Comparing Solar Minimum 24/25 with Historical Solar Wind Records at 1 AU

Lan Jian[1], N. Gopalswamy[1], J. G. Luhmann[2], C. T. Russell[3], A. B. Galvin[4]

[1]NASA Goddard Space Flight Center, Greenbelt, MD, USA

[2]Space Science Lab., Univ. of California, Berkeley, CA, USA

[3]Dept. of Earth, Planetary, & Space Sci., Univ. of California, Los Angeles, CA, USA

[4]Dept. Of Physics, Univ. of New Hampshire, NH, USA

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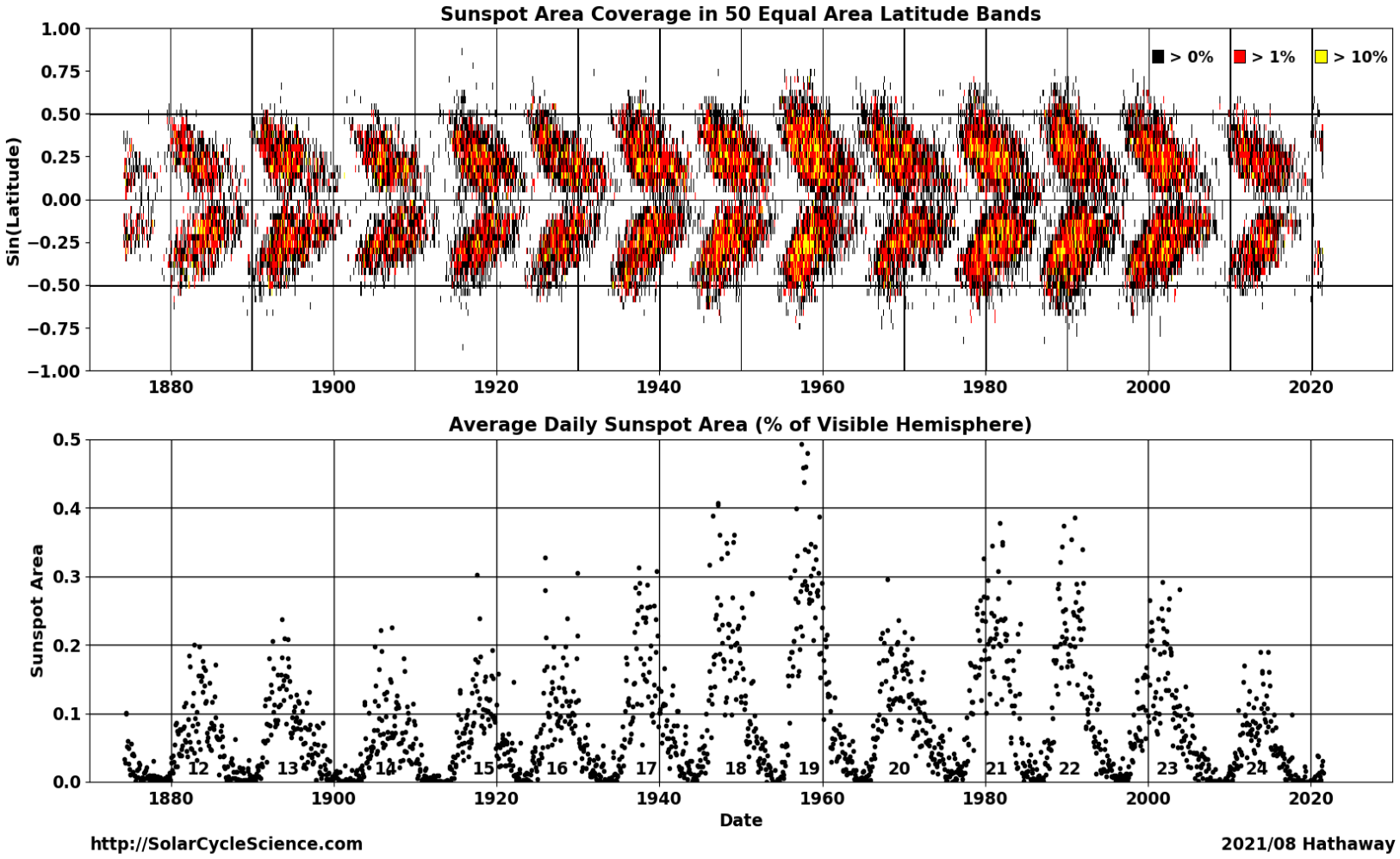
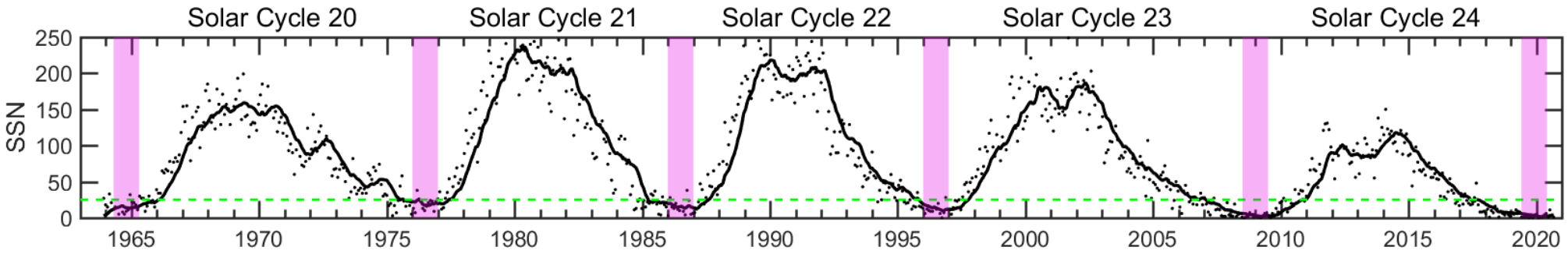
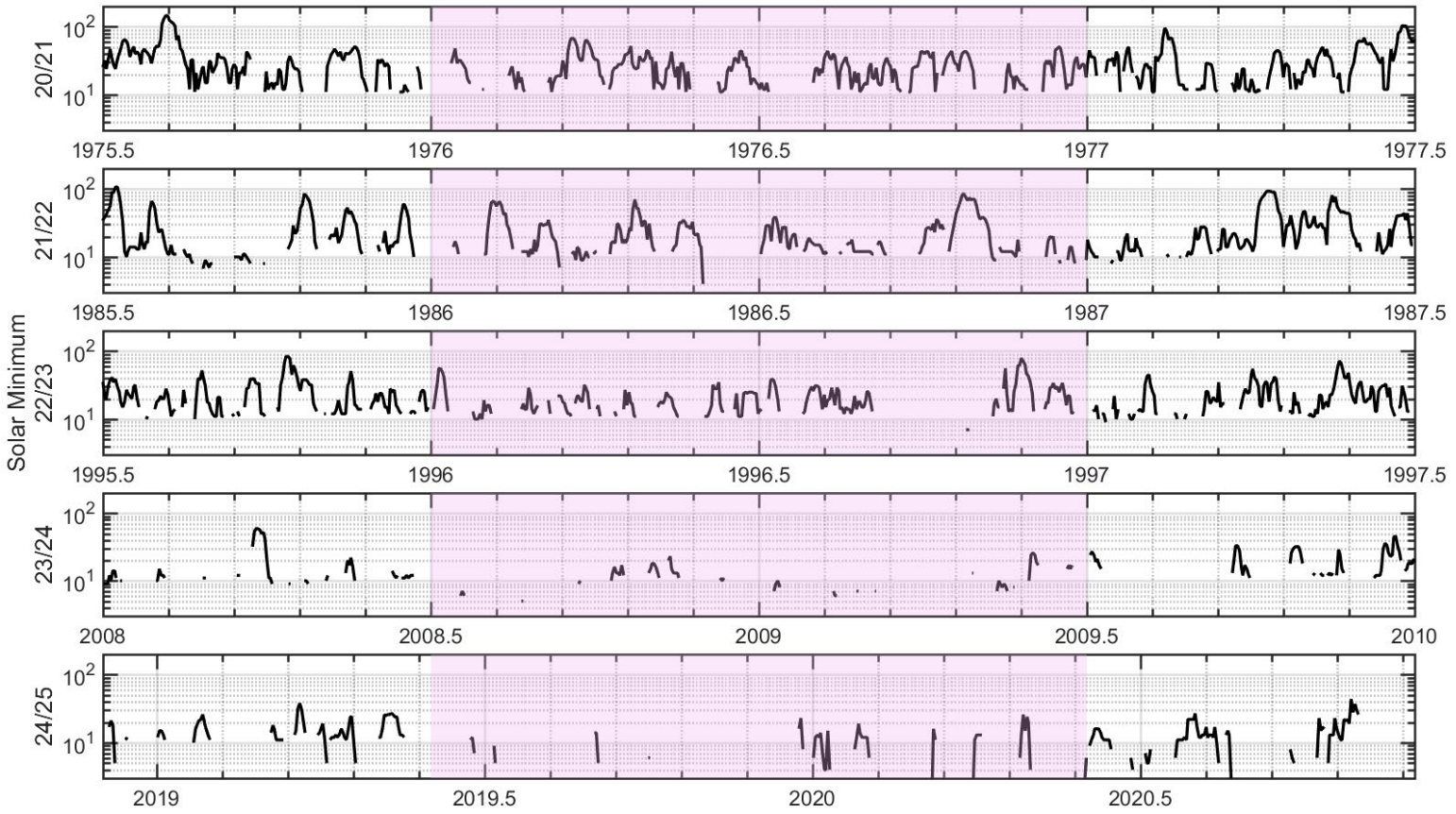
Introduction



