Sun-to-Earth Propagation and Geoeffectiveness of CMEs

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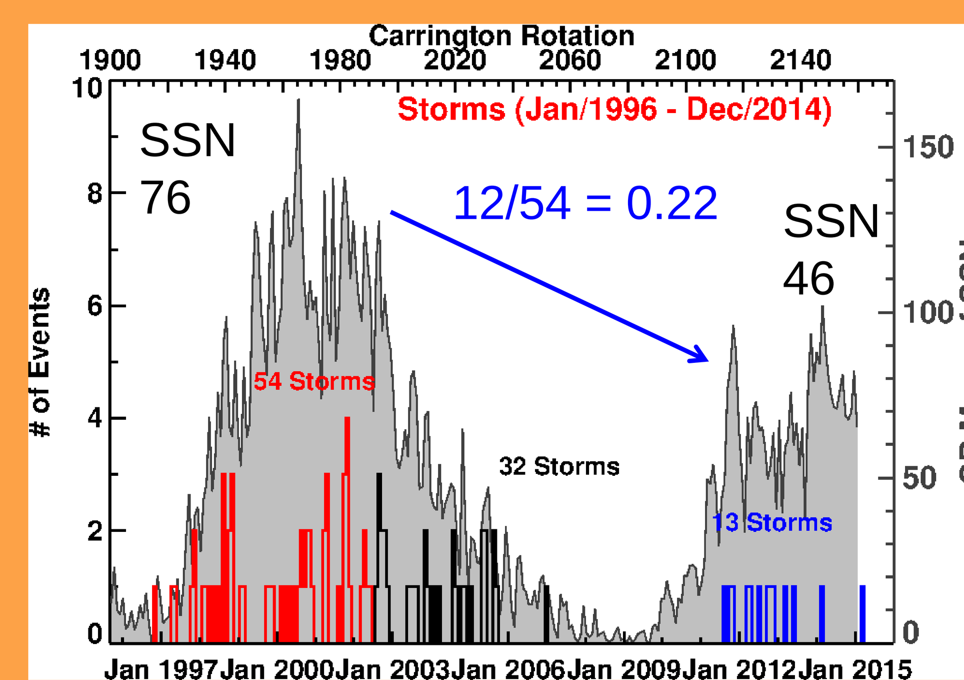
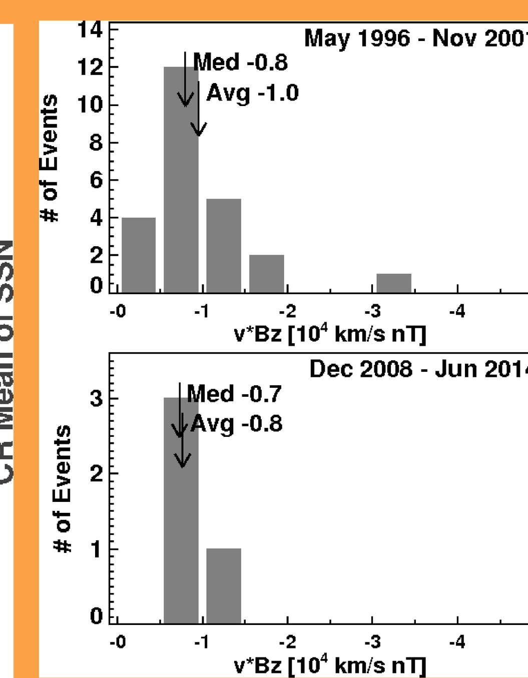
INTRODUCTION

Cycle 24 is the weakest cycle in the Space Age. The average sunspot number (SSN) dropped by 40% relative to SC 23 (76 to 46). However, the fast and wide CME rate dropped by only 25% (3.6/mo to 2.7/mo), while the number of major storms (Dst <-100 nT) dropped by 78% (54 to 12). Clearly, the drop in neither SSN nor CME rate is consistent with the decrease in major storms. Decrease in geoeffectiveness was explained by magnetic dilution of the magnetic content of CMEs (Gopalswamy et al. 2014). This result was based on only a dozen major storms. In order to obtain a statistically significant result, we consider all the magnetic clouds (MCs) of cycle 23 and 24 over corresponding epochs.



