Angular Momentum Transport

Marc Pinsonneault
Ohio State University

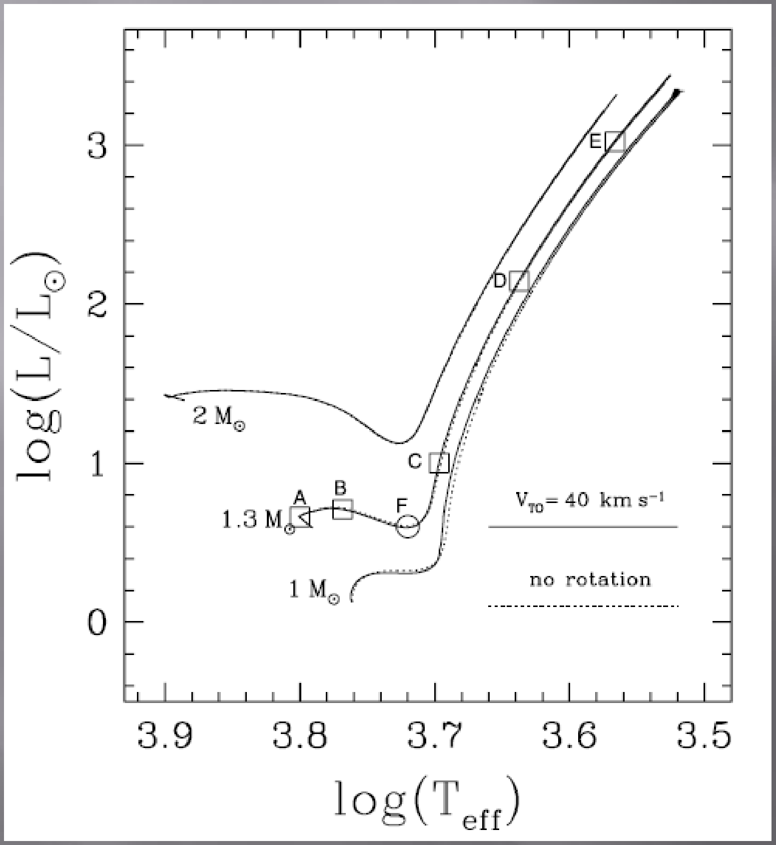
The Stakes

- Rotation is important
  - Basic initial condition (+ M, Xi)
  - Induces mixing
  - Impacts structure, winds, end state
- Rotation is complicated to model
  - Subtle interactions with convection and magnetism
  - Challenging experimental domain
  - Indirect (until recently!) constraints on internal behavior
- My focus: Angular Momentum Transport

The Big Picture

- Initial Conditions
  - “Time Zero” = hydrostatic equilibrium achieved
  - Interactions between protostars and accretion disks
- Boundary Conditions
  - Magnetized solar-like winds
  - Cool star winds (RGB, AGB)
  - Hot star winds (line-driven)
- Structural evolution
  - Contraction to MS
  - Core contraction + envelope expansion

