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Solar Convection and Mean Flows

Mark S. Miesch

HAO/NCAR†, Boulder, CO, 80301 email: miesch@ucar.edu

Abstract. We briefly review our current understanding of how the solar differential rotation and meridional circulation are maintained, which has important implications for understanding cyclic magnetic activity in the Sun and stars.

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Differential rotation and meridional circulation play an essential role in all current dynamo models of solar and stellar activity cycles so a thorough understanding of how mean flows are established is an essential prerequisite to a comprehensive dynamo model.

Our current understanding of how the solar differential rotation and meridional circulation are established rests heavily on two key concepts: thermal wind balance and gyroscopic pumping. The first is derived from the zonal component of the vorticity equation under the assumption that the inertia of the differential rotation dominates over the Reynolds, Lorentz, and viscous stresses (e.g. Miesch 2005)

$$\frac{\partial \Omega^2}{\partial z} = \frac{g}{r\lambda C_P} \frac{\partial \langle S \rangle}{\partial \theta} \tag{0.1}$$

where Ω is the mean angular velocity, g is the gravitational acceleration, S is the specific entropy, C_P is the specific heat at constant pressure, and brackets denote averages over longitude and time. Both spherical polar (r, θ, ϕ) and cylindrical (λ, ϕ, z) coordinates are used, with $\lambda = r \sin\theta$ and $z = r\cos\theta$.

The second key equation, expressing gyroscopic pumping, is derived from the zonal momentum equation and can be written as

$$\langle \rho \mathbf{v}_m \rangle \cdot \boldsymbol{\nabla} \mathcal{L} = \mathcal{F} \tag{0.2}$$

where ρ is the density, $\mathbf{v}_m$ denotes the meridional components of the velocity field, $\mathcal{L} = \lambda^2 \Omega$ is the specific angular momentum, and $\mathcal{F}$ represents the net torque due principally to the convective Reynolds stress (Miesch & Hindman 2011).

Much insight can be obtained merely from these two simple equations and the nature of the mean flows inferred from photospheric observations and helioseismic inversions. In particular, the conical nature of the solar rotation profile is attributed to (0.1), though the origin of the latitudinal entropy gradient is still unclear (Kitchatinov & Rüdiger 1995; Rempel 2005; Miesch *et al.* 2006; Balbus *et al.* 2009; Balbus & Schaan 2012). However, the differential rotation cannot be established solely by baroclinic forcing; the Reynolds stress must account for the observed super-rotation at the equator (Miesch *et al.* 2012, hereafter MFRT). Moreover, the meridional circulation cannot be strictly baroclinic either; rather, it must be maintained by the inertia of the differential rotation. This follows from equations (0.1) and (0.2) together with the observed sense of the rotational shear

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($\partial\Omega/\partial z < 0$ in the northern hemisphere) and the meridional flow (poleward in the upper convection zone; MFRT).

Equation (0.2) can also be used to probe the nature of the elusive deep convection that sustains mean flows. Since the left-hand-side is known in the upper convection zone (CZ) from helioseismic inversions, this equation can be used to estimate the amplitude of the turbulent stresses on the right-hand-side, and thus the convective amplitude (MFRT). This yields values of at least 30 m s^{-1} in the upper CZ ($r \sim 0.95R$), in apparent contradiction with the results of Hanasoge *et al.* (2012) who place an upper limit of less than 1 m s^{-1} on persistent (lifetime $\tau > 96$ hrs), large-scale (spherical harmonic degree $\ell < 60$) convective motions at $r \sim 0.95R$ based on local helioseismic inversions. The resolution of this apparent inconsistency poses a significant challenge to both observations and models of solar convection and mean flows (MFRT).

Further clues on the nature of solar convection are provided by the existence of the near-surface shear layer (NSSL), which is a "smoking gun" signifying a transition from high to low Rossby number R_o (Miesch & Hindman 2011). The Rossby number is a nondimensional measure of the influence of rotation on convection, $R_o = U/(2\Omega L)$, where U and L are characteristic convective velocity and length scales. Taking the estimate of $U \sim 30$ m^{-1} in the previous paragraph and assuming L is of order the density scale height suggests that this transition occurs at $R_o \gtrsim 0.3$. This value is consistent with that estimated from global convection simulations (Featherstone & Miesch 2013).

The mean flows in global convection simulations generally exhibit the same dynamical balances that are thought to prevail in stars, namely equations (0.1) and (0.2), although the detailed dynamics may differ. At high latitudes, inward angular momentum transport by convective plumes induces a single-celled meridional circulation profile in radius, with poleward flow in the upper CZ and equatorward flow in the lower CZ. Meanwhile, the low-latitude dynamics is dominated by "banana cells", convective columns aligned with the rotation axis that transport angular momentum cylindrically outward and thereby induce multiple-celled meridional circulation profiles in radius. The balance between these two regimes changes with Rossby number; Fast rotators ($R_o < 0.3$) exhibit solar-like differential rotation profiles (fast equator, slow poles) with multi-celled circulation profiles while slow rotators ($R_o > 0.9$) exhibit anti-solar differential rotation profiles (slow equator, fast poles) and single-celled circulation profiles (Featherstone & Miesch 2013). The Sun lies near the transition, which suggests that its cyclic dynamo may operate somewhat differently relative to other stars.

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