SC 23 SC 24



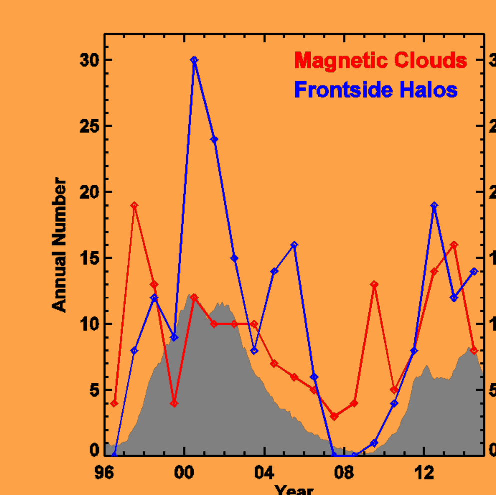
Note the narrow range of the product of ICME speed (V) and southward component of B (Bz). Since $Dst = -0.01VBz-32$ nT (Gopalswamy 2010), small VBz leads to weak storms.

DATA SELECTION & ANALYSIS

- We considered the corresponding epochs in cycles 24 (2008 Dec 1 to 2014 Dec 31) and 23 (1996 May 10 to 2002 June 9). The 73 months covers roughly the rise and maximum phases.
- 65 MCs in SC 24 vs. 68 in SC 23. For comparison, there were
- 267 frontside halos in SC 24 vs. 264 in SC 23
- MC and Halo CME abundances relative to SSN were higher in cycle 24
- Measure MC and sheath properties, derive parameters such as VBz and expansion rate in cycles 23 and 24
- Identify the Dst values corresponding to MCs
- Identify CMEs at the Sun and compare their properties
- Questions:

More non-spot CMEs?
CME expansion makes more CMEs appear as halos?
Smaller CMEs from the disk center arrive at Earth?

	Cycle 23*	Cycle 24	Ratio (24/23)
SSN	76	46	0.61
#MCs	68 (0.89/SSN)	65 (1.41/SSN)	0.96 (1.58)
#Front Halos	264 (0.048/SSN)	267 (0.080/SSN)	1.01 (1.67)



COMPARISON OF MC PROPERTIES

Table (right) compares many MC properties between cycles 24 and 23.
- Some quantities changed; others were invariant

• No significant changes in expansion factor, MC duration, and MC plasma density
• Magnetic content, speed, expansion speed, total pressures declined significantly in SC 24
• The mean Dst in SC 24 was -33 nT compared to -66 in SC 23 → 50% drop
• Confirms the weak geoeffectiveness of MCs in SC 24 and that the drop is primarily due to decrease in VBz
• Dst decrease is slightly more than the VBz decrease. Additional factors determine Dst?
• Annual Variation of V, Bz, VBz, and Dst are quite similar, further reinforcing the close connection between Dst and VBz.
• Smaller size in SC24 due to smaller MC speed: *size* ~ $V_c/2\Delta t$; Δt ~ *const)*
Invariant dimensionless expansion rate (Gulisano et al. 2010):

$\zeta = V_{exp}L/\Delta t V_c^2$

$d\zeta/\zeta = dV_{exp}/V_{exp} - 2dV_c/V_c$

This is approximately satisfied: $d\zeta/\zeta \sim 0$

$dV_{exp}/V_{exp} - 2dV_c/V_c = -0.07$

At $L = 1$ AU, $\Delta t \sim$ constant, so $\zeta \sim V_{exp}/V_c^2 \sim \Delta P_t/V_c^2$. The decrease in total pressure is balanced by the decrease in MC speed

