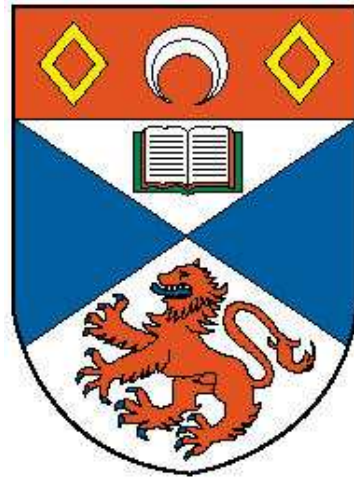


Solar Activity During Grand Minima: Open Flux Variation and State of the Heliosphere.



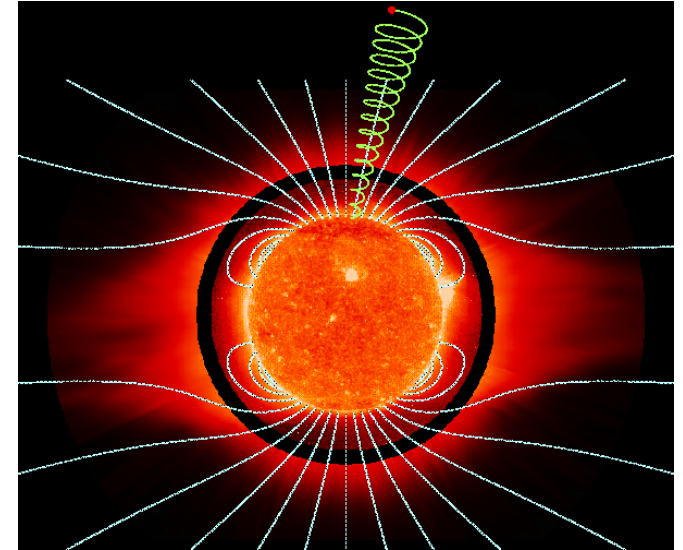
Duncan H Mackay
Solar Theory Group
University of St Andrews
Scotland.

Open Flux and Signatures of Variation

- Importance of Open Flux.

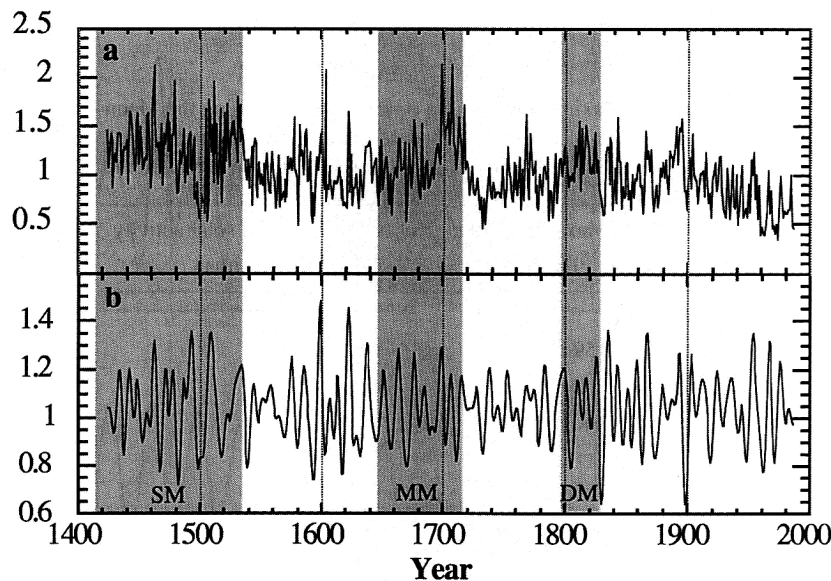
- Forms the Interplanetary Magnetic Field (IMF).

- IMF/Open Flux modulates Cosmic Ray hits.



Banasziewicz et al.1999.

- Beer, Tobias and Weiss (1998) studied ^{10}Be isotope abundances.



1423-1985 raw data

^{10}Be increases and end of MM

7-25yr bandwidth filter.

Magnetic cycles/Open Flux variation
existed throughout the MM.

