The Sun's Magnetic Field During The Maunder Minimum And Modern Risks From A Weak Field

Fatemeh Rahmanifard[1,2], Nathan A. Schwadron[1,2], CharlesW. Smith[1,2], Kenneth G. McCracken[3], Katharine A. Duderstadt[2], Noé Lugaz[1,2] and Larry Townsend

University of New Hampshire

1Physics Department, Space Science Center, University of New Hampshire, Durham, NH, USA
2Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH, USA
3Institute of Physical Science and Technology, University of Maryland, College Park, USA
4 University of Tennessee, Department of Nuclear Engineering, Knoxville TN (United States)

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Motivation

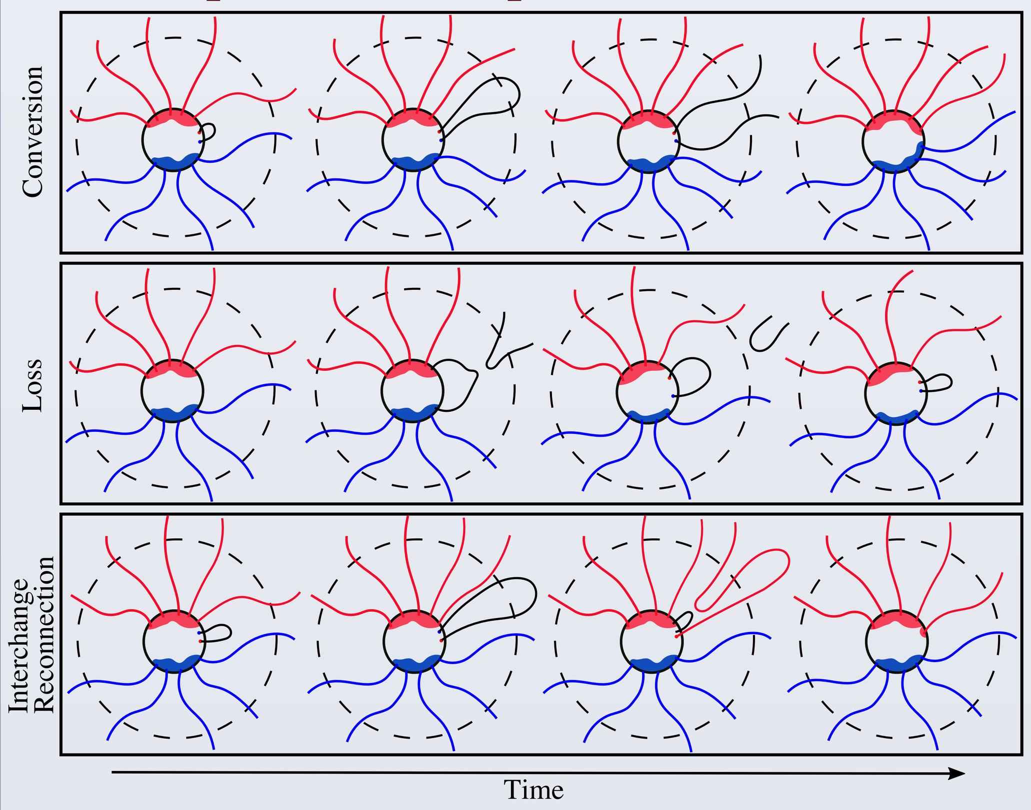
- Recent solar conditions include a prolonged solar minimum (2005-2009) and the recent solar maximum not fully recovered in terms of the Heliospheric Magnetic Field (HMF) strength compared to the previous maximum values. These anomalies may indicate that we are entering an era of lower solar activity.

Research objectives

- The past solar grand minima, especially the Maunder period (1645-1715) are studied to gain further insight into grand minima.
- The time scale parameters associated with the three processes attributed to the magnetic flux balance in the heliosphere are obtained using chi-square analysis.
- The existence of a floor in the heliospheric magnetic flux in the absence of the Coronal Mass Ejections (CMEs) is investigated .
- HMF time series reconstructed based on geomagnetic data and near-Earth spacecraft measurements (OMNI) data are used to find the fundamental timescales that influence heliospheric field evolution.
- Using the predicted HMF from this work, we are going to deduce the modulation potential of Galactic Cosmic Rays (GCRs) to obtain dose rates for the coming solar cycle.
- We can use these results to predict the most conservative estimations of the time to 3% risk of exposure-induced death (REID) in interplanetary space.