Param[a]	Cycle 23 (n=68)			Cycle 24 (n=65)			R^d	D^e	P^f
	Mean	Conf. Int.[c]	Med	Mean	Conf. Int.[c]	Med			
B_t	16.54	14.87 to 18.20	14.55	12.33	11.23 to 13.43	12.20	0.75	0.3995	0.000
B_z	-10.90	-12.43 to -9.37	-10.35	-7.80	-8.93 to -6.67	-7.50	0.72	0.2710	0.012
$\|B_z\|$	13.33	11.93 to 14.72	11.75	10.23	9.24 to 11.21	9.70	0.77	0.2572	0.020
V	473.9	439.9 to 507.8	445	402.1	384.5 to 419.7	399	0.85	0.2833	0.007
VB_z	-5119	-6098 to -4139	-4362	-3078	-3558 to -2599	-2904	0.60	0.3373	0.001
$\int VB_z$	-2910	-3429 to -2392	-2450	-1853	-2172 to -1535	-1595	0.64	0.2969	0.013
V^b_{exp}	51.0	33.78 to 68.22	42.50	25.28	14.62 to 35.93	25.00	0.50	0.2425	0.033
F_{exp}	1.053	1.038 to 1.068	1.050	1.032	1.020 to 1.045	1.030	**0.98**	**0.1769**	**0.225**
ζ	0.621	0.519 to 0.722	0.625	0.640	0.545 to 0.736	0.610	**1.03**	**0.1157**	**0.867**
P_t	155.8	123.9 to 187.7	121.8	92.17	77.58 to 106.8	79.70	0.59	0.4283	0.000
N_p	7.549	6.540 to 8.557	7.100	6.897	5.970 to 7.824	5.800	**0.91**	**0.1441**	**0.464**
Size	0.224	0.202 to 0.246	0.230	0.174	0.151 to 0.197	0.170	0.78	0.2704	0.012
Δt	21.99	19.56 to 24.42	21.45	19.19	16.68 to 21.70	18.00	**0.87**	**0.1762**	**0.229**
D_{st}	-65.54	-78.29 to -52.79	-56.00	-33.37	-42.27 to -24.47	-22.00	0.51	0.3318	0.001

[a]Units of the parameters: B_t, B_z in nT; MC speed V, and expansion speed V_{exp} in km s^{-1}; VB_z in

