Oscillations in Secondary to Primary Polar Crown Polarity Inversion Lines (PILs) around Solar Maximum (Smax) over Five Solar Cycles (SCs)

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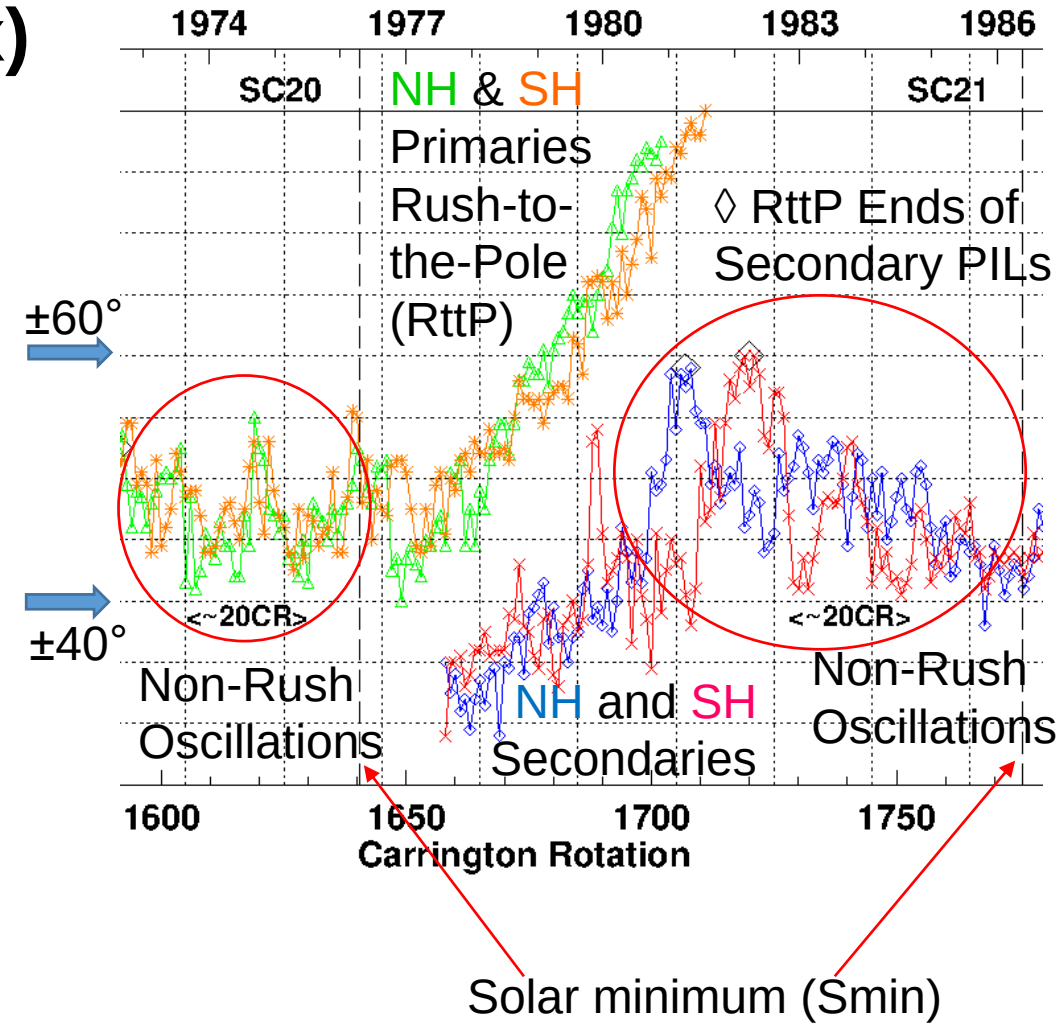
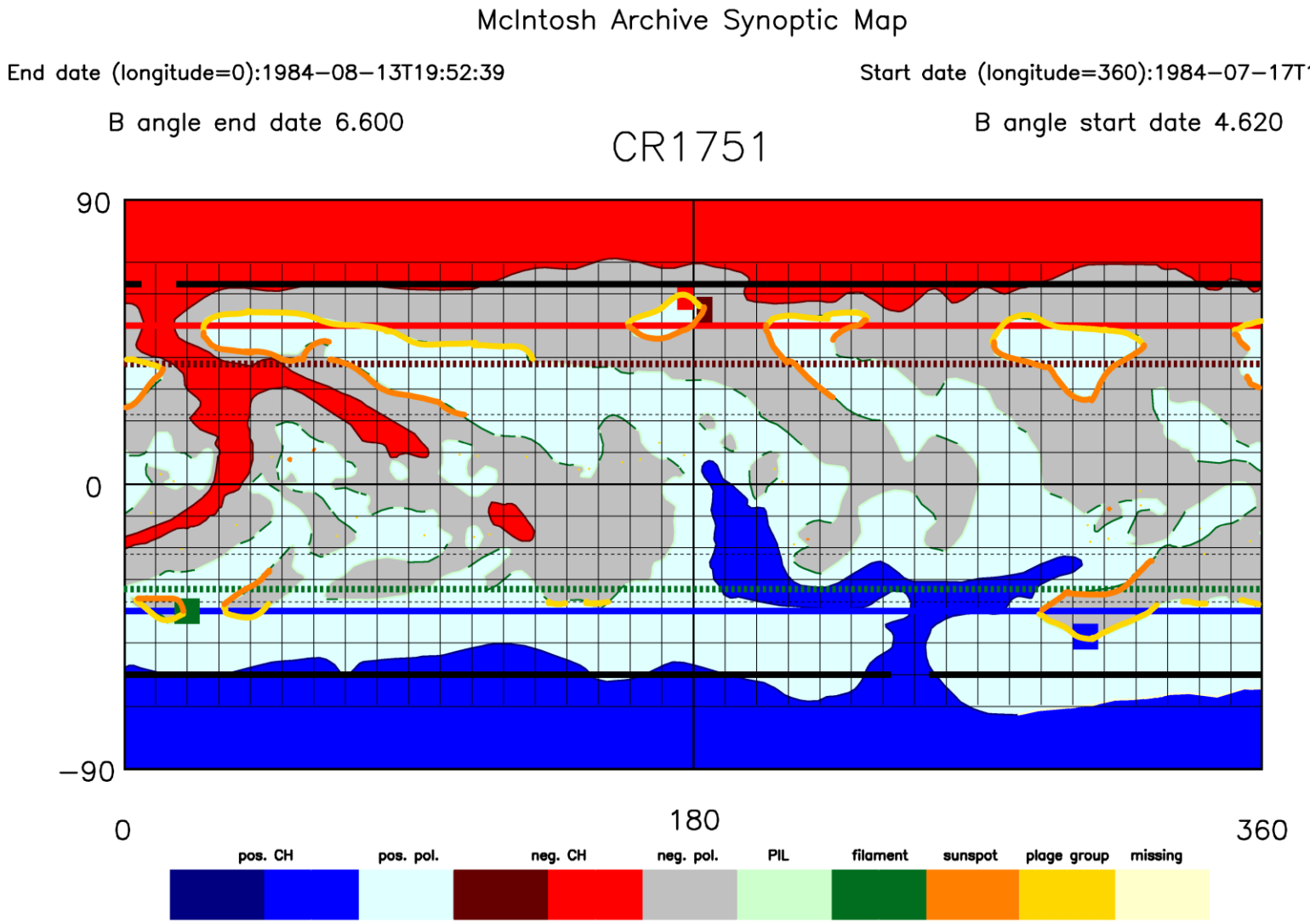
NH=Northern Hemisphere
SH=Southern Hemisphere



