Modeling solar cycle irregularities using flux transport dynamo models

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Sunspot number of last 300 years
Dikpati et al. (2008) claim that the Waldmeier effect does not exist in sunspot area data.

Karak & Choudhuri (2011) show:

**WE1**: anti-correlation between the rise times and the amplitudes

**WE2**: positive correlation between the rise rates and the amplitudes
**Grand minima:**

- Maunder minimum period = 1645 to 1715 (Eddy, 1976; Foukal, 1990; Wilson, 1994)

- 68% of days were observed (Hoyt & Schatten 1996)

- Study of cosmogenic isotopes - C\(^{14}\): 27 grand minima in last 11,000 years (Usoskin et al. 2007)
Flux Transport dynamo
(Durney 1995; Choudhuri, Schussler & Dikpati 1995)

High diffusivity model  Low diffusivity model

\[ \eta_t = 10^{12} - 10^{13} \text{ cm}^2 \text{ s}^{-1} \quad \eta_t = 10^{10} - 10^{11} \text{ cm}^2 \text{ s}^{-1} \]

Mixing length theory gives  \[(1/3) \times l \times v \sim 10^{12} \text{ cm}^2 \text{ s}^{-1}\]

Time scale of turbulent diffusion: \[\tau = \frac{L^2}{\eta_t}\] (where \(L\) = depth of the convection zone.)

\[\sim 2.8 \text{ years} \ (\eta_t = 5 \times 10^{12} \text{ cm}^2/\text{s}).\]

\[\sim 276 \text{ years} \ (\eta_t = 5 \times 10^{10} \text{ cm}^2/\text{s}).\]
Meridional circulation:

- Comes from the combination of Buoyancy forces, Reynolds stresses, Latitudinal pressure gradients and Coriolis forces acting on the mean zonal flow (Kitchatinov & Rudiger 1995; Miesch 2005)

- Near the surface its value ~ 20 m/s and it is poleward. (Hathaway 1996; Haber et al. 2002; Basu & Antia 2000)

- Using the mass conservation principle we construct the full profile of the MC.

Taken from Yeates et al. (2008)
Did the meridional circulation vary largely?

In flux transport dynamo:

\[ \text{Period} \propto \frac{1}{V_0^{0.89}} \]  
(Dikpati & Charbonneau 1999)

\[ \text{Period} \propto \frac{1}{V_0^{0.885}} \]  
(Yeates, Nandy Mackey 2008)

Wang et al. (2002); Hathaway et al. (2003); Javaraiah & Ulrich (2006)---amplitude of MC varied largely with the solar cycle.

Taken from Karak & Choudhuri (2010)
Sources of irregularities in flux transport dynamo

- Fluctuations in B-L process of generating poloidal field
  - High diffusivity
  - Low diffusivity
  
- Fluctuations in meridional circulation
  - High diffusivity
  - Low diffusivity

Can explain the correlation between the polar field and the next sunspot cycle

Jiang, Chatterjee & Choudhuri (2007)
Yeates, Nandy & Mackey (2008)
Effect of Fluctuations of Meridional circulation

\[ \frac{\partial A}{\partial t} + \ldots = \eta_t (\nabla^2 - \frac{1}{s^2}) A + S_\alpha \]

\[ \frac{\partial B}{\partial t} + \ldots = \eta_t (\nabla^2 - \frac{1}{s^2}) B + s(\nabla \cdot B) \Omega \]

Meridional circulation

More time to induct toroidal field

Stronger cycle

More time for the diffusion

Weaker cycle

In low diffusivity model

In high diffusivity model

(Yeates, Nandy & Mackey 2008)
Modeling last 23 cycles using variable meridional circulation

From High diffusivity Model (Chatterjee, Nandy & Choudhuri 2004)

In this model, Period \( \propto \frac{1}{v_0^{0.70}} \)

Karak (2010)
On repeating the same calculation in Low diffusivity Model (Dikpati & Charbonneau 1999)

Karak (2010)
Theoretical study of Waldmeier effect

Introducing stochastic fluctuations

in poloidal field source term

in meridional circulation

Karak & Choudhuri (2011)
1) Fluctuation in meridional circulation is required to explain WE.

2) Only high diffusivity model is able to explain WE.

Karak & Choudhuri (2011)
Can a large fluctuation in meridional circulation lead to a Maunder-like minimum?

It reproduces the strong asymmetry (Ribes & Nesme-Ribes 1993; Sokoloff & Nesme-Ribes 1994).

Karak (2010)
Sudden initiation of MM but gradual recovery (Usoskin et al. 2000)

Karak (2010)
If we decrease the poloidal field to a very low value at the beginning of the Maunder minimum, then we can reproduce a Maunder-like grand minimum.

Choudhur & Karak (2009)
Effect of Turbulent Pumping on Solar Cycles Memory: Investigations using a Kinematic Dynamo Model

Authors: Bidya Binay Karak & Dibyendu Nandy
Thank You
Repeat the same calculation in Low diffusivity model

Karak (2010)
From the study of $^{14}$C data in tree rings, Miyahara et al. (2004, 2010) say that the solar cycle was continued during Maunder minimum, but **with a period of 13–15 yr** instead of regular 11-yr period.

It explains the cyclic behaviour of solar activity (Schwabe cycle) during MM (Beer et al. 1998, Miyahara et al. 2004)

Karak (2010)