$V_{exp} = V_{LE} - V_{TE}$

$F_{exp} = V_{LE} / V_c$

$= 2V_{LE} / (V_{LE} + V_{TE})$

$\Delta t = t_{TE} - t_{LE}$

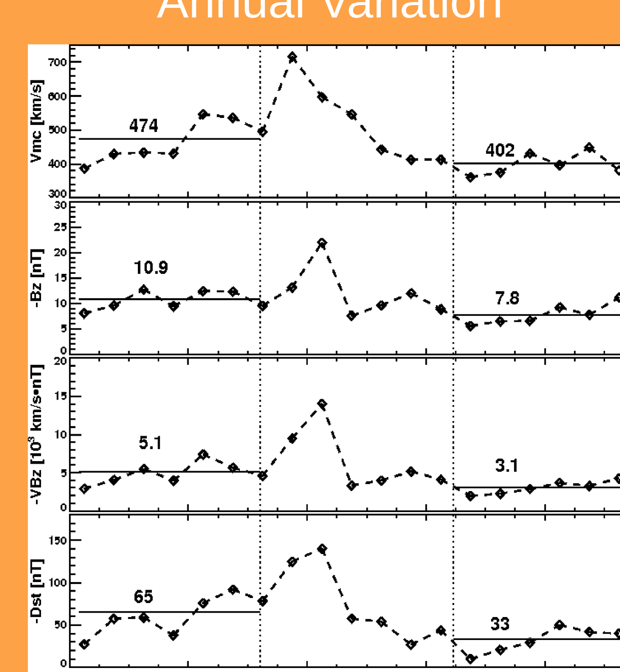
$\zeta = V_{exp}L/\Delta t V_c^2$

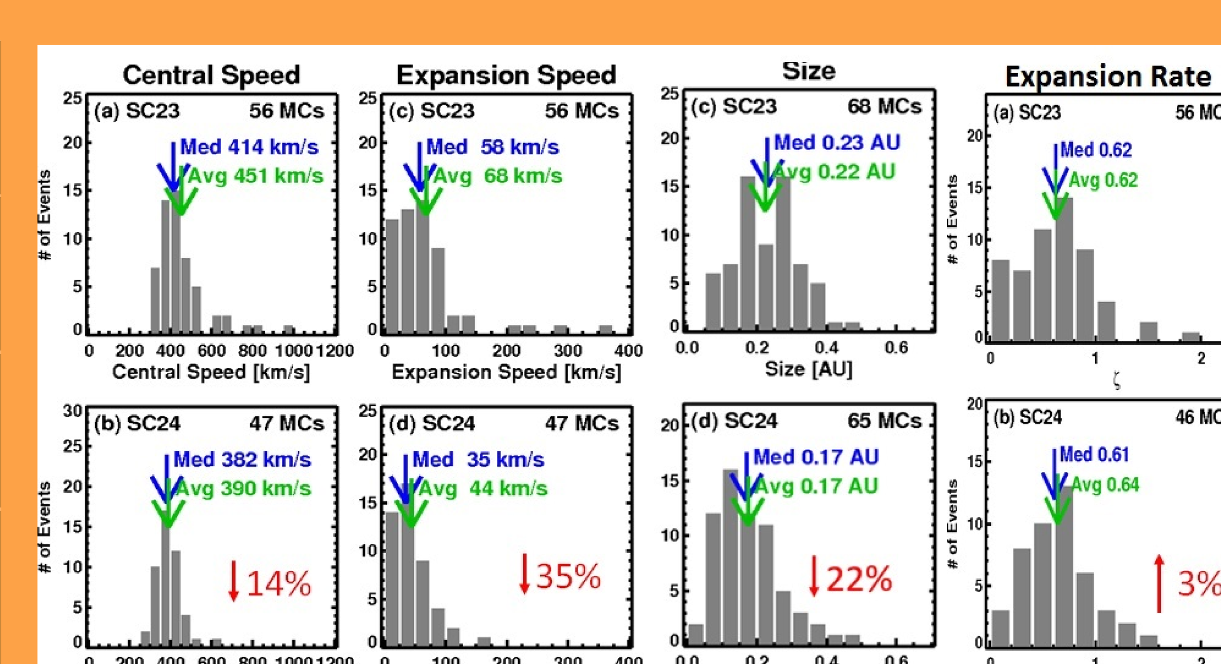
No significant change in F_{exp}, Δt, ζ, and N_p

What Changed (decreased): B_t, B_zV, VB_z, V_{exp}, P_t, size, D_{st}

LE, TE – MC Leading and trailing edges
L – Heliocentric distance
P_t – gas + magnetic pressure
V_c – central MC speed $(V_{LE}+V_{TE})/2$