McIntosh Archive of 55 years of PILs (SC 19-23) and 35 years of Coronal Holes (CHs, 4/74-8/09)



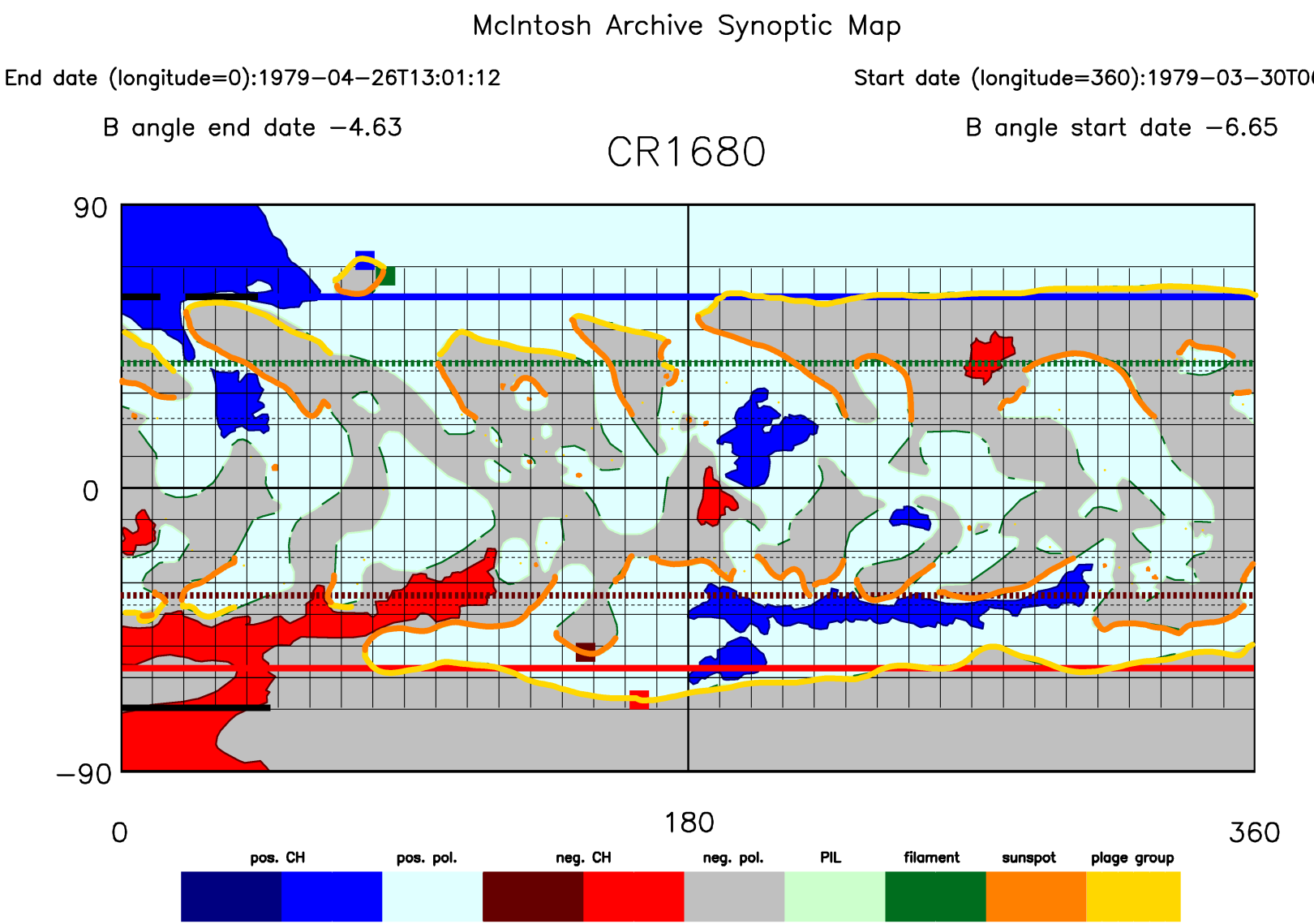
Solar minimum Jul-Aug 1984

Polar coronal hole (CH) latitudinal extent ~28-30°, with low-latitude extensions

