Implications of CME Deflection on the Fraction of ICMEs Observed as Magnetic Clouds

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Kay et al. 2014, submitting soon!

Quick Definitions

- **Coronal Mass Ejection (CME)** - Ejecta leaving the sun which is view remotely
- **Interplanetary CME (ICME)** - Interplanetary counterpart of a CME which is observed in situ
- **Magnetic cloud (MC)** - Subset of ICMEs which have smoothly rotating enhanced B and low plasma beta (signature of a flux rope)
- **Non-MC** - Subset of ICMEs that are not MCs
  - ICMEs = MCs + non-MCs

Observations of MC/ICME

- Cane + Richardson list of near-Earth ICMEs
- Solar Cycle 23: Rates of ICMEs and MCs tend to diverge during high solar activity (Cane & Richardson 2003, Richardson & Cane 2004, Riley+ 2006, Riley & Richardson 2013)
  - Solar activity increases → percentage of MCs Decreases (MC% = #MCs / #ICMEs)
- Trend persists through other solar cycles

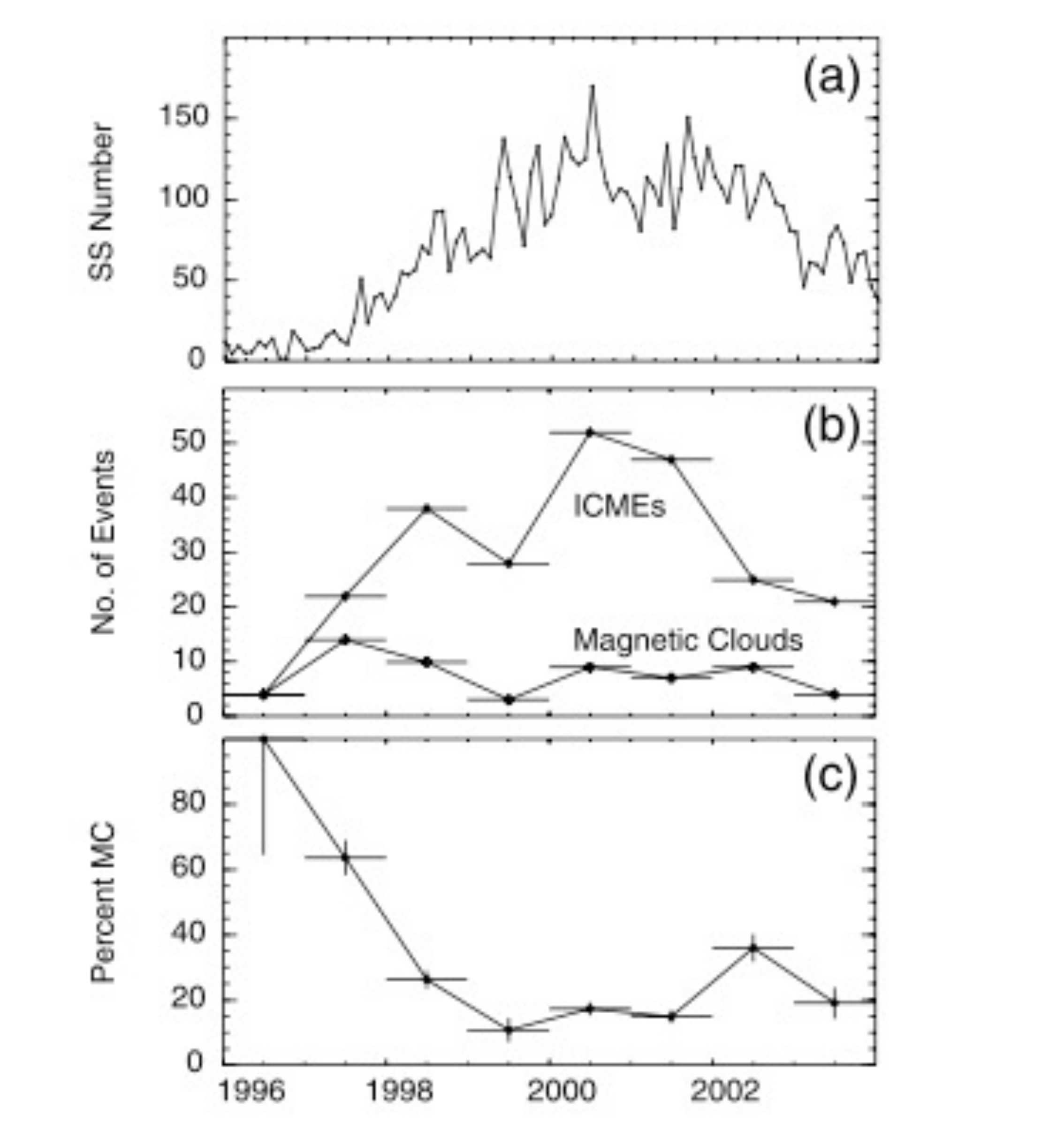


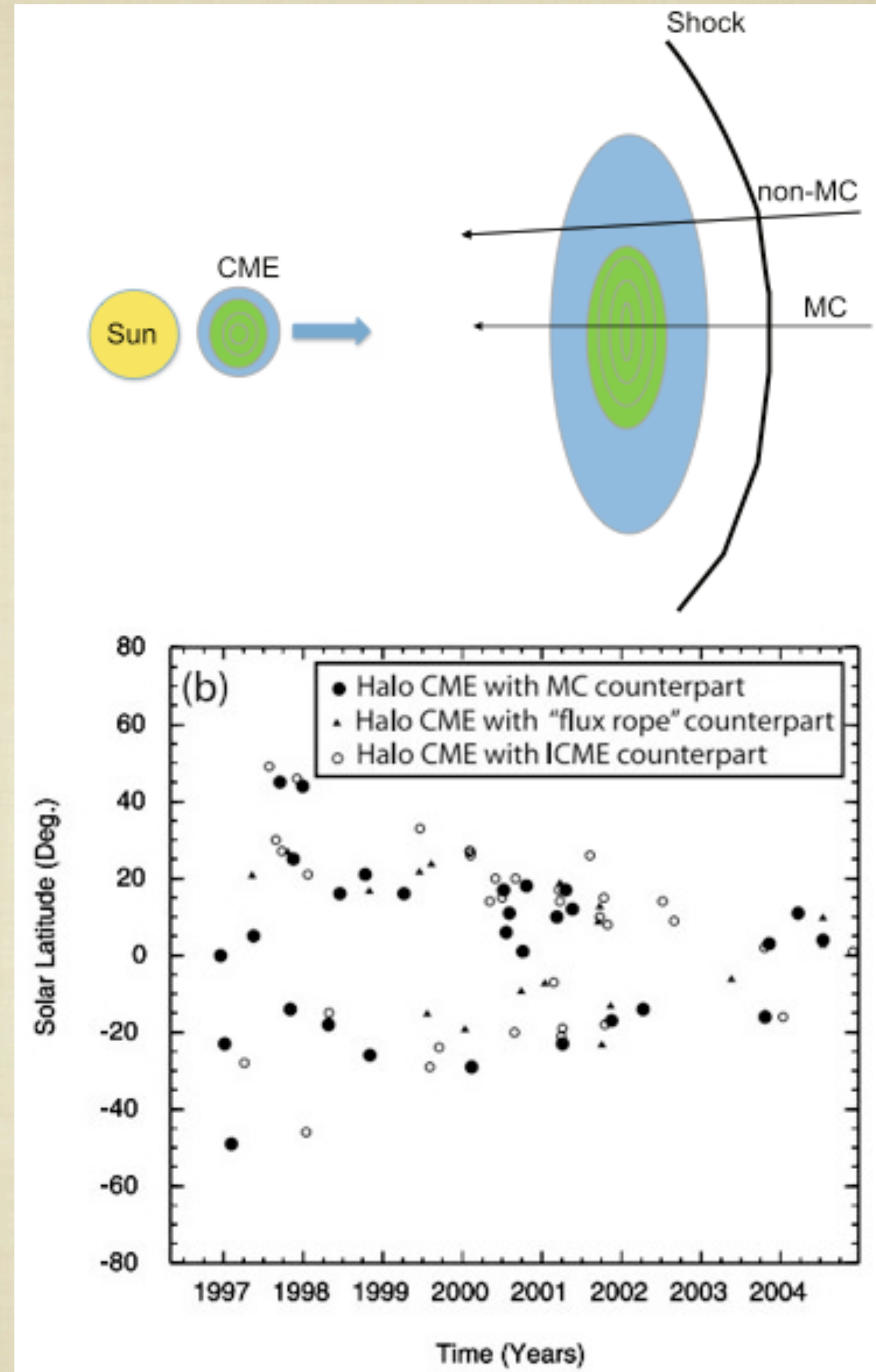
Figure from Richardson & Cane 2004

Causes of Variation?

