Coronal Mass Ejection Rates over 4 Solar Cycles

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OUTLINE

Coronal Mass Ejections (CMEs) are an important aspect of solar activity and space weather.

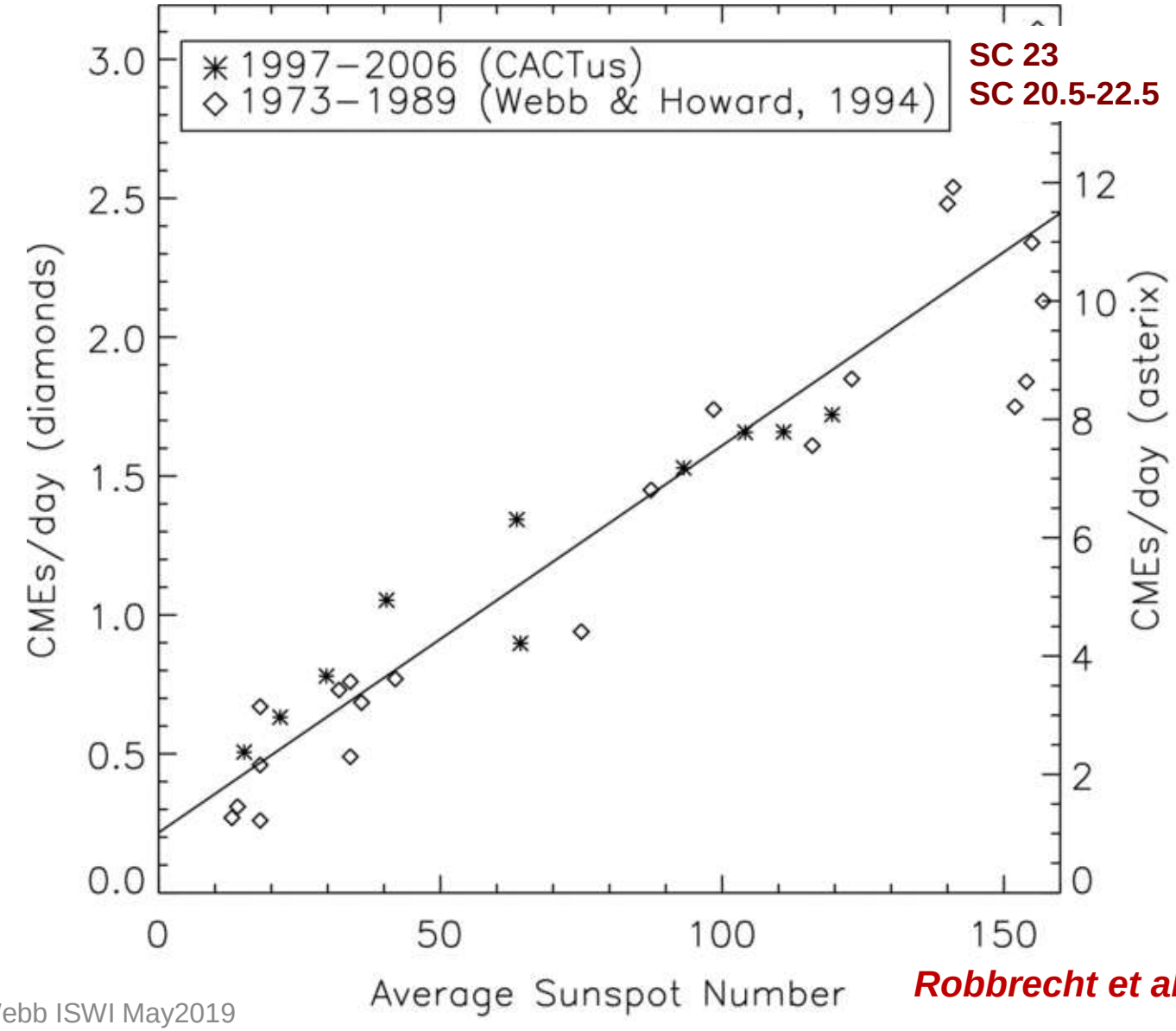
(A) Observations of CMEs now extend over last 4 solar cycles:

- ***LASCO observed entire SC 23 and most of current SC 24.***
- ***New: g-b Mauna Loa Mk CME counts to fill "coronagraph gap" in rates: 1989-1996.***
- ***Now: CME rates from both LASCO & STEREO coronagraphs since 2007 & in heliosphere since 2003 from SMEI and the SECCHI HIs.***
- ***Have rates from both visual observer counts ("manual") and "automatic" programs → SEEDS, CACTus, CORIMP, ARTEMIS.***
- ***However, there is a large spread in these CME rates.***

- ***In the past, CME rates tracked solar activity - SunSpot Number (SSN).***
- ***But SC 23 had an unusually long decline and flat minimum & CME and SSN rates diverged in SC 24.***

(B) Determination of a basal rate of CMEs at SC minima.