Primary PIL (polarity inversion line) 50.0°N, 40.5°S

Secondary PIL (polarity inversion line) 38.5°N, 33.5°S

PILs Can Be Close to CH Boundaries (or Extensions)
Average Distance is 16° Apart



Early in RttP SC 21

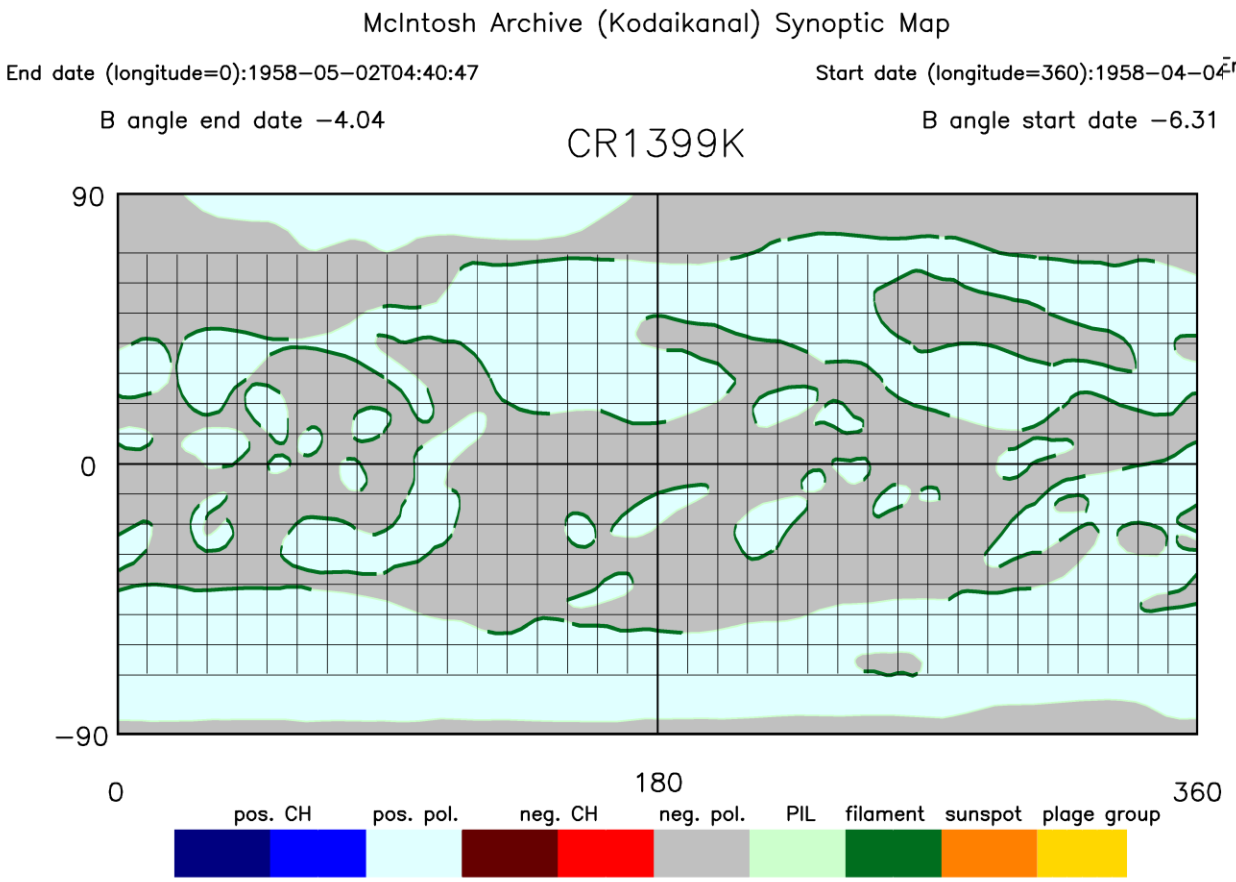
Polar CHs small (69.5cS, 60.5°N)

