Transient Dynamos in PNe Progenitors:

Isolated Stars vs. Common Envelopes

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Observational Clues...

- Magnetic Field Detections in

AGB stars	(Etoka & Diamond 2004; Vlemmings 2006)
pAGB objects	(Deacon et al. 2007; Suarez et al. 2007; Szymczak et al. 2007)
Central Stars of PNe	(Jordan et al. 2005)

- Additional Momentum

  $\sim 80\%$ of pPNe have fast outflow momenta significantly higher than that supplied by radiation pressure (Bujarrabal et al 2001)

- Binaries?

  $\sim 90-100\%$ of all PNe may harbor a central binary or interacted with a companion (De Marco et al 2004; Moe & De Marco 2006)

Magnetic Fields:
A launching and shaping mechanism?

- How are strong magnetic fields generated?

  Interplay of turbulence + differential rotation can amplify weak fields via dynamo action (Parker 1955)

- Dynamos in AGB stars may be responsible for producing bi-polar pAGB/PNe. (Pascoli 1997)

Blackman et al. 2001 Nature:

A steady dynamo over an AGB lifetime could unbind the star once enough matter has radiatively "bled-away".

Magnetic field growth drains differential rotation energy.

The back-reaction of the field on the flow must be incorporated.

Two Initial Cases

- Isolated AGB star

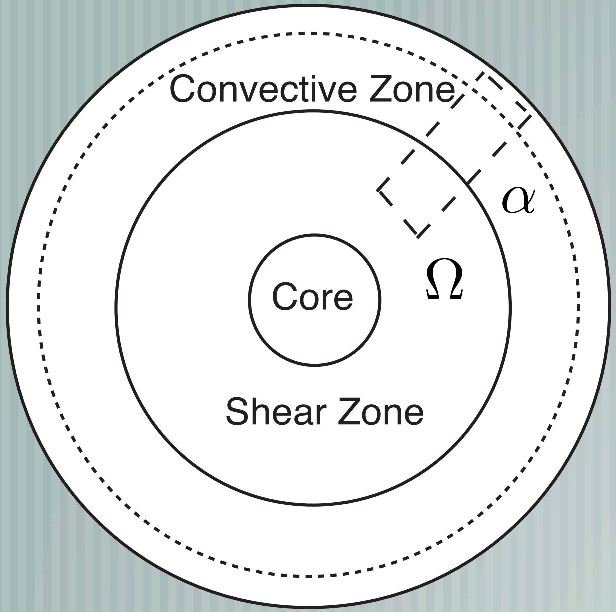
  (i) No re-seeding of differential rotation

  (ii) Re-seeding of differential rotation via convection

- Common Envelope Star

  In-spiral of a low-mass secondary spins up envelope; supplies additional source of differential rotation

Progenitor Geometry



We use a $3\,M_\odot$ AGB model star (courtesy of S. Kawaler)