(A) Annual CME & SSN Rates Well Correlated (r~0.9) in SCs 21-23

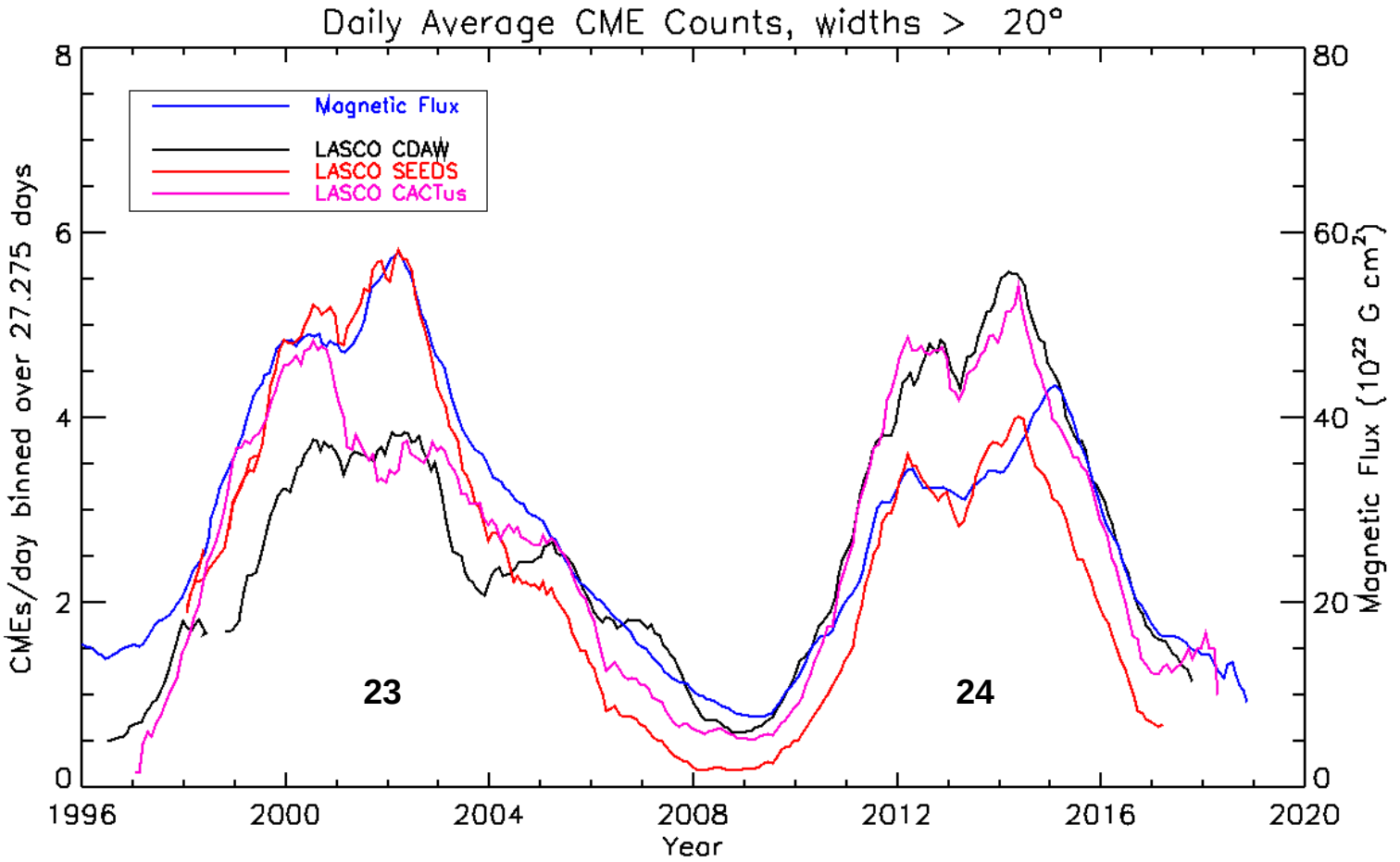


Robbrecht et al., ApJ (2009)

CME CME-SSN Correlations & Selection Effects

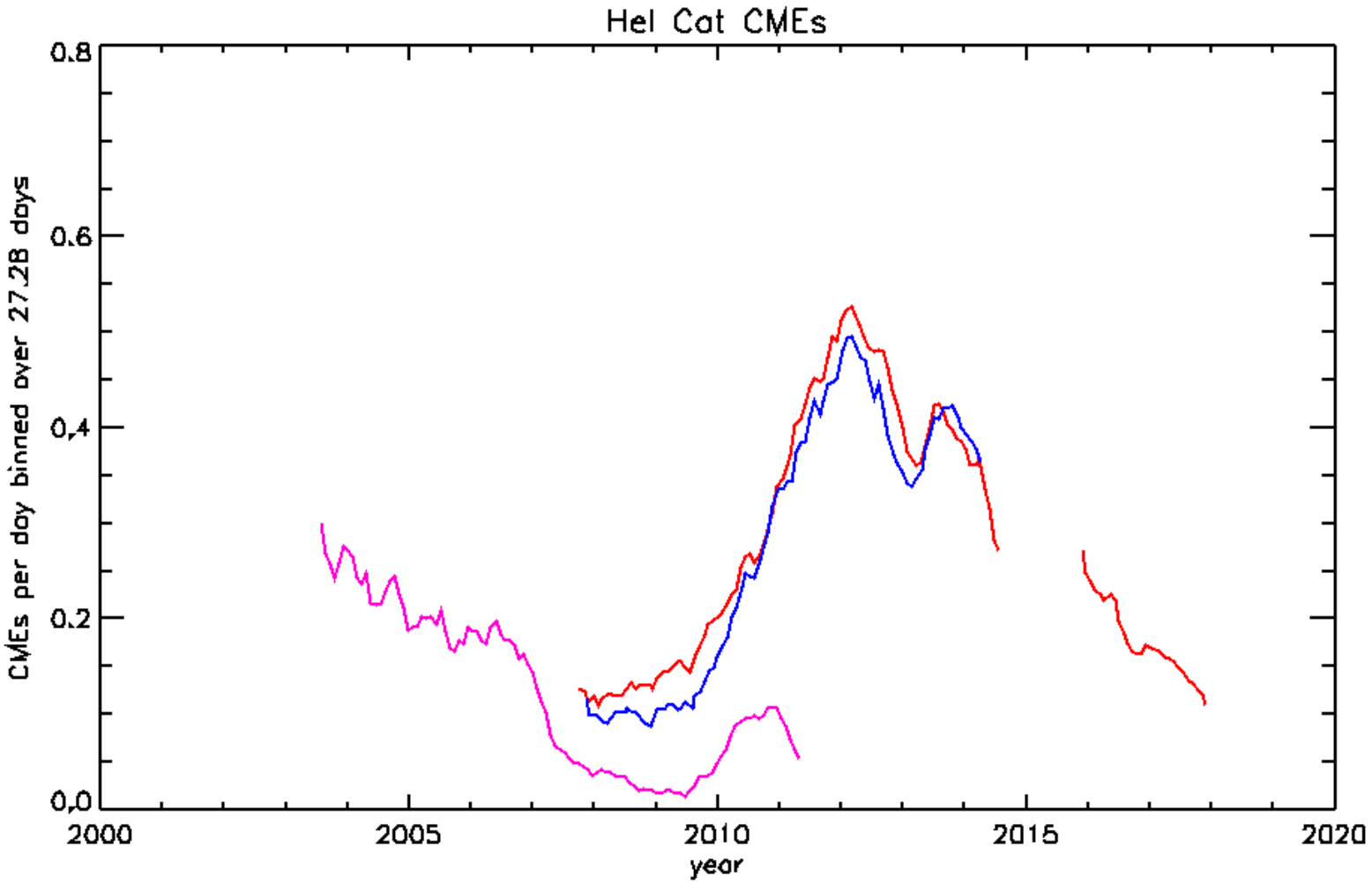
- **In the past occurrence rate of CMEs observed in white light tracked SC in both phase & amplitude.**
  - *CME and SSN rates diverged late in SC 23 & in SC 24 → similar CME rates but lower SSN rates.*
  - *First noted by Luhmann et al. (2011) & Petrie (ApJ, 2013) → suggested divergence related to weak solar polar mag fields during the extended SC 23/24 min. & SC 24.*
- **Selection Effects in CME Catalogs**
  - *Typically, CMEs identified & classified in coronagraph data by visual inspection → "manual" CME catalogs. Inherently subjective & depend on instrument char.*
  - *Recently augmented by "automatic" catalogs of CMEs. Auto methods more objective, but results inconsistent with each other & with manual catalogs.*
  - *Wang & Colaninno (ApJL, 2014) → eliminating so-called "very poor events" from (CDAW) LASCO catalog results in lower CME rates, esp. since 2005 & better CC.*
  - *Others suggest eliminating "narrow" CMEs has same effect.*
  - *Wang & Colaninno also → an increase in the LASCO data cadence since 2010 caused an increase in the auto catalogs CME rate!*
- **In this study we exclude all CMEs with widths < 20° when using CME catalogs.**
  - *Also our CME rate data corrected for periods of missing data & smoothed, & we use total magnetic flux, not SSN to track solar activity.*