Stellar Evolution Generates Strong Shears



Chaname et al. 2005: MS -> RGB, 1.3 Msun

MS

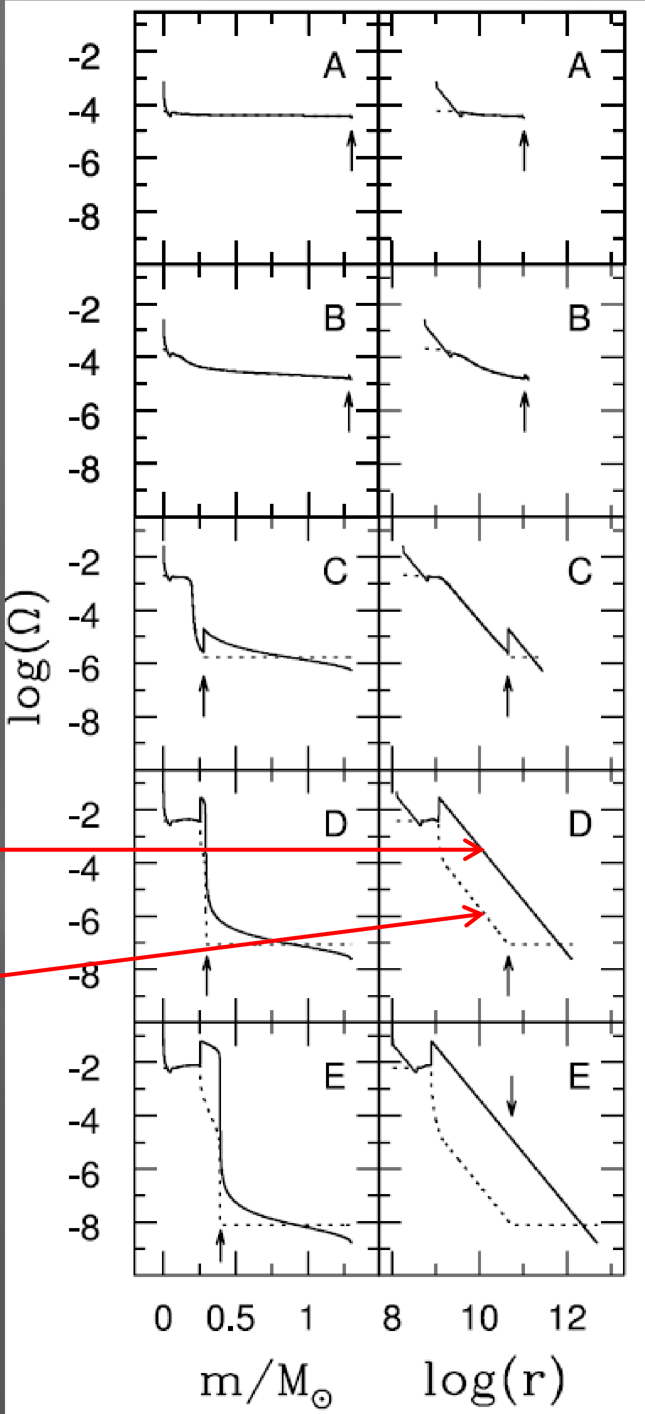
SG

RGB

CZ
J/M const

CZ
SB

RGB
tip



Convection and Rotation

- $\tau_{cz} << \tau_{nuc}$ BUT
- Many possible solutions…
  - Rapid rotation $\omega << \tau_{cz}$
    - Decreased relative differential rotation
  - Moderate rotation $\omega \sim \tau_{cz}$
    - Solar-like
  - Slow rotation $\omega << \tau_{cz}$

Three Families

- There are three fundamental classes of mechanisms that could transport angular momentum in stars:
- Hydrodynamic
  - Efficient at mixing and momentum transport
- Waves
  - Efficient at momentum transport; non-local
- Magnetic
  - Efficient at momentum transport; geometry-dependent; non-local

Hydrodynamics

- There is a basic tension between the natural axis of symmetry for rotation and the strong vertical stratification in stars
- Meridional circulation (Eddington 1926)
  - Advective
  - Small pole to equator temperature differences drive flows
- Instabilities (shear, GSF, baroclinic…)

Shellular Rotation

- No stabilizing force for a shear on a level surface
- => anisotropic turbulence; physical motivation for 1D rotation modeling (Zahn 1992 and daughters)
  - Sets ratio of mixing coefficients to momentum transport
- Problem: Treatment of the quadrupole term; interaction between composition gradients and rotational mixing (Theado & Vauclair 2003)