Background

Three processes responsible for transformation of CMEs:



- **The top panel**: conversion of transient CME magnetic flux to ambient heliospheric magnetic flux
- **The middle panel**: removal or loss of the ambient heliospheric field through magnetic reconnection.
- **The bottom** CME magnetic flux and ambient heliospheric magnetic flux

The theory of *Schwadron et al.* [2010] describes the evolution of the heliospheric magnetic flux including the closed flux from CMEs and the balance provided by conversion, loss and interchange reconnection of magnetic flux.

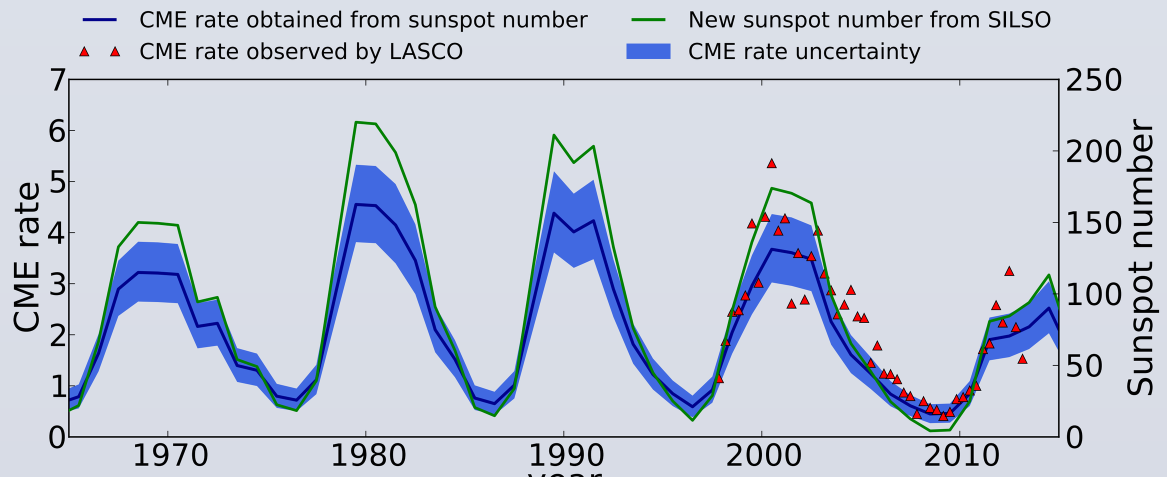
$$\frac{d\varphi_{ej}}{dt} = f\,(1-D)\,\varphi_{CME} - \varphi_{ej}\left(\frac{1}{\tau_c} + \frac{1}{\tau_l} + \frac{1}{\tau_{ic}}\right)$$

$$\frac{d\varphi_{HMF}}{dt} = \frac{\varphi_{HMF} - \varphi_{flr}}{\tau_l} + \frac{\varphi_{ej}}{\tau_c}$$

$$\frac{d\varphi_{tot}}{dt} = \frac{\varphi_{tot} - \varphi_{flr}}{\tau_l} + f\,(1-D)\,\varphi_{CME} - \frac{\varphi_{ej}}{\tau_{ic}}$$

$$\varphi_{tot} = \int B_P \,.\, \hat{n} dS$$

ϕ_{ej} is the transient CME associated magnetic flux, ϕ_{HMF} is the ambient heliospheric magnetic flux, f is the frequency of CME ejections, D is the fraction of CME ejecta that reconnects immediately, ϕ_{CME} is the flux of a typical CME. τ_c , τ_l *and* τ_{ic} are timescales of conversion, loss, and interchange reconnection.