LASCO CME-MF Rates, SC 23-24



- **Smoothed plots of LASCO CME and total solar magnetic flux from Wilcox Solar Obs. for SCs 23 & 24.**
  - **Similar CME rates but lower MF rate.**
  - ***(The SSN & total fluxes are similar so SSN is a good proxy for total flux.)***
- **Large spread of manual (CDAW) and auto (SEEDS and CACTus) CME rates during maxima.**
- **There is significant magnetic flux at cycle *minima*.**

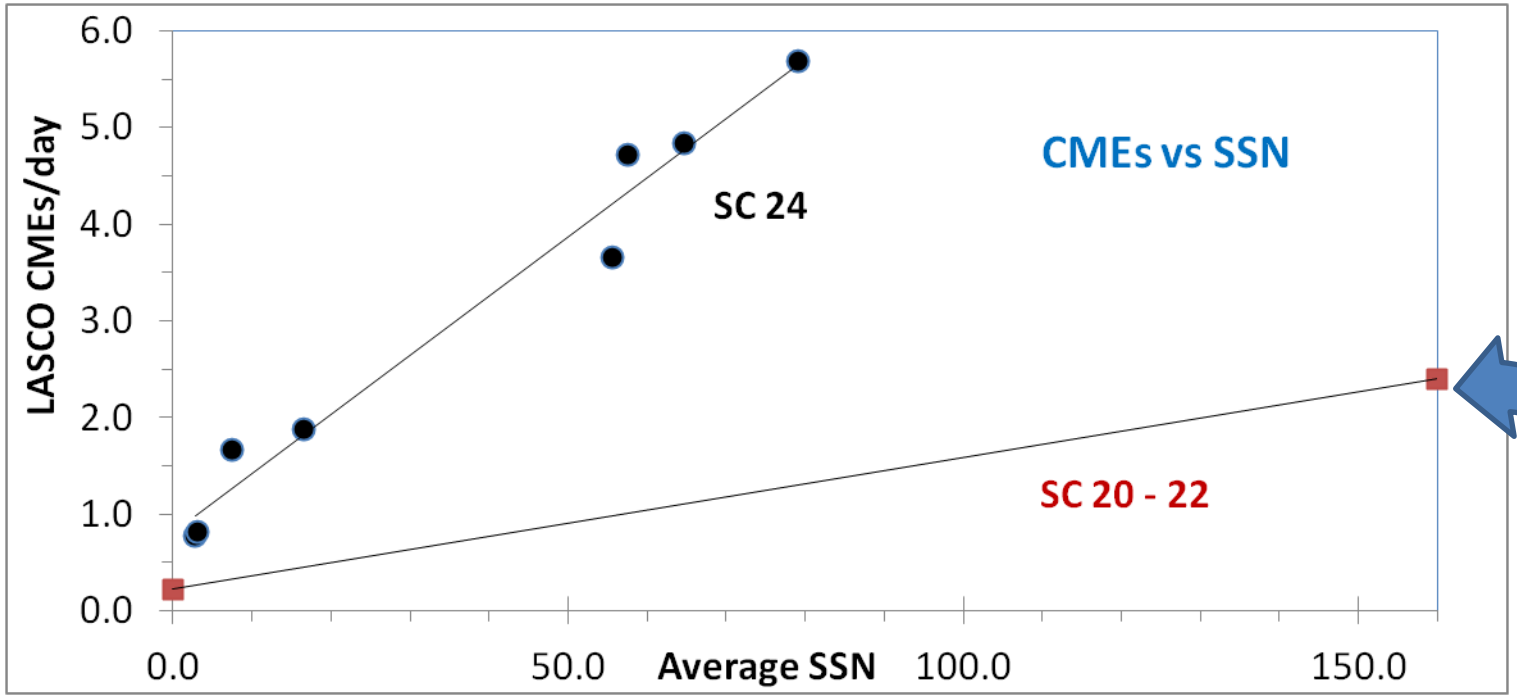
Heliospheric CME Rates



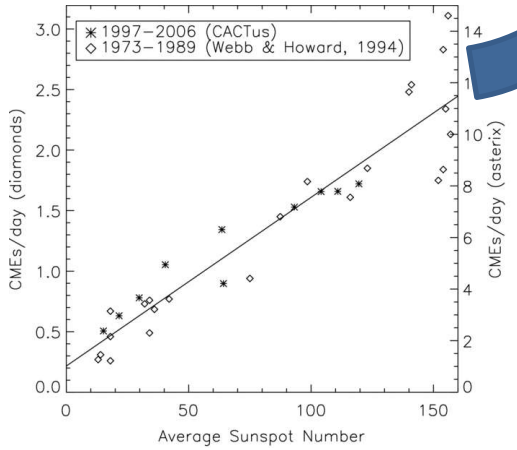
Monthly count rates of heliospheric CMEs from STEREO HI-A (2007-present), HI-B (2007-2014), and SMEI (2003-2011). The heliospheric CME rate is lower than near the Sun, but the SC trend is similar and tracks solar activity.

