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Open Flux and Signatures of Variation

- Importance of Open Flux.
  - Forms the Interplanetary Magnetic Field (IMF).
  - IMF/Open Flux modulates Cosmic Ray hits.

  1423-1985 raw data
  $^{10}$Be increases and end of MM
  7-25yr bandwidth filter.
  Magnetic cycles/Open Flux variation existed throughout the MM.
Present Day Understanding: Observations


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

- 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**
- Lockwood, Stamper & Wild (1999)
- Solanki et al. (2000, 2002)

**Spatial Distribution Models**
- Two component models
  - Photospheric BC + Coronal Model
    - Obs. Br: MWO/WSO, Kitt Peak
    - Sim. Br: Flux Transport Model
      - PFSS
      - CSSS
      - Non-pot.

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-emperical 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 (\(\tau_o \sim 3.6\)yr).

Model predicts why during longer/shorter cycles the open flux decays/increases.
PFSS Extrapolation: Two Views


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 & B:

/2, \( u_0 = 11 \text{m/s} \), PFSS
out of phase with
bipole fluxes

tilt angles (\( \gamma = 0.15*\lambda \),
0Rs) model.
Non-potential Models

  
  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).

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.