- Can use Statistical properties of MCs and non-MCs to rule out many suggestions (Riley & Richardson 2013)
  - CMEs begin complicated and "relax" into MC
  - MC-MC interactions result in non-MC
- Suggestions that cannot be eliminated
  - Complexity of CMEs increases throughout solar Cycle
  - Two distinct CME mechanisms
  - **MC vs. non-MC is simply matter of spacecraft perspective**

MCs as Observational Bias

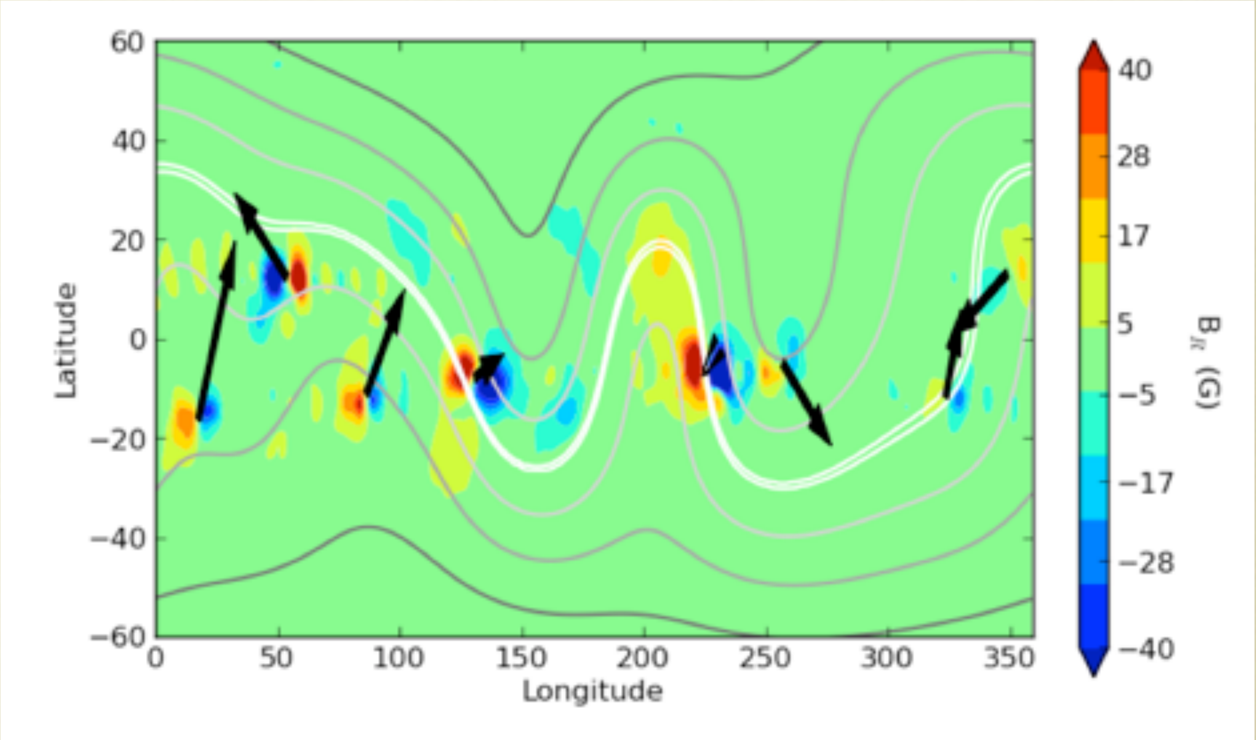
- Assume all CMEs have a flux rope
- Spacecraft must encounter flux rope to see as MC
  - Glancing encounters = non-MC
- Expect CMEs from lower latitudes more likely to be MCs → not observed (Riley+ 2006)



Figures from Riley+ 2013, 2006

Effects of Deflection

- Deflection can affect whether a CME is observed as ICME (Kilpua+ 2009)
- Deflection tends to move CMEs away from high magnetic energy to low magnetic energy (Gopalswamy+ 2009, Gui+ 2011, Lugaz+ 2011, Shen+ 2011, Makela+ 2013, Xie+ 2013)
- Magnetic deflection model **ForeCAT** (kay+ 2013, Kay & Opher 2014, in prep) shows that CMEs deflect toward "magnetic minimum" (Heliospheric Current Sheet (HCS) on global scales)

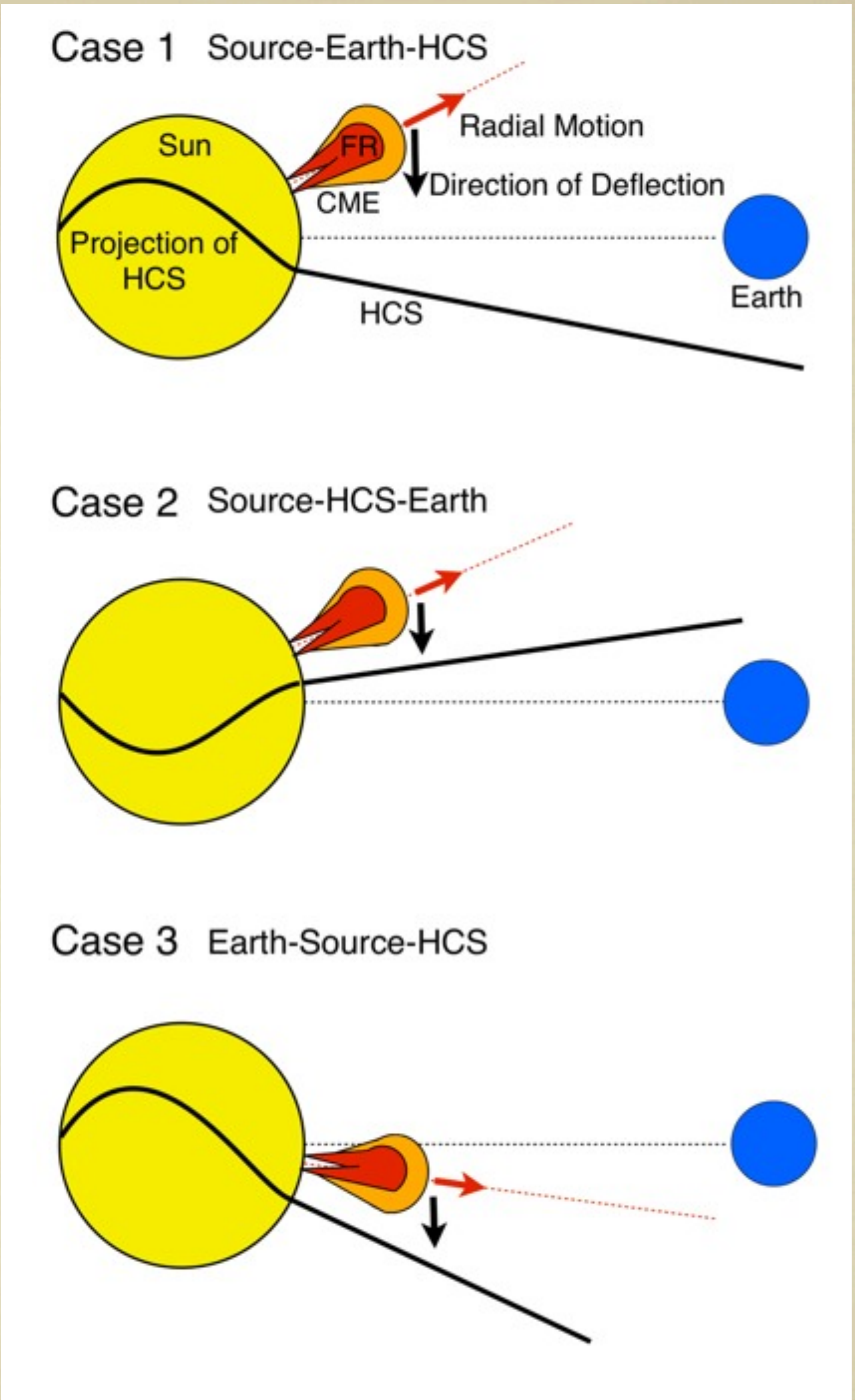


Deflection + MC%

- If all CMEs contain a flux rope and CMEs tend to deflect toward the HCS then the MC% should vary with the distance between the Earth and the HCS
  - Expect a higher percentage of MCs when the HCS is close to Earth

Possible Deflections

- Deflection can move CME toward or away from Earth depending on relative orientation of Earth, HCS, and CME source
- Precise locations highly uncertain → forced to use average values for individual Carrington rotations (CRs)



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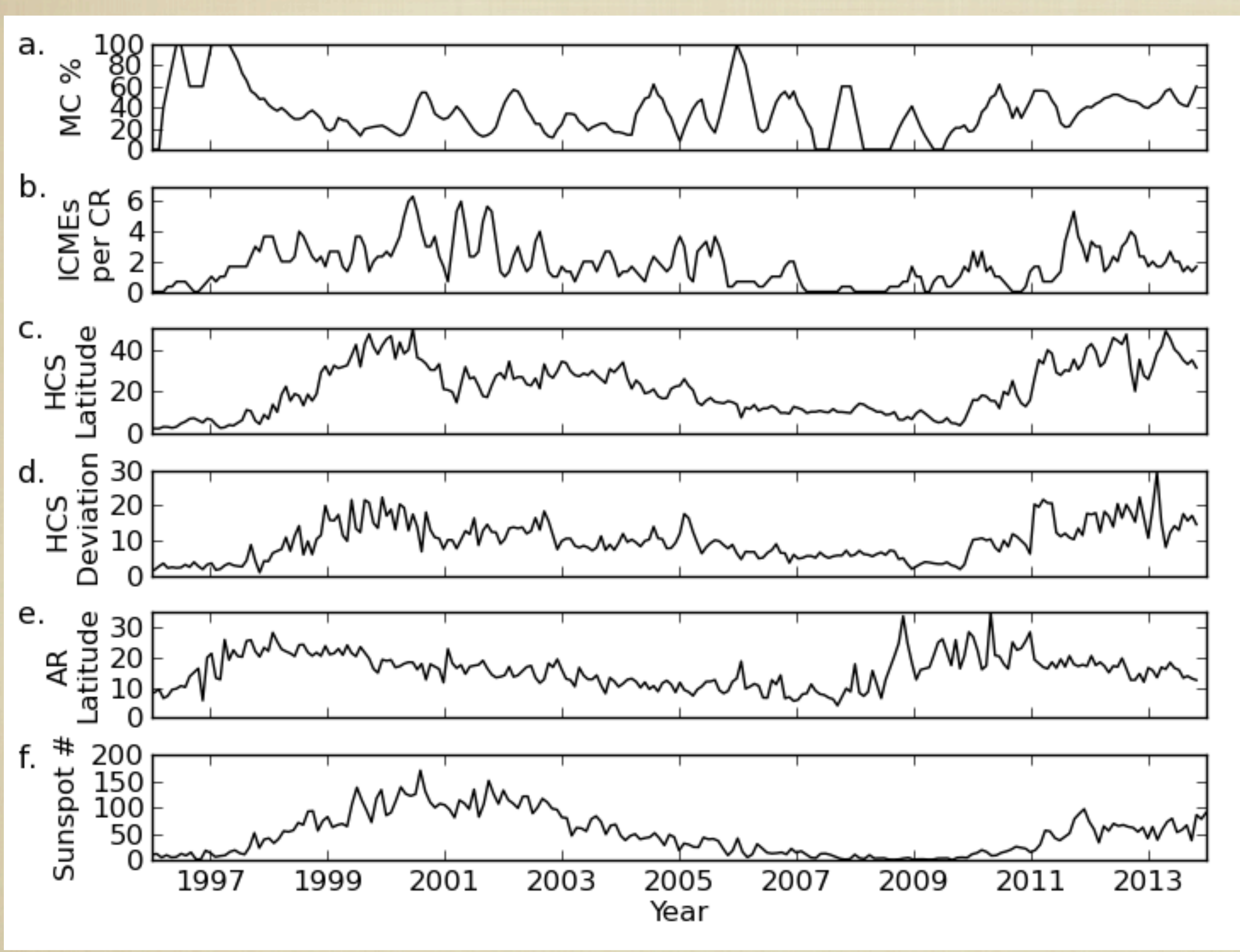