(HI-A CME counts courtesy EU FP7 HELCATS project)

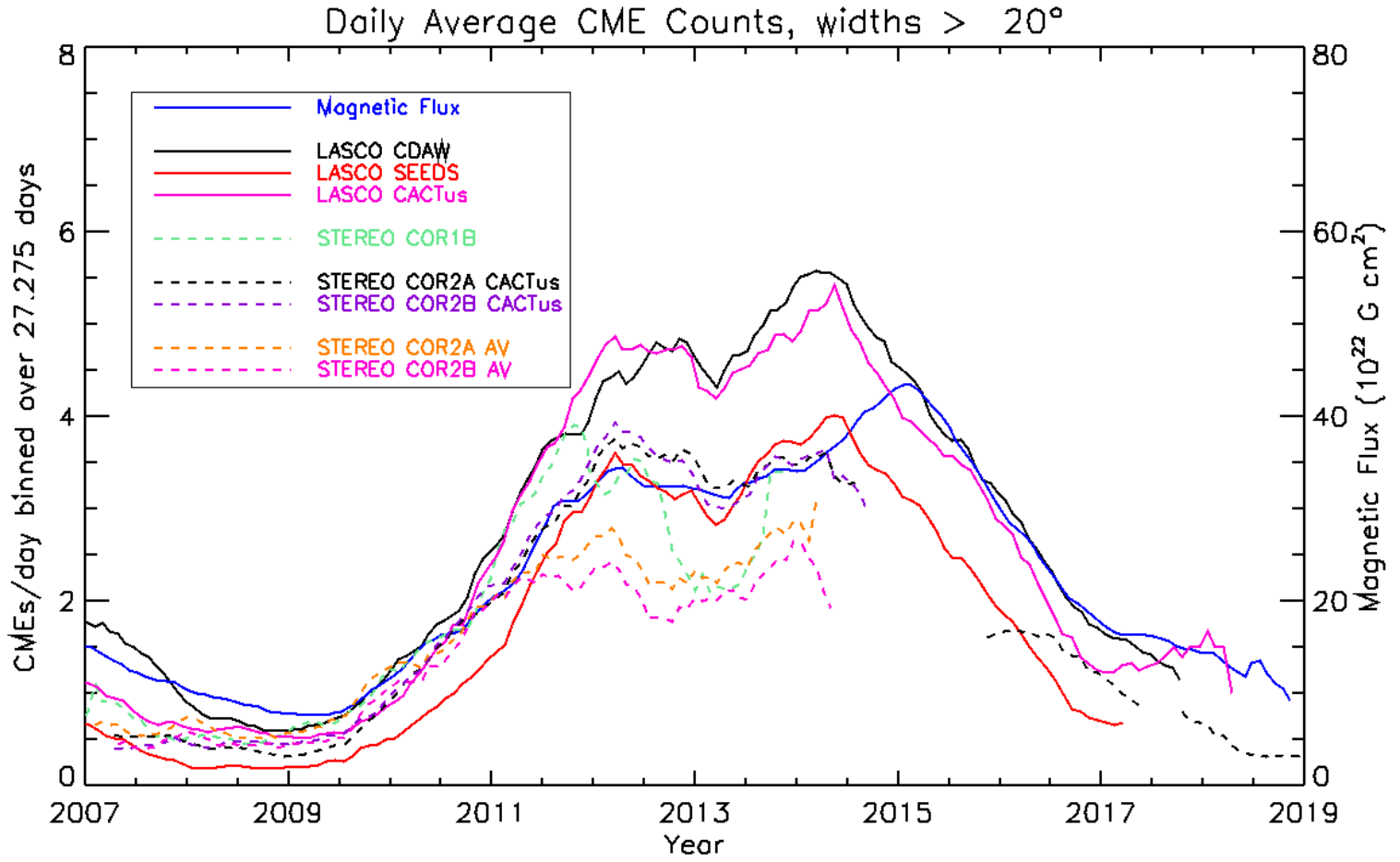
Annual CME-SSN SC 24: Steeper Slope



- **Comparison plot of LASCO CME vs SSN rates compared to previous rates from *Webb & Howard (JGR, 1994)* & *Robbrecht et al. (ApJ, 2009)*.**
- **Indeed the slope is steeper → more CMEs per unit SSN this cycle. Also evidence of weakening of solar activity tracers in general.**

