Exploring the Sun and its effects on the Earth's atmosphere and physical environment...

HIGH ALTITUDE OBSERVATORY

Energetics of the large scale solar dynamo

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Outline

- Energetics of the large scale solar dynamo
  - How much power required for the large scale solar dynamo?
    - Trivial or do we have to worry about energetic constraints?
  - Potential implications for stellar dynamos
    - Activity rotation relation ship
- Difficulty
  - No large scale dynamo model from first principles
    - Order of magnitude estimate
    - Non-kinematic mean field models

Saturation of dynamos

- Solar dynamo: $\alpha\Omega$-dynamo
  - α-effect: Change of topology
  - Ω-effect: Primary energy source
- Saturation:
  - Microscopic:
    - Quenching of turbulent induction effects
    - Helicity constraints .... (Axel's talk yesterday)
  - Macroscopic:
    - Quenching of large scale flows (differential rotation, meridional flow)

$$\langle \boldsymbol{F} \rangle = \langle J \rangle \times \langle B \rangle + \langle J' \times B' \rangle$$

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Meanfield model

- Axisymmetric MHD equations, parameterization of small scales
- Differential rotation model:
  - Parameterization of transport turbulent angular momentum transport drives DR and MF (Kitchatinov & Rüdiger):

$$\langle v_i' \, v_k' \rangle = \underbrace{\lambda_{ikl}\Omega_l}_{\Lambda_{ik}} + \nu_t \left(\frac{\partial \bar{v}_i}{\partial x_k} + \frac{\partial \bar{v}_k}{\partial x_i} \right)$$

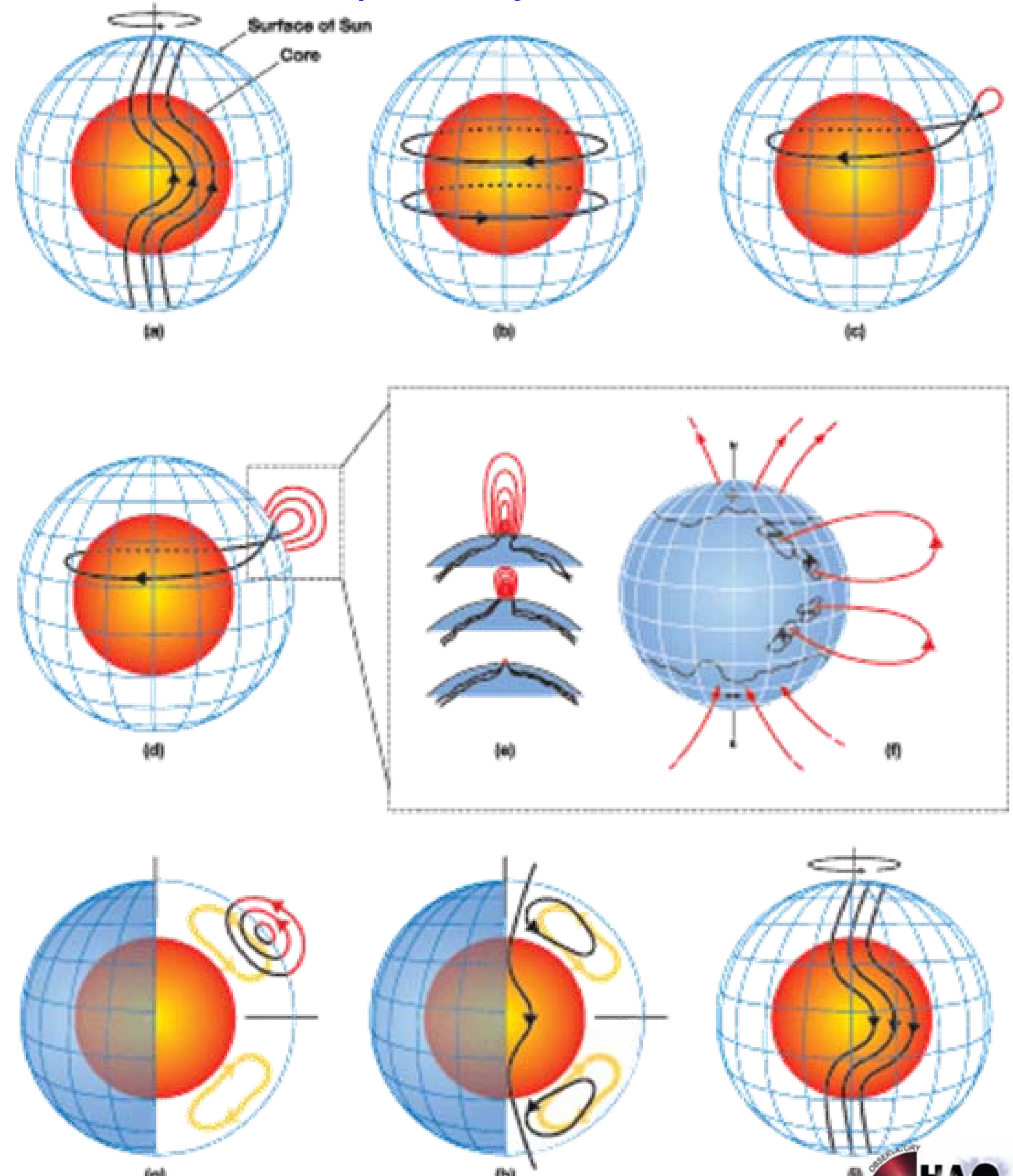
  - Entropy perturbation originating in tachocline causes deviation from Taylor-Proudman state
- Dynamo model:
  - Flux-transport dynamo, only surface α-effect (rising flux tubes twisted by Coriolis force)
  - Macroscopic Lorentz-force feedback on DR and MF