Use extend Richarson + Cane ICME list

WSO + PFSS

USAF/NOAA sunspot data

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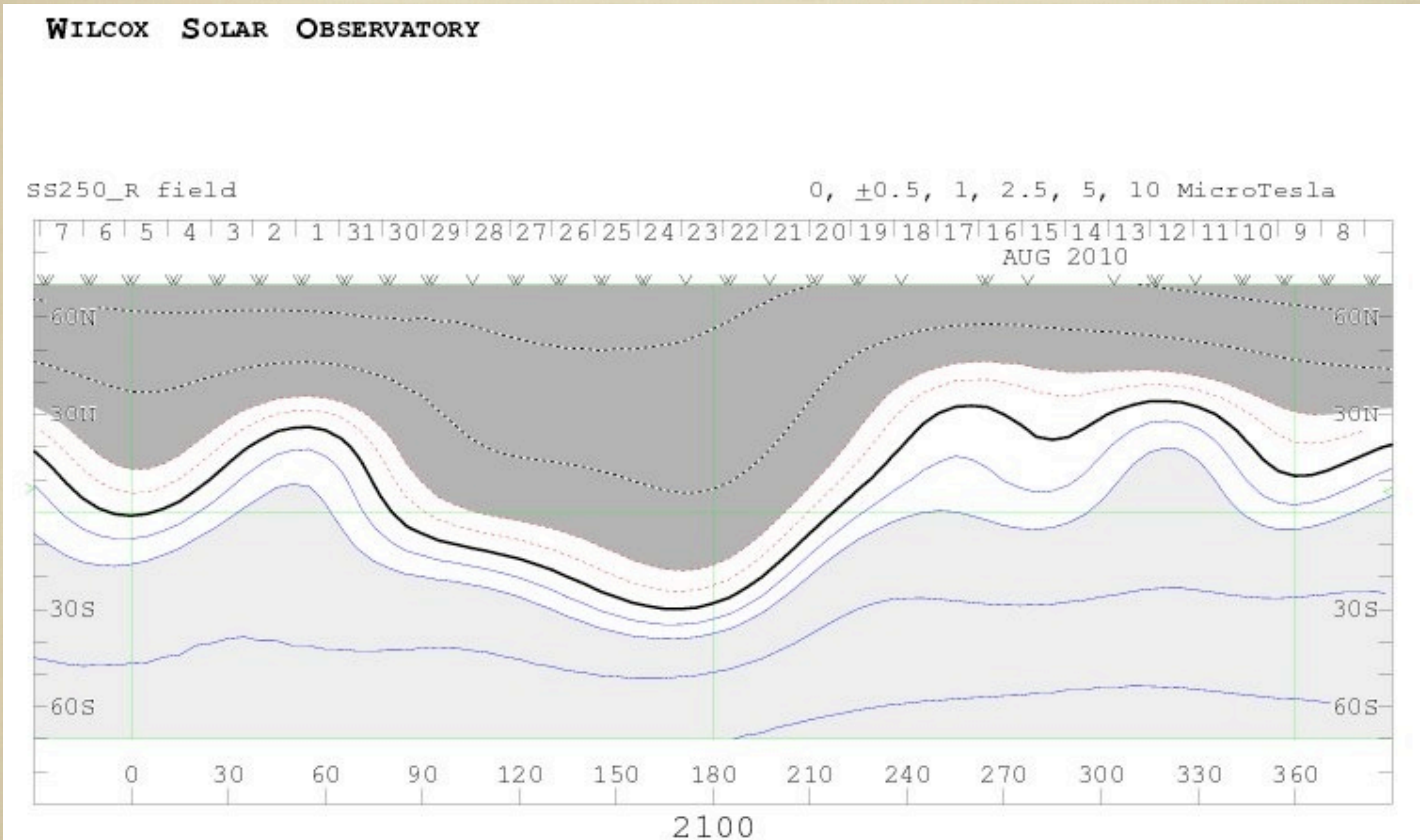
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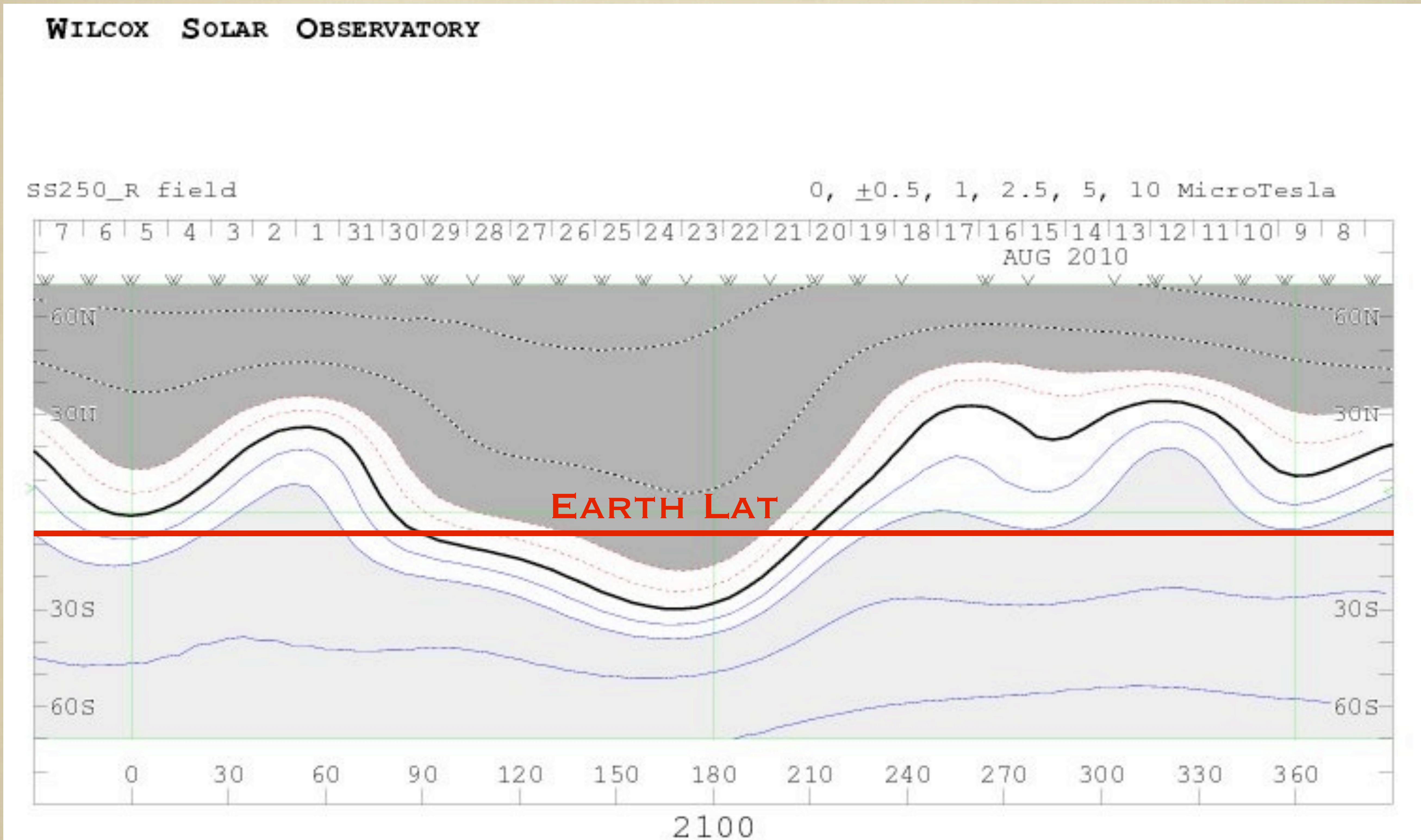
MC Data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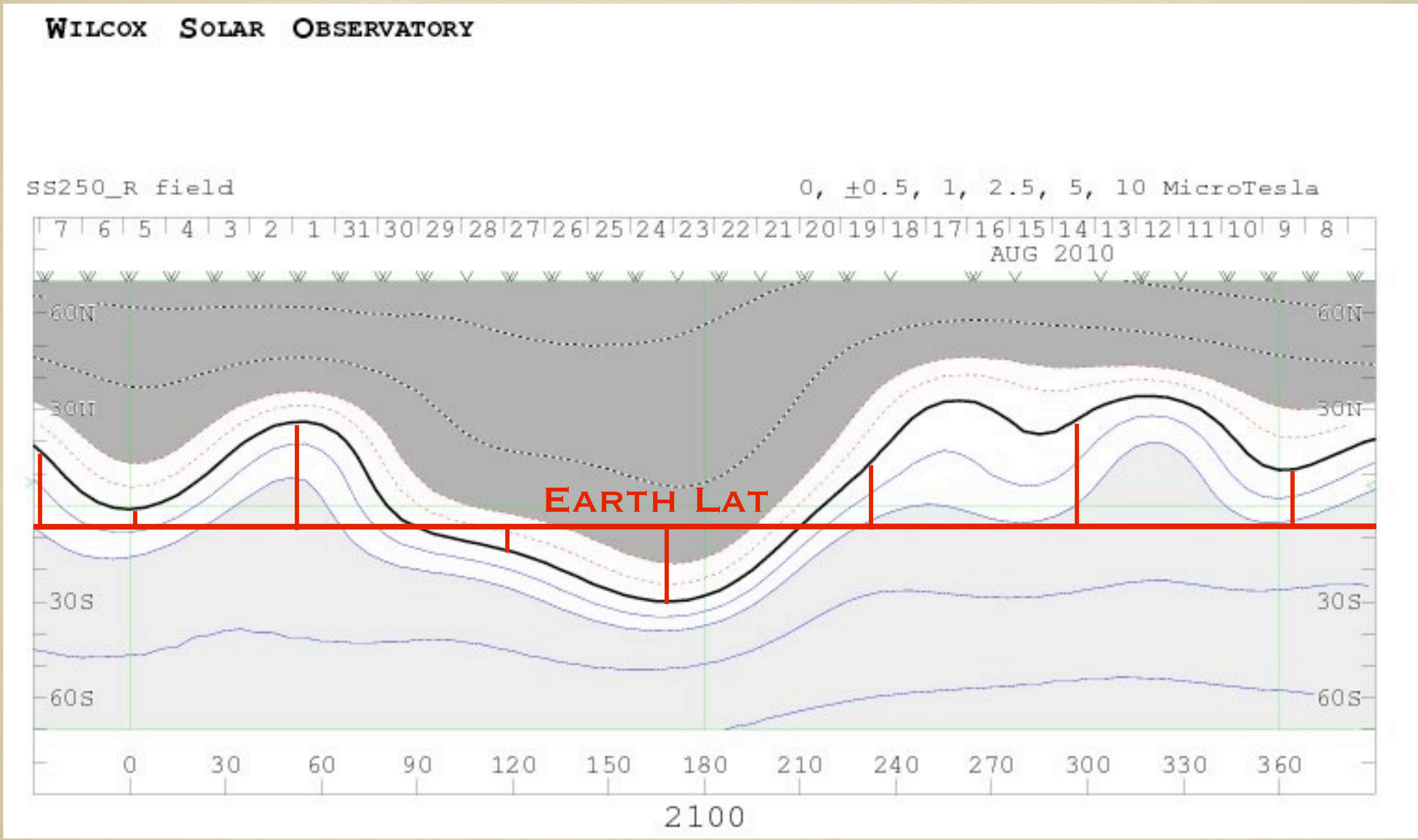