- The Solar Cycle 25 Prediction Panel announced the last solar minimum happened in **December 2019**, marking the start of solar cycle 25
- For solar minimum 23/24, we published its comparison with historical solar wind records in Jian et al. (Solar Physics 2011)
- This study extends it to the last solar min 24/25, and also compares the large-scale solar wind structures (ICMEs and Stream Interaction Regions) in the recent two solar cycles

Sunspot Number (SSN) Distribution in Recent Five Solar Minima

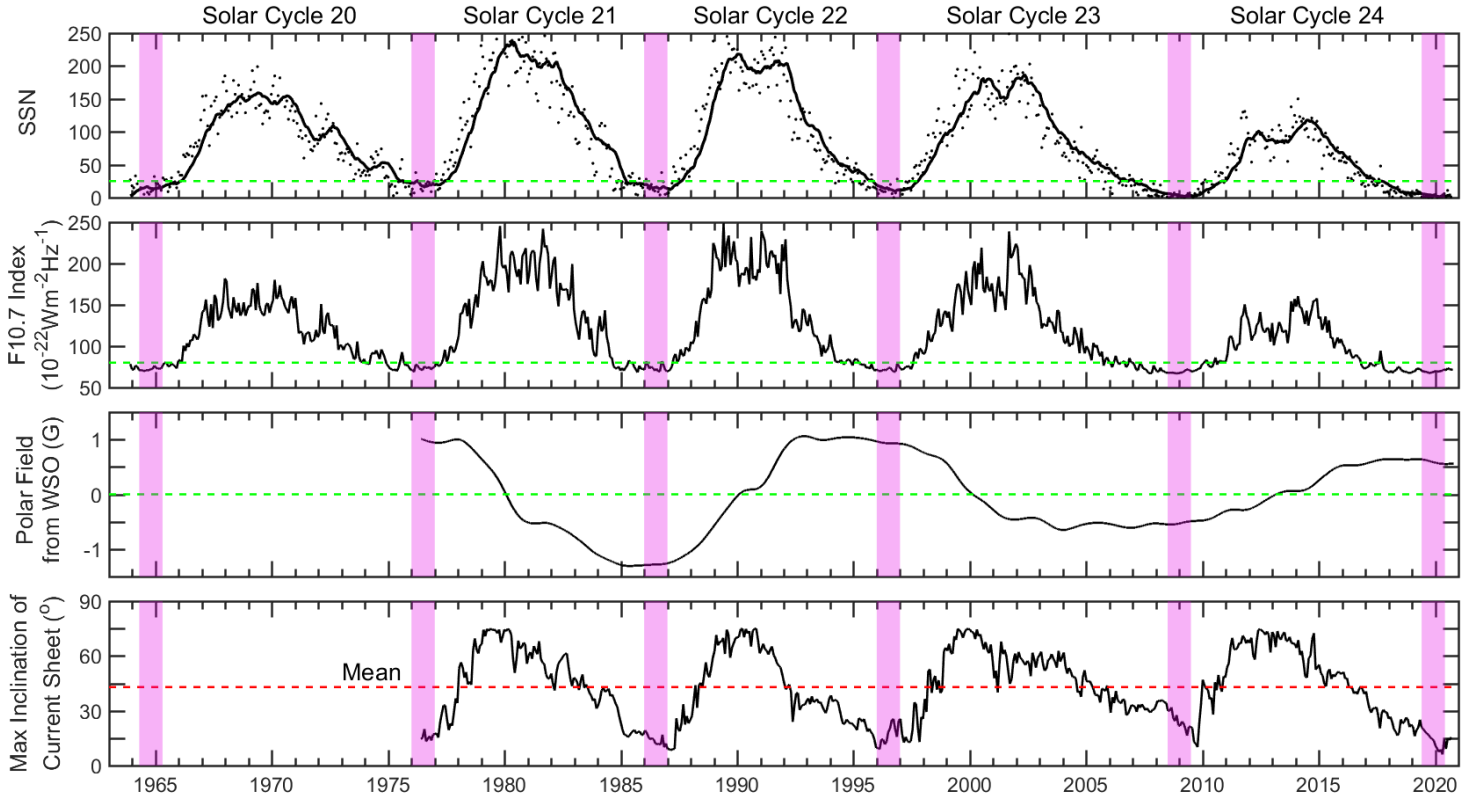




SSN relates to magnetic flux emergence. The solar magnetic flux at solar min strongly modulates the SSN and strength of the following cycle

Solar Minimum	Spotless Days	Fraction of Spotless Days (%)	Mean SSN/day
20/21	105	28.7	18.4
21/22	129	35.3	14.8
22/23	165	45.1	11.6
23/24	294	80.5	2.3
24/25	307	84.1	1.6

Solar Activity & Solar Magnetic Field

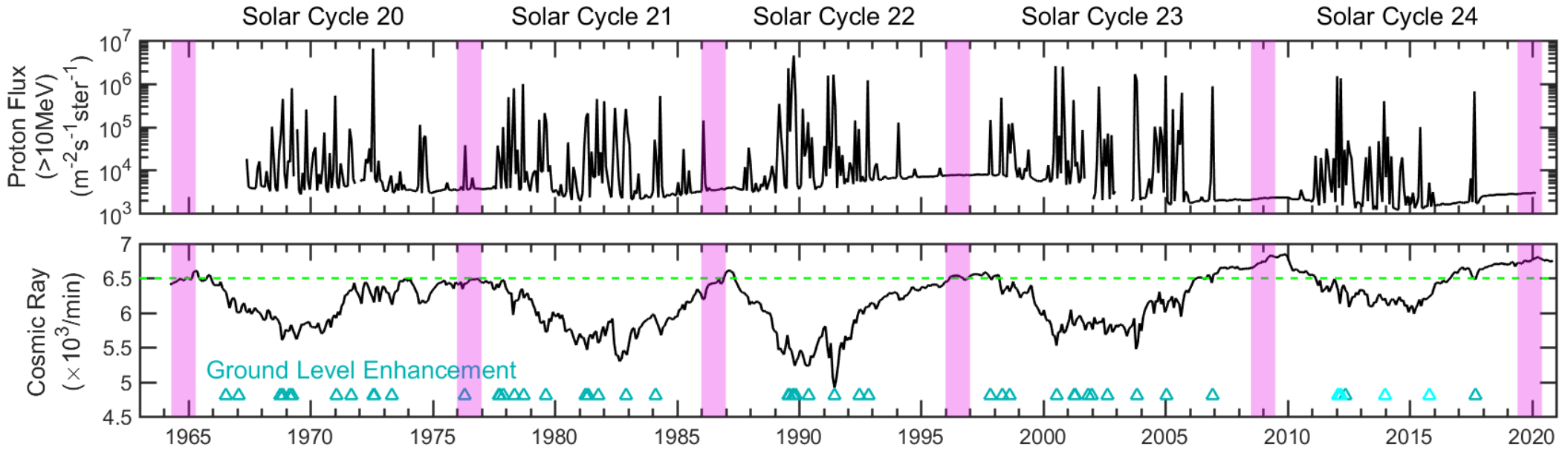


- **F10.7 index** is the flux of radio emission from the Sun at a wavelength of 10.7 cm (2.8 GHz)
  - It tends to follow the changes in the solar ultraviolet that influences the Earth's upper atmosphere and ionosphere
  - Many ionospheric and atmospheric models use F10.7 flux as input
- The F10.7 flux and polar magnetic field in solar min 24/25 are **slightly higher** than solar min 23/24, but they are **weaker** than solar min 20/21, 21/22, and 22/23
- The heliospheric current sheet (HCS) in solar min 24/25 is **flattest** among the recent five solar minima

Solar Min	20/21		21/22		22/23		23/24		24/25	
	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median
F10.7 (10^{-22} $Wm^{-2}Hz^{-1}$)	73.36±0.05	72.6	73.99±0.07	71.6	72.03±0.06	70.4	71.14±0.52	68.1	69.37±0.02	69.3
$\lvert B_P \rvert$ (nT)	0.972±0.005	0.97	1.280±0.001	1.28	0.935±0.002	0.93	0.528±0.003	0.53	0.583±0.004	0.58
HCS Tilt (°)	15.6±0.8	15.1	14.0±0.8	14.2	17.0±1.6	15.7	24.3±1.2	23.6	12.5±1.1	13.6

Solar Energetic Protons & Cosmic Ray Intensity

- Energetic protons are a significant radiation hazard to spacecraft and astronauts
- Ground Level Enhancement (GLE): sharp increases in the cosmic ray count by >=10% recorded by ground-based detectors, often associated with SEPs (cyan for sub-GLE)
- Galactic Cosmic Ray (GCR) from Oulu neutron monitor in solar min 24/25 is comparable to solar min 23/24, and higher than solar min 20/21, 21/22, and 22/23

