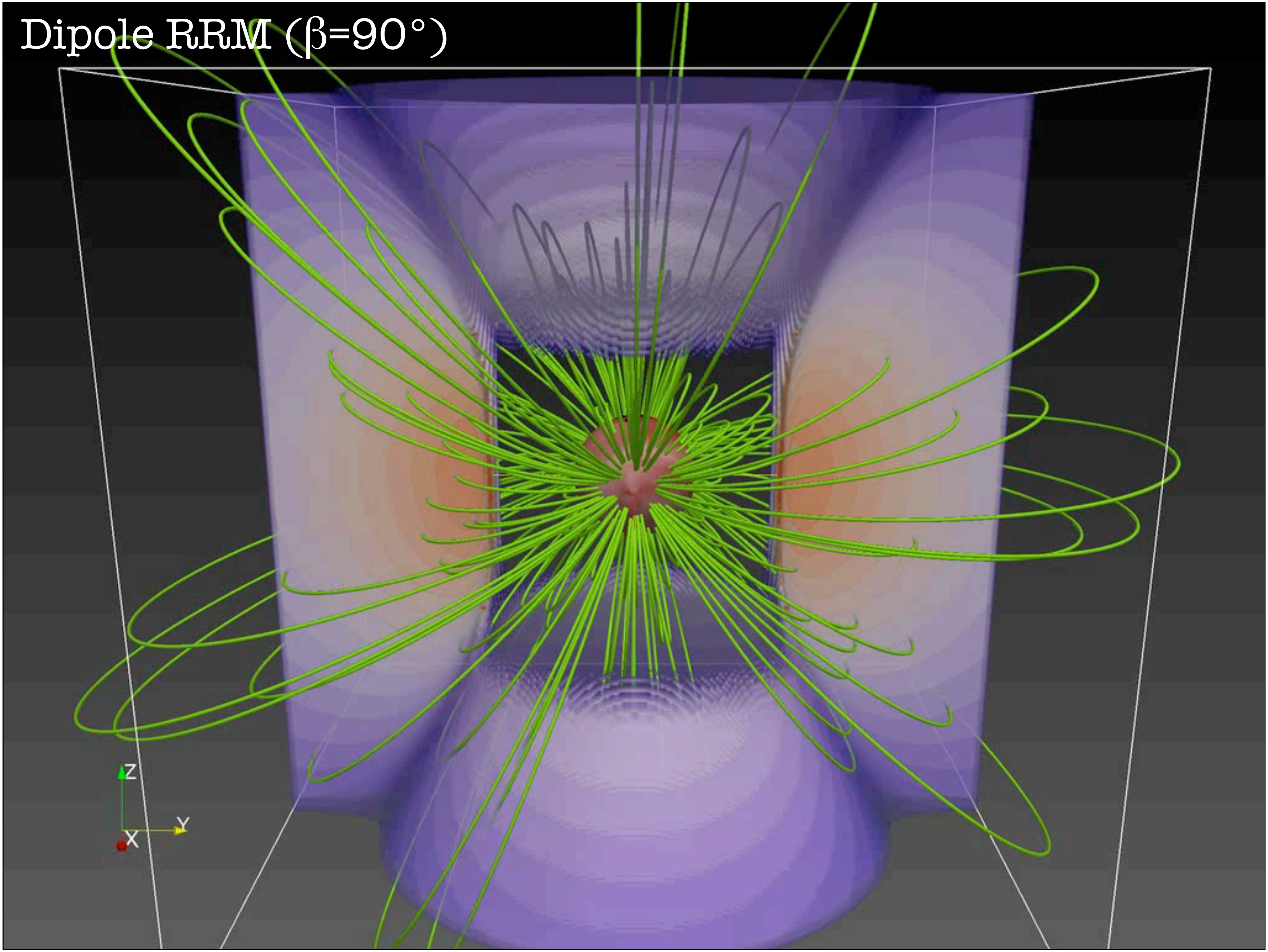
$$\frac{1}{\rho} \frac{dp}{ds} = -\frac{d\Phi_{\mathrm{grav}}}{ds} - \frac{d\Phi_{\mathrm{cen}}}{ds}$$

$$\rho \propto e^{-(\Phi_{\mathrm{grav}} + \Phi_{\mathrm{cen}}) \mu m_{\mathrm{H}} / kT}$$