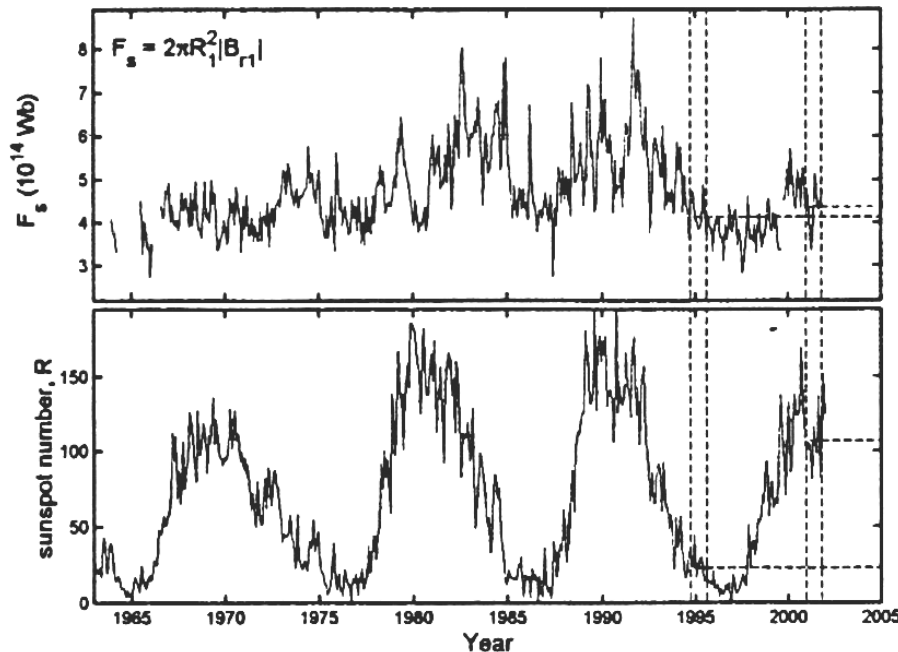
(Stuiver 1989,1998 ; Miyahara et al. 2004, 2007
Castagnoli and Lal 1980, Masarik and Beer 1999).

Present Day Understanding: Observations

- Ulysses : Magnitude of radial IMF component independent of heliocentric latitude (Balogh et al. 1995, Smith and Balogh 2003, Suess and Smith 1996).

$$\Phi_{\text{open}} = 4\pi r_e^2 |B_{\text{rel}}| / 2$$

- IMF data shows that the open flux has varied for last 3.5 cycle (Lockwood 2002).



Smaller variation of open flux ~ factor of 2
less for cycle 23 & 20.

Horizontal/Vertical lines – Ulysses passes.