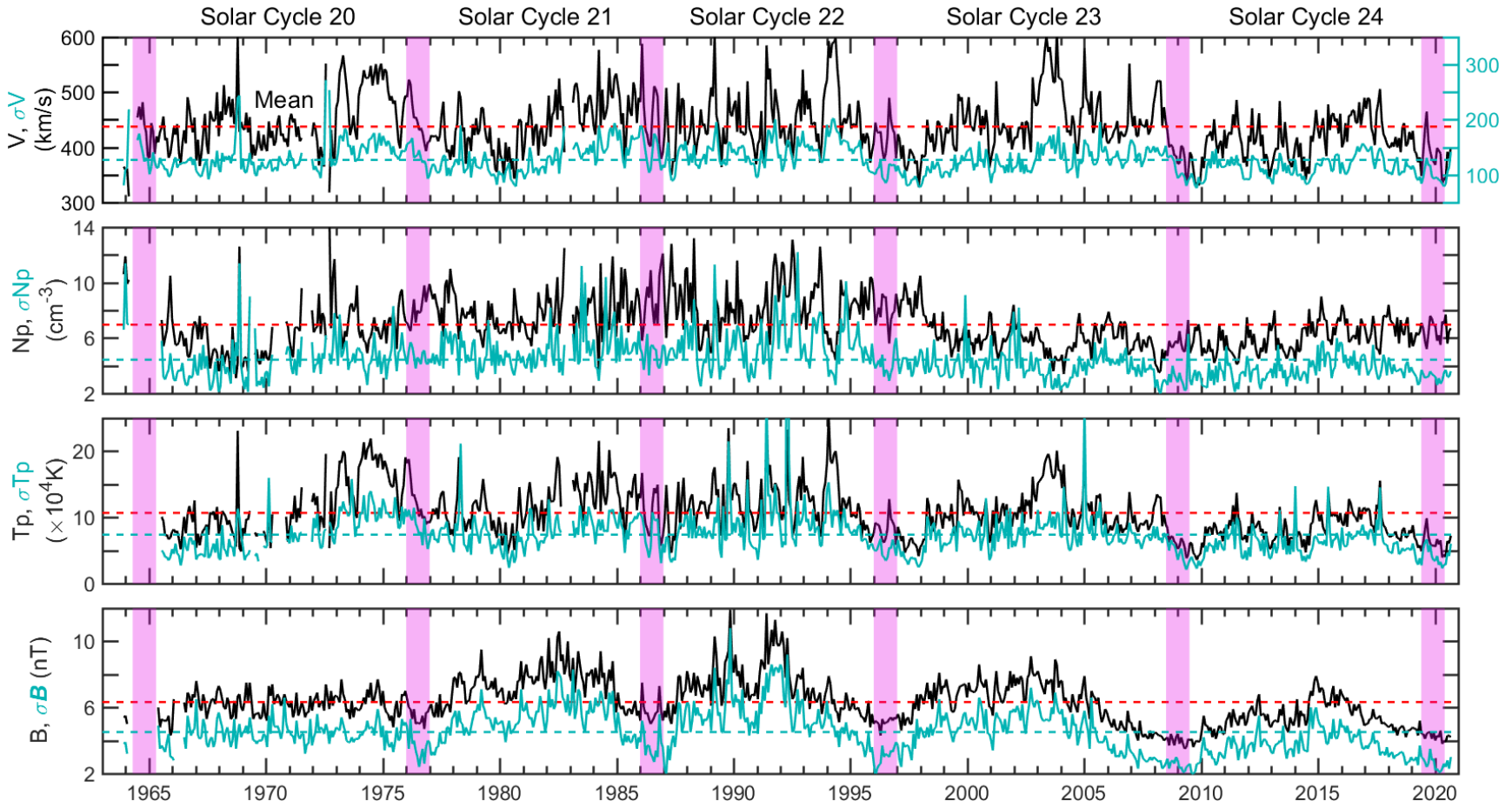


Solar Min	20/21		21/22		22/23		23/24		24/25	
	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median
CR Intensity (10^3/min)	6.45±0.01	6.45	6.39±0.03	6.42	6.51±0.01	6.51	6.74±0.02	6.74	**6.76±0.01**	**6.76**

Solar Wind Parameters - I

The solar wind speed, proton density, temperature and magnetic field strength in solar min 24/25 are **NOT as low as** in solar min 23/24, but they are all **lower** than in solar min 20/21, 21/22, and 22/23

Statistics in the tables is based on hourly OMNI data



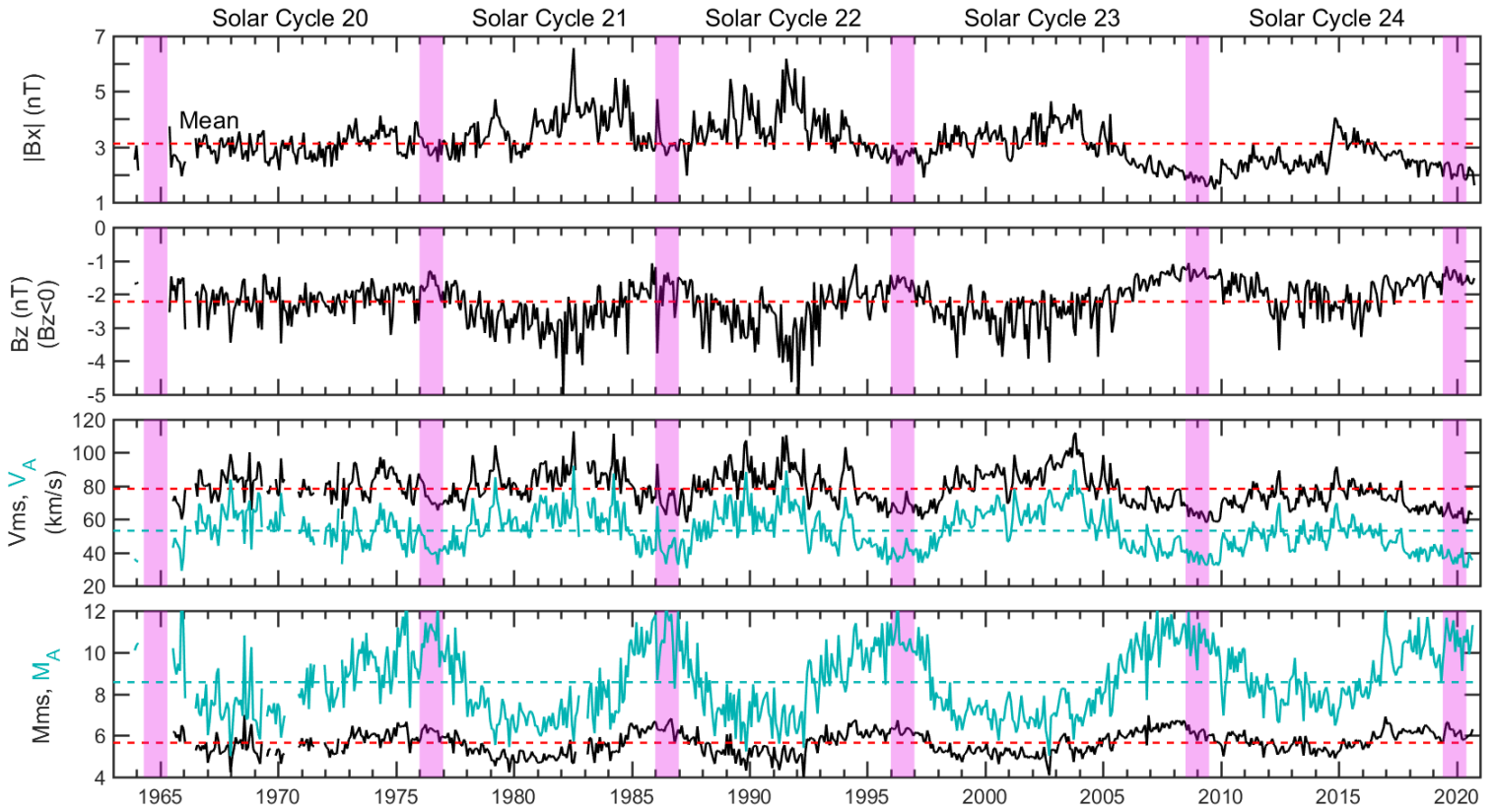
Solar Min	20/21		21/22		22/23		23/24		24/25	
	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median
V (km/s)	445±1	413	454±2	418	423±1	406	388±1	361	388±1	369
Np (cm^{-3})	8.20±0.7	6.7	8.62±0.09	7.3	7.89±0.05	6.6	5.65±0.05	4.7	6.56±0.04	5.6
Tp ($\times 10^3$ K)	121.6±1.2	86.4	106.0±1.5	71.4	84.3±0.6	69.0	62.3±0.6	43.6	62.1±0.6	48.0
B (nT)	5.47±0.03	5.1	5.75±0.04	5.3	5.12±0.02	4.8	3.98±0.02	3.6	4.26±0.02	3.9

Solar Wind Parameters - II

The absolute radial magnetic field (|Bx|) and southward magnetic field (Bs) in solar min 24/25 are **not as weak as** in solar min 23/24, but **weaker** than solar min 20/21, 21/22, and 22/23

The **magnetosonic and Alfven speeds** in solar min 24/25 are **slowest** among the recent five solar min

The magnetosonic and Alfven Mach numbers in solar min 24/25 are both similar to the ones in solar min 23/24