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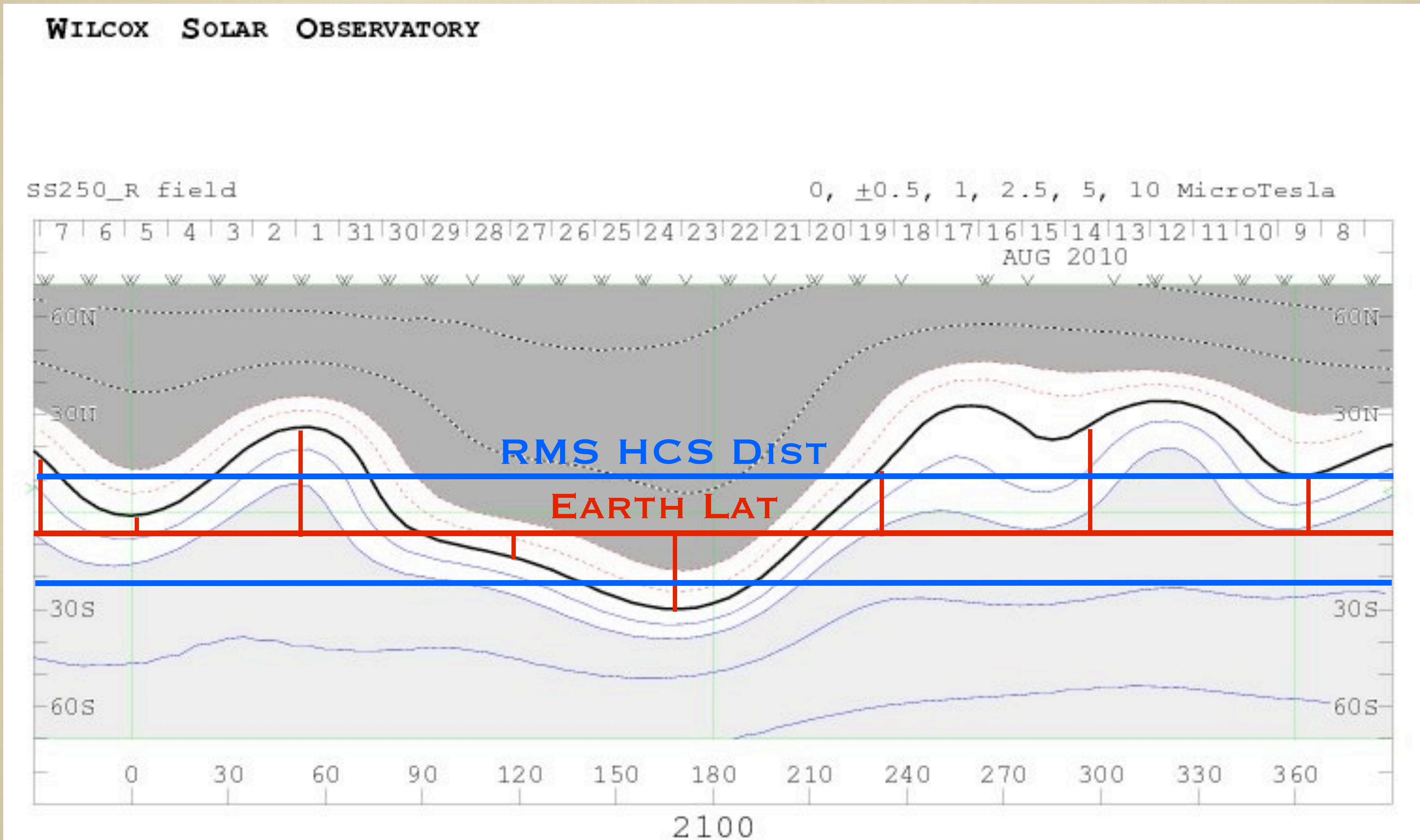
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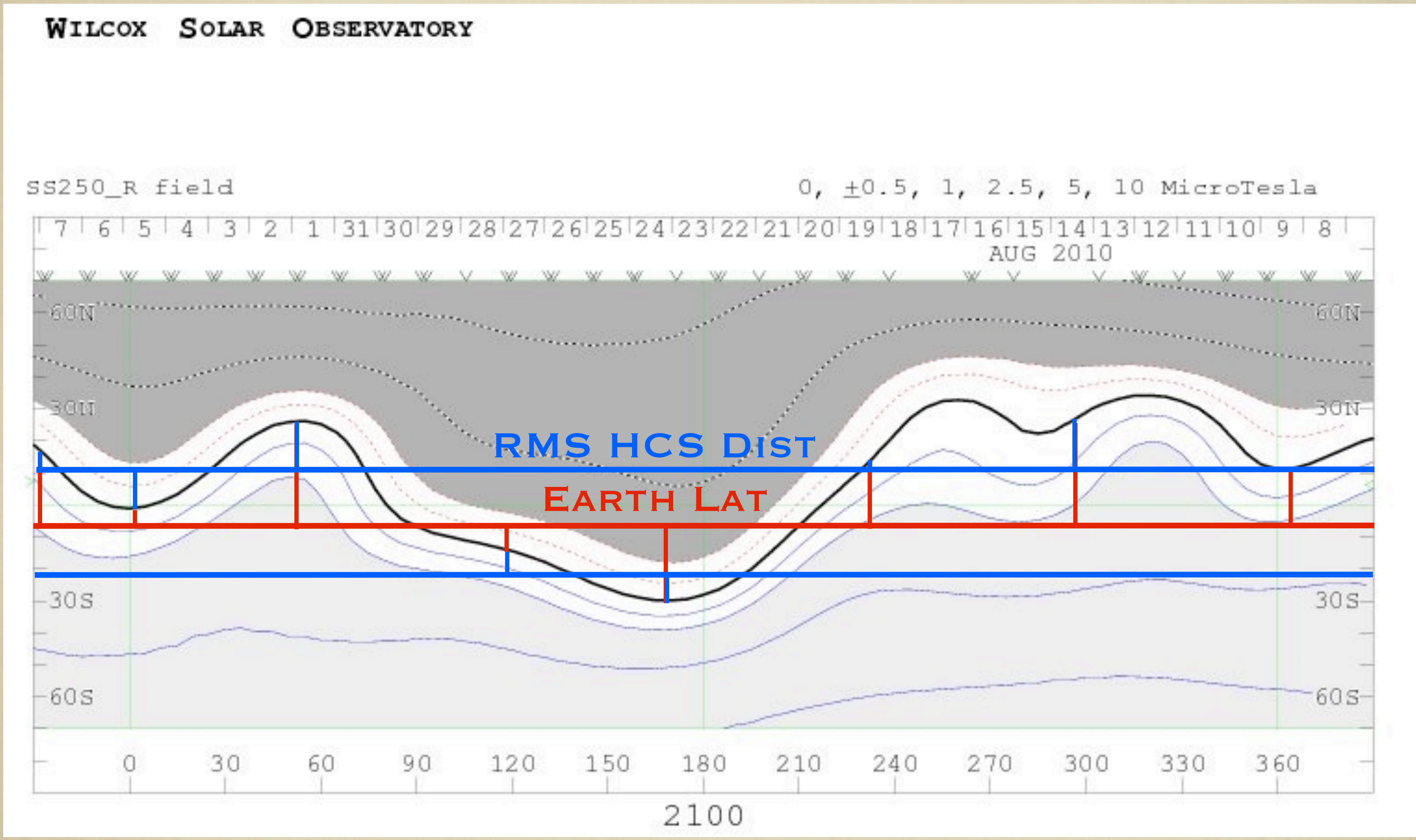
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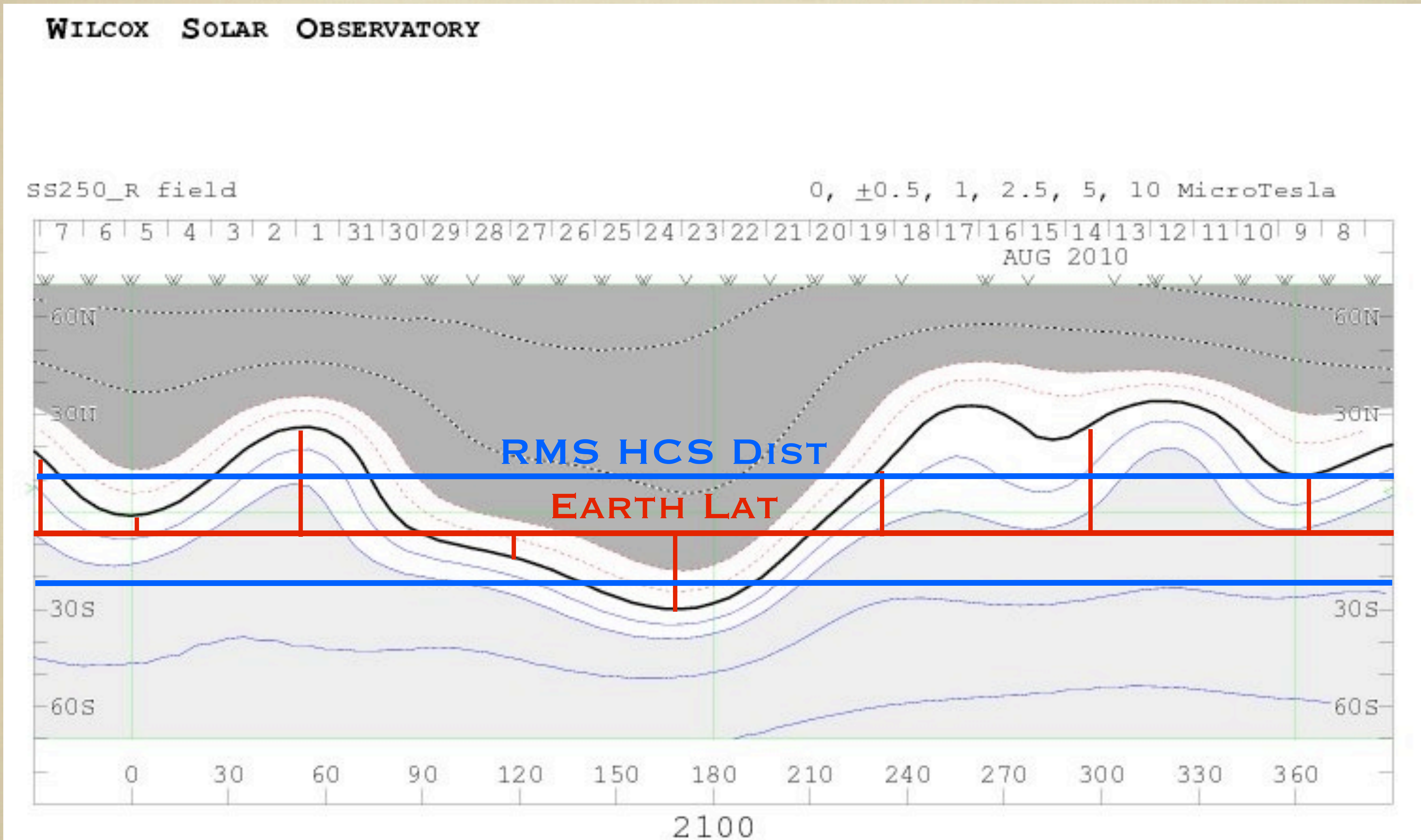