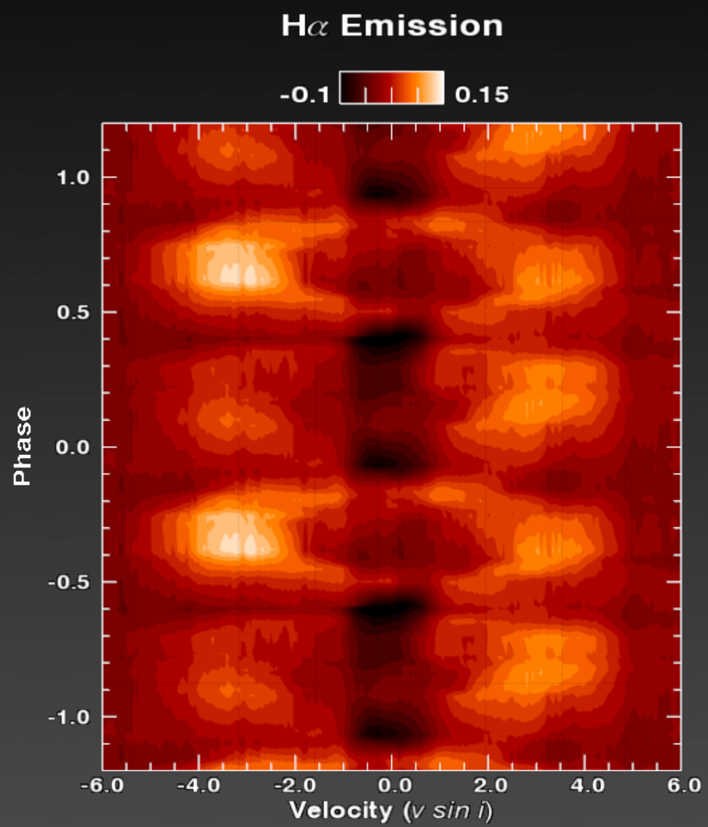

Dipole RRM (β=0°)
Z
Y
X

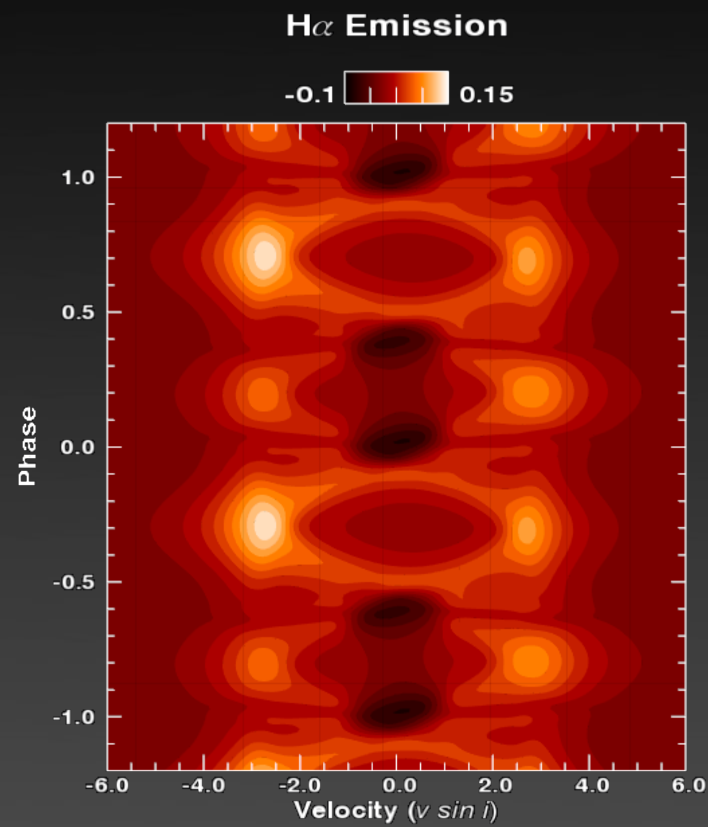


Dipole RRM (β=55°)
Z
Y
X


