Spoke-like Differential Rotation in a convective Dynamo with a Coronal Envelope

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Dynamo is quenched at high magnetic Reynolds numbers
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CMEs might be one possibility to transport magnetic helicity out (Blackman and Brandenburg 2003, Thompson et al. 2012).
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CMEs might be one possibility to transport magnetic helicity out (Blackman and Brandenburg 2003, Thompson et al. 2012).

A realistic boundary condition for the magnetic field is important.
The Two Layer Model

Lower layer:
- Convection zone
- Dynamo action
- Generation of magnetic field

Upper layer:
- Simplified coronal model
- Magnetic (helicity) flux emerges from the lower layer and gets ejected.

Both layers are in one simulation.
The Setup
Setup

Convection zone

Self-consistent convection

Solar radii

0.7

1.0

1.6/2.0

Simplified corona

75°

0°

0°

90°

φ
Setup

Self-consistent convection with a coronal layer
Self-consistent convection with a coronal layer

Equations:
Setup

Self-consistent convection with a coronal layer

Equations:

\[ \frac{\partial A}{\partial t} = u \times B + \eta \nabla^2 A \]
Setup

Self-consistent convection with a coronal layer

Equations:

\[
\frac{\partial A}{\partial t} = u \times B + \eta \nabla^2 A
\]

\[
\frac{D \ln \rho}{Dt} = -\nabla \cdot u
\]
Self-consistent convection 
with a coronal layer

Equations:

\[
\frac{\partial A}{\partial t} = u \times B + \eta \nabla^2 A
\]

\[
\frac{D \ln \rho}{Dt} = -\nabla \cdot u
\]

\[
\frac{Du}{Dt} = g - 2\Omega_0 \times u + \frac{1}{\rho} \left( J \times B - \nabla p + \nabla \cdot 2\nu \rho S \right)
\]
**Setup**

Self-consistent convection with a coronal layer

**Equations:**

\[
\frac{\partial A}{\partial t} = u \times B + \eta \nabla^2 A
\]

\[
\frac{D \ln \rho}{D t} = -\nabla \cdot u
\]

\[
\frac{D u}{D t} = g - 2\Omega_0 \times u + \frac{1}{\rho} \left( J \times B - \nabla p + \nabla \cdot 2\nu \rho S \right)
\]

\[
T \frac{D s}{D t} = \frac{1}{\rho} \nabla \cdot \left( K \nabla T + \chi_t \rho T \nabla s \right) + 2\nu S^2 + \frac{\mu_0 \eta}{\rho} J^2 - \Gamma_{cool}(r),
\]
Stratification

$\rho/\rho_0$

$p/p_0$

$s/c_p$

$T/T_0$

$r/R$

10th of April 2013

Differential Rotation and Magnetism across the HR Diagram, Nordita Program Conference, Stockholm
Stratification

\[ \frac{\rho}{\rho_0}, \quad \frac{p}{p_0}, \quad \frac{s}{c_p}, \quad \frac{T}{T_0} \]

\[ r/R \]

10th of April 2013  Differential Rotation and Magnetism across the HR Diagram, Nordita Program Conference, Stockholm
Stratification

\[ \frac{\rho}{\rho_0} \]

\[ \frac{p}{p_0} \]

\[ \frac{T}{T_0} \]

\[ \frac{s}{c_p} \]

\[ \tau/R \]

\[ r/R \]

10th of April 2013

Differential Rotation and Magnetism across the HR Diagram, Nordita Program Conference, Stockholm
Results
Differential rotation
Differential Rotation and Magnetism across the HR Diagram, Nordita Program Conference, Stockholm
Differential Rotation and Magnetism across the HR Diagram, Nordita Program Conference, Stockholm

\[ C_0 = \frac{2\Omega_0}{u_{rms}k_f} \]
Differential Rotation and Magnetism across the HR Diagram, Nordita Program Conference, Stockholm

\[ \text{Co} = \frac{2\Omega_0}{u_{rms}k_f} \]

\[ \text{Co} = 11 \]

\[ \text{Co} = 5.2 \]
The Baroclinic Term

\[ \frac{\partial \omega_\phi}{\partial t} = r \sin \theta \frac{\partial \Omega^2}{\partial z} + \left( \nabla T \times \nabla s \right)_\phi + \ldots \]
The Baroclinic Term

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\]

\[R \nabla_\theta \bar{s} / c_P\]
Turbulent heat conductivity
Turbulent heat conductivity

\[ \overline{F_i} = -\chi_{ij}\overline{\rho T} \nabla_j \overline{s} \]
Turbulent heat conductivity

\[ \overline{F_i} = -\chi_{ij} \overline{\rho T \nabla_j s} \]

\[ \overline{F_i} = c_P \overline{\rho u_i' T'} , \]
Turbulent heat conductivity

\[ F_i = -\chi_{ij} \rho T \nabla_j \bar{s} \]

\[ F_i = c_P \rho u_i' T', \]

\[ \chi_{\theta r} \approx -c_P u_\theta' T' / T \nabla_r \bar{s}. \]
Turbulent heat conductivity

\[ \chi_{\theta r}/\chi_{t0} \]