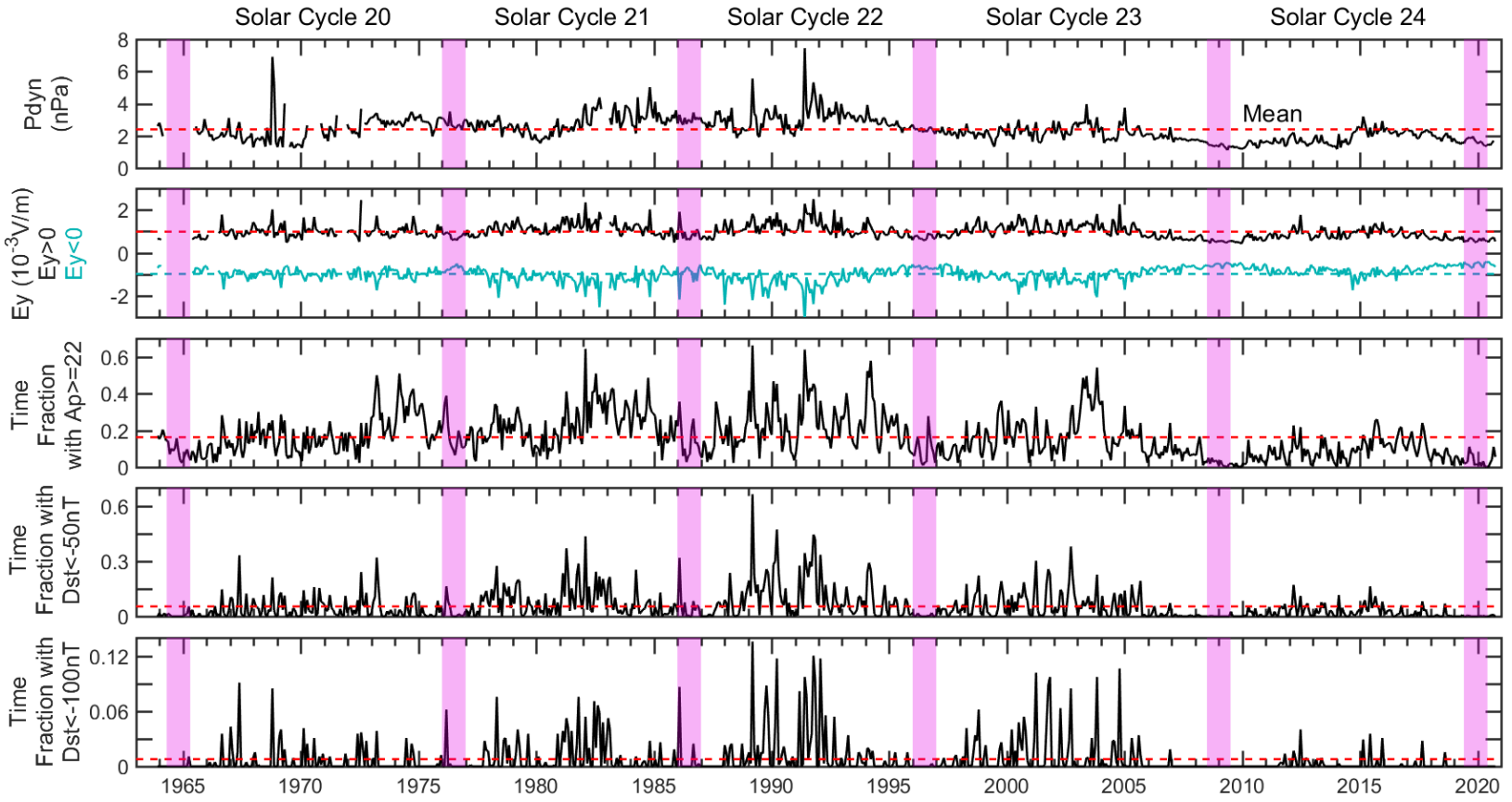
Solar Min	20/21		21/22		22/23		23/24		24/25	
	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median
|Bx| (nT)	2.93±0.03	2.8	3.11±0.03	2.9	2.72±0.02	2.6	1.85±0.01	1.7	2.14±0.02	2.0
|Bs| (nT)	1.78±0.04	1.3	1.89±0.05	1.3	1.67±0.02	1.3	1.37±0.02	1.1	1.49±0.02	1.2
V_{MS} (km/s)	75.8±0.1	71.7	75.7±0.4	69.7	70.8±0.2	68.7	66.4±0.2	63.1	66.0±0.2	62.7
V_A (km/s)	46.8±0.3	44.3	48.7±0.4	44.2	44.4±0.2	42.8	40.7±0.2	38.3	40.2±0.2	37.4
M_{MS}	6.12±0.01	6.2	6.26±0.02	6.3	6.20±0.01	6.3	6.05±0.01	6.0	6.06±0.01	6.1
M_A	12.27±0.09	11.0	12.00±0.09	10.7	12.11±0.06	10.9	12.32±0.06	11.3	12.33±0.06	11.3

Solar Wind Impact on Geomagnetic Activity - I

The solar-wind **dynamic pressure** in solar min 24/25 is stronger than in solar min 23/24, but much weaker than in solar min 20/21, 21/22, and 22/23

Ey = -VBz, where hourly data are used

The eastward and westward **electric fields** of solar wind in solar min 24/25 are comparable with the ones in solar min 23/24, and weaker than in previous three solar min



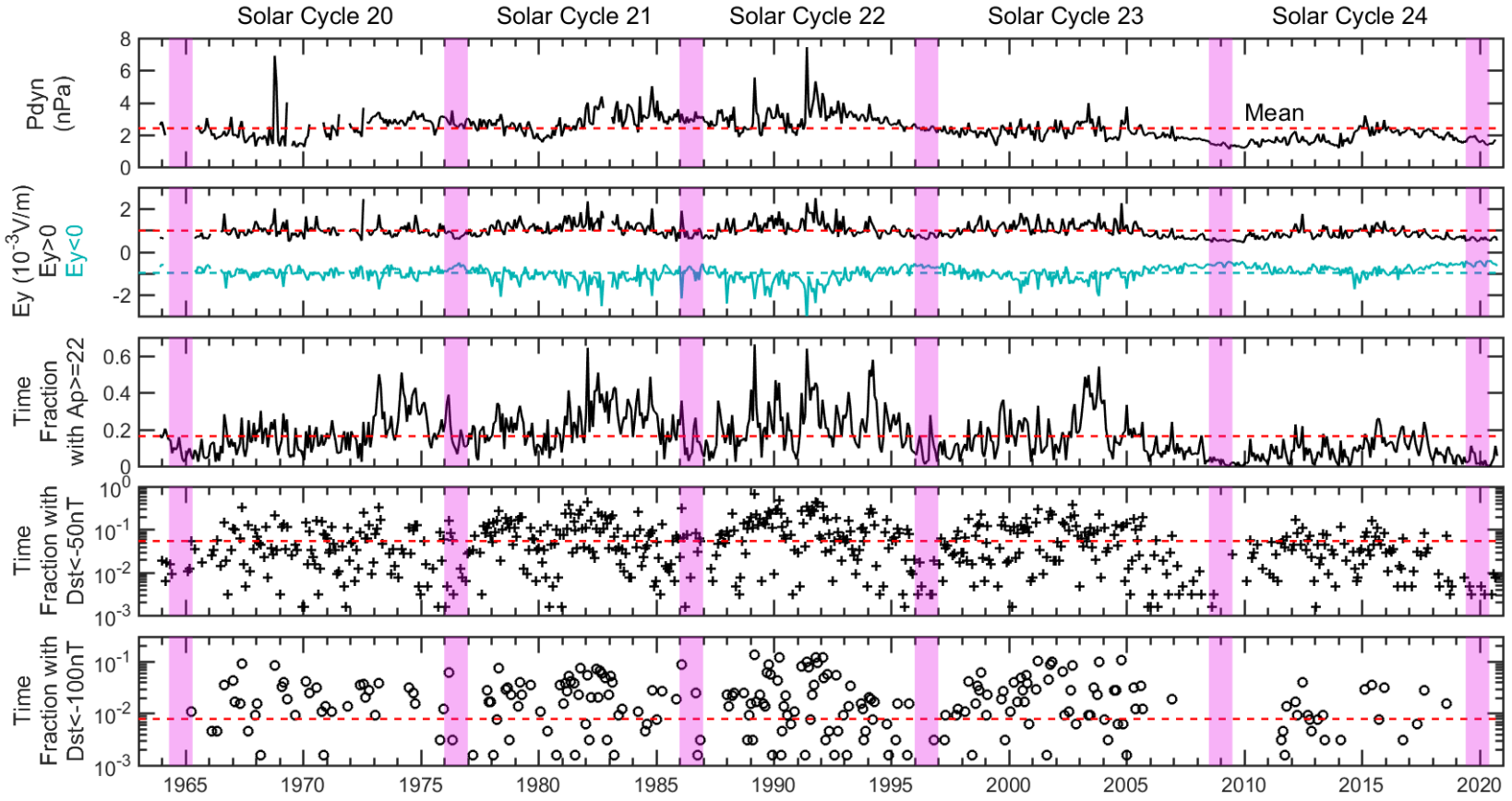
Solar Min	20/21		21/22		22/23		23/24		24/25	
	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median
Pdyn (nPa)	2.76±0.02	2.43	2.95±0.02	2.69	2.38±0.01	2.15	1.39±0.01	1.18	1.65±0.01	1.44
Ey>0 (mV/m)	0.79±0.02	0.57	0.83±0.03	0.56	0.72±0.01	0.57	0.53±0.01	0.39	0.59±0.01	0.45
Ey<0 (mV/m)	-0.73±0.01	-0.54	-0.95±0.02	-0.68	-0.69±0.01	-0.52	-0.58±0.01	-0.42	-0.54±0.01	-0.40

Solar Wind Impact on Geomagnetic Activity - II

Ap: changes of magnetic field arising from the Earth's mid-latitude ionospheric current systems

Dst: strength of longitudinally-averaged depression in the geomagnetic field at the equator, mainly due to ring current

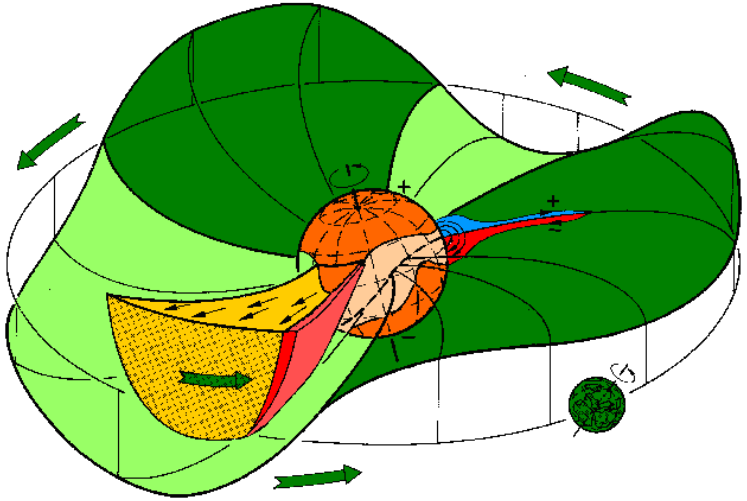
The **geomagnetic activity** in solar min 24/25 is not as weak as in solar min 23/24, but much weaker than solar min 20/21, 21/22, and 22/23