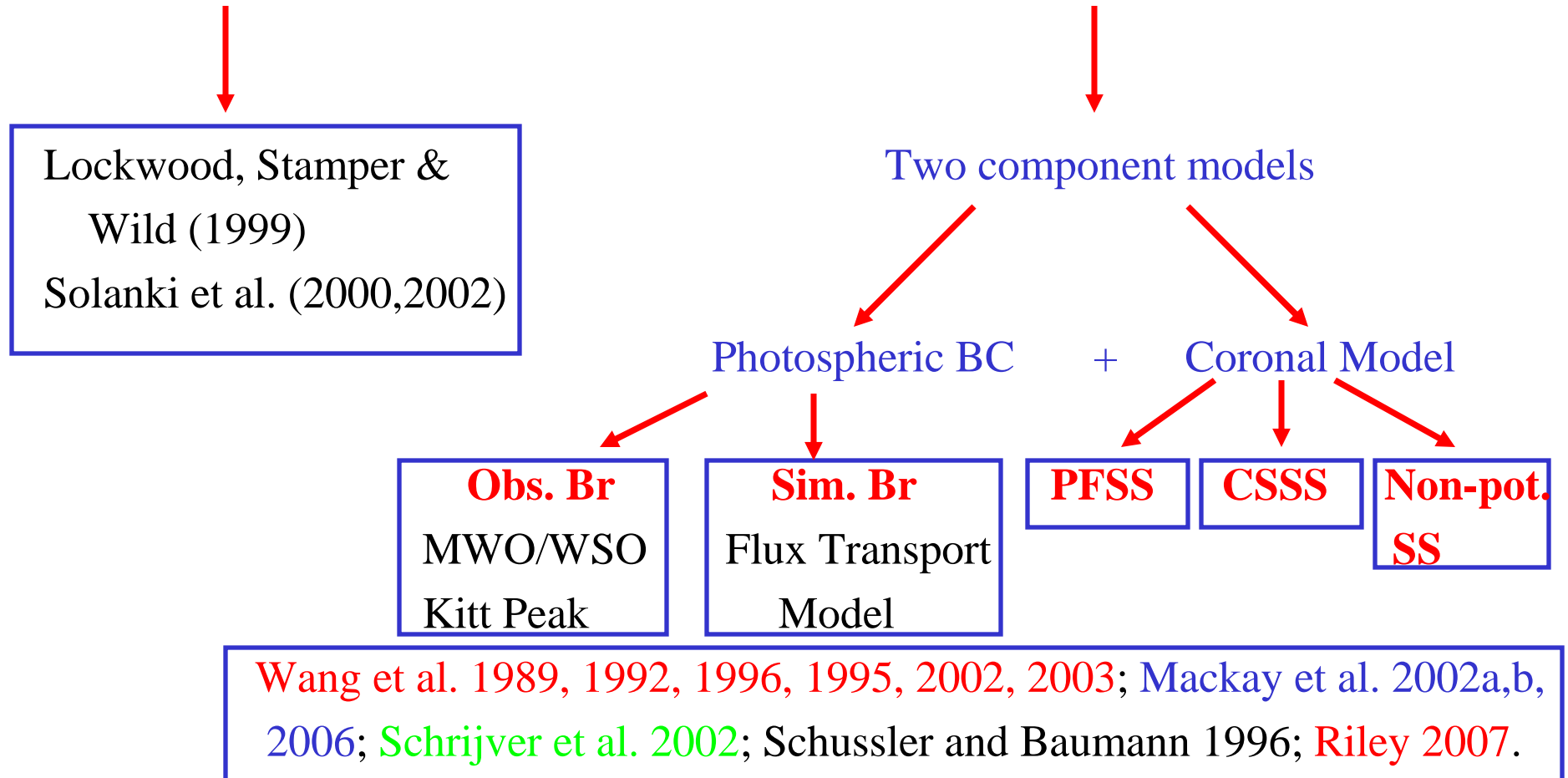
Open Flux out of phase with cycle (1-2 yr).

Theoretical Models

- A wide range of techniques exist for modelling the open flux.

Magnitude Variation Models

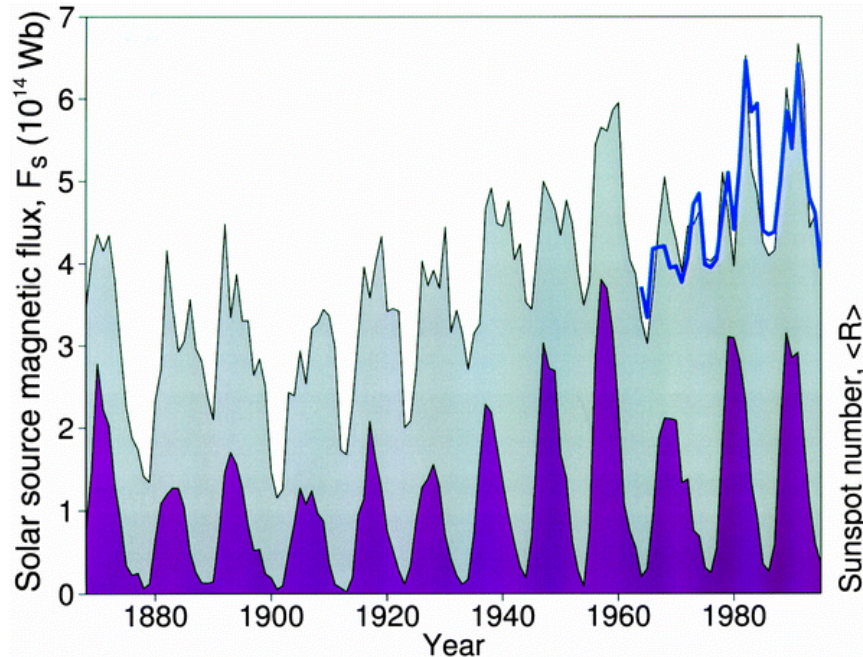
Spatial Distribution Models.



Alternative model : Fisk and Schwadron 2001, Fisk 2005, Gilbert et al (2007).