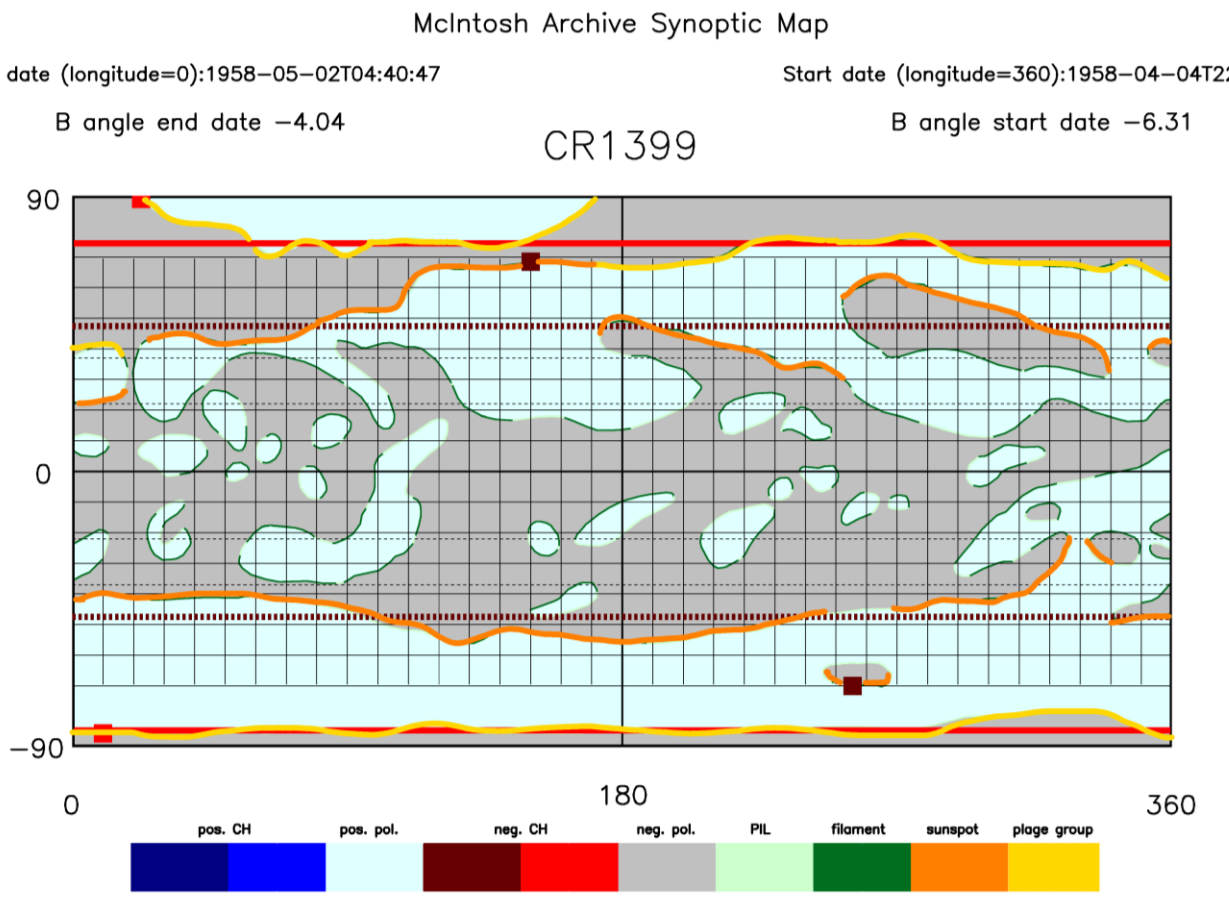
Chevron shapes of PILs from differential rotation (segments)

Average Distance of Primary-Secondary PILs is 14° apart

Polar CHs Disappear in Solar Maximum (end RttP SC 19)
Nearly Continuous Secondary PILs (or Polar Crown Filaments)