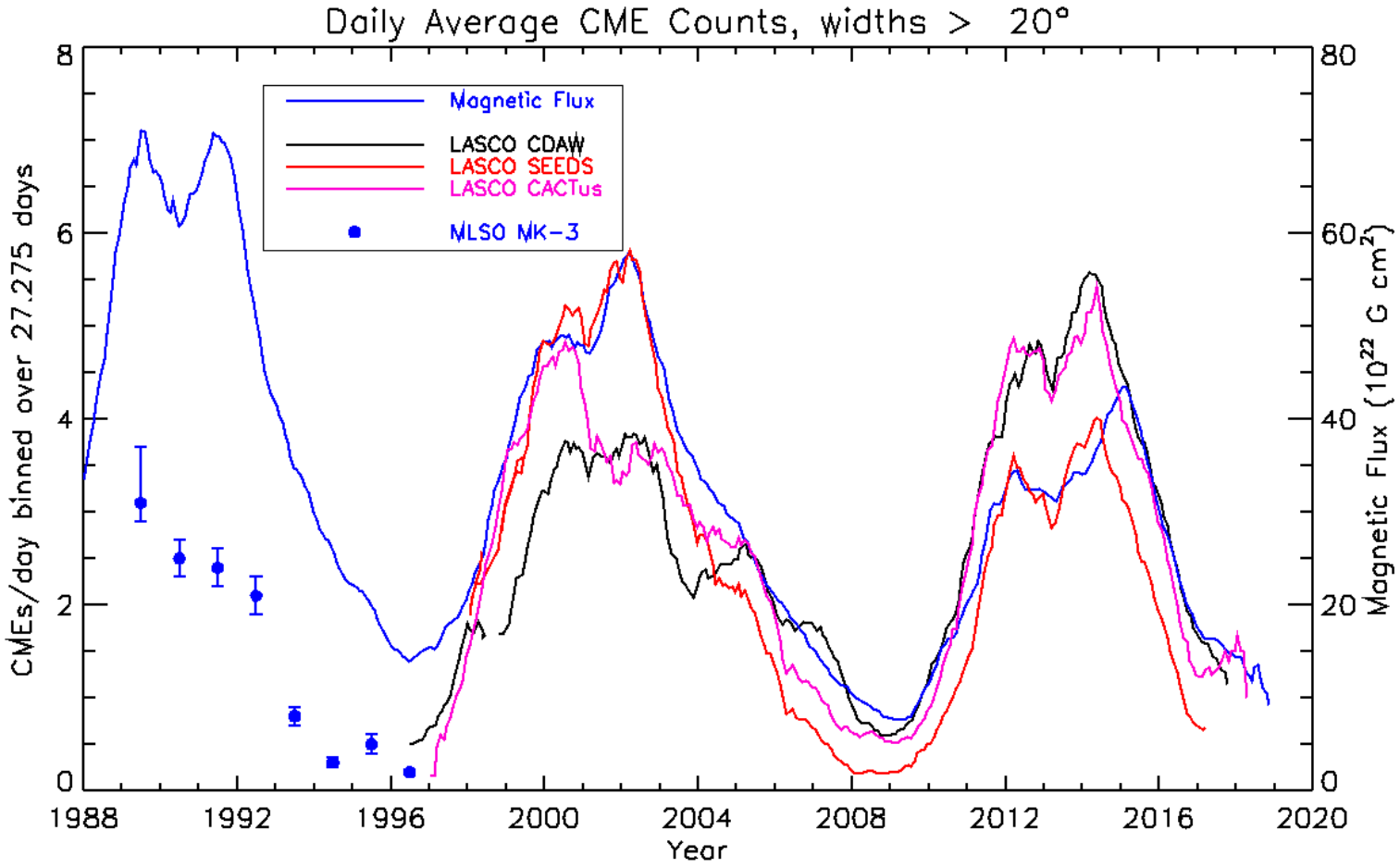


CME-MF Rates: SC 23-24 Min. → SC 24



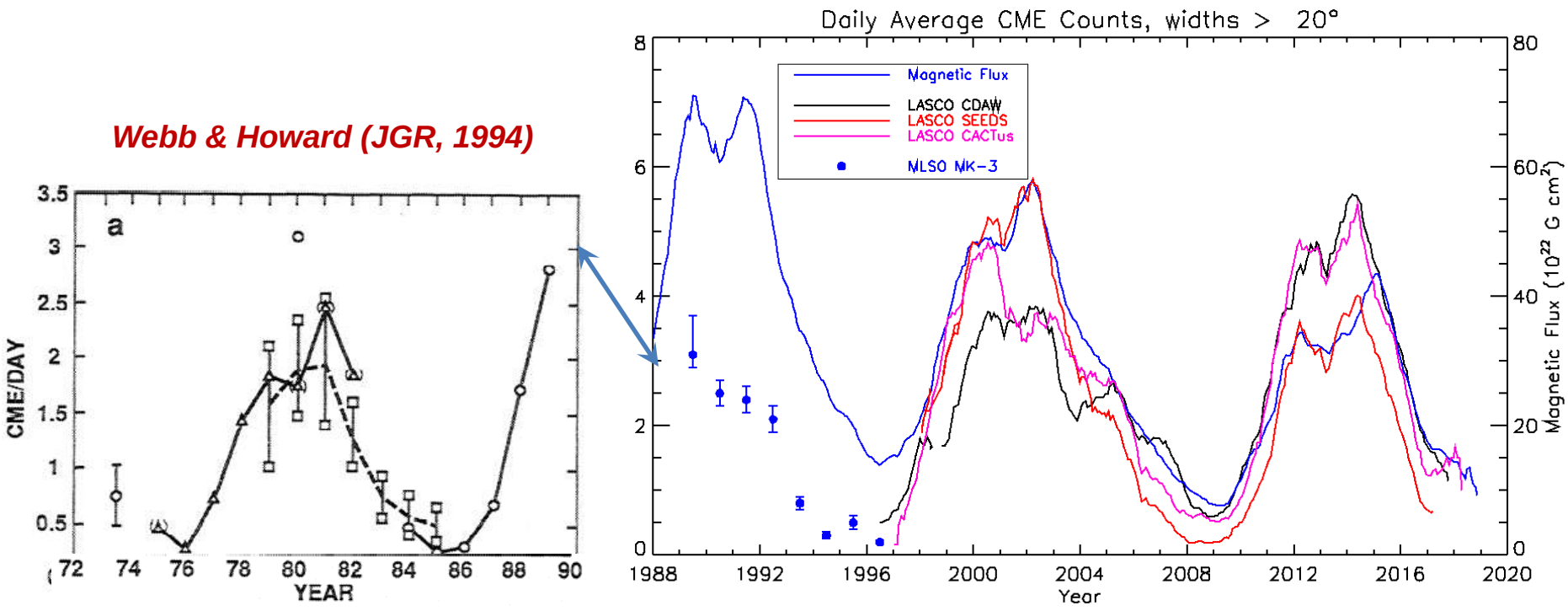
- **2007 → present. Manual & automatic CME rates from LASCO & STEREO coronagraphs provide *8 independent measurements*. LASCO → solid lines; STEREO → dashed lines.**
- **STEREOs in solar conjunction after late 2014. ST-A recovered, ST-B lost!**
- **Note SC 24 has double peaks; both CME and MF higher in 2nd peak in 2014.**
- **CME rates track MF during decline.**

CME-MF Rates: SC 22-24



- **To LASCO plot we add preliminary CME rates for 1989-1996 during SC 22 from ground-based MLSO MK-3 K-coronameter *(St. Cyr et al., SP 2015)*.**
- **Allows us to bridge gap in CME *coronagraph* observations. MK instruments help to "calibrate" CME rates from different telescopes over different SCs.**

CME Rates: Add SC 21 from Webb & Howard *(1994)*



- **Good match between Webb & Howard SC 21 and current SC 22-24 CME rates:**
  - **SMM & Mk-3 rates similar in 1989**
  - **But different telescope rates need to be normalized**
- **Note double peaks in CME and MF rates. CME peaks lag MF peaks by months to ~ 1 year. Lag related to two main sources of CMEs: Emerging flux & ARs (SSN) & Polar Crown filaments → move poleward and erupt around time of polarity reversal**

SC Max-Min CME-SSN/MF Rates

SC No.	Year	CME Rate (CMEs/day)	SSN Rate[6]	Total Mag. Flux (10^{22} Mx)
Minimum (Webb et al., 2017)				
20/21	1976	0.3	18	17
21/22	1986	0.3	16	20
22/23	1996	0.7; 0.8[1]	11	14
23/24	2009	0.5; 0.7[2]	2	8
Maximum (work in progress)				
21	1979-80	2.5	231	66
22	1989-90	(3.5)[3]	206	66
23	2001-02	4.4[4]	182	58
24	2014	3.8[5]	117	36 [44]