Waves

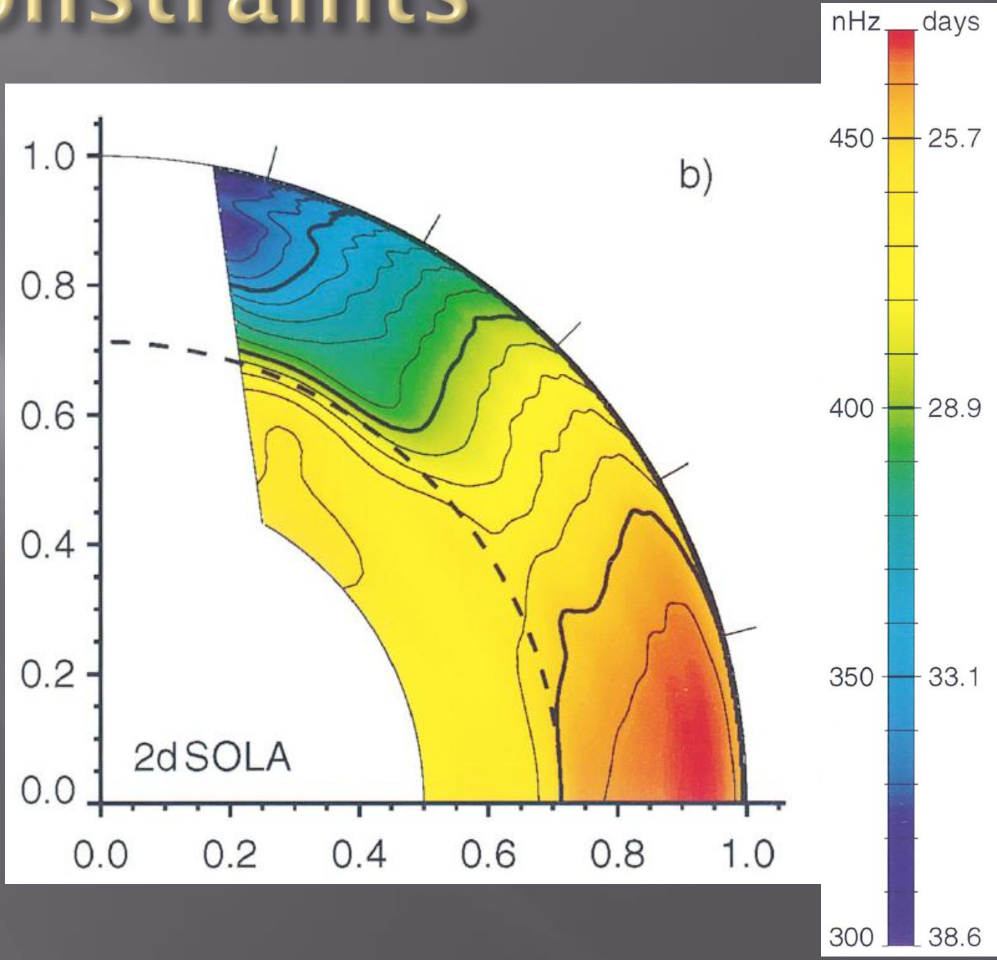
- Convection generates waves, which can effectively transport angular momentum in stellar interiors (Kumar & Quateret 1997; Zahn et al. 1997)
  - Timescales are interesting (tens of Myr)
- Computation of wave-driven transport has been numerically challenging
- Proper wave spectrum?

Magnetic Fields

- Strong tendency to enforce corotation along field lines (Ferraro’s Law)
- Implies that large scale organized fields will efficiently suppress differential rotation
  - Solid body radiative models (plus m.c. mixing) are physically well motivated (e.g. Spruit 1999, 2002)
- Problem: how does one specify the proper magnetic field configuration? MRI?

Internal Differential Rotation: Solar Constraints

Schou et al. 1998



- Latitudinal differential rotation in the CZ
- Radiative core strongly coupled to surface CZ
  - Contrary to expectations from hydrodynamic alone (Pinsonneault et al. 1988)
- $\tau_{coupling} < \tau_{sun}$

Is this universal?

Evidence for Internal Magnetic Fields:
Gough & MacIntyre 1998
See Wood et al. 2011 astro-ph/1106.5250

Questions

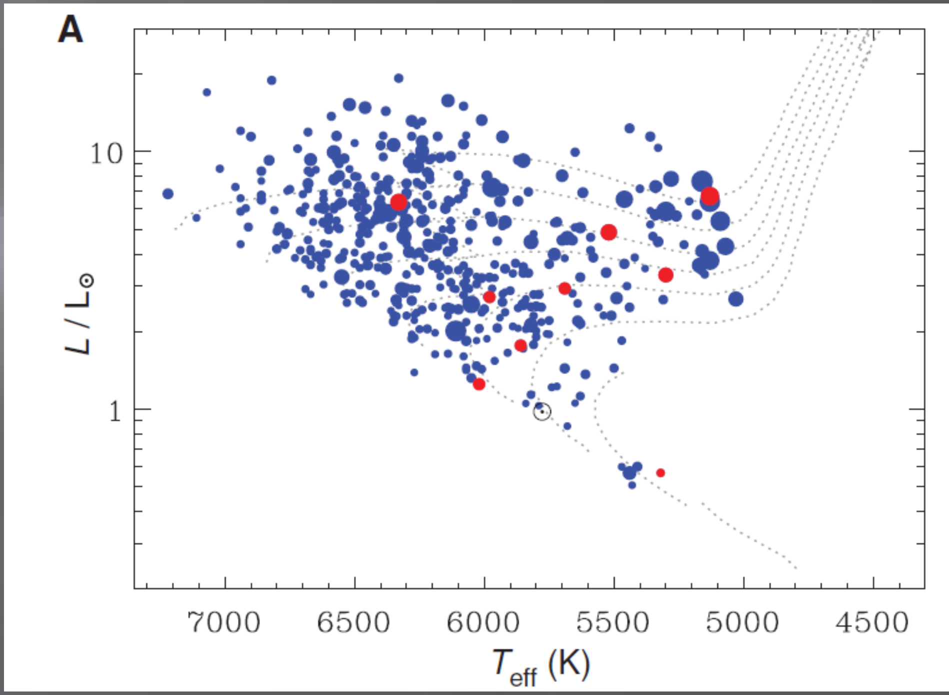
- What family of mechanisms is the most important, and over what time scale?
- Do the same ones predominate in low and high mass stars?
- Are they universal, or do they depend on the initial conditions?
- How do momentum transport and composition gradients interact?