Dipole RRM (β=90°)
Z
Y
X

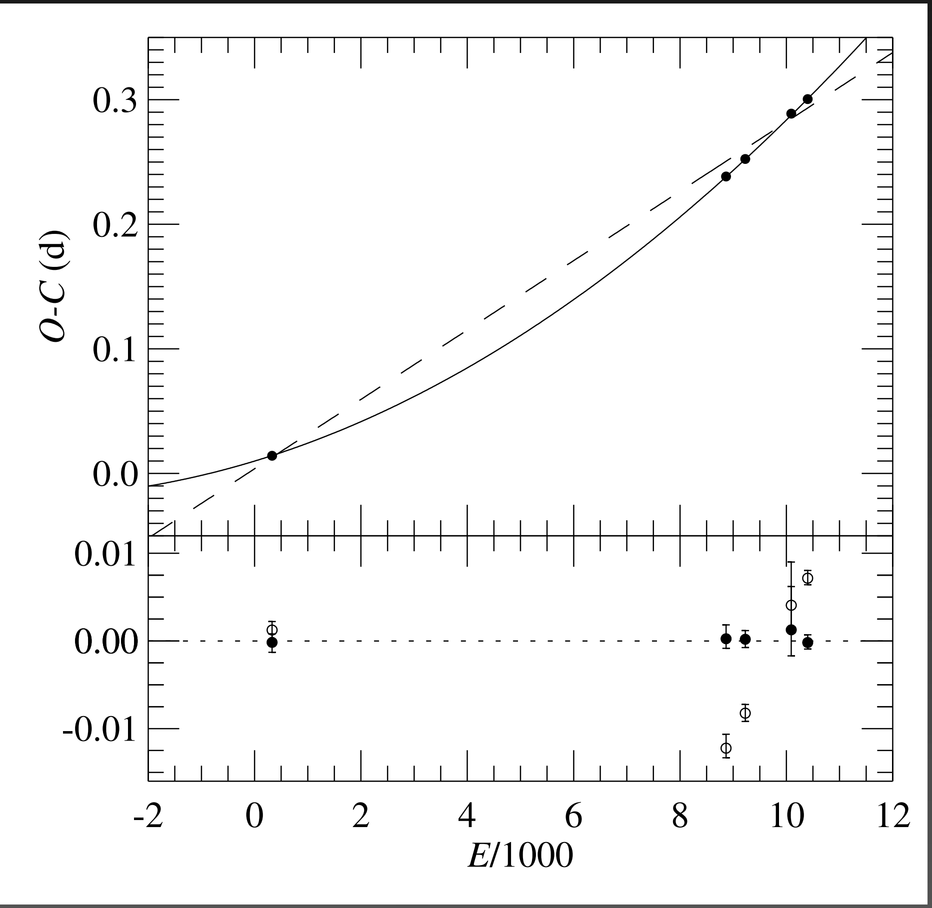
# Observations vs. Theory



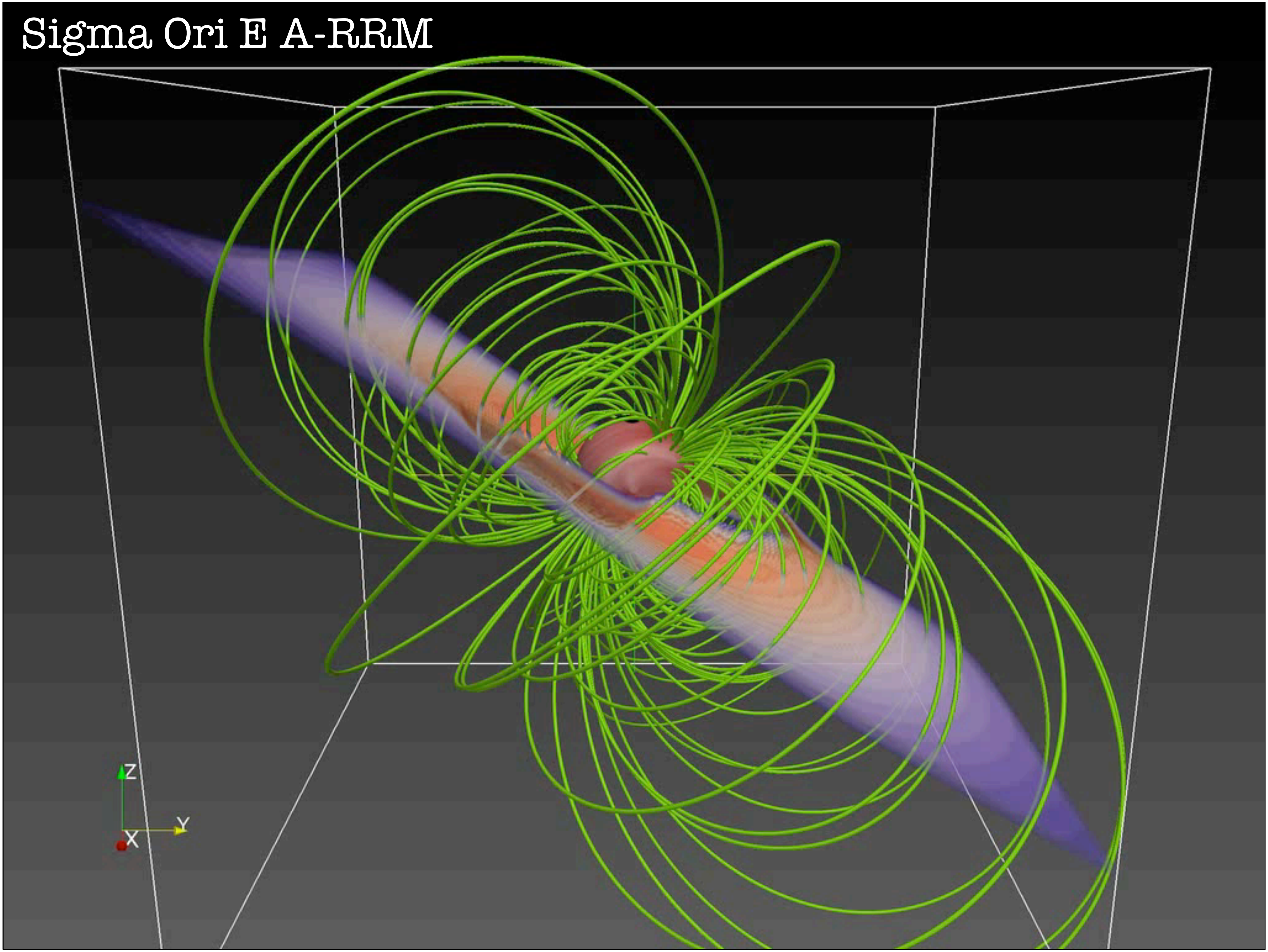

# Magnetospheric Braking

- Eclipses = clock
- Measure braking rate
- $\sigma$ Ori E:
  - $\tau_{obs} \sim 1.3$ Myr
  - $\tau_{MHD} \sim 1.4$ Myr