[1] = LASCO C2 - St. Cyr et al. (2000); S. Yashiro (2019, p.c.)
[2] = Avg COR-2A & 2B; LASCO C2 (S. Yashiro, 2019, p.c.)
[3] = SMM max value under review
[4] = Avg of 3 LASCO meas.
[5] = Avg of 8 meas. *excluding* COR2 SEEDS
[6] = Avg monthly SSN *(V2; SILSO, ROB, Belgium)*

"Visibility" Corrections

• **CME rates must be corrected (normalized) for each instrument's "visibility function" to make meaningful comparisons of CME rates bet. SCs.**

• **VF includes the detection threshold for events in the skyplane and detectability of CMEs away from this plane.**

- Webb & Howard, JGR (1994); St. Cyr et al., JGR (2000)

• **The sensitivity or dynamic range of LASCO & STEREO CCD detectors orders of magnitude improved over older coronagraph detectors.**

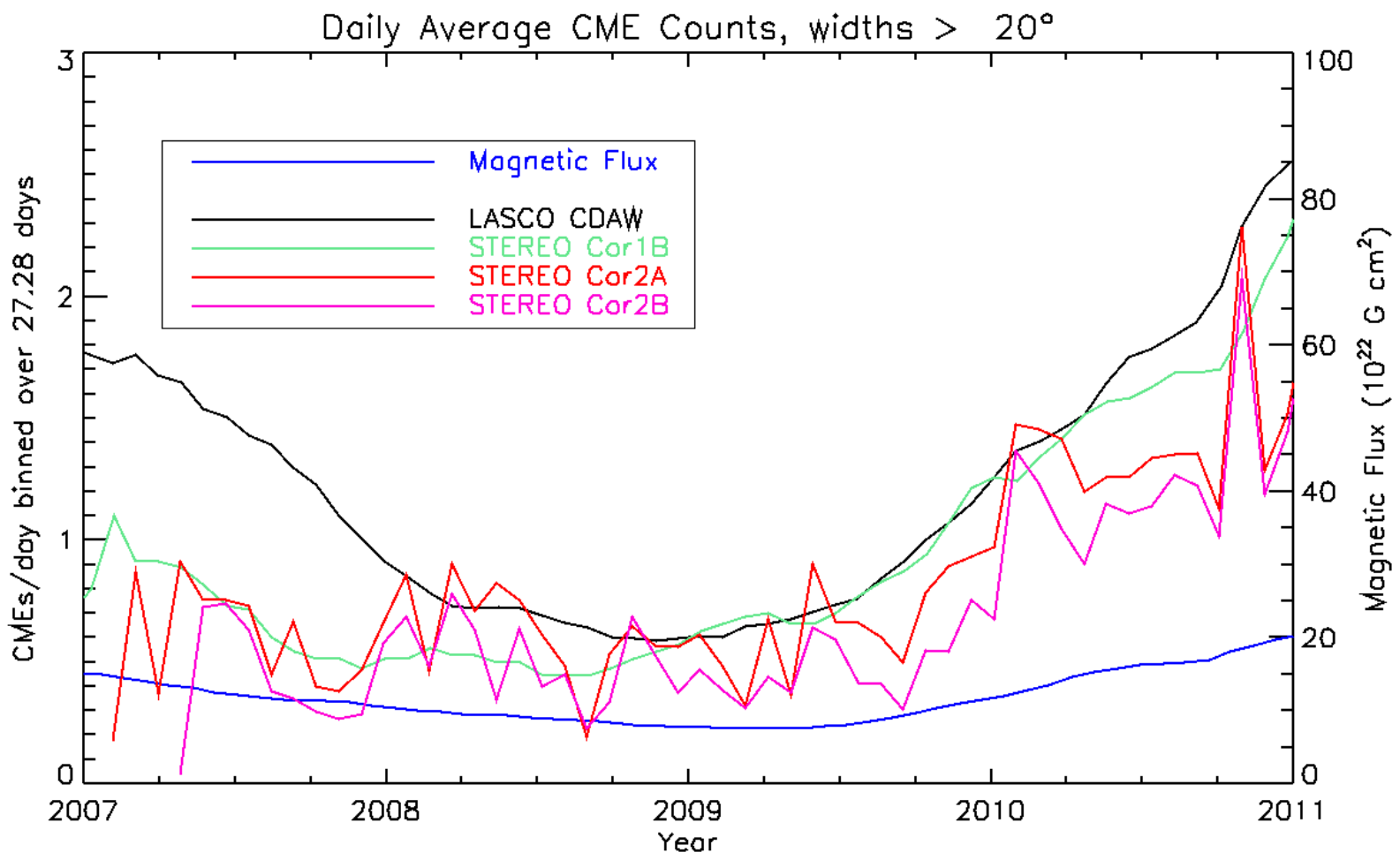
- ***Several studies suggest that LASCO detects ~95% of all CMEs***
- ***"True" coronagraph rate → Comparing LASCO & STEREO CME rates when aligned in 2007 and during quadrature in 2010-2011***
- ***Careful consideration of the VF correction is needed for the g-b MK data because its viewing background includes both sky and coronal brightness***

• **We are evaluating these issues of sensitivity and VF to determine a comprehensive CME rate over the last 4 SCs.**

(B) Is There a Basal Rate of CMEs at Solar Cycle Minima?

- **With recent prolonged minimum question is whether there is a base level of solar magnetism that yields a "floor" in activity levels.**
  - ***Schrijver et al. (GRL 2011)* argued the recent minimum approached extreme levels of the Maunder Minimum.**
  - ***Suggest a base level of solar mag. activity in form of small bipolar regions that maintain a floor in magnetic activity.***
  - ***Other researchers → this solar base level yields a floor in the solar wind IMF caused by either slow solar wind (Cliver et al.) or base level of CME activity (Owens et al.).***
- **We asked question: Is there a basal rate or floor in the CME rate?**
  - ***To address this we determined & compared annual averages of CME rates during last 4 SC minima with several tracers of global mag. field.***
  - ***We conclude (Webb, Howard, St. Cyr & Vourlidas, ApJ 2017) → typical basal rate of 1 CME every ~1.5 to 3 days during the last 4 minima.***
  - ***Modeling and simulations suggest that, under assumption that CME rate $\propto$ the total magnetic flux, the basal CME rate is true activity floor extending back to MM.***

CME Rates – SC 23-24 Minimum



- **One-year average time of SSN minimum was 2008.5 - 2009.5.**
- **CME and SSN/MF rates track well. Avg CME rate is 0.5/day (ST. CORs) – 0.7/day (LASCO).**

Data Rates at SC Minima

SC No.	Year	CME Rate (CMEs/day)
20/21	1976	0.3
21/22	1986	0.3
22/23	1996	0.7; 0.8
23/24	2009	0.5; 0.7

- **From our previous table → basal rate of 1 CME every ~1.5 to 3 days during the last 4 minima.**

  - The VF-corrected CME rates in 1976 and 1986 are similar to each other & the rates in 1996 and 2009 are also similar to each other.