Magnitude Variation Model

- Lockwood et al. (1999) - compute open flux from aa-index using a physics based model.



Matches IMF variation (blue line)

Factor of 2 increase during 20th Century
(35% increase since 1963, IMF data) .

Down turn since 1987.

- Solanki et al. (2000, 2002)- use semi-empirical model to consider the rate of change of open flux. Equation contained two terms

- 1) Sunspot number (input).
- 2) linear decay rate

$$\frac{d\Phi_o}{dt} = \gamma E - \frac{\Phi_o}{\tau_o}$$

Determined a good fit to IMF data since 1963 ($\tau_o \sim 3.6\text{yr}$)..

Model predicts why during longer/shorter cycles the open flux decays/increases.

PFSS Extrapolation: Two Views

- Wang and Sheeley (1995, 2000, 2002) use PFSS models to deduce the open flux from Br synoptic magnetograms.

1971-1976, 1995-1998 : MWO

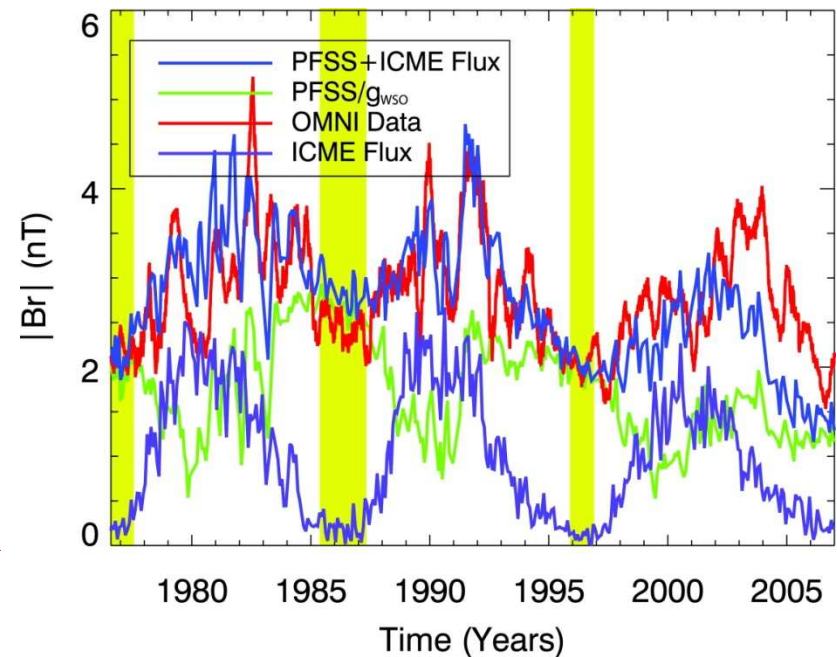
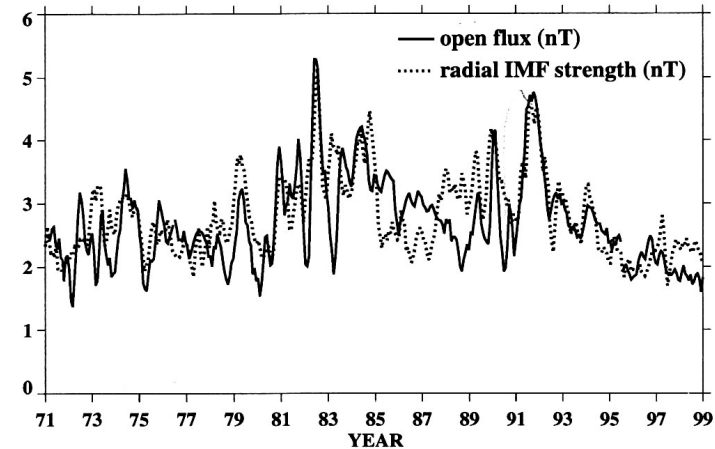
1976-1995 : WSO

To match observed data a **strong latitude dependent correction factor** (from MWO) needs to be applied ($4.5 - 2.5 \sin^2 \lambda$).

- Riley (2007) has questioned the use of the MWO correction factor to WSO data (**constant correction factor 1.85** Svalgaard 2006).