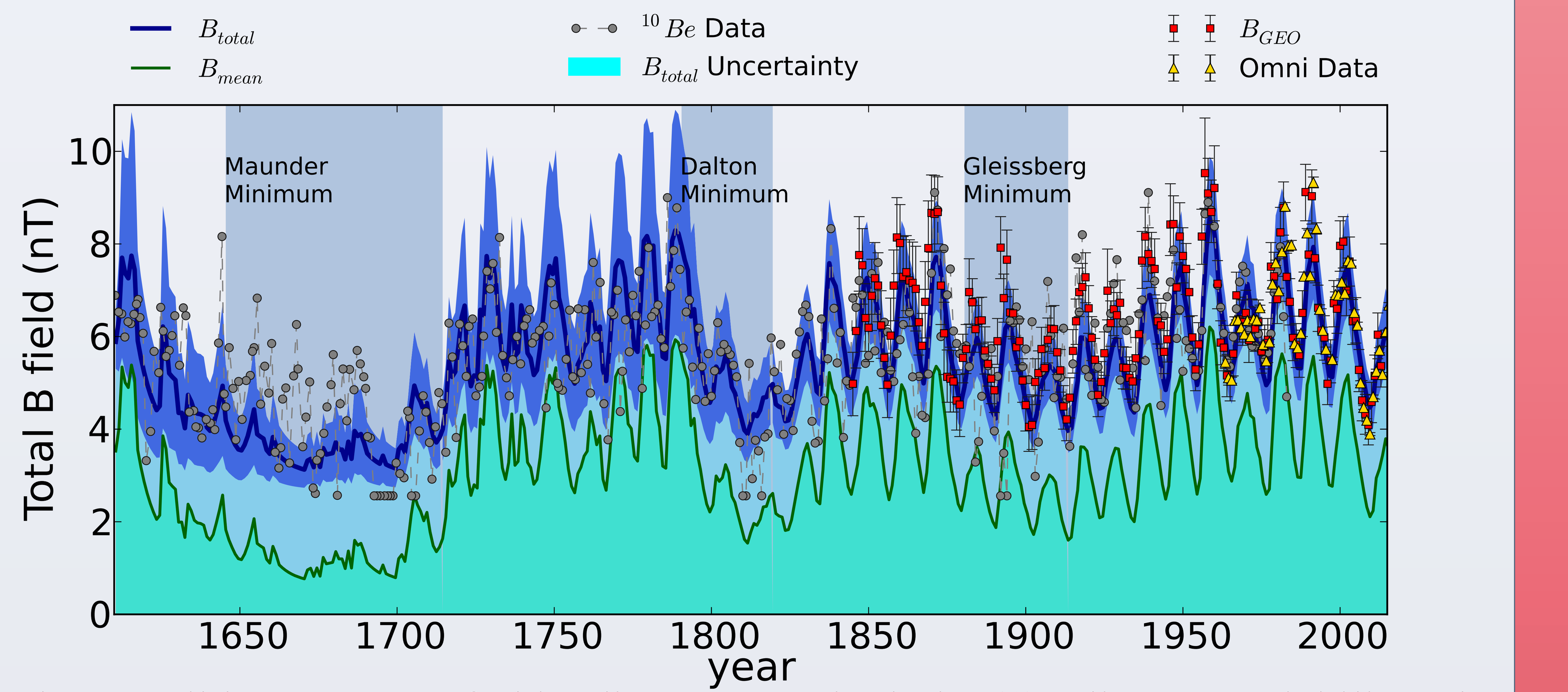


Using chi-square analysis we found a relationship between CME rates and sunspot numbers:

$$f = 0.019 \pm 0.002 \times (\text{sunspot number}) + 0.37 \pm 0.13$$

Results

- We have employed the theory of *Schwadron et al.* [2010] to model the generation of HMF back to 1610 using the new release of the sunspot group number [*Svalgaard and Schatten*, 2016] .
- A chi-square analysis method is used to find the set of parameters (conversion, loss, and interchange reconnection timescales along with the floor flux) that yields the closest agreement between the predicted HMF and reconstructed geomagnetic-based HMF and OMNI data.
- An average value of 2.36 ± 0.08 nT has been added to the predicted mean heliospheric field value in order to compensate for the role of the turbulent and toroidal components of the HMF [*Goelzer et al.*, 2013].
- The best-fit parameters are $\tau_c = 3.07 \pm 0.03$, $\tau_l = 5.91 \pm 0.06$ years, $\tau_{ic} = 24.00 \pm 0.18$ days and zero for the floor flux.
- There is reasonable agreement between the model predicted HMF and paleocosmic (^{10}Be) data despite an underestimation during Maunder period.



- The possible sources of this discrepancy include (1) climate variability, the production of energetic particles by solar events, and variability in ^{10}Be-based data; (2) the uncertainty of the sunspot numbers during the Maunder Minimum; (3) variability in CME rate deduced from sunspot number; (4) the magnetic flux excess attributed to inverted HMF.

Conclusions

- We apply a chi-square minimization technique to fit our simulated model to geomagnetic-based data and OMNI data in order to find conversion, loss, and interchange reconnection timescales along with a floor flux .
- Using chi-square minimization we show there is no floor in the heliospheric flux in the absence of CMEs.
- Our model results favorably reproduce paleocosmic data and show how the heliospheric magnetic field may evolve through periods of extremely low activity.
- The minimum value for the HMF at 1 AU in the model predicted historic record is 3.13 ± 0.40 nT.
- As the HMF continues to weaken over time, the GCR radiation can be a worsening factor that limits space missions.

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Contacts

fle4@wildcats.unh.edu