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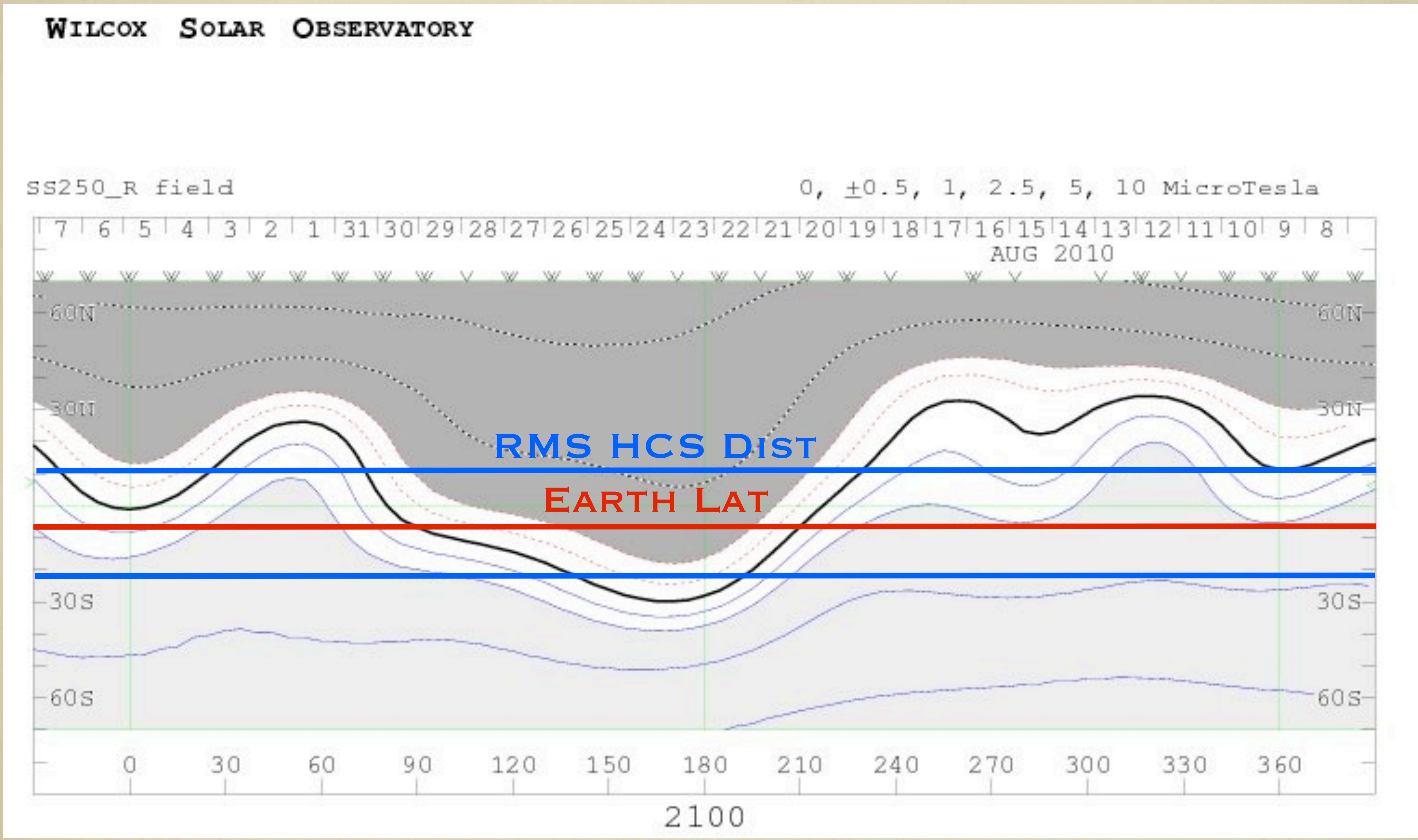