Explains open flux by:

- **Variable background from potential field**
- **ICME contribution.**



Solar Cycle Simulations

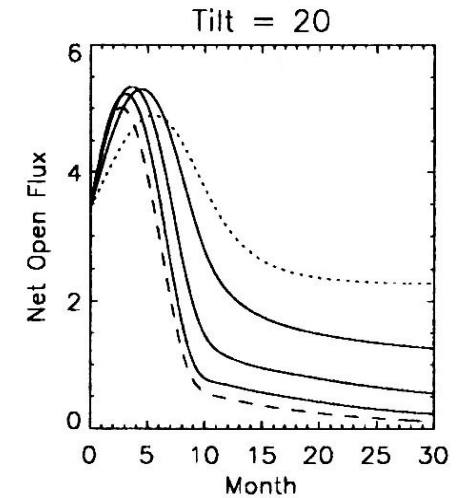
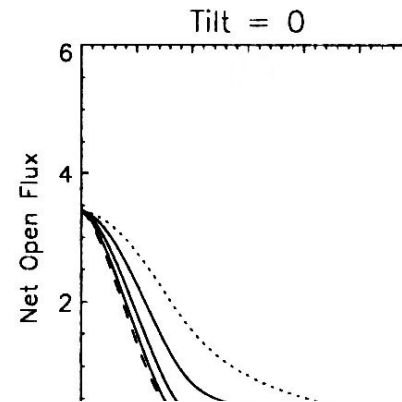
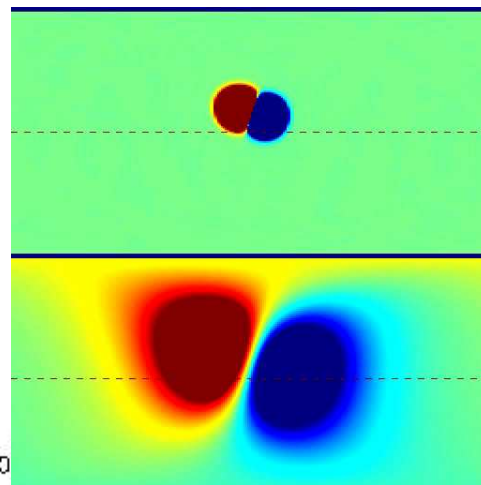
- Wang et al. (2000) and Mackay et al. (2002) - single bipole + PFSS.

Lat. of emergence

Tilt angle

Merd. flow

Diff. Rot.