Subgiants

- Sebastien Deheuvels talk on the KITP site (watch it!)
- P-mode rotational splittings are sensitive mostly to the outer layers
  - Solar rotation (from p-modes) not reliable, inner 0.2
- Mixed modes are observed in subgiants
  - Implies that we can see rotational splittings of stellar cores in this evolutionary phase
  - Strong differential rotation evidence emerging…

Low and High Mass Stars: Subgiants

- Subgiants are available which cross the break in the Kraft curve; can test differences in transport timescales
  - Crucial test of consistency, high vs. low mass
- Core size vs. rotation, independent from surface mixing vs. rotation: test of rotational mixing and momentum transport



Angular Momentum Evolution As Inferred From Open Clusters

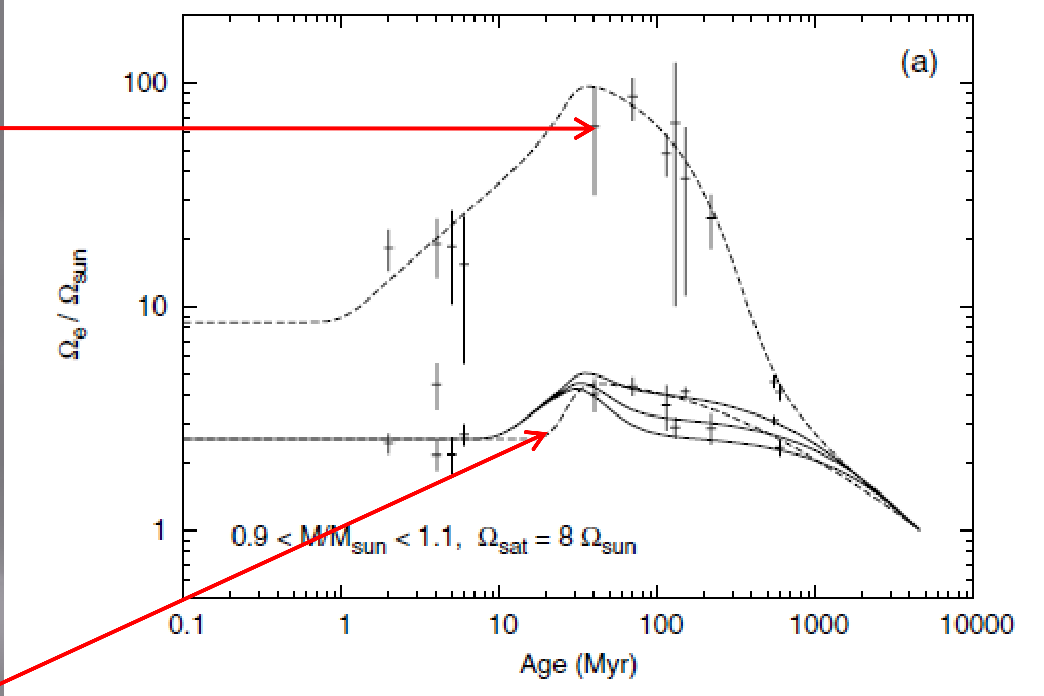
- Wide Range of Initial Rotation Rates
  - Generated in star and planet formation phase
- Severe Angular Momentum Loss
  - Scales as ω^3 for slow rotation
  - Saturates at a mass-dependent threshold
- Internal Angular Momentum Transport Sets Core-Envelope Coupling
  - Waves, Magnetic Fields, Hydrodynamic Mechanisms all viable candidates