Convective Zone

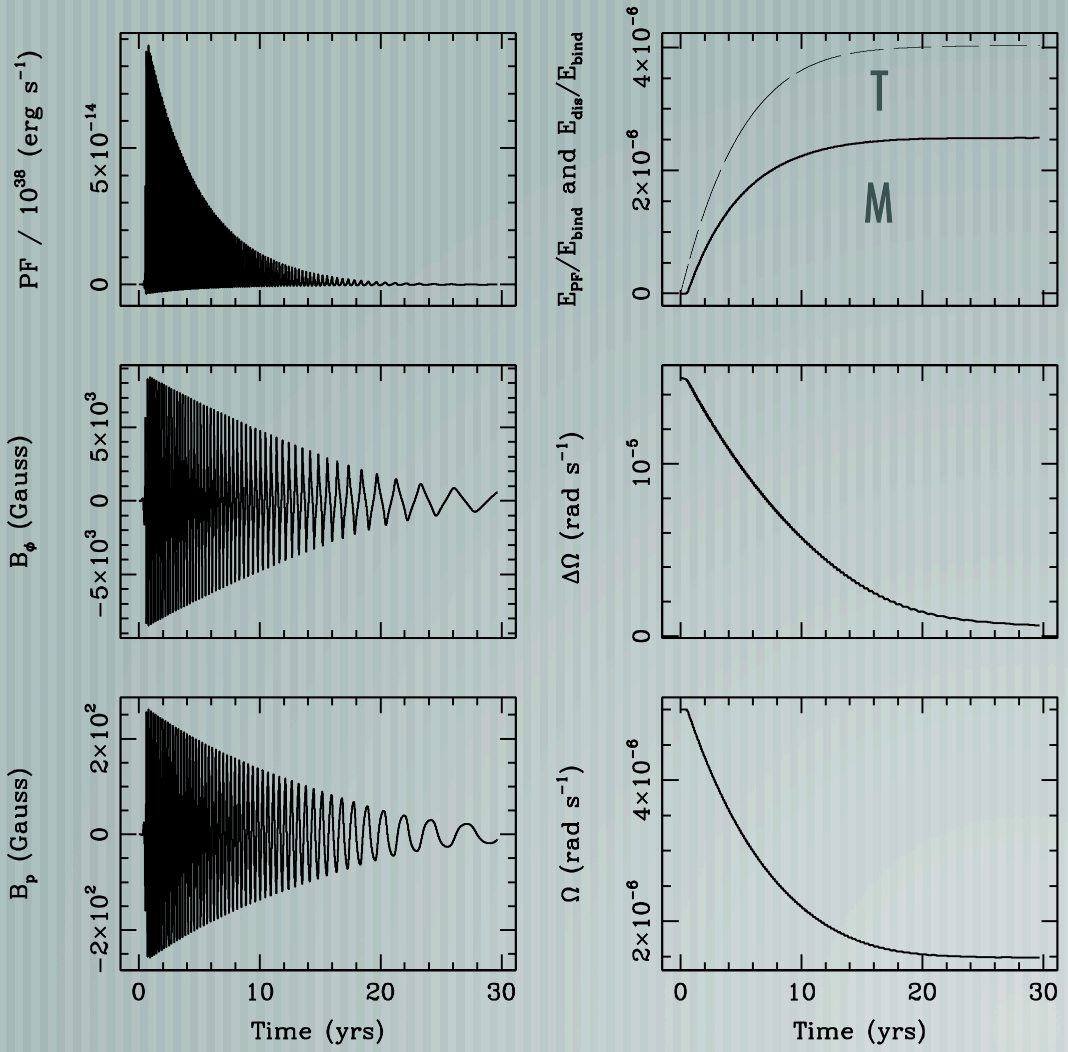
Highly turbulent with diffusion coefficient β_p