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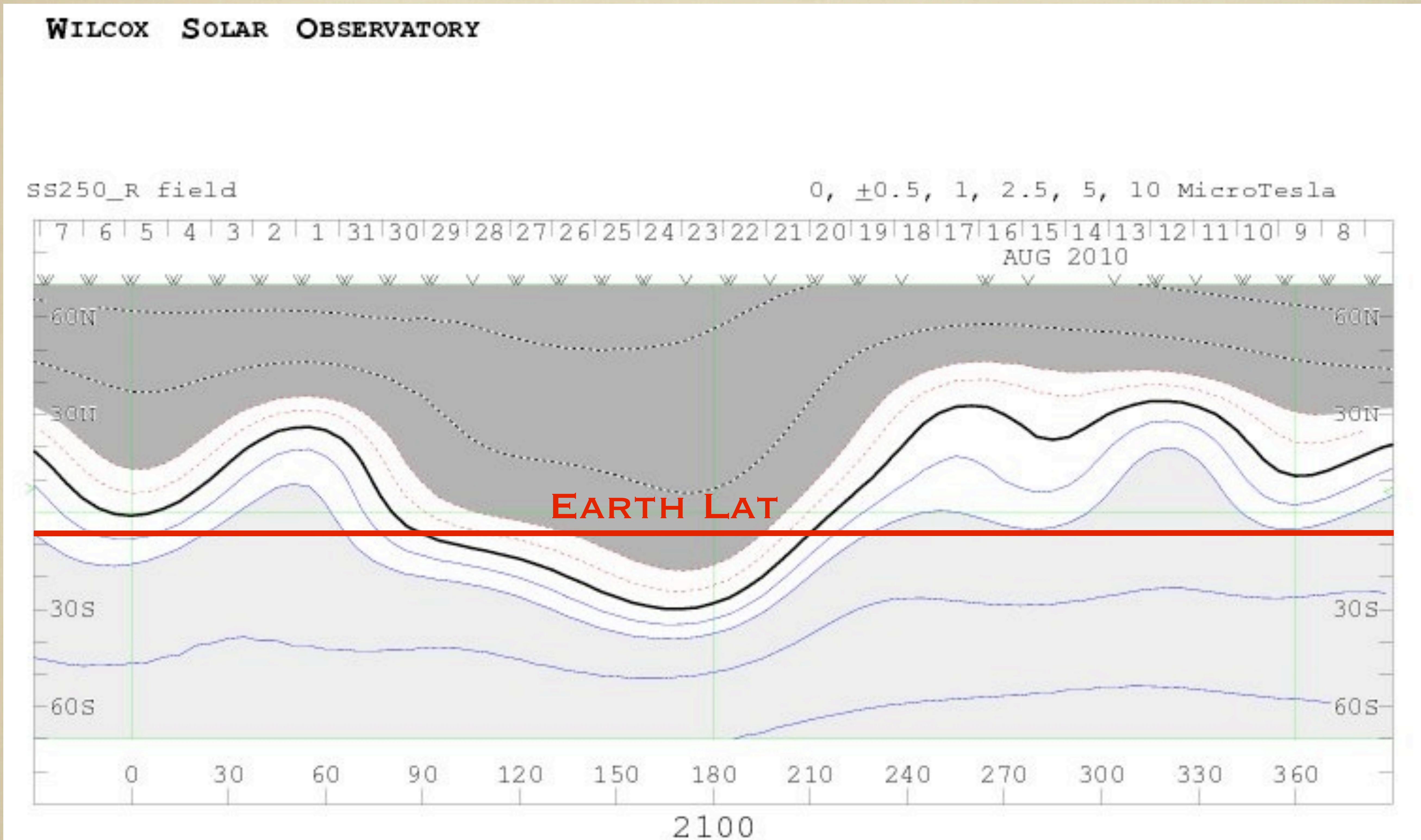
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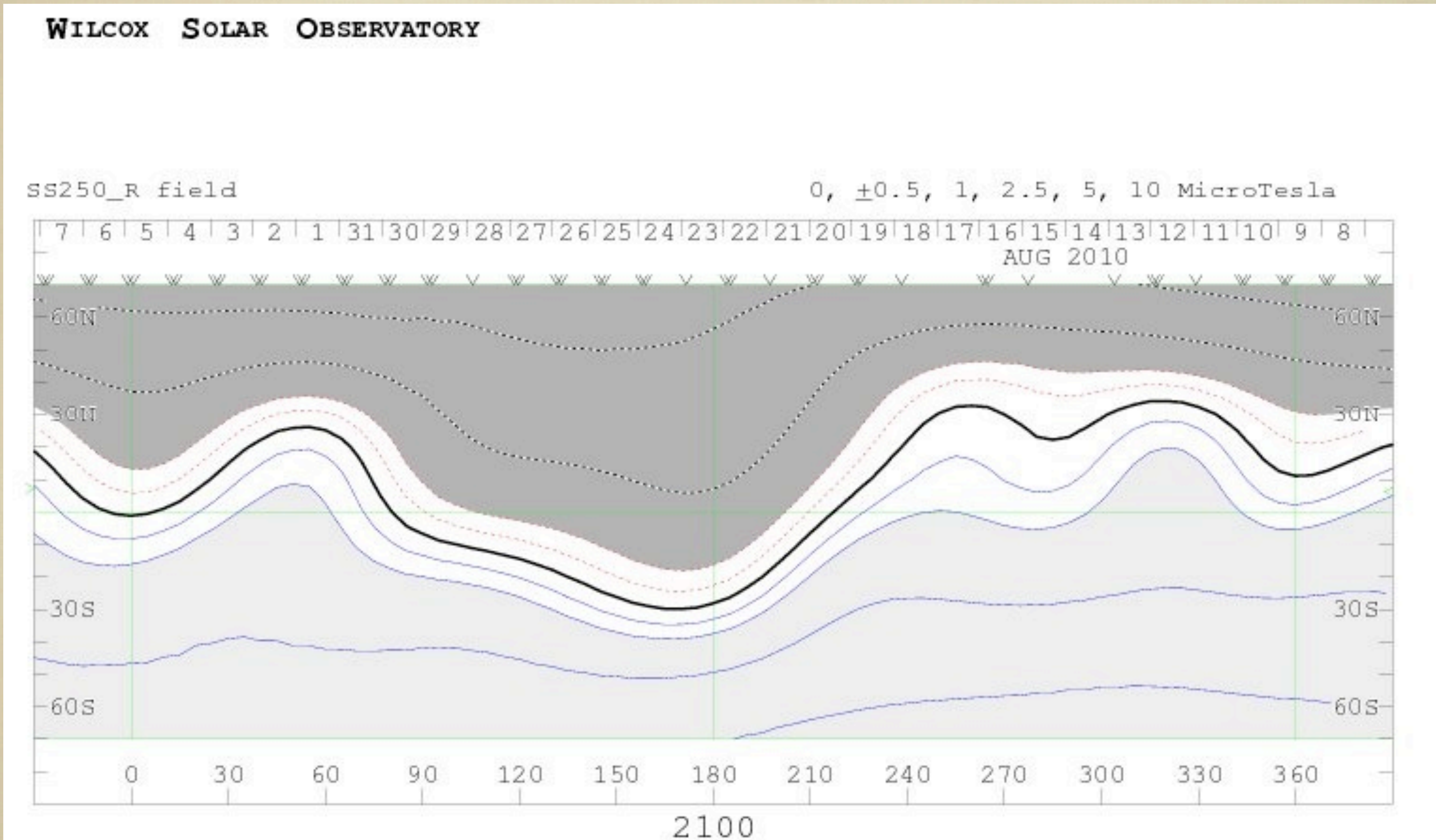
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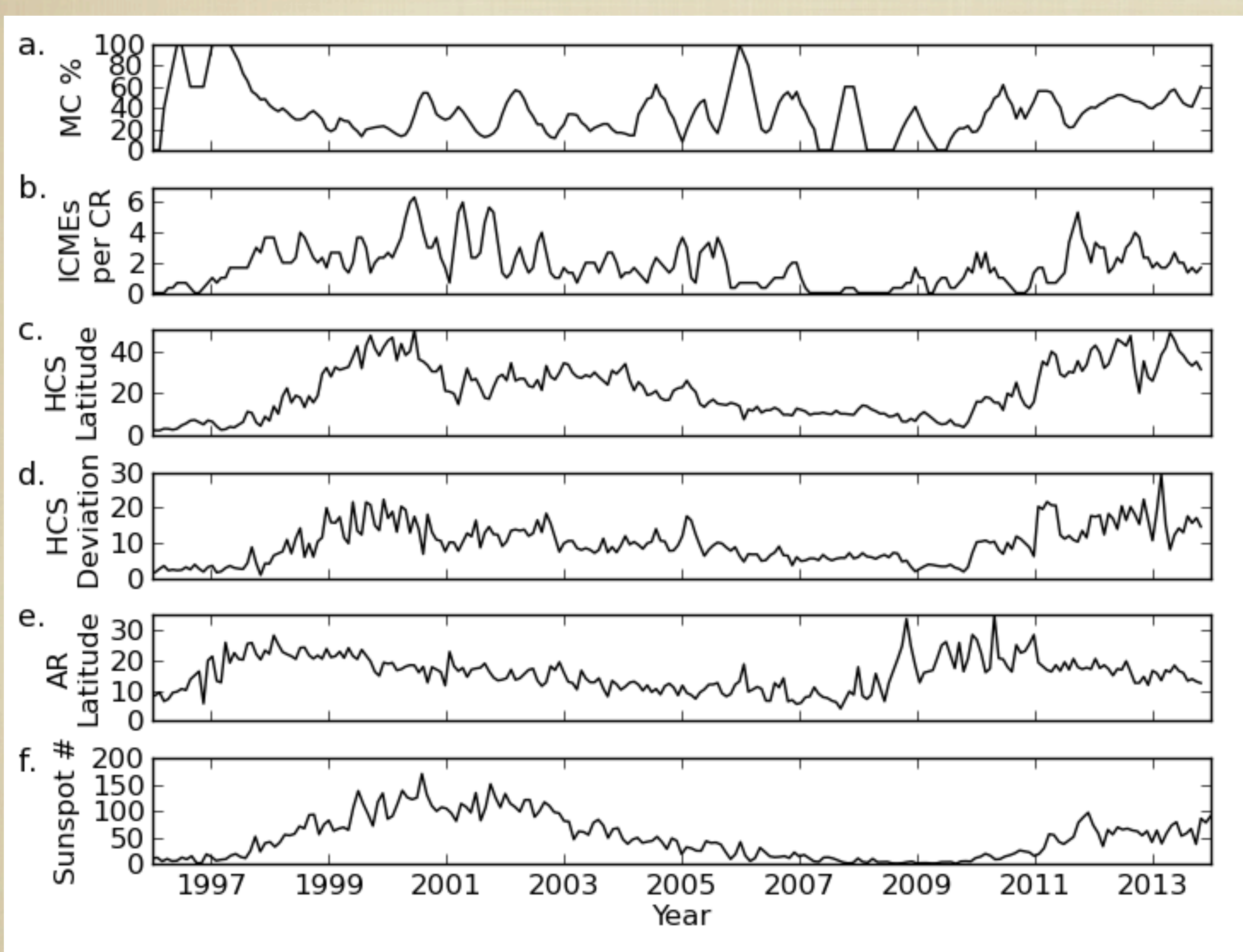