Core-Envelope Decoupling

- Rapid rotators are strongly coupled (Irwin et al. 2008)
- Slow rotators inconsistent with SB rotation (many studies…)
  - τ ~ 50 Myr

Rapid: SB is a good fit

Slow: SB is a poor fit



Denissenkov et al. 2010

Endal & Sofia 1979: Differential Spindown signature

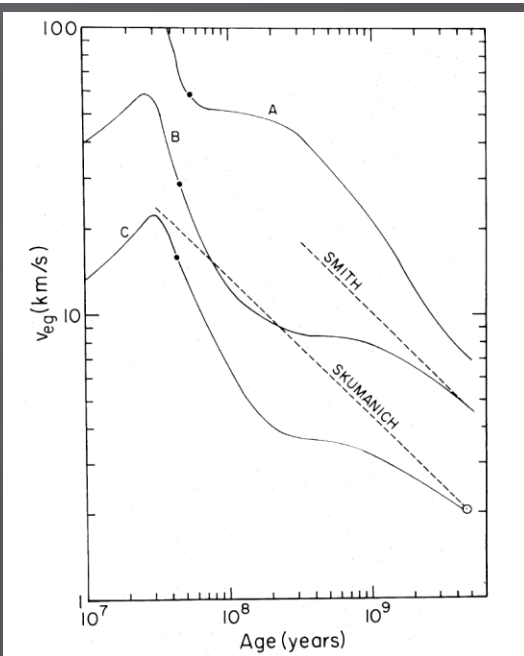
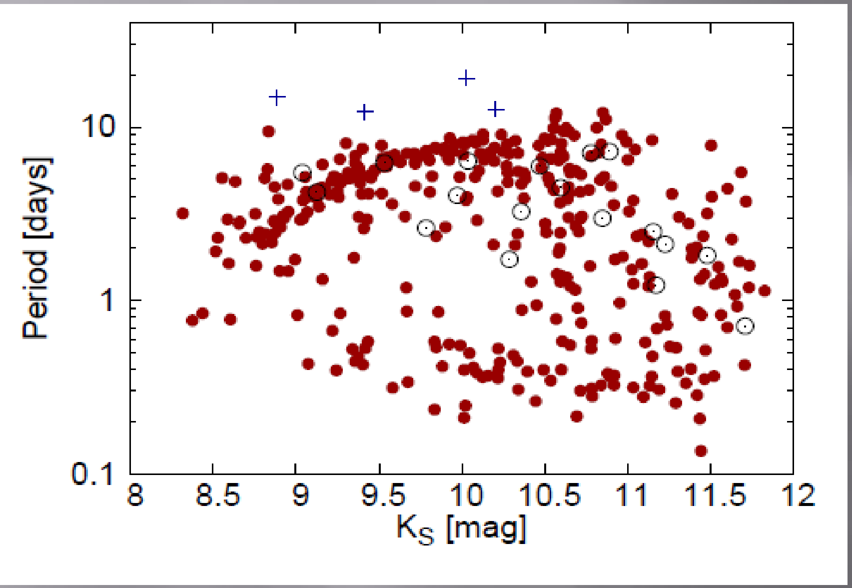
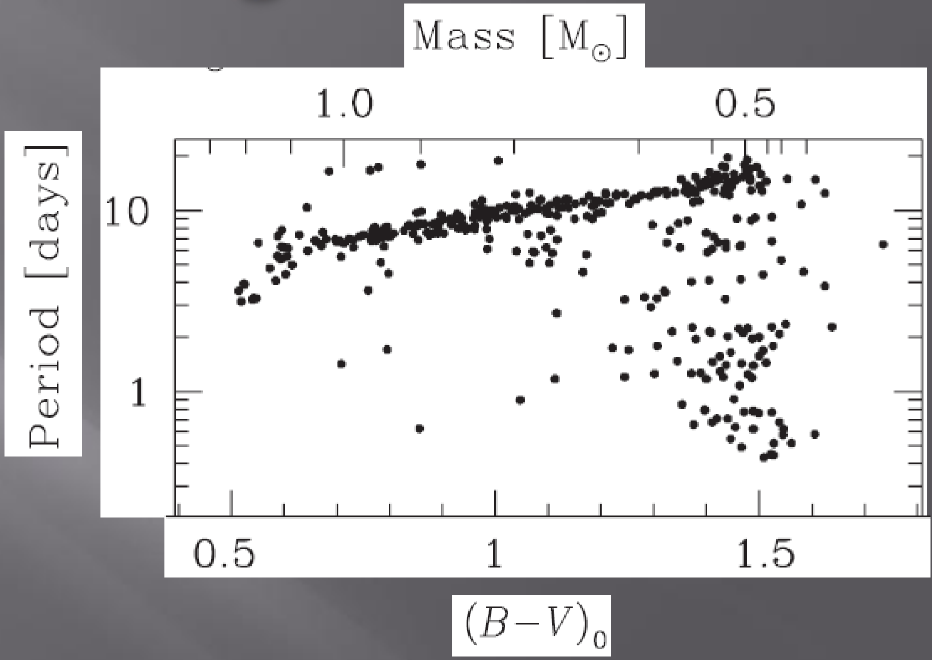