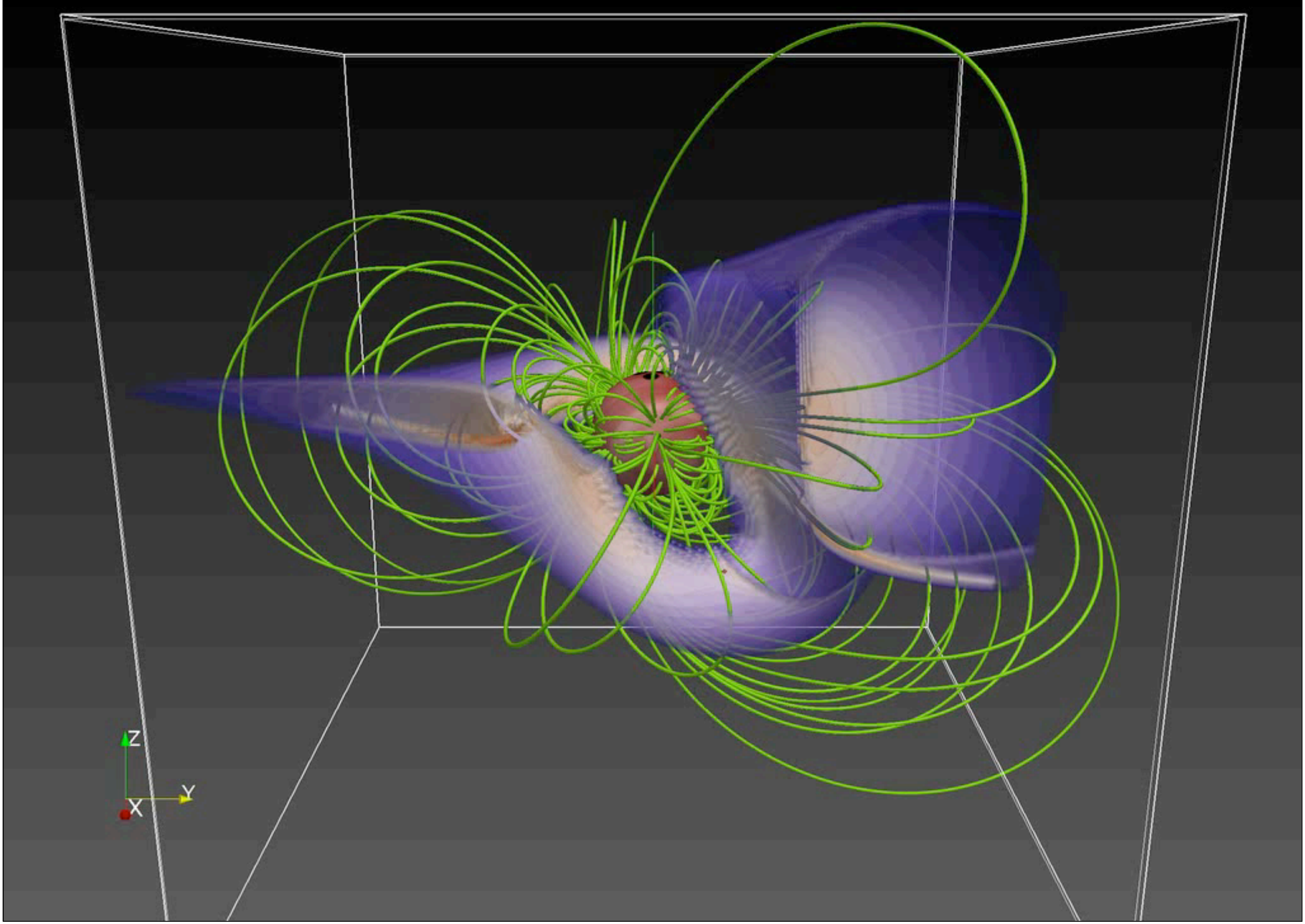


# Arbitrary-Field Rigidly Rotating Magnetospheres

Foz do Iguaçu — March 2012


Sigma Ori E A-RRM
Z
Y
X

# HD 37776 A-RRM

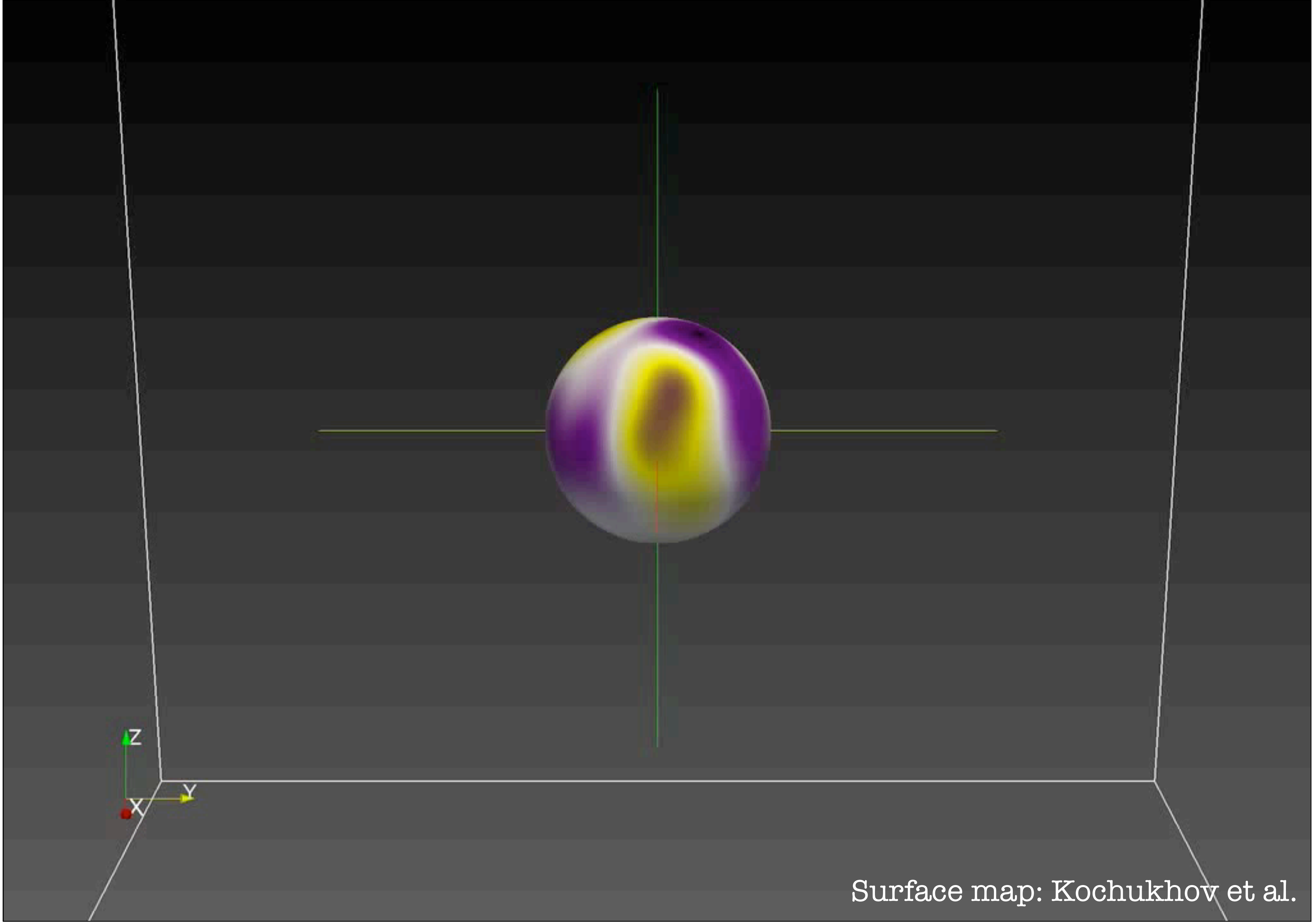


# Reconstructing Force-Free Fields

$$\mathbf{F}_{\mathrm{lor}} = \mathbf{J} \times \mathbf{B} = 0$$

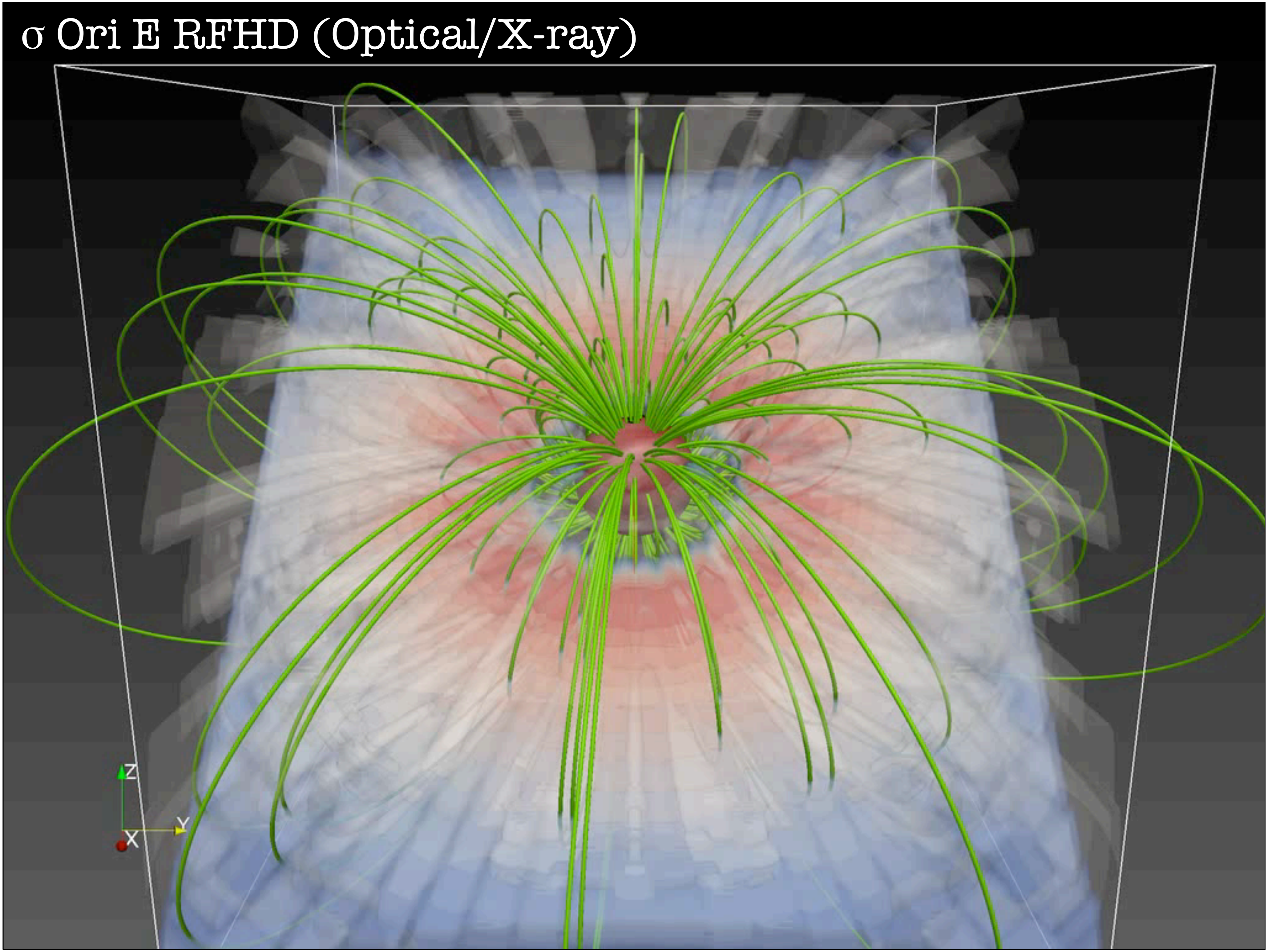
- Potential: $\mathbf{J} = 0 \quad \longrightarrow \quad \mathbf{B} = -\nabla \Phi_{\mathrm{B}}$
- Linear: $\mathbf{J} = \alpha \mathbf{B}$ $\quad$ ($\alpha$ globally const.)
- Non-linear: $\mathbf{J} = \alpha \mathbf{B}$ $\quad$ ($\alpha$ const. along line)

# HD 37776 Potential Field Reconstruction




Surface map: Kochukhov et al.

# Rigid Field Hydrodynamics


σ Ori E RFHD (Optical/X-ray)
Z
Y
X

# Ongoing Challenges

# Magnetospheric Mass Redistribution & Loss

- $\sigma$ Ori E:
  - $M_{RRM} \sim 10^{-9}\ M_{\odot}$
  - $M_{obs} \sim 10^{-11}\ M_{\odot}$

  - Clouds more compact (cf. Alex)
  - Plasma drifting over the lines?

# Magnetospheric X-Rays

- Do all magnetospheres emit X-rays?
  - Apparently not (surveys)
  - Apparently not (σ Ori E; cf. Vero)
- Why not?

# Conclusion

(Centrifugal) Massive-Star Magnetospheres formed from a balance between radiative driving, rotation and magnetic fields.