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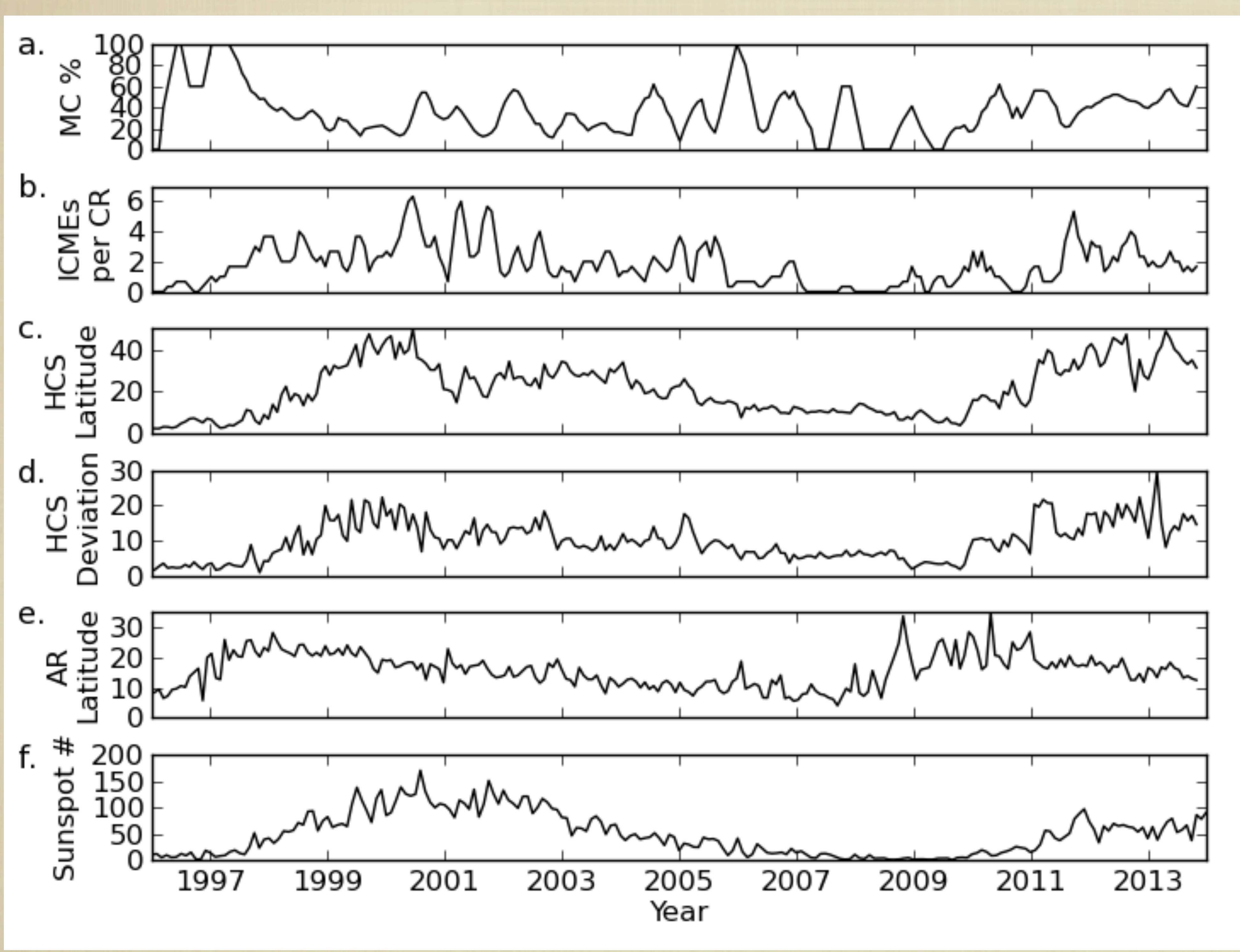

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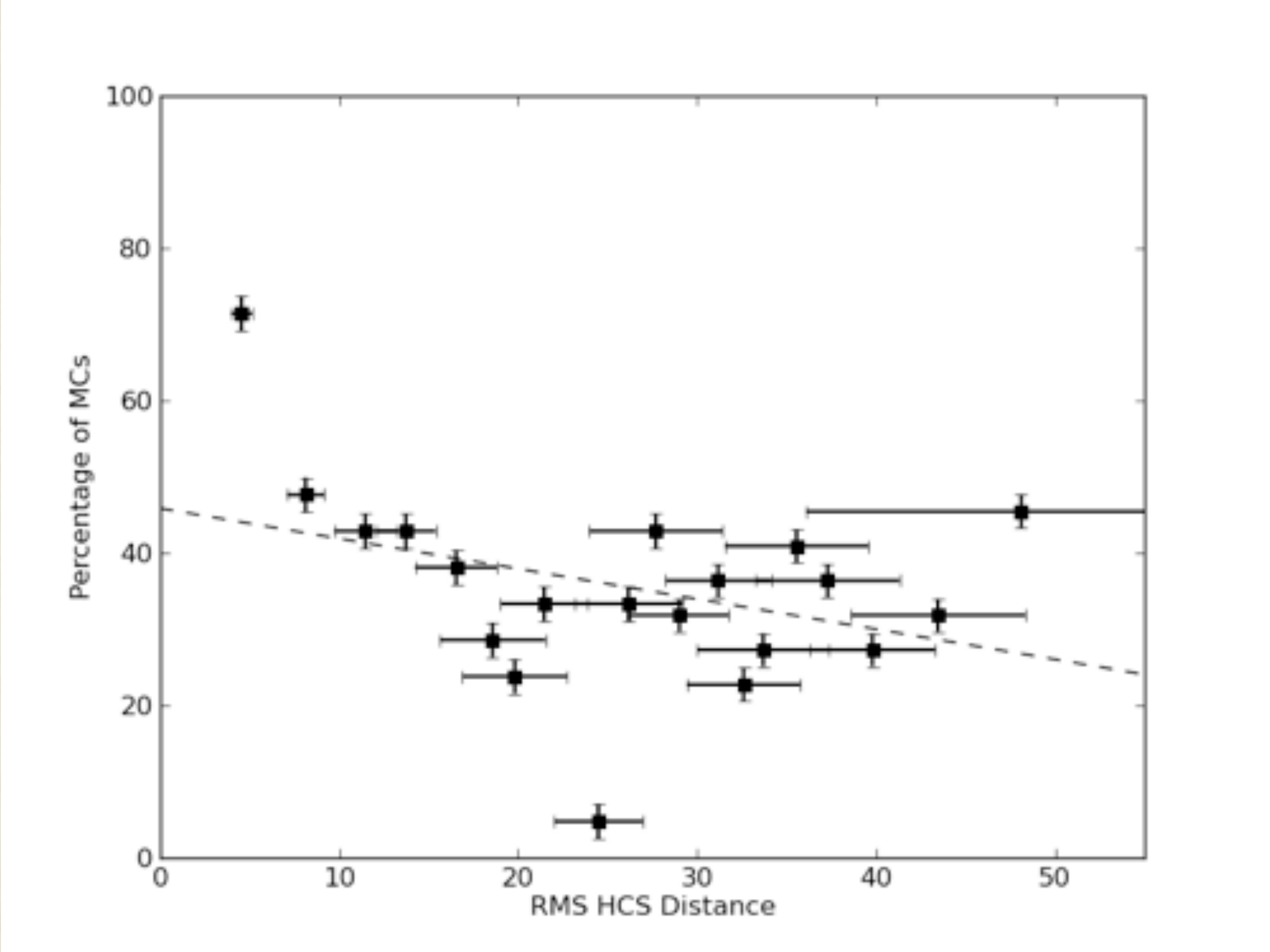
Variation with HCS Distance

- Match ICMEs to a CR and determine HCS distance
- Bin ICMEs by HCS distance and determine MC% for each bin
- Error bars - change in MC% for additional ICME or HCS deviation from rms value
- No trend for large distances (>25°)