  - But the recent rates are ~ twice those in 1976 and 1986. Those rates (Webb and Howard, 1994) required large correction factors.

  - The more recent higher rates also likely reflect the superior performances of LASCO and STEREO coronagraphs which require only small corrections.

CME Sources at SC Minima

- **Large-scale coronal activity at solar minima → gradual reconfigurations of streamer structures that characterize the flattened HCS.**

  - Many involve CMEs that disrupt or completely blowout pre-existing streamer.

- **Source regions of streamers and associated CMEs at minima lie along global polarity inversion line (PIL) that is the base of the HCS.**

  - Usually has a minimal tilt of ~20° about the solar equator.

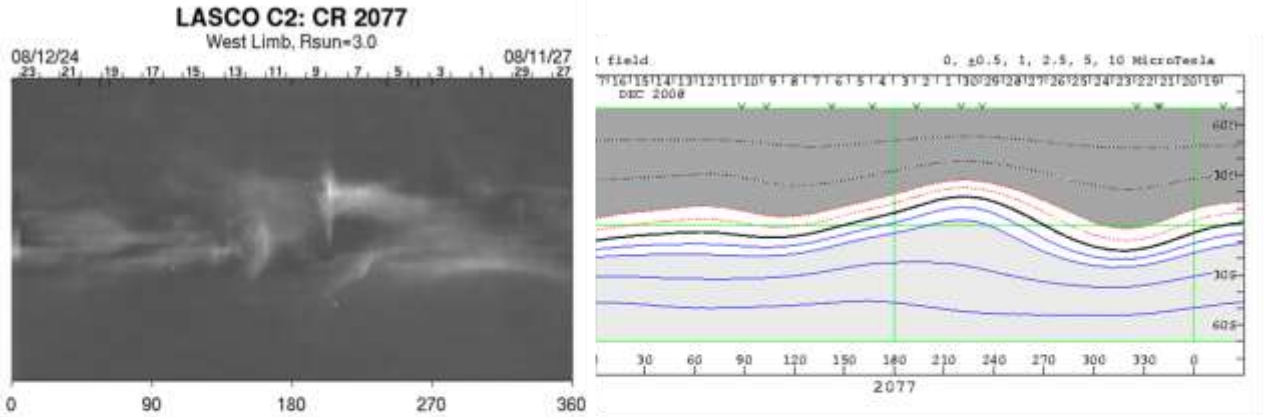
  - Some streamer-disruption CMEs assoc. with prominence eruptions, ~2 per month.

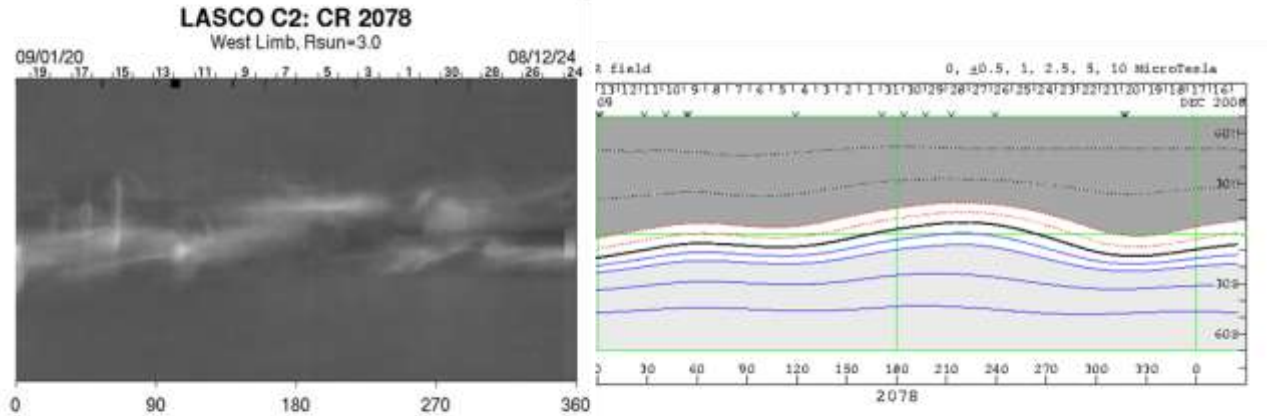
  - Not unexpected as prominences typically assoc. with CMEs throughout cycle & lie along PILs.

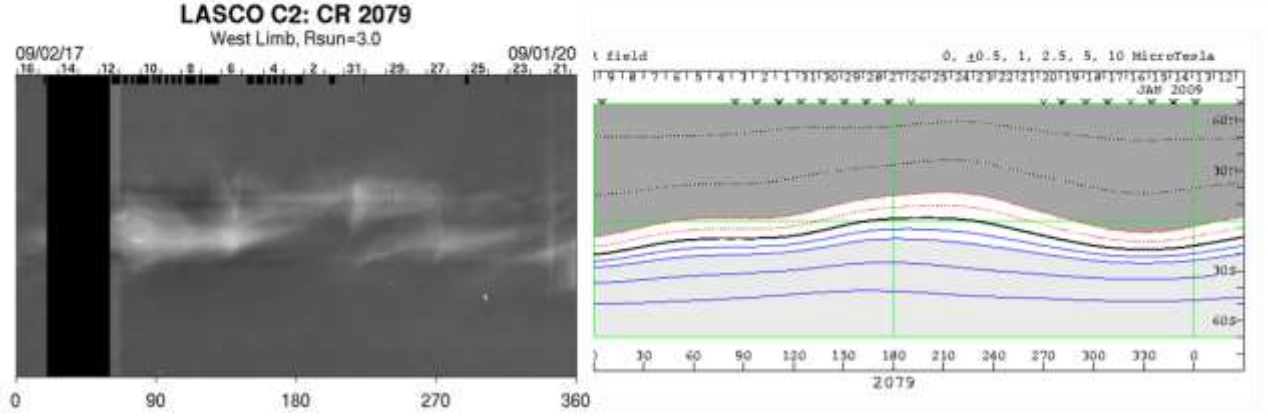
- **Not surprisingly, given the lack of sunspots around activity minima, very few CMEs assoc. with sunspots-active regions**

  - Supports our current understanding that CMEs arise from large-scale, closed-field magnetic regions, NOT small-scale structures.