FIG. 4.—Surface rotation velocities at the equator as functions of age for sequences A, B, and C (*solid lines*). The heavy dots indicate the ZAMS stage. The dashed lines show the observed rotation velocity-age relationship for solar-type stars, according to

Convergence in *Surface* Rotation Rates of Solar Analogs is Seen



Pleiades, 120 Myr



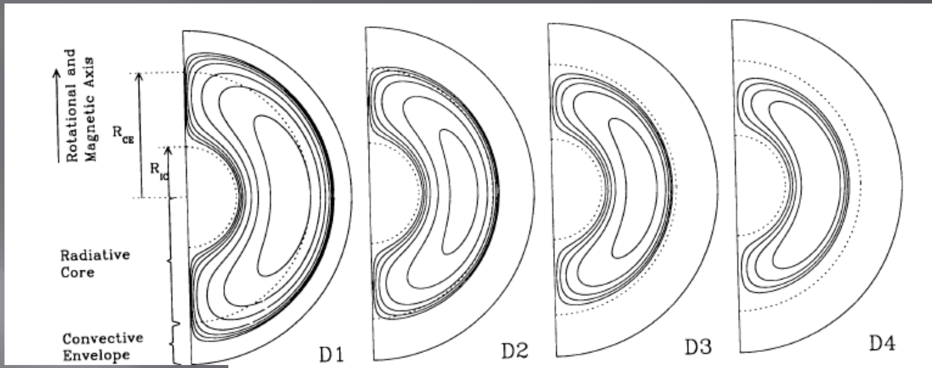
M37 (550 Myr)

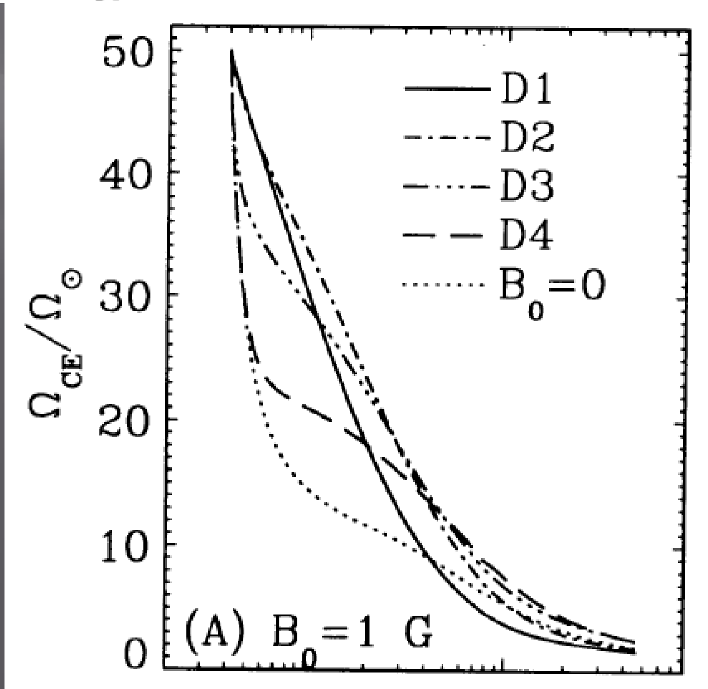
Convergence is slow
for late-type stars,
feasible for GK

Rotation vs. Age: Seismology

- Fundamental Test:
  - If hydrodynamics or convection are the main mechanisms, expect stars to lose memory of initial conditions
- If global magnetic fields drive transport:
  - Stars will not converge to a unique rotation rate at late ages