Shear Zone

Weakly turbulent with diffusion coefficient $\beta_\phi \ll \beta_p$

Magnetic Prandtl Number $Pr_p \equiv \dfrac{\beta_\phi}{\beta_p}$

Isolated Star I: No Re-seeding



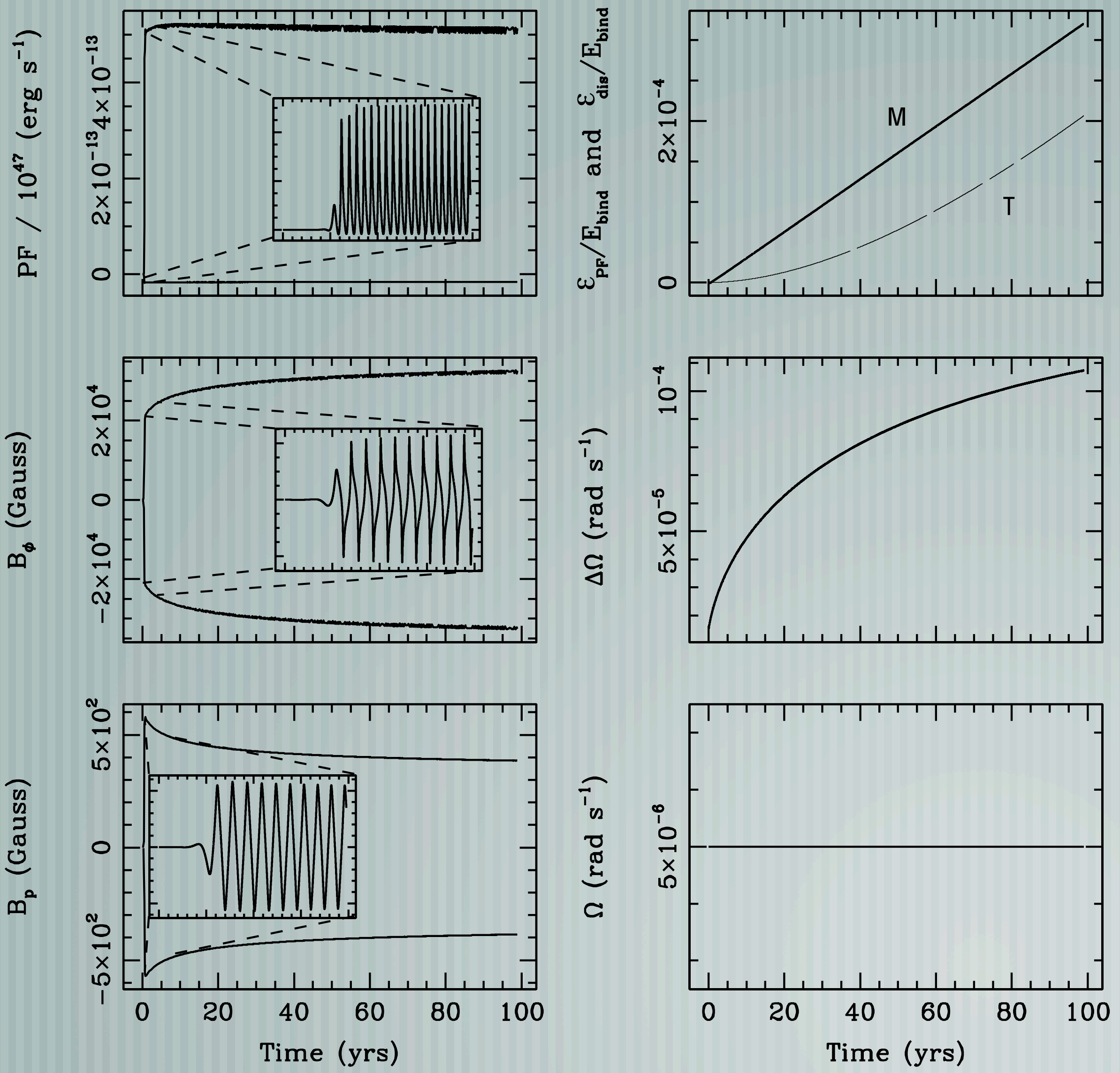
Nordhaus, Blackman & Frank 2007

Peak field $\sim$ 5 - 10 less than values from Blackman et al. 2001

Dynamo duration < 20 yrs

With a fixed amount of differential rotation, a single star can not unbind its envelope via a dynamo.

Isolated Star II: With Re-seeding



Convection can re-supply differential rotation analogous to the sun.

A Poynting flux of $\sim 5 \times 10^{34}$ erg/s maintained over AGB lifetime of $\sim 10^5$ yrs can unbind the envelope.

Required:

i. Resupply of $\Delta\Omega$

ii. Constant Ω

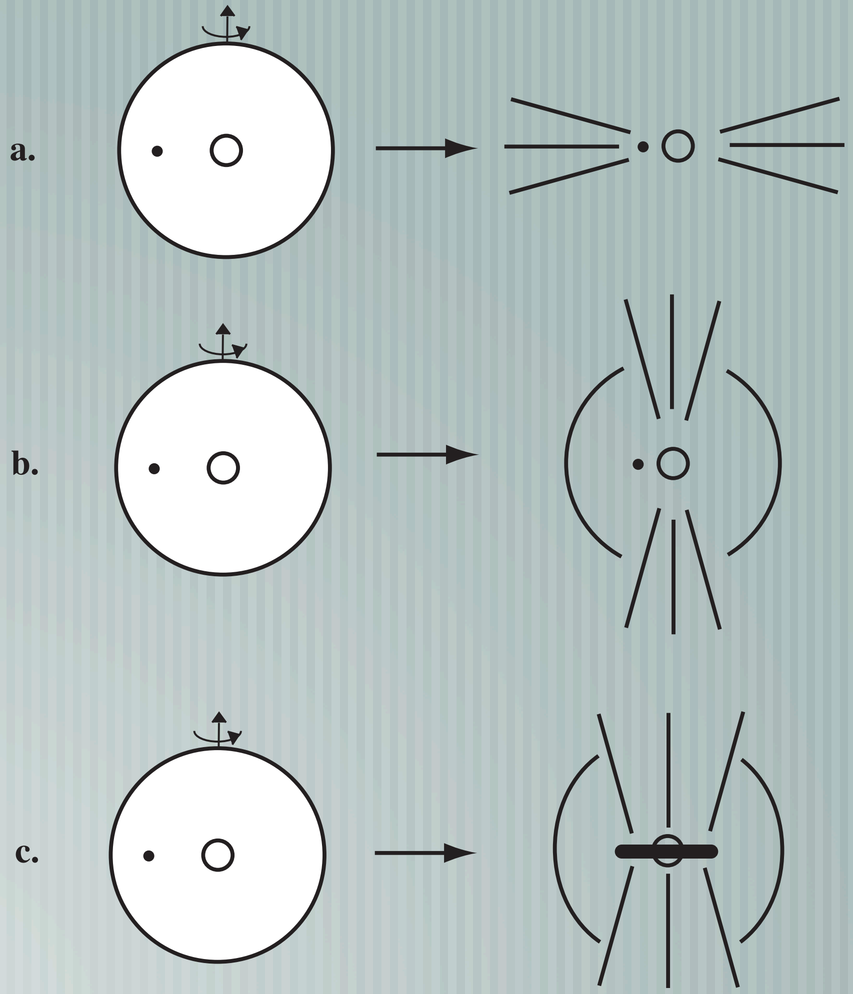
Common Envelopes

Ejection Scenarios

In-spiral of a low-mass companion supplies additional energy and angular momentum

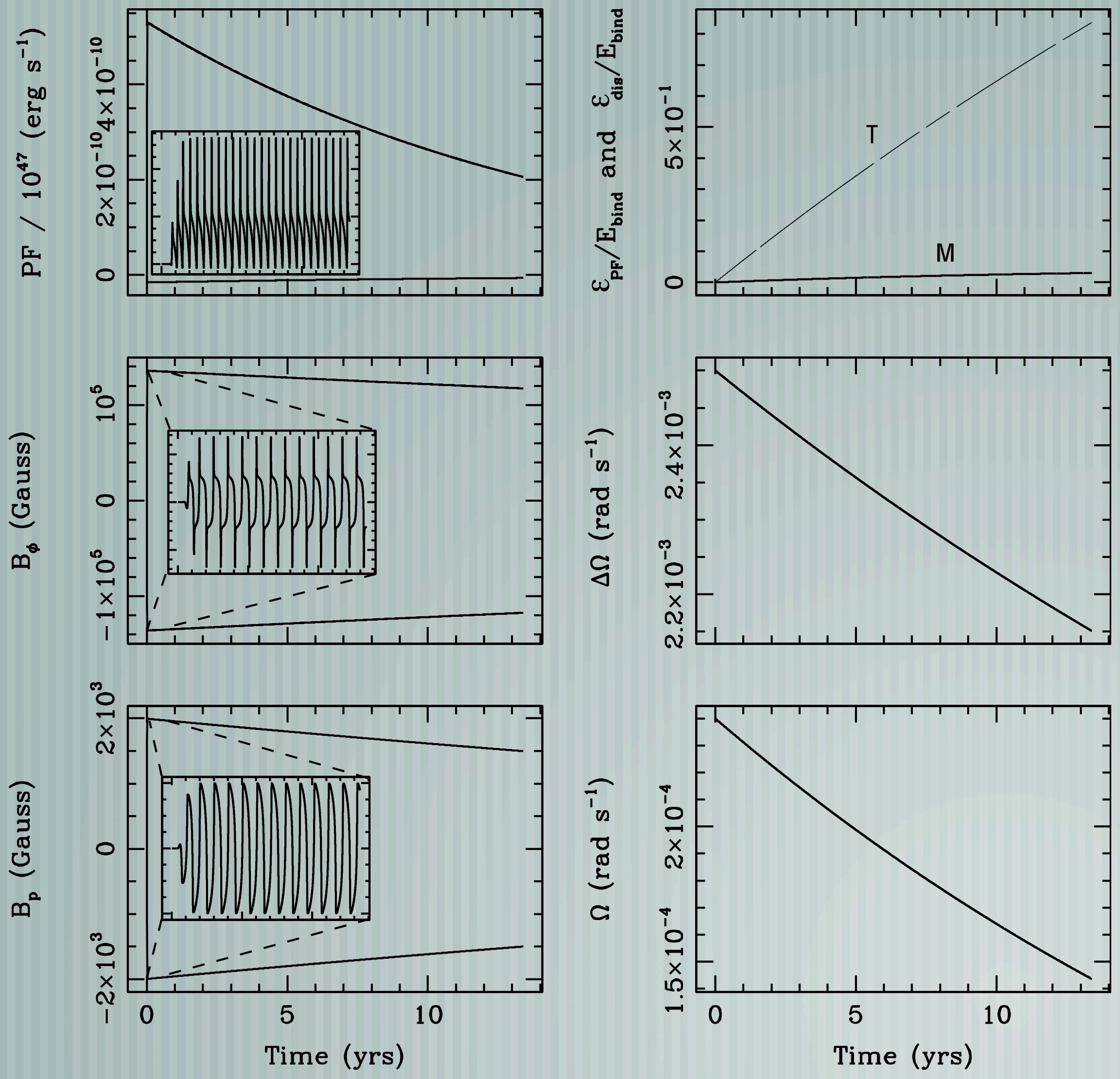
Three ejection scenarios:

a. Direct Ejection (toroidal outflow)
b. Dynamo-driven Ejection (poloidal outflow)
c. Disk-driven Ejection (poloidal outflow)



Nordhaus & Blackman 2006

CE I: Thermally Dominated



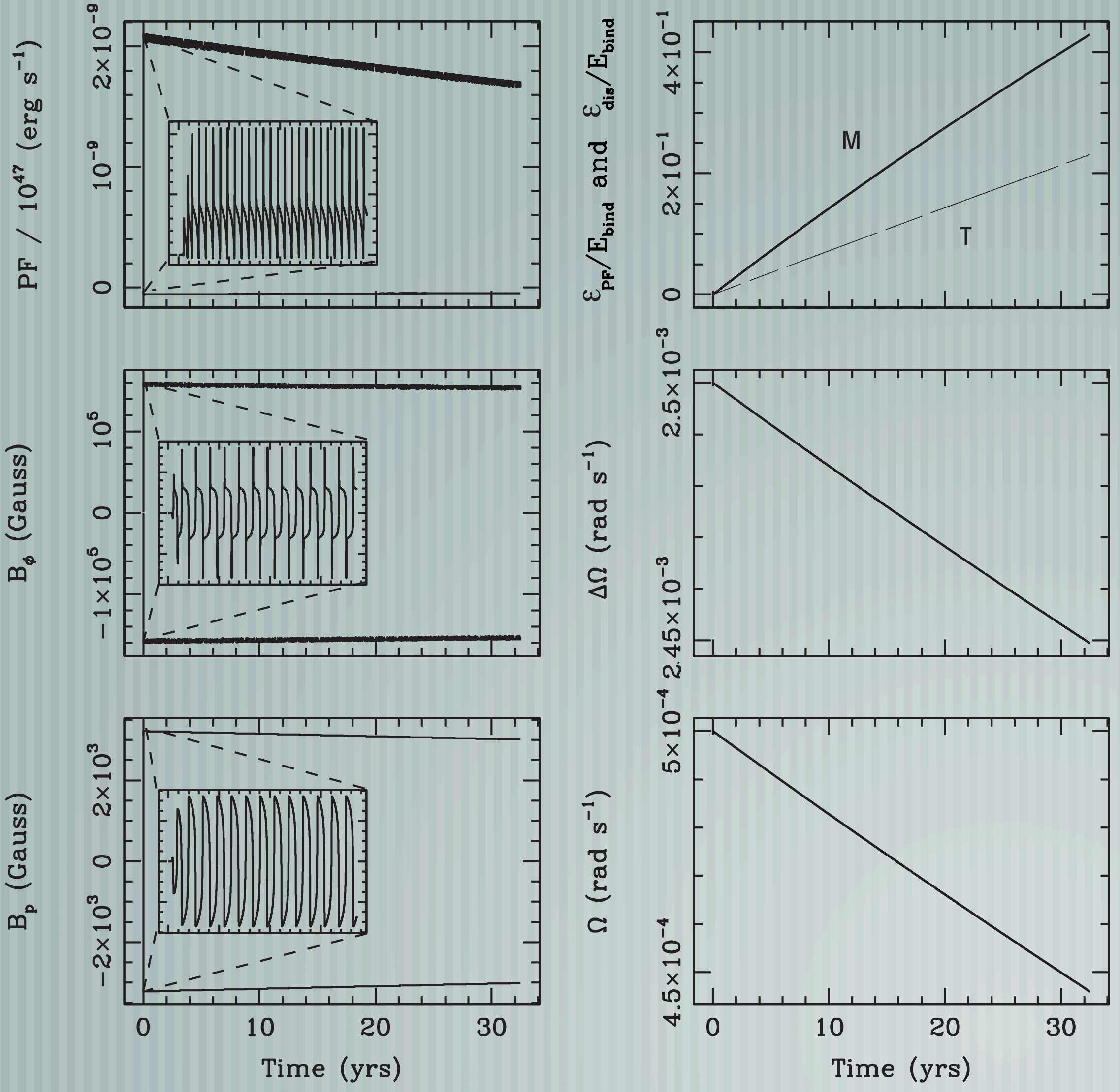
$0.02M_{\odot}$ Brown Dwarf Companion

Heat from turbulent dissipation is the primary driver.

$\tau_d \leq 50$ yrs. $Pr_p = 10^{-4}$

Resulting outflow quasi-spherical.

CE II: Magnetically Dominated



$0.05M_\odot$ Brown Dwarf Companion

Poynting Flux is the primary driver

$\tau_d \leq 100$ yrs. $Pr_p = 10^{-6}$

Resulting outflow is poloidal and likely collimated.

Conclusions...

- Rotational energy is likely fundamental in PPNe/PNe
- Magnetic fields can facilitate the extraction of rotational energy

Isolated Stars

- Unlikely to be dynamically important unless...

  i. Resupply of $\Delta\Omega$
  ii. Constant Ω

Common Envelopes

- Energy and angular momentum supplied quickly (< 1 yr)

Magnetically-induced outflow (poloidal, collimated)

Thermally-induced outflow (quasi-spherical)

Nordhaus, Blackman & Frank 2007 MNRAS, 376 599

Saturn Nebula

Rotten Egg Nebula

Extra Slides

Dynamical Equations:

Mean-field:

$$\partial_t \overline{\mathbf{B}} = \nabla \times \mathcal{E} + \nabla \times \left(\overline{\mathbf{U}} \times \overline{\mathbf{B}}\right) + \lambda \nabla^{\mathbf{2}} \overline{\mathbf{B}}$$
$$= \nabla \times (\alpha \overline{\mathbf{B}}) + \nabla \times \left(\overline{\mathbf{U}} \times \overline{\mathbf{B}}\right) + \nabla \times \left(\beta \nabla \times \overline{\mathbf{B}}\right) + \lambda \nabla^2 \overline{\mathbf{B}}$$