Schematic summary of flux-transport dynamo model

Shearing of poloidal fields by differential rotation to produce new toroidal fields, followed by eruption of sunspots.

Spot-decay and spreading to produce new surface global poloidal fields.

Transport of poloidal fields by meridional circulation (conveyor belt) toward the pole and down to the bottom, followed by regeneration of new toroidal fields of opposite sign.



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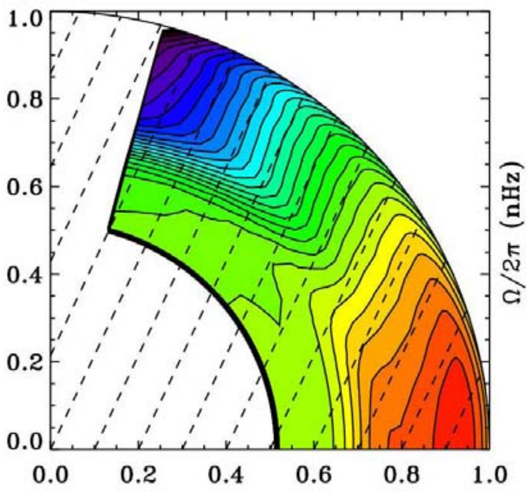
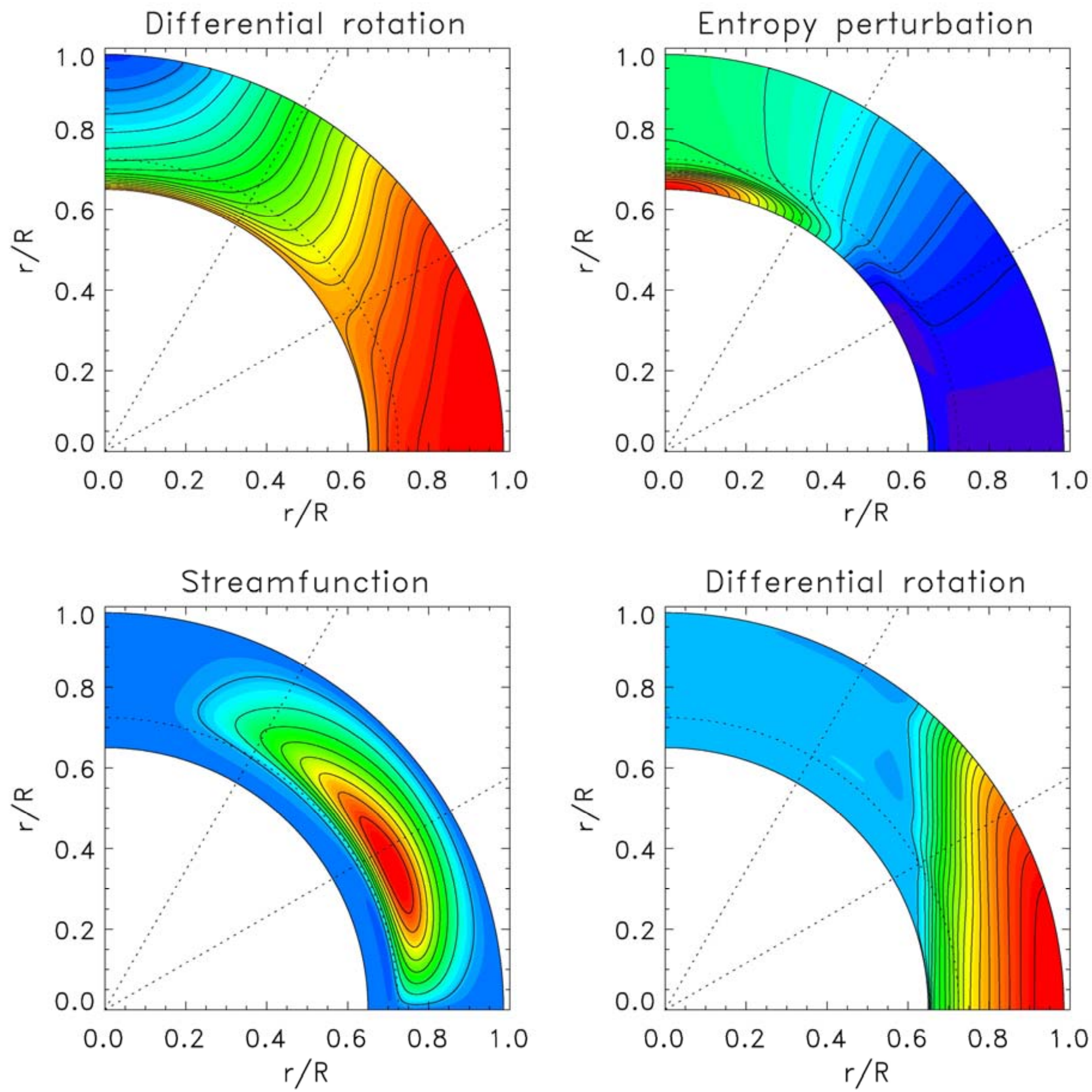
Differential rotation and meridional flow