\[ \overline{F_i} = -\chi_{ij} \overline{\rho T} \nabla_j \overline{s} \]

\[ \overline{F_i} = c_P \overline{\rho u'_i T'} , \]

\[ \chi_{t0} = u_{\text{rms}}/3k_f \]

\[ C_0 = 11 \]

\[ \chi_{\theta r} \approx -c_P u'_\theta T'/\overline{T} \nabla_r \overline{s}. \]
Differential Rotation and Magnetism across the HR Diagram, Nordita Program Conference, Stockholm

\[ \bar{F}_i = -\chi_{ij} \bar{\rho} \bar{T} \nabla_j \bar{s} \]

\[ \bar{F}_i = c_P \bar{\rho} u_i' T' \]

\[ \chi_{t0} = u_{rms} / 3k_f \]

\[ \text{Co} = 11 \]

\[ \chi_{\theta r} \approx -c_P \frac{u'_{\theta} T'}{\bar{T} \nabla_r \bar{s}} \]

\[ \chi_{rr} \approx -c_P \frac{u'_r T'}{\bar{T} \nabla_r \bar{s}} \]
Meridional circulation

$r/R \cos \theta$

$r/R \sin \theta$

Co=11

10th of April 2013

Meridional circulation

Co=11
Meridional circulation

Surface

\( r = R \)

\( (r/R)\cos\theta \)

\( (r/R)\sin\theta \)

Co=11
Meridional circulation

(r/R)\cos\theta

(r/R)\sin\theta

Surface

r=R

30°

15°

7°

ρ\mu_0/\rho_0 u_{\text{rms}}

r/2

r_1

r_2

+7°

+15°

+30°

Co=11

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Meridional circulation

\( Co = 11 \)

\[
\frac{\rho u}{\rho \sigma_{\text{rms}}} \]

\( r/R \sim r \approx R \)

\( \theta \sim 7^\circ, 15^\circ, 30^\circ \)

\[(r/R)\sin\theta \]

\[(r/R)\cos\theta \]

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Meridional circulation

\[ u = 20 \text{ m/s} \]

\[ r = R \]

Surface

\[ (r/R) \cos \theta \]

\[ (r/R) \sin \theta \]

\[ 0.1 \]

\[ 0.2 \]

\[ 0.3 \]

\[ 0.4 \]

\[ 0.5 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1.0 \]

\[ 0.01 \]

\[ 0.02 \]

\[ r_1 \]

\[ r_2 \]

\[ +7^\circ \]

\[ +15^\circ \]

\[ +30^\circ \]

\( \rho u_\varphi / \rho u_{\text{rms}} \)

\[ \text{Co} = 11 \]
What is new?
What is new?

Magnetic fields
What is new?

\[ \frac{B_\phi}{B_{eq}} \]

Co = 11
Equatorward migration of the magnetic field

$B_\phi / B_{eq}$

$C_0 = 11$
Equatorward migration of the magnetic field

$B_{\phi}/B_{eq}$

$Co=11$
Equatorward migration of the magnetic field

$T_{\text{cyl}} = 150$ turnover times $\approx 12$ years

$B_\phi / B_{\text{eq}}$

$C_0 = 11$
Corona supports dynamo action
Corona supports dynamo action

Warnecke et al., 2013b (in prep.)
CME-like Ejections

Current helicity density
CME-like Ejections

Current helicity density
CME-like Ejections

Current helicity density
CME-like Ejections

Current helicity density

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CME-like Ejections

Current helicity density
CME-like Ejections

Current helicity density

$\tau = 341$

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CME-like Ejections

Warnecke et al. 2011
(A&A 534, A11)
Self-consistent convection with a coronal layer
Self-consistent convection with a coronal layer
Self-consistent convection with a coronal layer

Warnecke et al. 2012
(Sol. Ph. 280, 299)
Convection driven Ejections

Figure 14. Time series of a coronal ejection zoomed into the region of the ejection near the equator ($\theta = \pi/2$). The dashed horizontal lines show the location of the surface at $r = R$. Left column: normalized current helicity, $\mu R_0 J \cdot B/\langle B^2 \rangle_t$. Middle column: magnetic field, contours of $r \sin \theta A_\phi$ are shown together with a color-scale representation of $B_\phi$. The contours of $r \sin \theta A_\phi$ correspond to field lines of $B$ in the $r \theta$ plane, where solid lines represent clockwise magnetic field lines and the dashed ones counter-clockwise. Right column: density fluctuations $\Delta \rho(t) = \rho(t) - \langle \rho \rangle_t$. For all plots, the color-scale represents negative as dark blue and positive as light yellow. Taken from Run A5.

SOLA: sol_paper.tex; 2 April 2012; 23:41; p. 18
Conclusions
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• Solar-like (and spoke-like) differential rotation.
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- Ejections with forced and convective dynamos.
- Shape and bipolar structure is similar to observations.
Future research
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• Parameter study of Co and Re, Rm.
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- Measure the helicity fluxes (Eqwrd migr).
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- Measure the helicity fluxes (Eqwrd migr).
- Comparison with simulation without corona.
- Calculate the transport coefficients (Eqwrd migr).
- Analyses the plasmoid ejections.
- Including solar wind