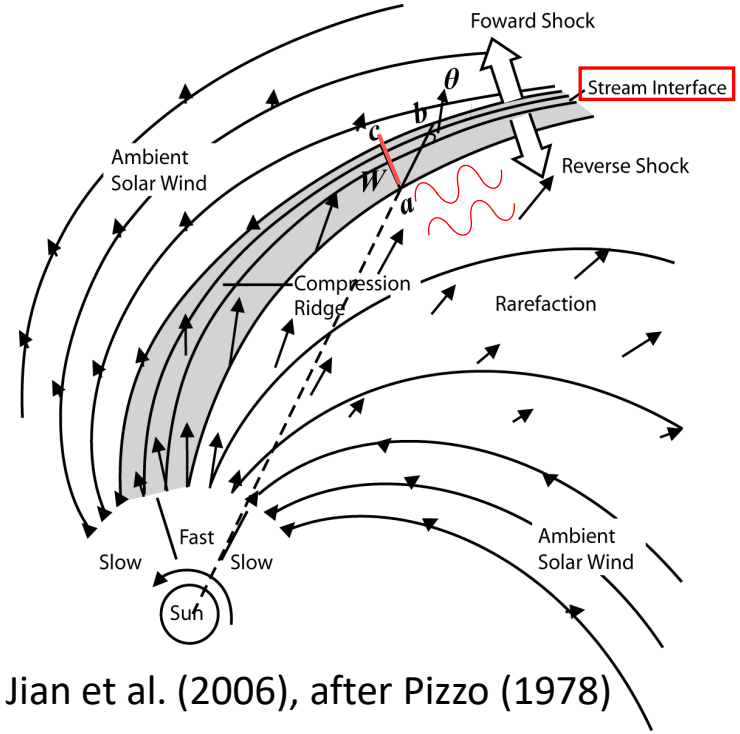
Solar Min	20/21		21/22		22/23		23/24		24/25	
	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median
Pdyn (nPa)	2.76±0.02	2.43	2.95±0.02	2.69	2.38±0.01	2.15	1.39±0.01	1.18	1.65±0.01	1.44
Ey>0 (mV/m)	0.79±0.02	0.57	0.83±0.03	0.56	0.72±0.01	0.57	0.53±0.01	0.39	0.59±0.01	0.45
Ey<0 (mV/m)	-0.73±0.01	-0.54	-0.95±0.02	-0.68	-0.69±0.01	-0.52	-0.58±0.01	-0.42	-0.54±0.01	-0.40
Time fraction with **Dst < -50 nT** (%)	3.11		5.31		0.51		0.03		0.11	

Stream Interaction Regions (SIRs)

- Fast wind from coronal holes is kinetically hot and tenuous, while slow wind from streamer belt is generally cool and dense. They are threaded by different magnetic field lines and prevented from interpenetrating
- As the Sun rotates, fast wind can overtake the preceding slow wind and form a **stream interaction region (SIR)** with a pressure ridge at the stream interface
- If the flow pattern is roughly time-stationary, these compression regions form spirals in the solar equatorial plane that corotate with the Sun → **Corotating Interaction Regions (CIRs)**
- SIRs = CIRs + Transient SIRs (which do not recur in one or more Carrington rotations)
- The pressure waves associated with the collision steepen with radial distance, eventually forming **shocks**, sometimes a pair of forward-reverse shocks

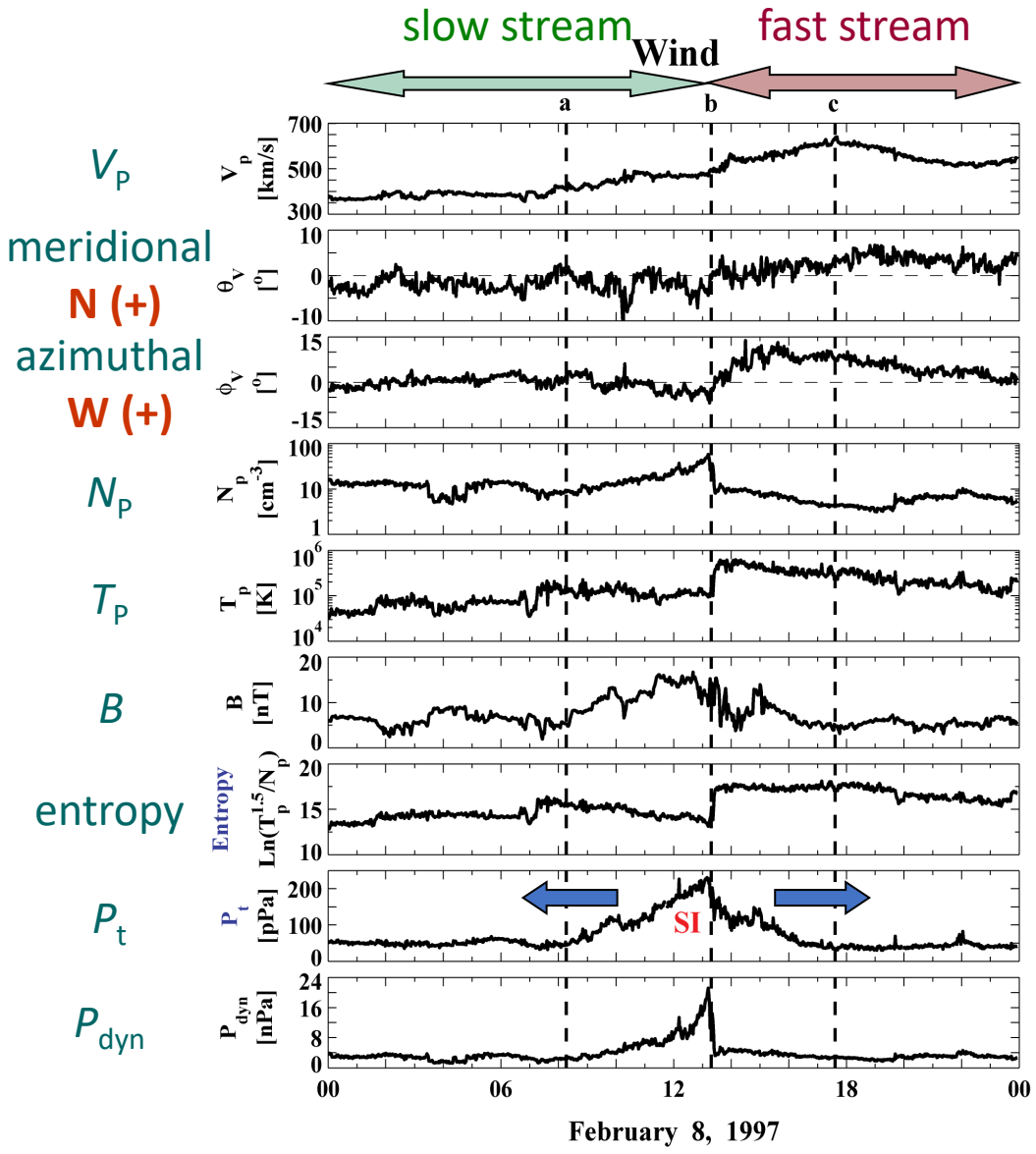


according to Alfvén (1977)



Jian et al. (2006), after Pizzo (1978)

Identification of SIRs



Jian et al. (2006)

* Criteria

① Increase of V_p

② Flow deflection

③ A pile-up of **total pressure P_t** (*magnetic pressure + perpendicular plasma thermal pressure*) with gradual declines at two sides

④ Increase and then decrease of N_p

⑤ Increase of T_p

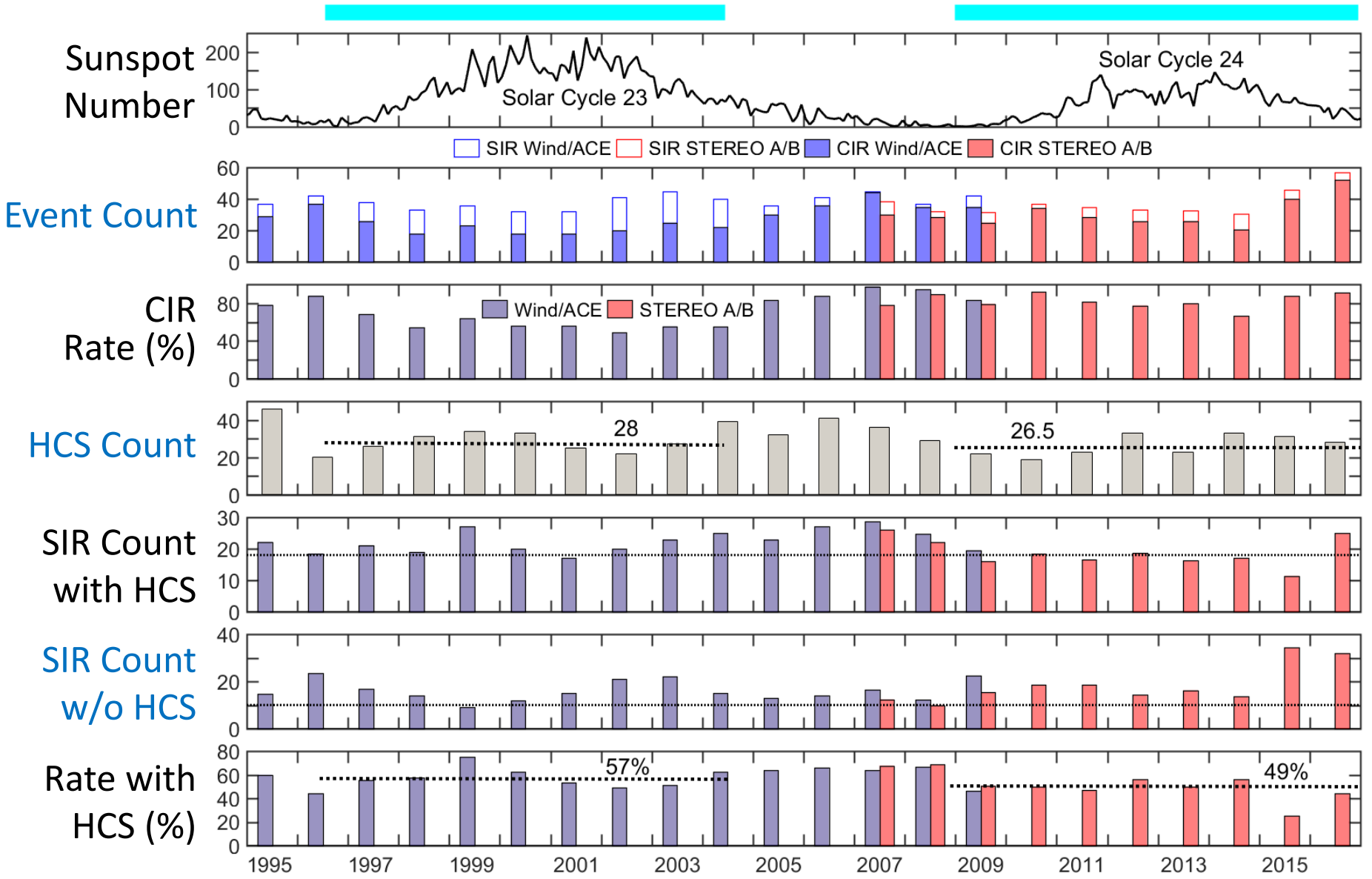
⑥ Compression of **B**, usually associated with **B** shear