Axisymmetric, decompose into components: $\overline{\mathbf{B}} = \overline{B}\hat{e}_\phi + \nabla \times (\overline{A}\hat{e}_\phi)$

Toroidal Field

$$\partial_t \overline{B} = \alpha {k_x}^2 \overline{A} - i k_x r_c \overline{A} \frac{\Delta\Omega}{L} - iuk_z \overline{B} - u\overline{B}/L - \beta_\phi k^2 \overline{B}$$

Poloidal Field

$$\partial_t \overline{A} = \alpha \overline{B} - \beta_p k^2 \overline{A}$$

Back Reaction of Magnetic Fields:

Momentum Conservation:

$$\partial_t \overline{\mathbf{U}} = -\overline{\mathbf{U}} \cdot \nabla \overline{\mathbf{U}} + \frac{\mathbf{1}}{\mathbf{4}\pi\rho} \left(\overline{\mathbf{B}} \cdot \nabla \right) \overline{\mathbf{B}} + \beta_\phi \nabla^{\mathbf{2}} \overline{\mathbf{U}}$$

Using $\partial_z \overline{U} \simeq -r_c \Delta\Omega / L$ we link the mean-field fluid velocity with the shear across the differential rotation layer.

$$-\partial_t \left(r_c \Delta\Omega \right) = \partial_t \left(\overline{U} \left(r_c \right) - \overline{U} \left(r_c - L \right) \right) \simeq \partial_t \left(L \partial_x \overline{U} \right)$$

↓

$$\partial_t \Delta\Omega = \frac{L}{4\pi r_c \rho} \left[-k_x k_z^2 \left(Re(\overline{A}) Re(i\overline{B}) + Re(i\overline{A}) Re(\overline{B}) \right) - \frac{\partial_z \rho}{\rho} k_x k_z Re(i\overline{A}) Re(i\overline{B}) \right] - \frac{\beta_\phi}{L^2} \Delta\Omega$$