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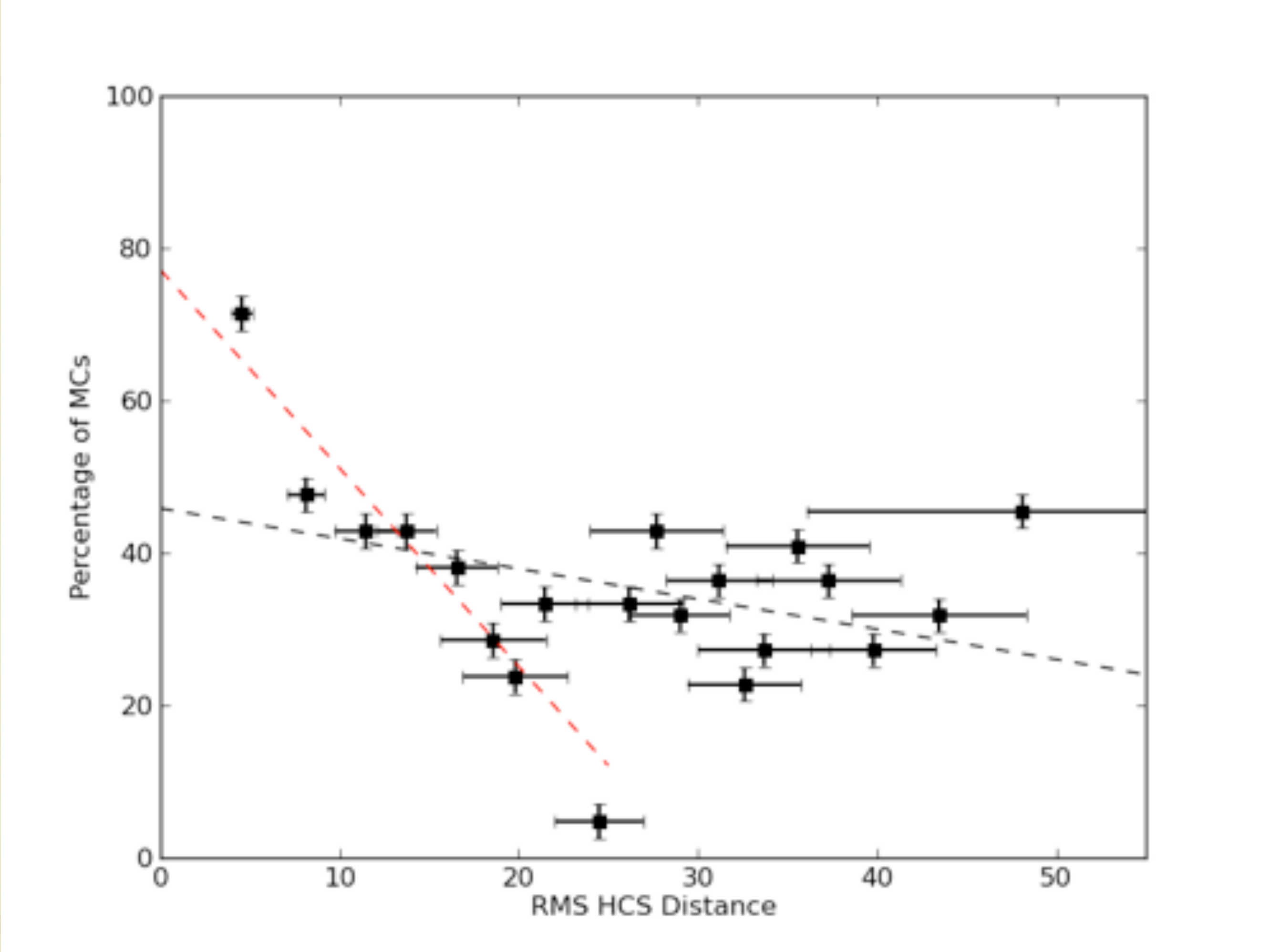
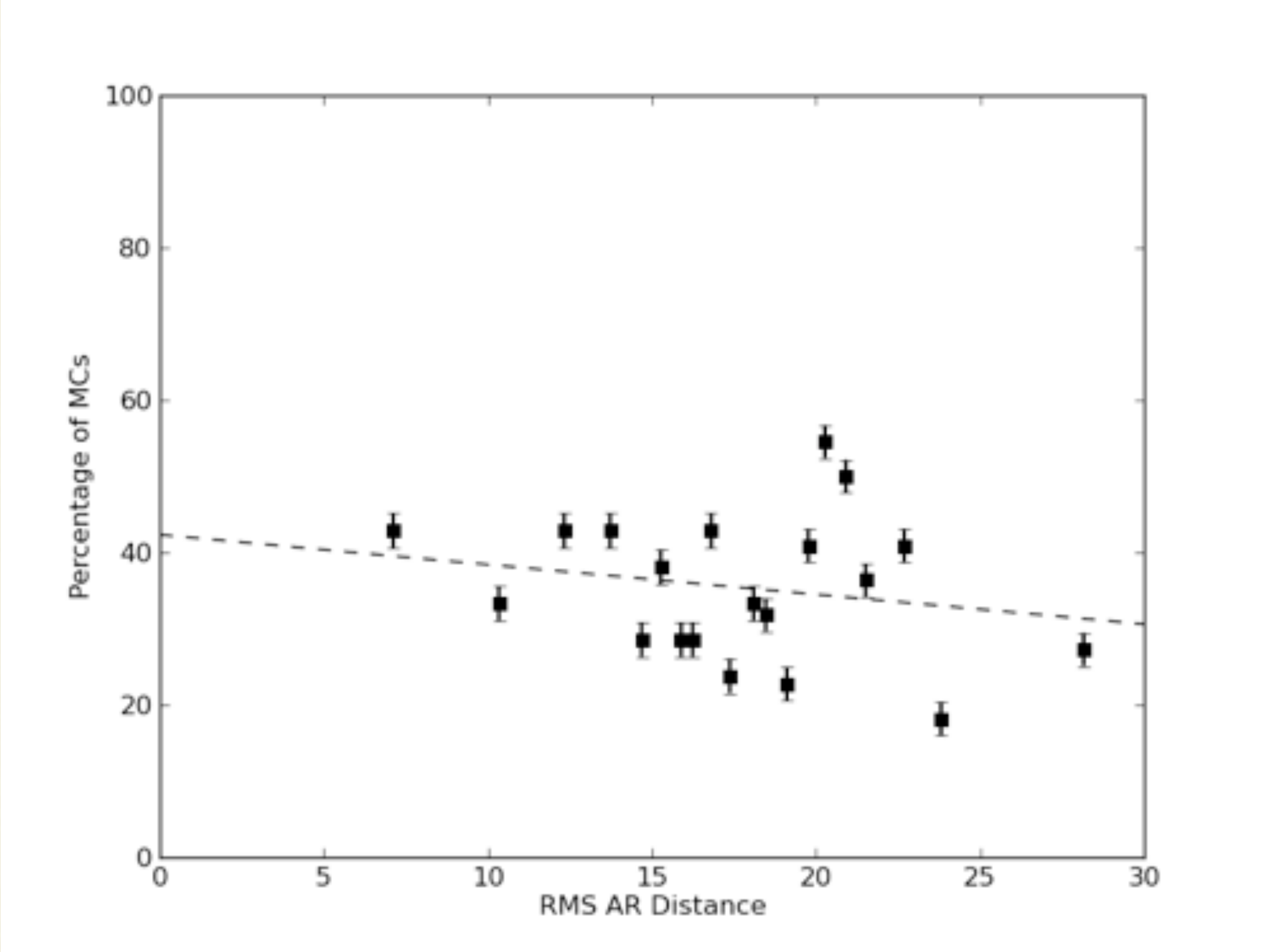


Variation with Source Latitude

- Find same lack of trend as seen in previous works



Correlations + P-values

- Look at Pearson correlation coefficients and the associated confidence levels
- Expect slower CMEs to deflect more
- See strongest correlations for slow CMEs (<500 km/s) with small HCS distances (<25°)

Reject null hypothesis at 99% confidence

	99%
Full	✓
<25°	✓✓✓
≥25°	x

Factors Affecting Correlation

- CME-CME interations (lugaz & Farrugia 2014)
- Reconnection within CME (Fermo+ 2014, in review)
- Reconnection with solar wind (Ruffenach+ 2012, Lavraud+ 2014)

- Used global CR values - distances may vary significantly for individual cases
- Not accounting for longitudinal effects

Conclusions

- If all CMEs contain a flux rope and CMEs tend to deflect toward the HCS then the MC% should vary with the distance between the Earth and the HCS
  - Deflection alone can explain the general solar cycle trend in the percentage of MCs
- The MC% shows much stronger correlation with the HCS-Earth distance than the source-Earth distance
- See strongest correlation near solar min when uncertainties are also smallest

solar Cycles 23 and 24

- MC% variations obvious during min of SC23 but trend not clear elsewhere
- Similar behavior in HCS latitude but do have weaker magnetic field → weaker deflection forces

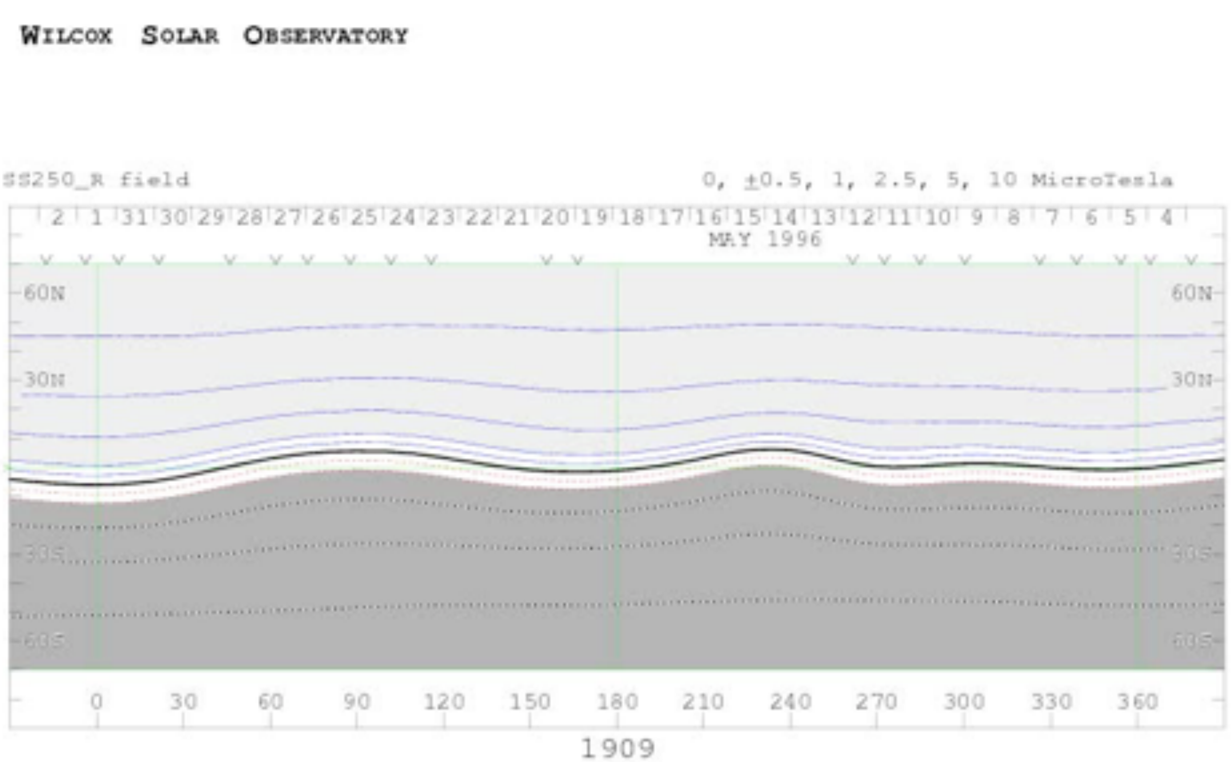
Solar Cycle 23

Solar Cycle 24

SOLAR CYCLES 23 AND 24

- MC% VARIATIONS OBVIOUS DURING MIN OF SC23 BUT TREND NOT CLEAR ELSEWHERE
- SIMILAR BEHAVIOR IN HCS LATITUDE BUT DO HAVE WEAKER MAGNETIC FIELD → WEAKER DEFLECTION FORCES

SOLAR CYCLE 23



SOLAR CYCLE 24