⑦ Change of entropy $S=\ln(T_p^{1.5}/N_p)$

* Stream Interface (SI)

- The boundary separating the fast and slow wind streams
- Because many SIRs don't have clear interface from plasma data, we define SI to be at the peak of P_t

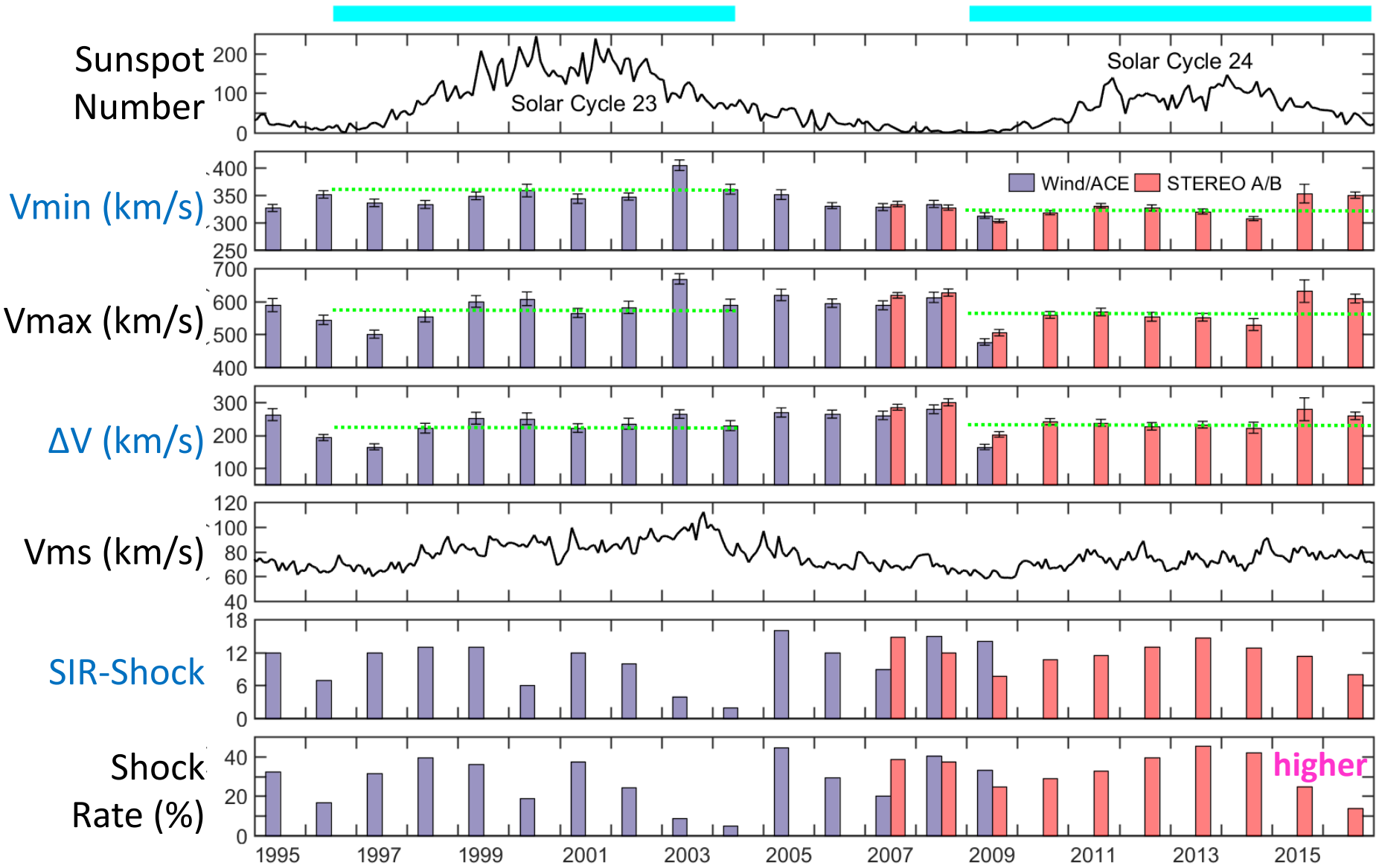
Solar Cycle Variations of SIR Properties - I



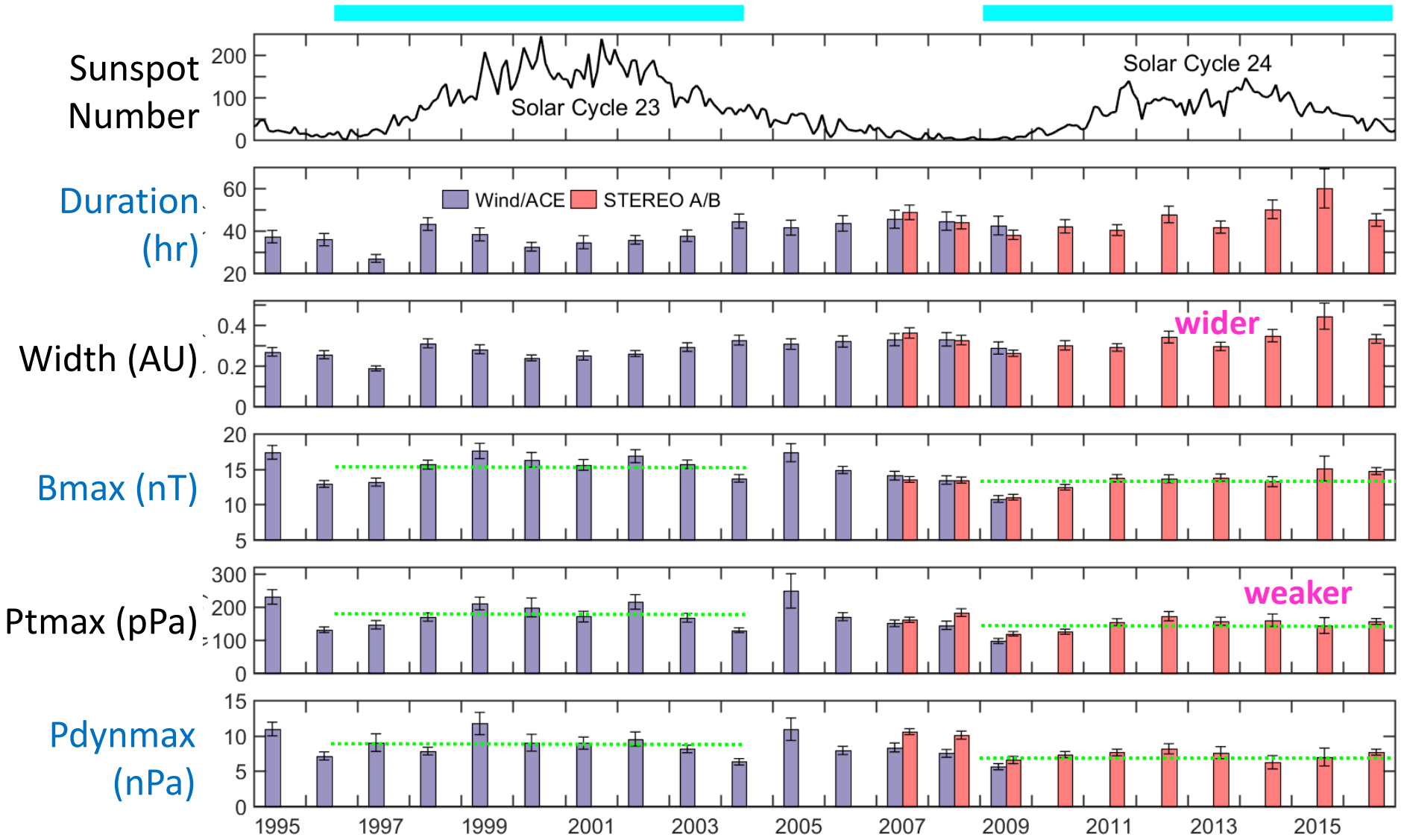
53, 51, 52 in 2017 - 2019

Jian et al. (Solar Phys., 2019)