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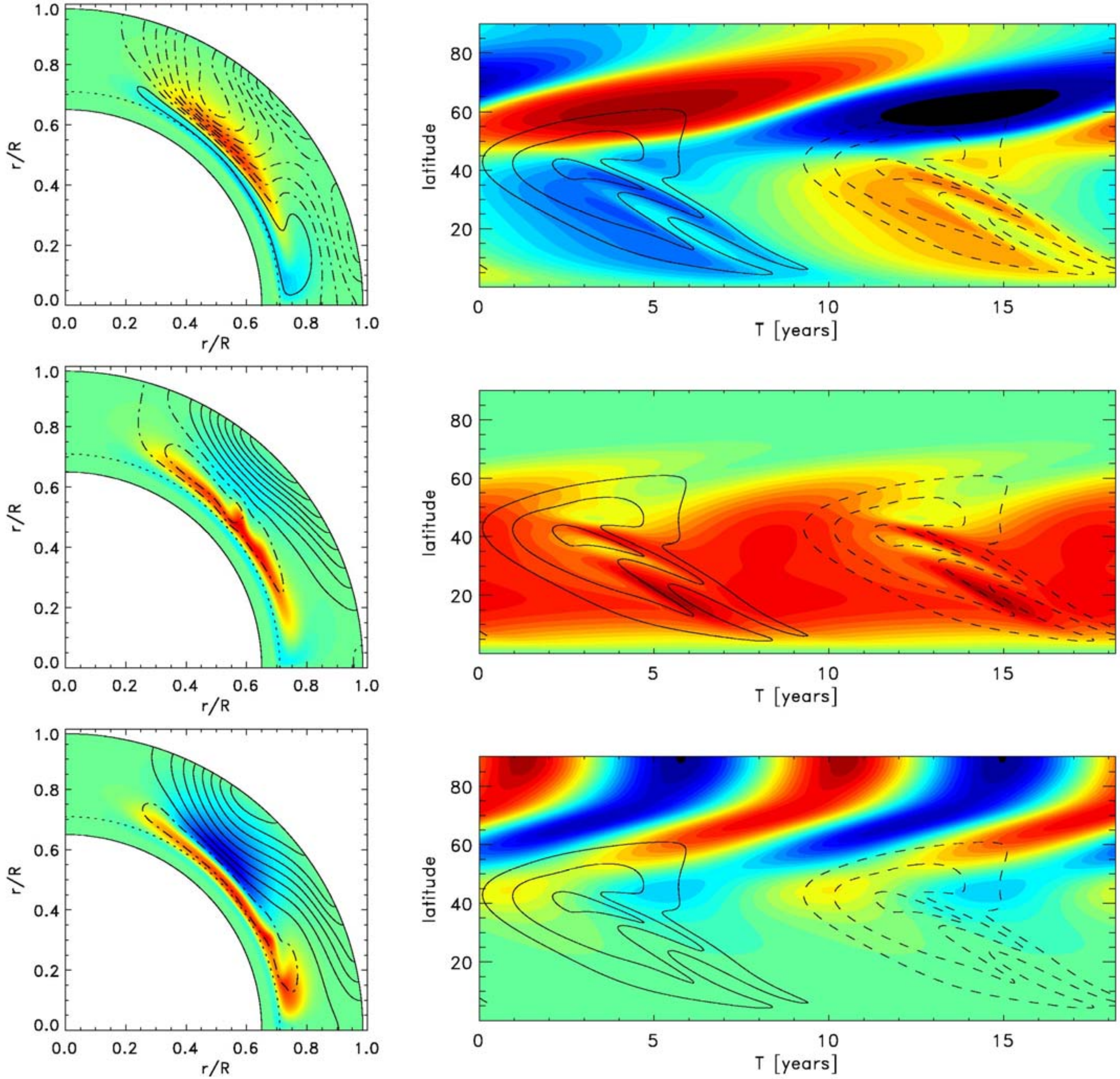