Charbonneau & MacGregor 1992





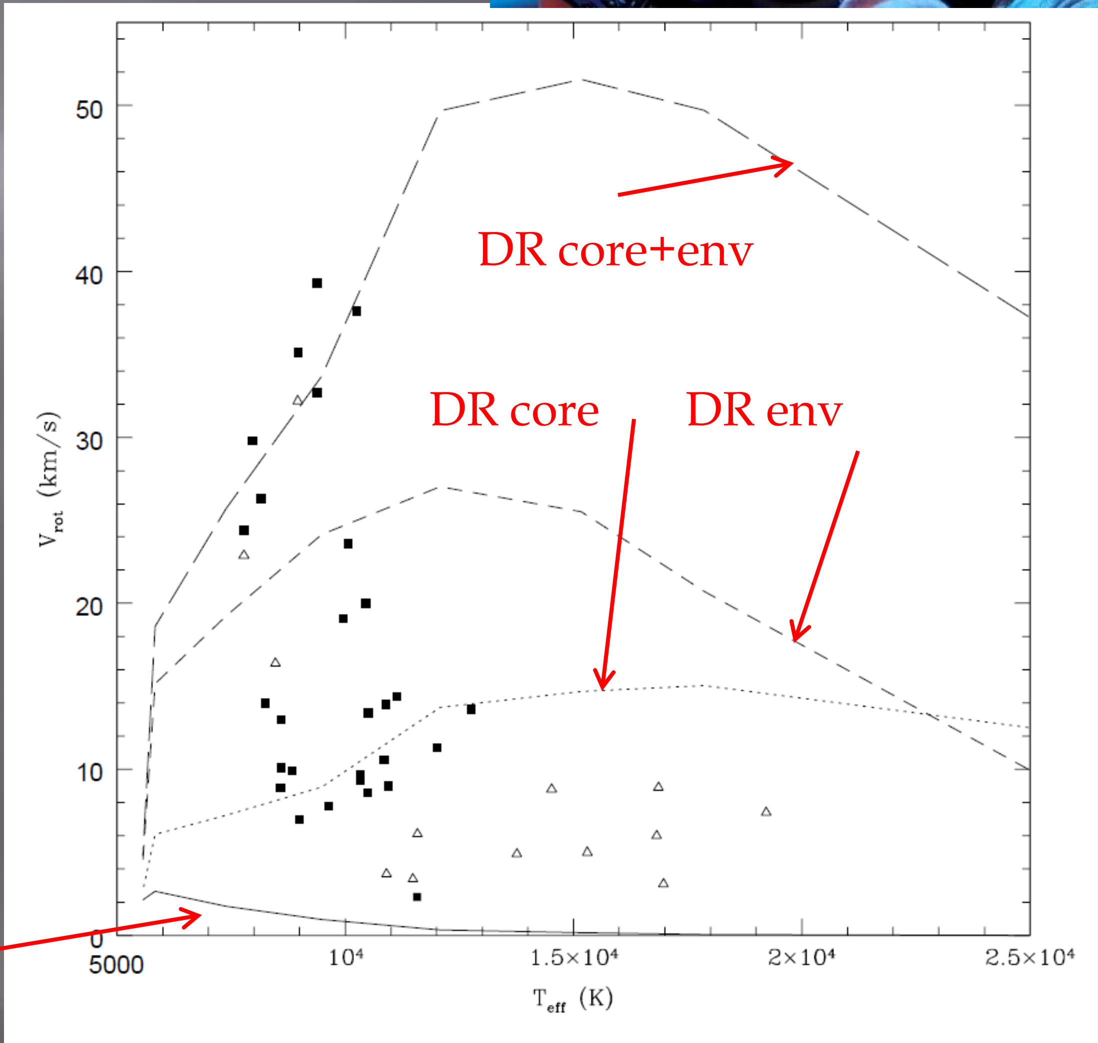
On the Virtues of Complementary Constraints

- Blue HB stars in globular clusters are observed to rotate rapidly (Peterson 1983)
- MS precursors are slow rotators
- RGB stars lose mass
- This combination of data *requires* strong differential rotation with depth in the envelopes of low mass giants (Pinsonneault et al. 1991, Sills & Pinsonneault 2000)