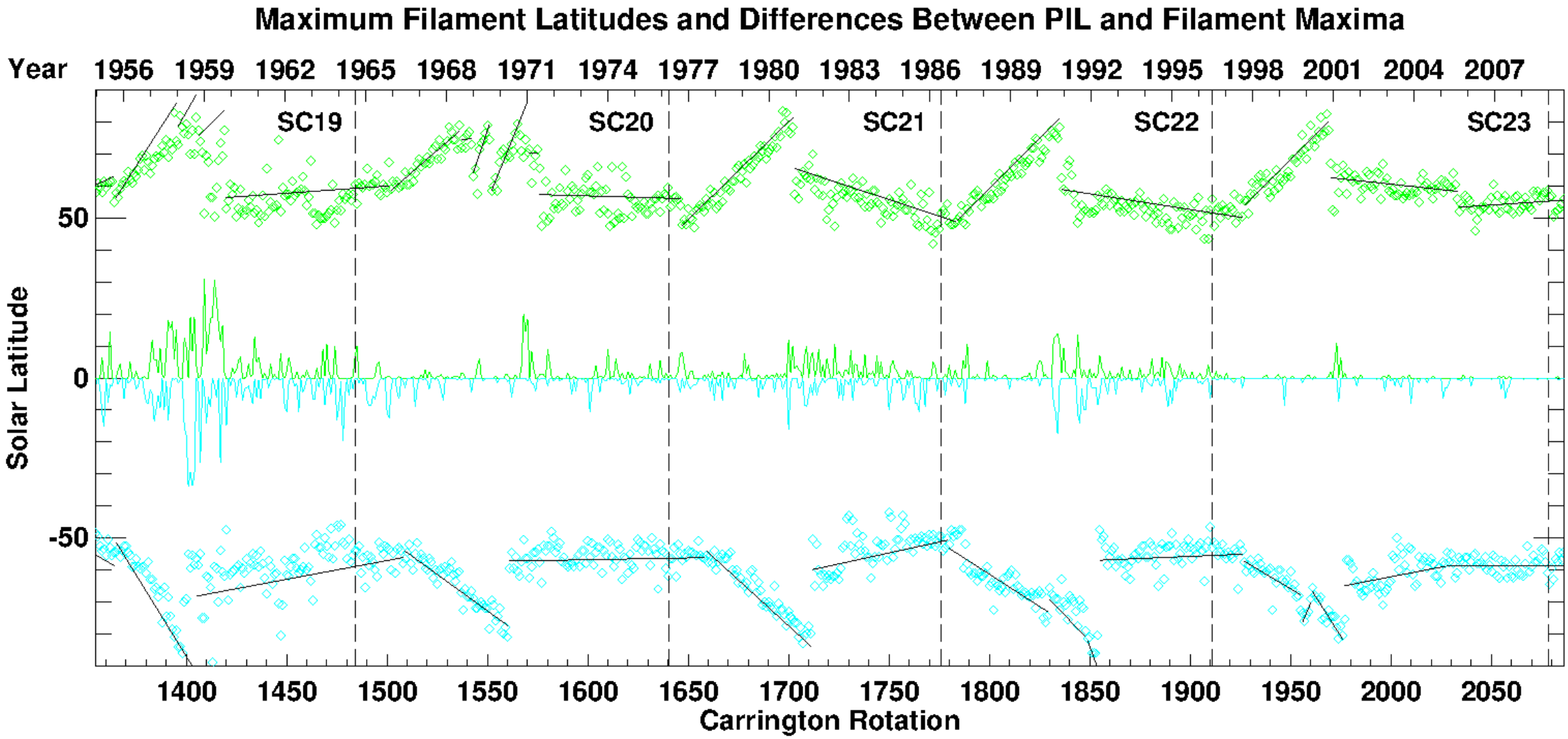
SC 19 from Kodaikanal (Makarov and Sivaraman, 1986 Atlas), no ARs
No CH data until Mk2 and He 10830Å in SC 20
Some hyperlong filaments (green) and lack of filaments in polar regions