Poynting Flux

Total integrated Poynting flux at the interface is given by:

$$\begin{aligned} L_{mag} &= \frac{c}{4\pi}\int (\overline{\mathbf{E}} \times \overline{\mathbf{B}}) \cdot \mathbf{dS_c} \\ &\simeq -Re(\overline{B})Re(\partial_x \overline{A})\Omega r_c^3 \end{aligned}$$

The rotational energy of the shear layer is given as:

$$E_{rot} \sim M_{\Delta\Omega} r_c^2 \Omega^2 / 2 \sim 4E_{bind}$$

Equating the time derivative of the rotational energy with the magnetic luminosity gives:

$$\partial_t \Omega \simeq \frac{Re(\overline{B})Re(\partial_z \overline{A}) L r_c}{M_{\Delta\Omega}\delta}$$

Penetration Depth and α- Quenching

Shear layer penetration:

$$\delta \sim (\beta_\phi \tau)^{\frac{1}{2}}$$

Depth that poloidal field can diffuse downward in a cycle period.

$$\frac{\delta}{L}$$

Fraction of shear layer available for field amplification.

α- Quenching formalism:

Can be understood through magnetic helicity conservation

(Kleeorin & Ruzmaikin 1982; Blackman & Field 2002)

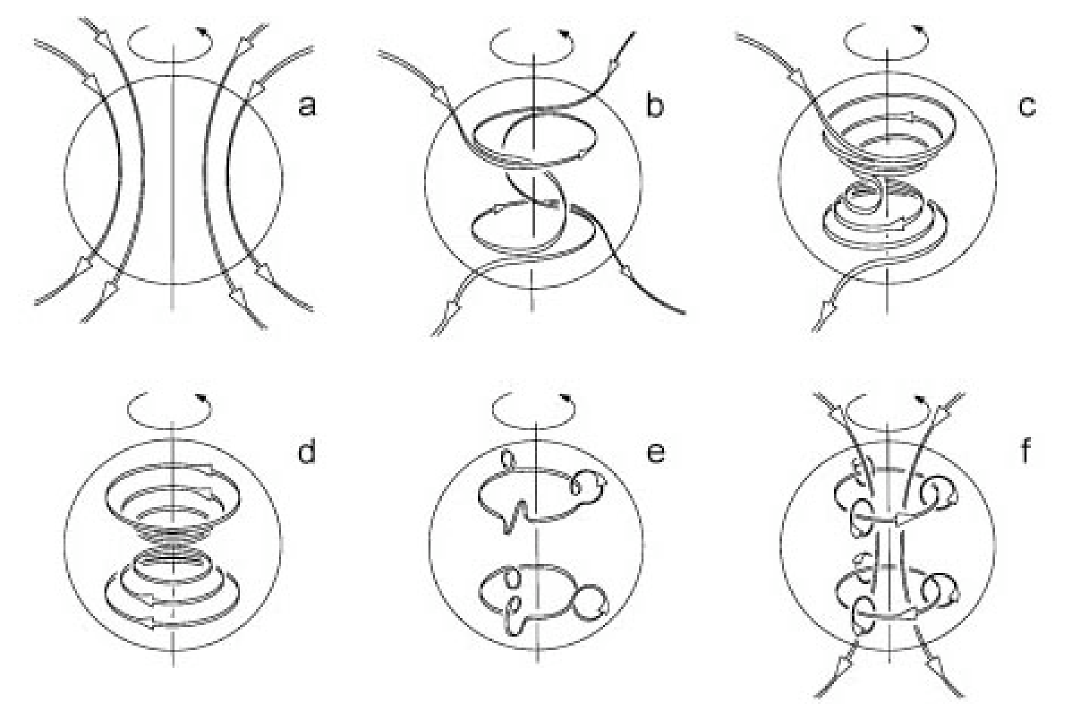
$$\alpha = \alpha_0 \left(\Omega/\Omega_0\right) Exp\left[-\gamma \frac{\overline{B}^2/8\pi}{\rho_1 v^2/2}\right]$$

$\alpha - \Omega$ Dynamos:

Differential Rotation + Turbulence (Convection)

Poloidal to Toroidal
Ω- effect

Toroidal to Poloidal
α - effect



Love, J. J., 1999. Astronomy & Geophysics, 40, 6.14-6.19.