Another Prediction

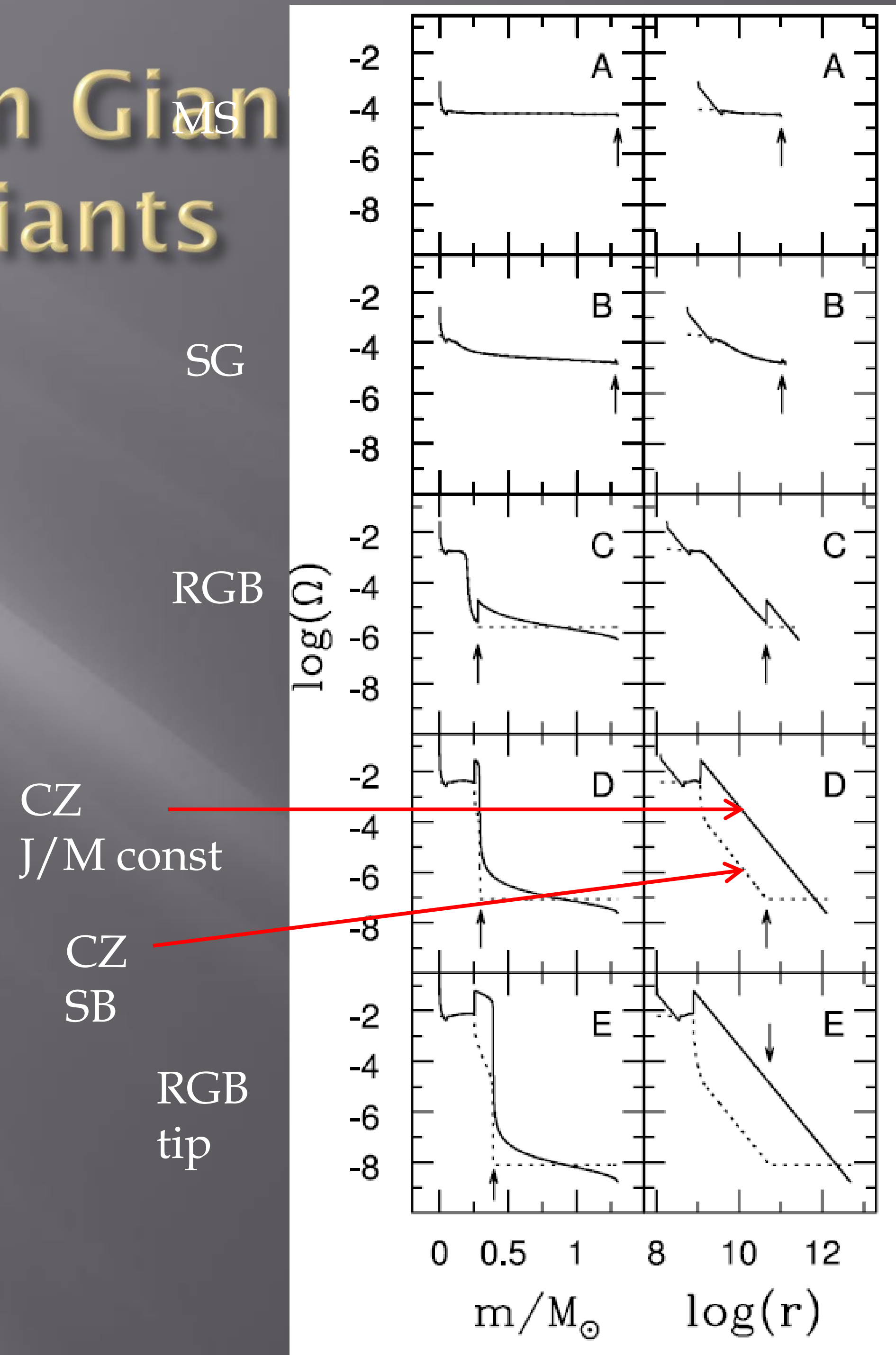
- Differential rotation with depth in stars with strong surface gravitational settling…

SP 2000



Lessons from Gian Subgiants

- Subgiants: relatively shallow surface CZ
  - tests internal differential rotation in radiative regions
- Giants: different rotation profiles in convective envelopes will set very different core rotation zero-points
  - Core rotation tests convective envelope rotation law



Predictions and Prospects

- Rigid rotation enforced on short timescales will not work
- Three domains of magnetoconvection:
  - Rapid (weak latitudinal differential rotation)
  - Sunlike
  - Slow (Giants; constant J/M?)
- Seismic diagnostics will provide direct tests:
  - transport timescales
  - high/low mass concordance
  - mu sensitivity
- Mixed modes are a blessing!