Radial surface field

Meridional flow at base of CZ

Torsional oscillation at surface

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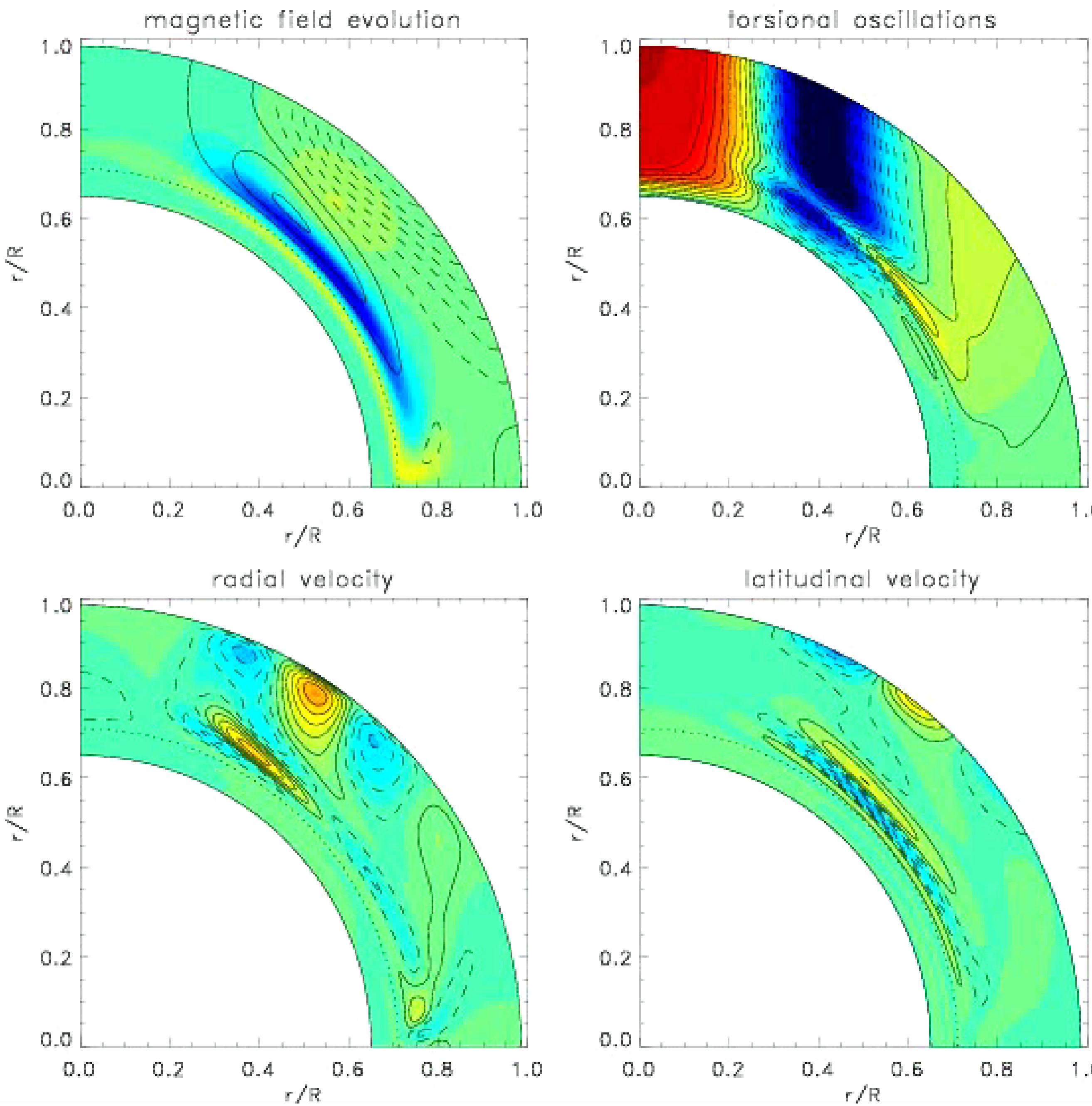
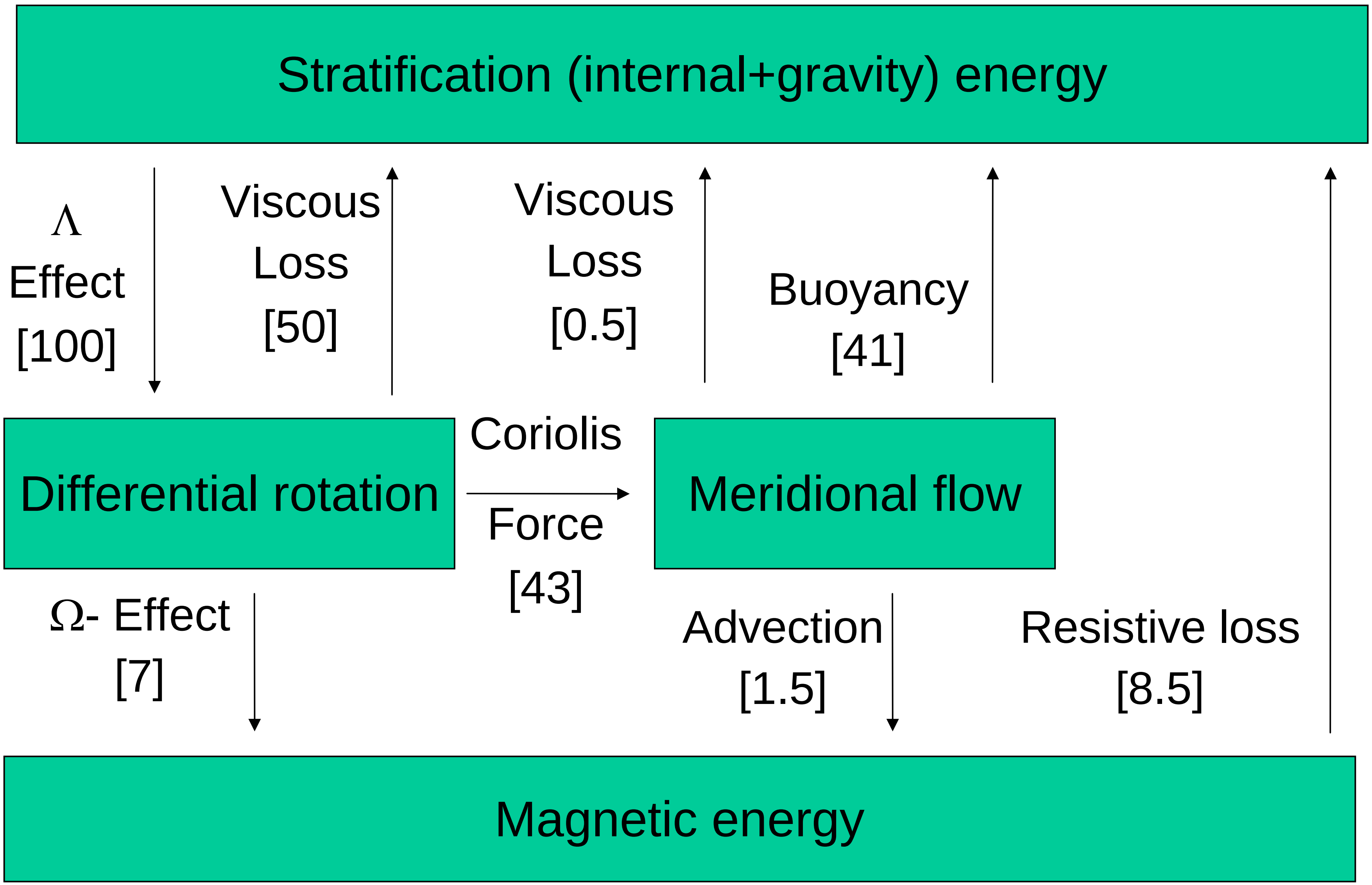