LASCO & WSO synoptic maps – SC 23-24 min. in 2008-09







Models of Coronal Magnetic Field Evolution

- **Early models used potential-field extrapolations:**

  - First approx. of Sun's open flux & coupled to heliospheric models like WSA.
  - But allow no free energy or currents, so underestimate total flux.

- **Global MHD models have advanced & even account for plasma thermodynamics.**

  - But they depend on potential-field extrapolations & can't simulate long-term evolution.

- ***Schrijver et al. (GRL 2011)* used a flux-transport model *(Schrijver et al., ApJ 2002)* to estimate the total surface magnetic flux back to the 1600s.**

  - Their total magnetic flux est. in 2008-2009 agrees with ours & they suggest this is lowest SC minimum flux since Maunder Minimum.

- **Improving models difficult because of complex magnetic topology. *Van Ballegooijen, Mackay, Yeates* group developed pragmatic approach using nonlinear, force-free models of local structures → initialized with a flux-rope structure in corona.**

  - Yeates (2014) used this model to simulate continuous mag.-field evolution in global solar corona over 15 years; 1996-2012.
  - Model allows for buildup & transport of free mag. energy, electric currents, and mag. helicity.
  - Helicity tends to concentrate in FR structures overlying PILs. When too much helicity accumulates, the FRs "erupt" & are ejected out of simulation domain.

- **Large-scale coronal activity at SC minima appears as gradual reconfigurations (& CMEs) of streamer structures that characterize the flattened HCS.**

  - Likely related to min. threshold for magnetic energy dissipation or ejection of mag. helicity.

Flux Transport w/ Magneto-Friction Model and CME Rates

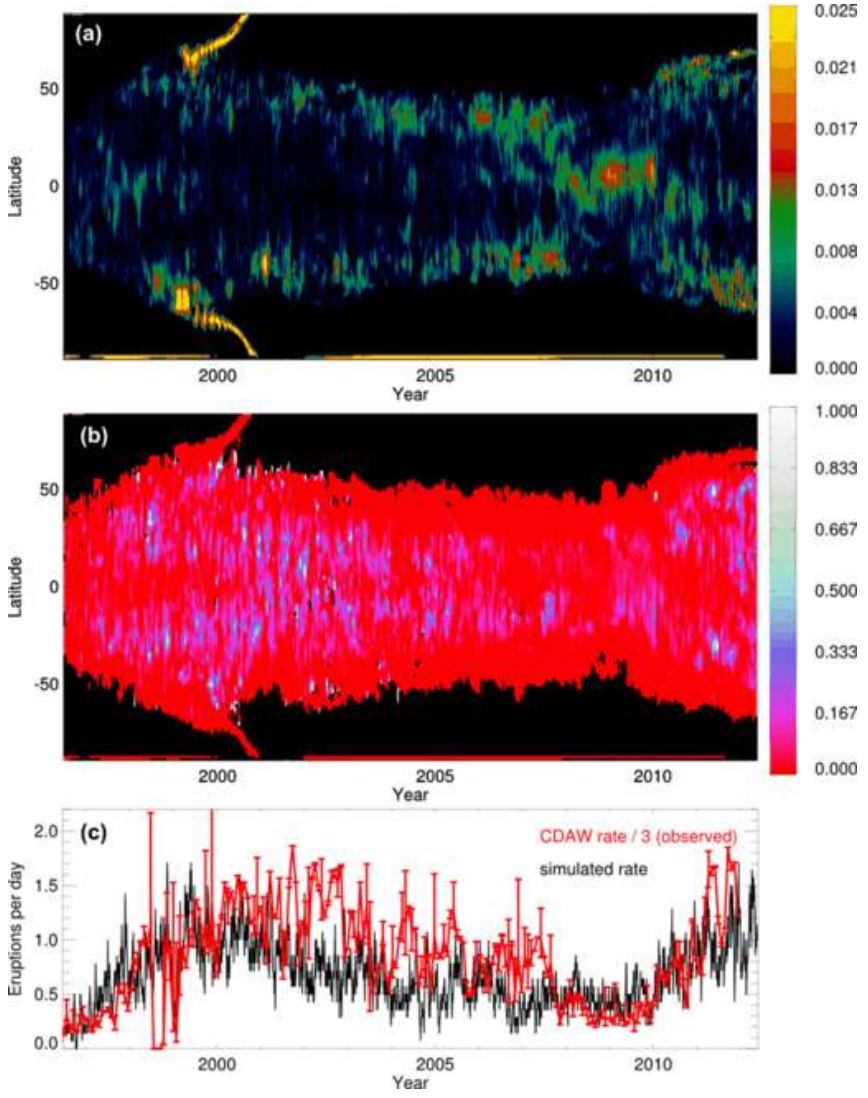
Resulting modeled Flux Rope distributions:

- Latitude–time distributions of:
(a) flux ropes and
(b) FR eruptions

- (c) *Yeates (2014)* FR eruptions (black) vs LASCO CDAW CME rates / 3 (red).

- These simulation results are in remarkable agreement with overall shape of LASCO CME rate distribution.

- Rates similar to actual CME rates at last 2 minima and support idea of a base level of activity.



CONCLUSIONS

- **CMEs are an important aspect of solar activity and space weather.**
- **Into SC 23 CME rate continued to track SSN/MF in both phase & amplitude:**
  - ***Late SC 23 & SC 24 rates diverged → more CMEs per unit SSN.***
  - ***Related to weak polar magnetic fields during extended SC 23/24 minimum.***
  - ***Correlation of CME and SSN/MF rates varies over different SC phases → likely because there are two solar sources of CMEs.***
- **Observations of CMEs now extend over ~ 4 SCs:**
  - ***MLSO observations used to fill "coronagraph gap" from 1989-1996.***
  - ***Have CME rates for 4 SC minima (0.3 - 0.8/day) and maxima (2.5 - 4.7/day).***
  - ***LASCO & STEREO SC 23/24 rates higher than earlier coronagraphs due to increased sensitivity.***
- **CMEs never cease during a solar cycle but maintain a base level of 1 CME every 1.5 – 3 days at minima.**

Thanks for your attention.

Data Sources & Analyses:

Tom Kuchar; ISR, Boston College
Chris St. Cyr, Hong Xie, Laura Balmaceda, Nat Gopalswamy; NASA GSFC
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