Annual Variation

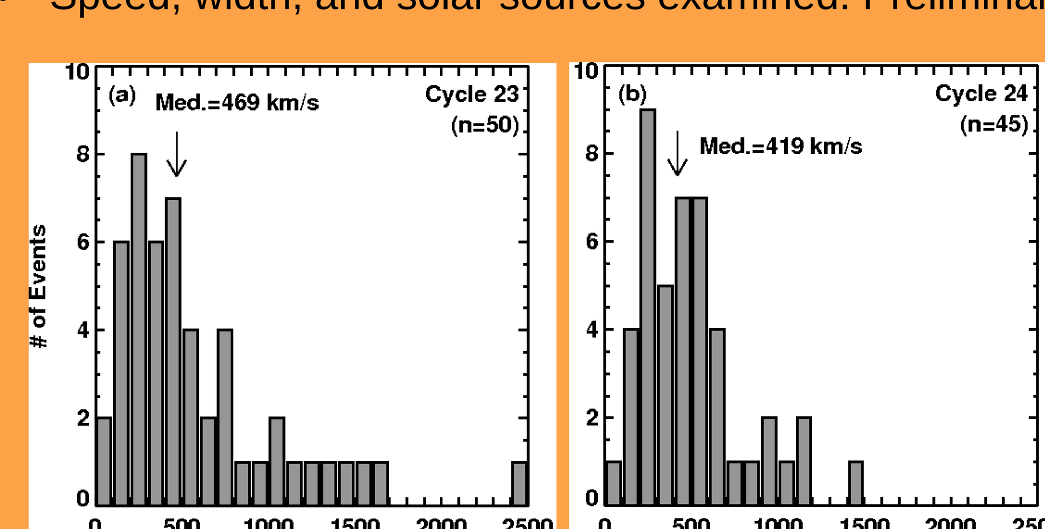


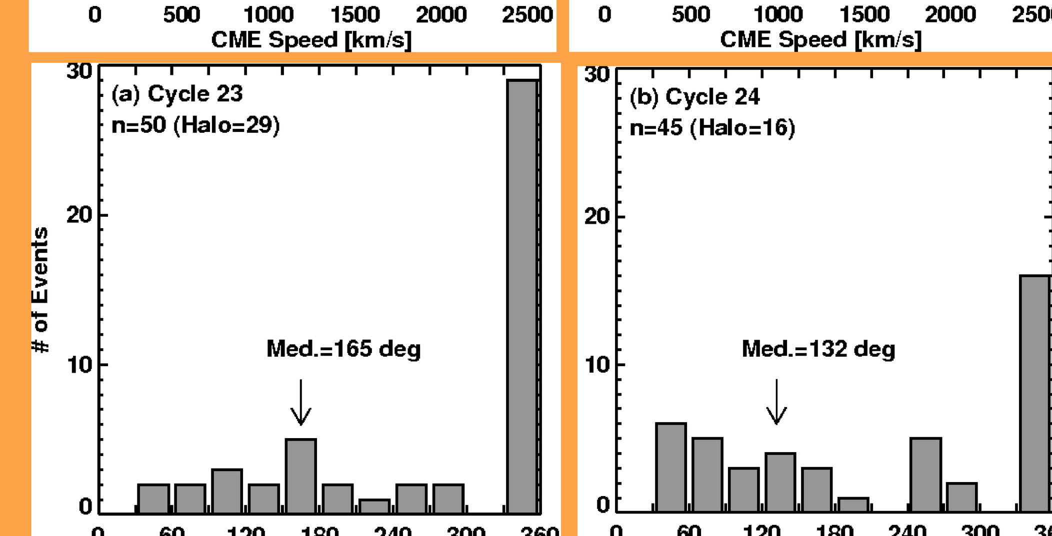


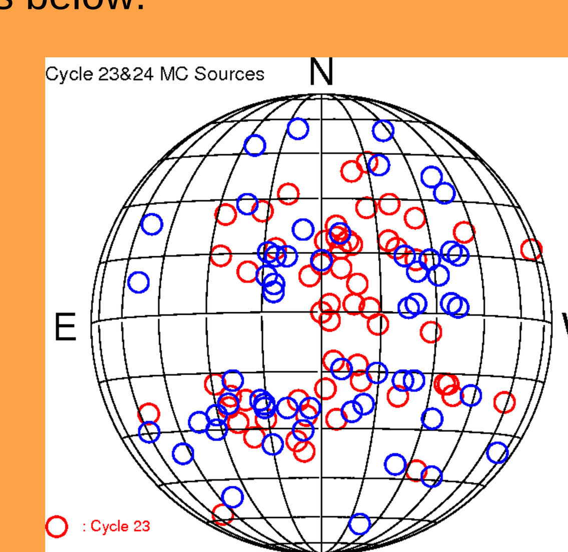
- CME size in SC 24 is larger near the Sun, but MC size is smaller at 1 AU
- $S = S_o (L/L_o)^\zeta$; S_o is the initial FR size R at L_o (where FR - ambient pressure balance is reached Gulisano et al. 2010)
- $S_{24}/S_{23} = (S_{o24}/S_{o23})(L_{o23}/L_{o24})^\zeta$
- $S_{o24}/S_{o23} = W_{24}/W_{23} = 1.38$ (CMEs wider in SC 23; Gopalswamy et al. 2014)
- $S_{24}/S_{23} = 0.78$ (Observations at 1 AU, Gopalswamy et al. 2015)
- $\zeta = 0.64$
- → $L_{o23}/L_{o24} = 0.41$
- $L_{o23} = 5$ Rs
- → $L_{o24} = 12.2$ Rs. Pressure balance is reached at a larger distance in SC 24
- Flux rope size and CME width are defined differently. Measure main body?

CMEs AT THE SUN

- Best possible CME candidate selected based by looking at coronagraph images 1-5 days earlier
- STEREO images used in SC 24: Some CMEs not observed in LASCO
- Speed, width, and solar sources examined. Preliminary results below:







- The speeds are similar
- The halo fraction in cycle 24 is smaller - Narrower CMEs in SC 24 able to reach 1 AU?
- The solar sources are similar – except slightly larger number of mid-latitude CMEs reaching 1 AU (due to equatorward deflection)

CONCLUSIONS

- Intense storms tend to occur during the maximum phase of solar cycles
- The weaker geoeffectiveness can be directly attributed to the drop in VBz
- Bz reduction due to enhanced expansion in cycle 24
- Dilution of magnetic content occurs near the Sun
- The pressure balance happens at a larger distance from the Sun in cycle 24 (12 Rs vs.5 Rs). Explains the contradictory relationship between sizes at 1 AU & at the Sun
- The parameters (V_L, B_t, P_t, VB_z, B_z) that are directly linked to the solar sources show clear solar cycle variation
- Smaller MC speed and expansion speed in SC24, consistent with smaller ΔP_t
- *CME speeds at the Sun are similar in the two cycles; but smaller halo fraction*
- *Solar source distributions are similar*
- *Need to see if the pressure balance distance changes if the initial flux rope sizes are different*

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