magnetic field evolution
torsional oscillations
radial velocity
latitudinal velocity
r/R
0.0
0.2
0.4
0.6
0.8
1.0

Energy fluxes within model



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Saturation of dynamo

- Dynamo saturates through reduction of DR
  - Saturation field strength ~ 10 to 15 kG
  - Significant reduction of mean DR (from ~35% to 25%)
    - Cyclic variation of DR (torsional oscillation) minor effect
    - Not essential for saturation of dynamo
  - Magnetic flux @ BC ~ 10^{24} Mx
- Feedback on meridional flow not significant for B < 15 kG
  - Operation of flux-transport dynamo not significantly impacted
- Dynamo converts ~ 0.1% L_{sun} (~ 10% of flux required to maintain DR)
  - Close to observed irradiance variation (coincidence?)
  - <u>Overall: Solar dynamo seems to operate at limit differential rotation can supply! (~$10^{24....25}$ Mx appear at surface!)</u>

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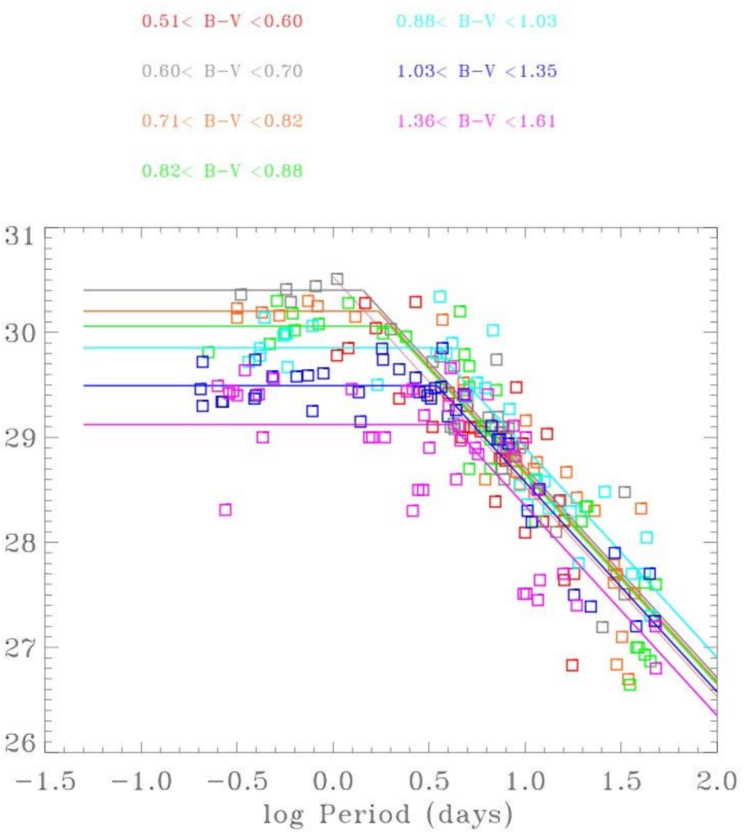
How robust are these estimates?

- Amplitude of α-effect:
  - Does not matter as long sufficiently supercritically
- Type of dynamo: Used here flux-transport dynamo
  - Does not matter as long as $\alpha\Omega$-dynamo: differential rotation main energy supply
- Parameterization of Reynolds stresses:
  - Turbulent viscosity as free parameter
    - $\nu_t = 3 \times 10^8$ m^2/s assumes $\Lambda \sim \nu_t \Omega \sim 0.01 \ldots 0.05\ v_{rms}^2$
  - Energy of differential rotation replenished in about 10 years, similar to what is seen in numerical simulations
  - Larger values of ν_t would lead to meridional flow inconsistent with observations $v_m \sim \nu_t / D$

Activity rotation relation ship

➢ Stars with outer convection zones show an increase of magnetic activity with rotation rate



X-ray flux (Pizzolato et al 2003)

- X-ray and Calcium HK flux indication of total magnetic flux on stellar surface
- $\phi \sim \Omega^{n}$ n = 1.2 …. 2.8
- Typical interpretation:

Dynamo activity increases with rotation rate

Does this work energetically?

Do fast rotating stars have more active dynamos?

- $P_{dyn} \sim 0.1\ P_{DR} \sim 0.001\ L$
  - $P_{dyn} \sim 0.1\ P_{DR}$: Unlikely to change with Omega
  - $P_{DR} \sim 0.01\ L$: At best scale up ~ Omega
  - Star with 10 times solar rotation has at best 10 times more energy available for dynamo
- Differential rotation maintained by Reynolds stress
  - Reynolds stress saturates for $Co = 2\Omega\tau > 1 \ldots 10$
  - Co ~ 5 already reached at base of CZ
- $\phi \sim \Omega^2$, $P_{dyn} \sim \Omega^{3 \ldots 4}$ unlikely explainable (larger field strength required to store flux for geometric reasons)

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Three possible solutions

- Overestimation of the energy requirements for the solar dynamo?
  - $\phi \sim 10^{24 \ldots 25}$ Mx
  - B~10 kG (geometric storage constraint)
  - Recreate flux every $\tau \sim 11$ years

    > leads to 0.001 L
- Different type of dynamo in faster rotators
  - See recent work of B. Brown 'faster rotating suns'
  - Does only solve energy problem if not relying on Ω-effect
- Dynamos in faster rotating stars are not more active, just surface flux scales up
  - Solar flux $\phi \sim 10^{25}$Mx sufficient to cover entire surface, if active regions would decay slower
    - In fast rotators scales of AR heavily influenced by rotation
    - Alternative explanation for mixed polarities observed in high latitudes (traditional explanation is more flux + faster meridional flow)

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