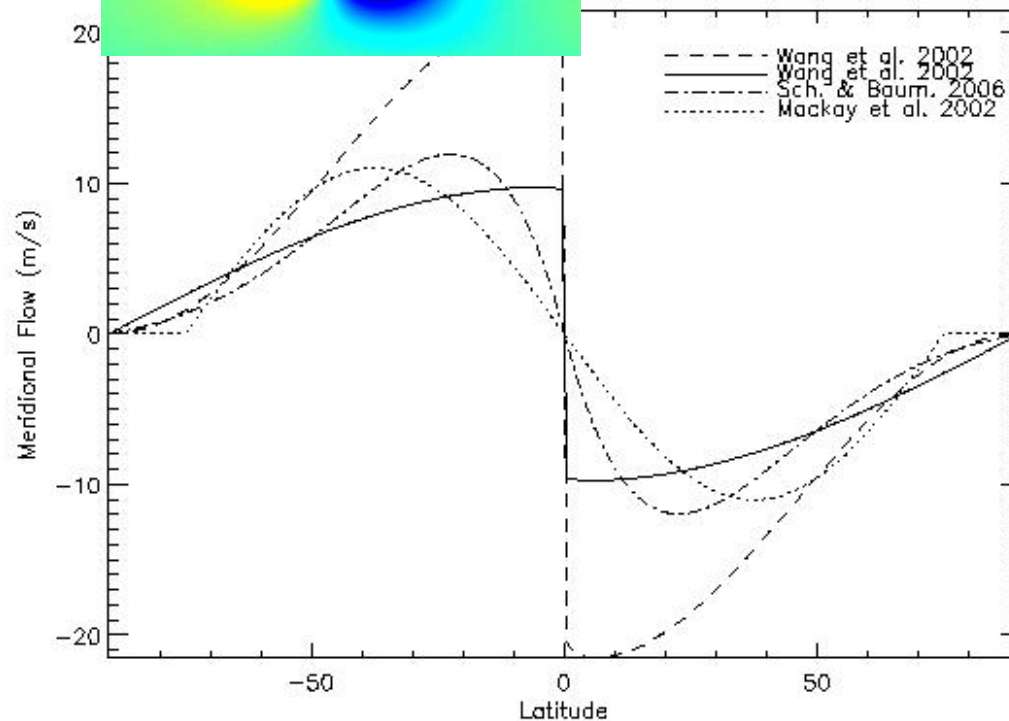


Full Sun Si

Mackay & Loc

Wang & Sheel

Schussler & Ba



$u_{\theta} = 11 \text{ m/s}$, PFSS

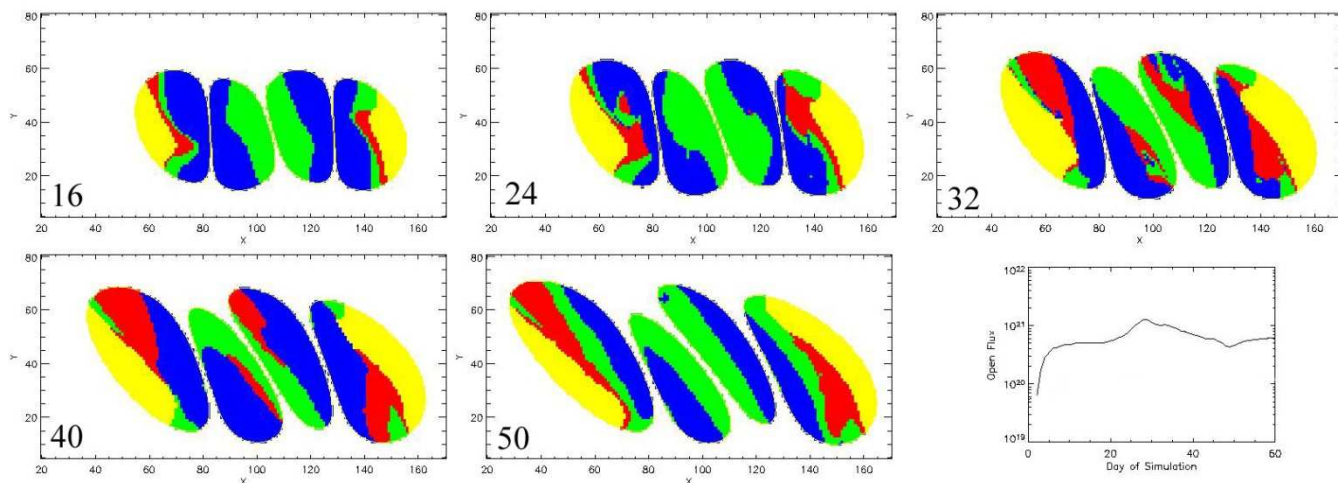
it of phase with

bipole fluxes

tilt angles ($\gamma = 0.15 * \lambda$,
ORs) model.

Non-potential Models

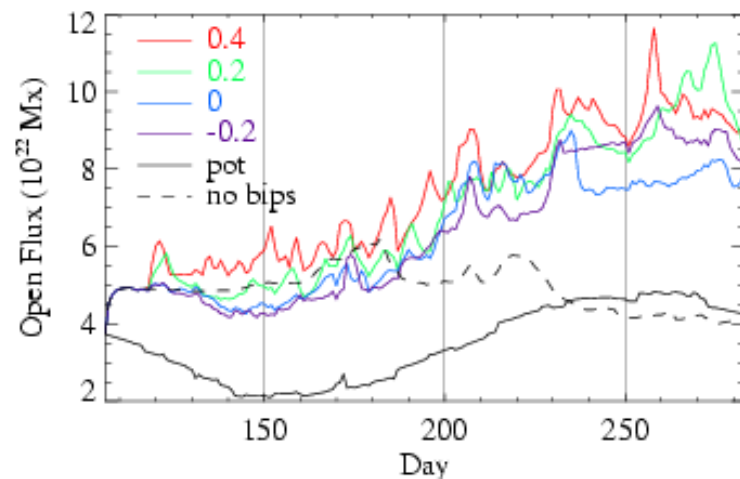
- Mackay and van Ballegooijen (2006) : open flux through nlfff simulations.



Open flux (red) evolves by **interchange reconnection**.

Multiple enhancements due to flux rope ejections.