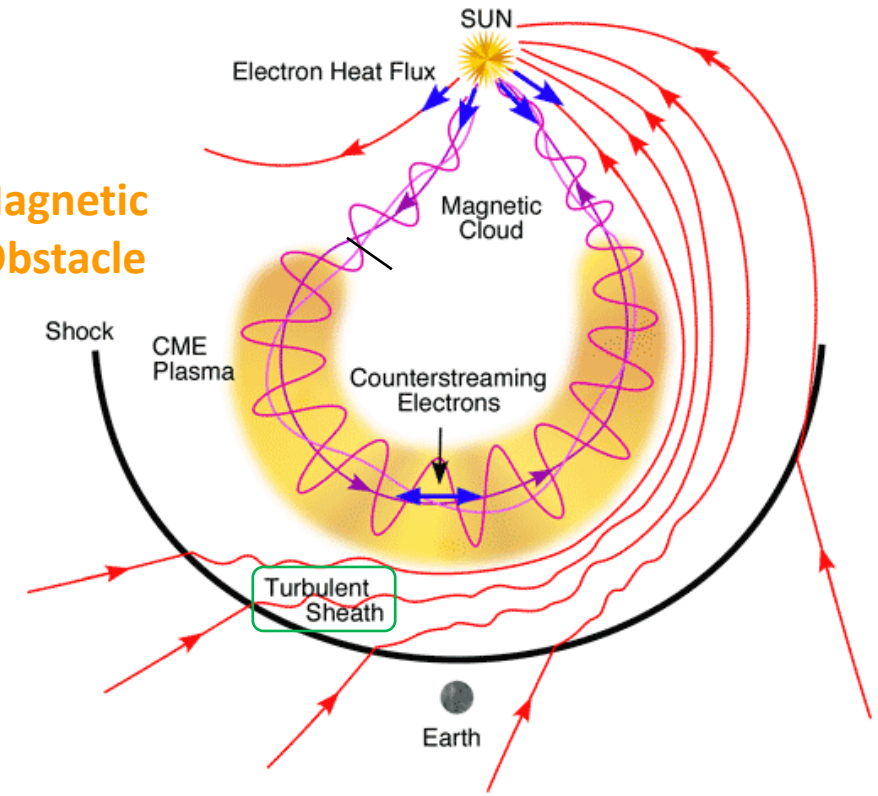
Solar Cycle Variations of SIR Properties - II



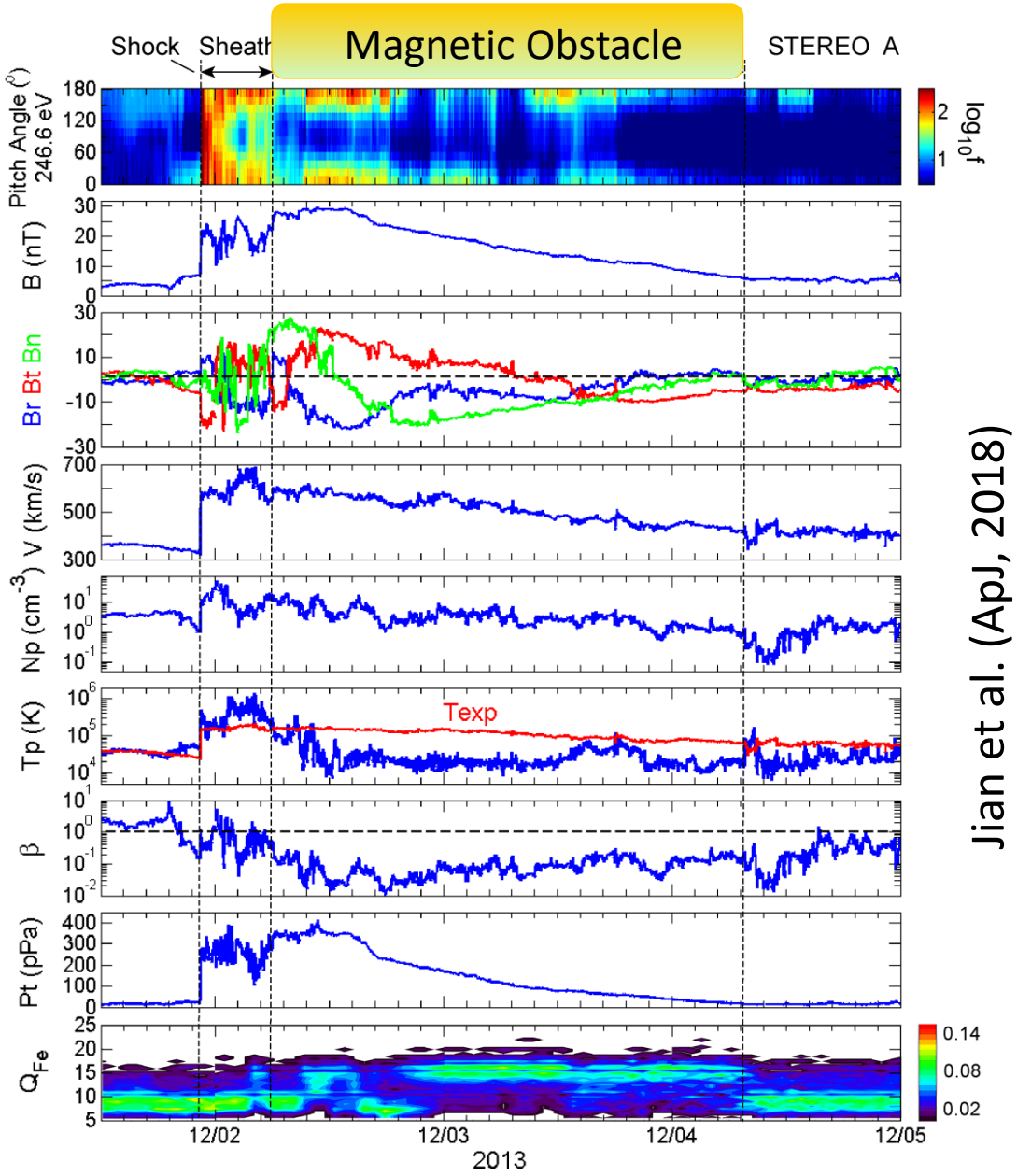
Solar Cycle Variations of SIR Properties - III



Introduction of ICME

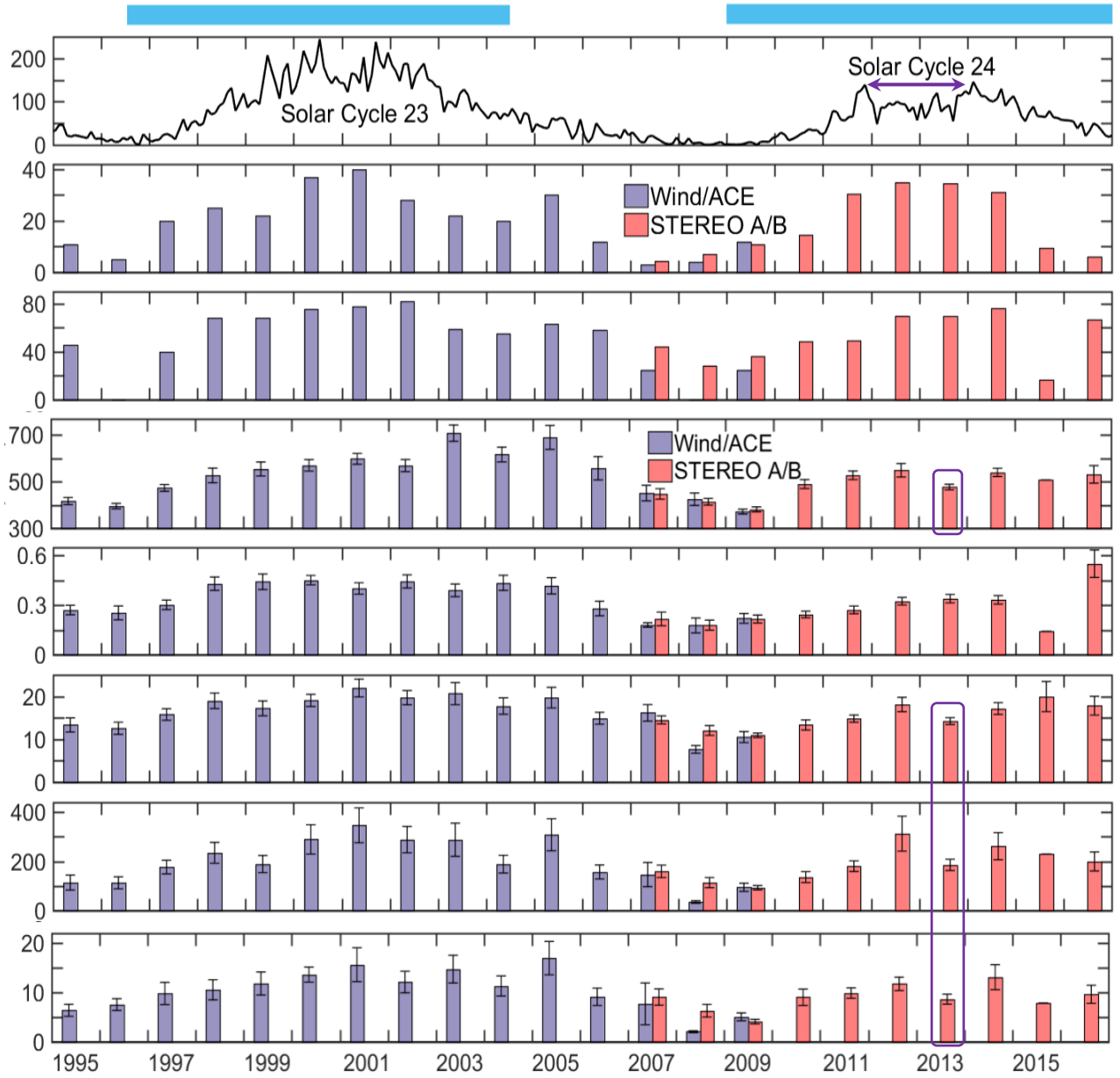


Zurbuchen and Richardson (2006)



Jian et al. (ApJ, 2018)

Solar Cycle Variations of ICME Properties



Sunspot Number — 43% fewer

ICME Count — 11% fewer

9, 3, 9 in 2017-2019

ICME Shock Rate (%) — 8% lower

Maximum V (km/s) — 10% slower

Size (AU) — smaller

Maximum B (nT) — 18% weaker

Maximum Total Pressure (pPa) — 18% weaker

Max. Dynamic Pressure (nPa) — 21% weaker

Jian et al. (ApJ, 2018)

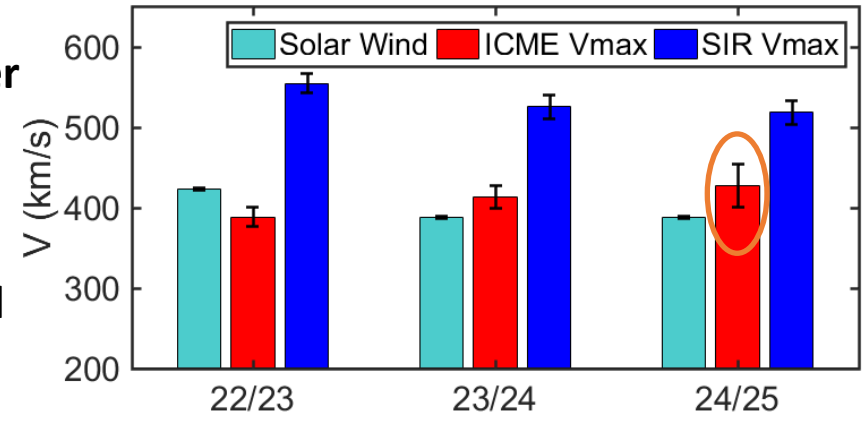
Properties of ICMEs & SIRs in Three Recent Solar Minima

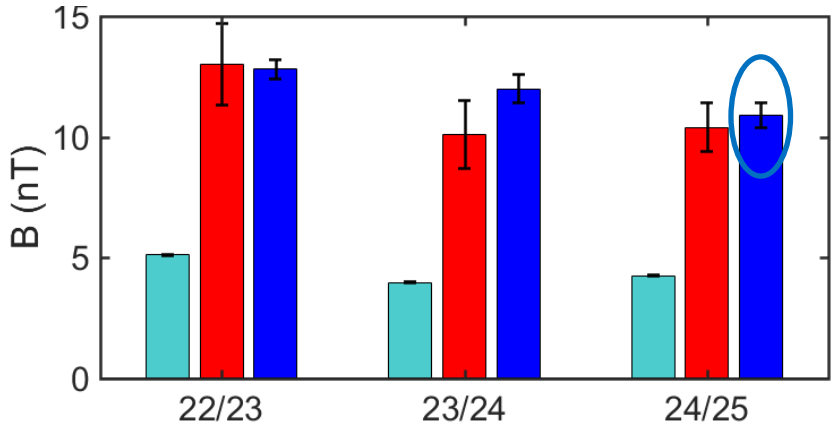
Solar Min	ICME Number	Shock Rate (%)	Duration (hr)	Expansion Speed (km/s)
22/23	4	0	32±5	57±15
23/24	8	25	21±3	68±10
24/25	8	50	29±6	72±14

Solar Min	SIR Number	HCS Associ-ation Rate	Recurrent Rate	Shock Rate	Duration (hr)	Speed Increase (km/s)
22/23	42	40%	88%	17%	44±4	205±9
23/24	41	51%	95%	39%	43±4	203±13
24/25	52	**24%**	83%	**10%**	38±3	186±13

Different Variations of Solar Wind, ICME, and SIR Parameters Among the Three Recent Solar Minima

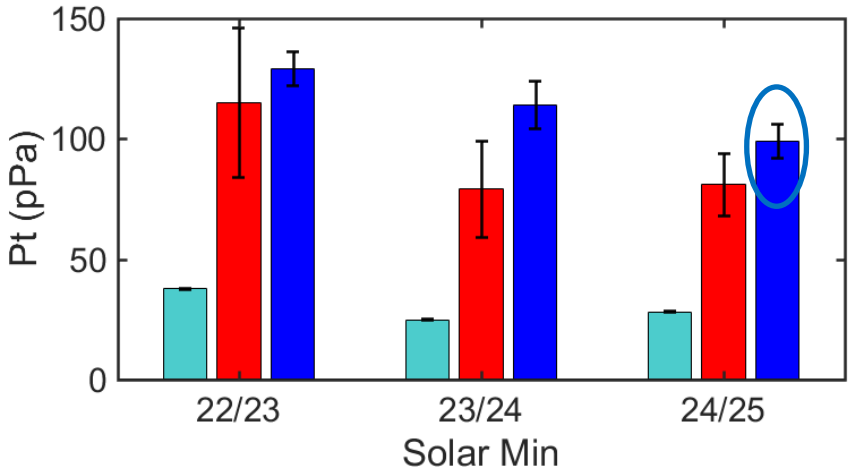
V_{max} of ICMEs in min 24/25 is **faster** than two former minima, different from the trends for solar wind and SIR

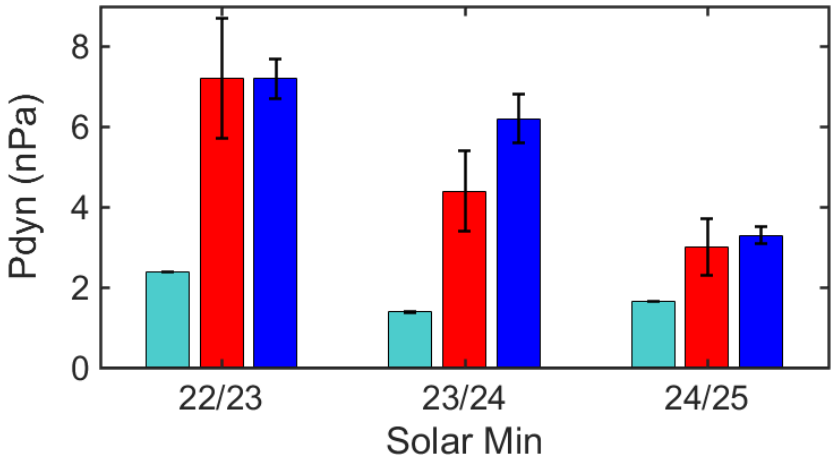




B_{max} of SIRs in min 24/25 is **weaker** than former two minima, different from the trends for solar wind and ICMEs

P_{tmax} of SIRs in solar min 24/25 is **weaker** than two former minima, different from the trends for solar wind and ICMEs





P_{dynmax} of ICMEs and SIRs are weaker in solar min 24/25

- For the same parameter, the variation trends of solar wind, ICME, and SIR are not always the same
- Deep solar minimum (e.g., min 23/24) does not imply fewer ICMEs or weaker ICME/SIR parameters

Summary and Discussion

- We have compared the 1-year period around solar minimum for the recent five solar minima
- Among them, the solar min 24/25 has most spotless days, flattest HCS, strongest GCR intensity, slowest magnetosonic and Alfven speeds, amplitude of Ey<0
- The following parameters of solar min 24/25 fall between the values of solar min 23/24 and the values of former three minima
  - F10.7 flux, polar magnetic field
  - Solar wind speed, proton density & temperature
  - Interplanetary magnetic field, |Bx|, |Bs|
  - Magnetosonic and Alfven Mach numbers of solar wind
  - Solar wind dynamic pressure
  - Amplitude of Ey>0
  - Geomagnetic activity (fraction with Dst < -50 nT)
- In comparison with solar cycle 23, the SIRs in solar cycle 24
  - Occur more often with higher recurrent rate, slightly lower HCS association rate
  - Lasting longer, wider
  - Slower minimum and maximum speeds, higher shock rate
  - Weaker peak magnetic field, total pressure, and dynamic pressure
- In comparison with solar cycle 23, the ICMEs in solar cycle 24
  - Occur less often (not as less as SSN reduction)
  - Slower, smaller, weaker peak magnetic field, total pressure, and dynamic pressure

Backup

Solar Minimum	Time Period	Fraction of Spotless Days	F10.7 (10^{-22} $Wm^{-2}Hz^{-1}$)	HCS Tilt (°)	Solar Polar Field (nT)	IMF |Br| (nT)	Time Rate with Dst<-50nT
20/21	1976	29%	72.6	15.1	0.97	2.8	3.11%
21/22	1986	35%	71.6	14.2	1.28	2.9	5.31%
22/23	1996	45%	70.4	15.7	0.93	2.6	0.51%
23/24	July 2008 – June 2009	81%	68.1	23.6	0.53	1.7	0.03%
24/25	June 2019 – May 2020	84%	69.3	**13.6**	0.58	2.0	0.11%

- Among the five solar minima, the solar min 24/25 has most spotless days, **flattest heliospheric current sheet** (HCS), strongest GCR intensity, slowest magnetosonic and Alfven speeds, weakest westward electric field
- The following parameters of solar min 24/25 fall between solar min 23/24 and former three minima
  - F10.7 flux, solar polar magnetic field, IMF strength, radial and southward IMF
  - Solar wind speed, proton density and temperature, magnetosonic and Alfven Mach numbers
  - Solar wind dynamic pressure, eastward electric field, geomagnetic activity (fraction with Dst < -50 nT)