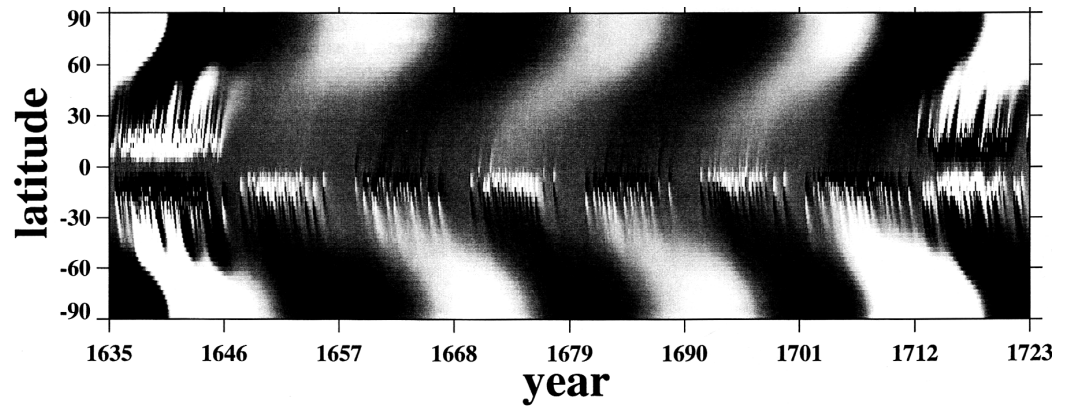
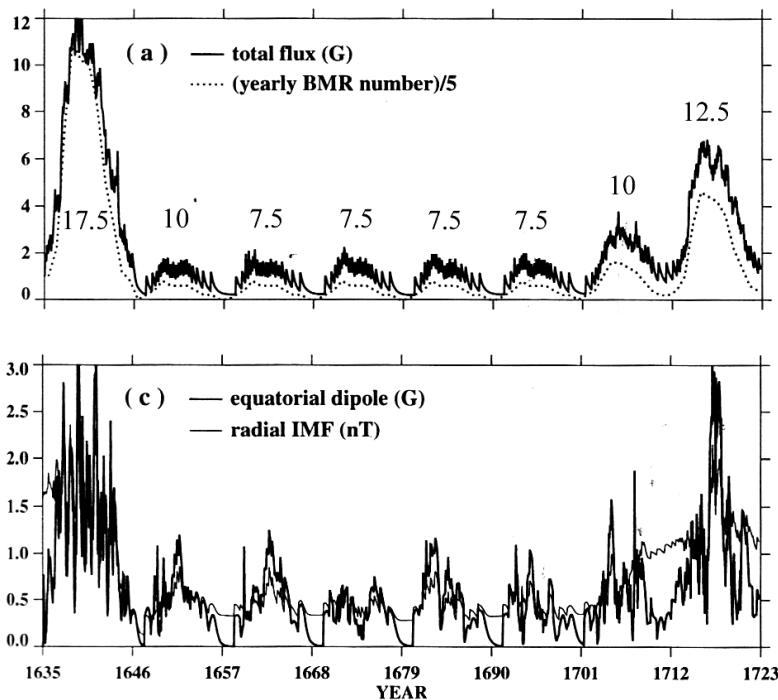
- Full Sun simulations for 6-months driven by observations (see Yeates et al. 2008).



- open flux for nlfff higher than for potential
 - significant variations due insertion of new bipoles and flux rope ejections.
- (for more details see poster).

Maunder Minimum Scenario

- The majority of papers consider the Sun's surface flux and open flux from the end of the Maunder minimum to present day.
- Wang and Sheeley (2003) consider the MM.



Show that regular oscillations of polar fields may occur – variable m.f. rate.
Give value if IMF field $\sim 0.7\text{nT}$ (1/7 smaller).

- Consistent with results of Scherer & Fichtner (2004): predict a factor of 4 decrease in heliospheric field using dynamic multi-fluid model of global heliosphere.

Summary

- Observations of the behaviour of the Sun's open flux over last 3 cycles
- Observations and model show that open flux is variable with large variations over long periods of time.
- Wide variety of models constructed to consider the origin and variation of the Sun's open flux – magnitude models/spatial distribution

Issues to resolve – potential/non-potential models

- During the Maunder Minima magnetic cycles existed at reduced levels
 - models predict a factor of 4-7 decrease in open flux.