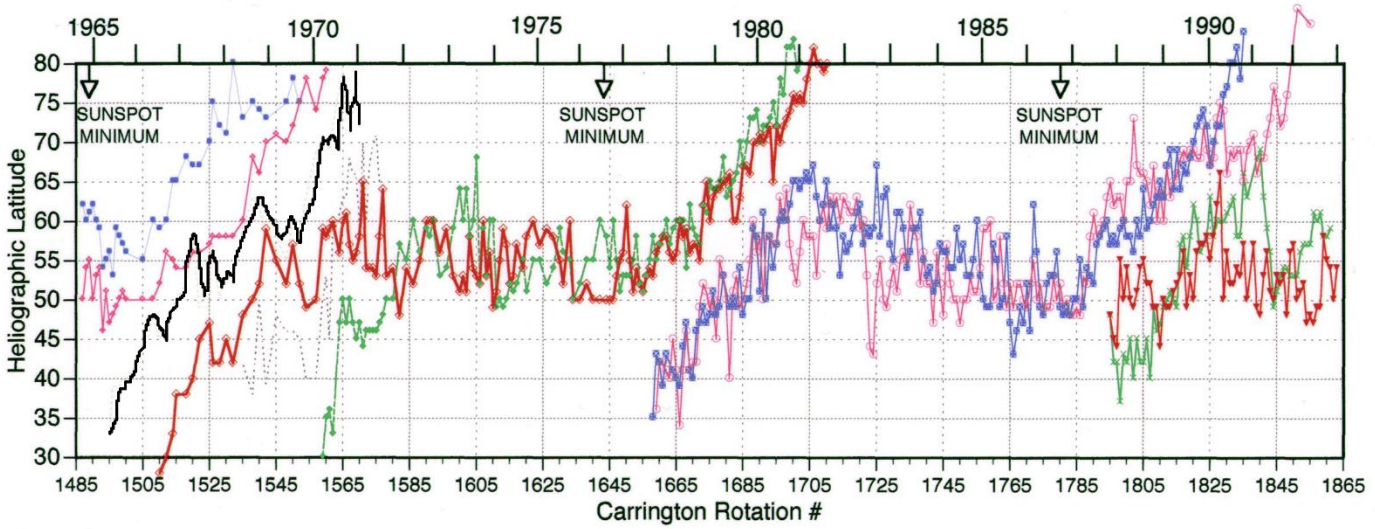


Maximum Filament Locations Very Close to Maximum PIL Locations

Ave Deviation 1.2° (6°) SC 20-23, 4.3° (12°) SC 19

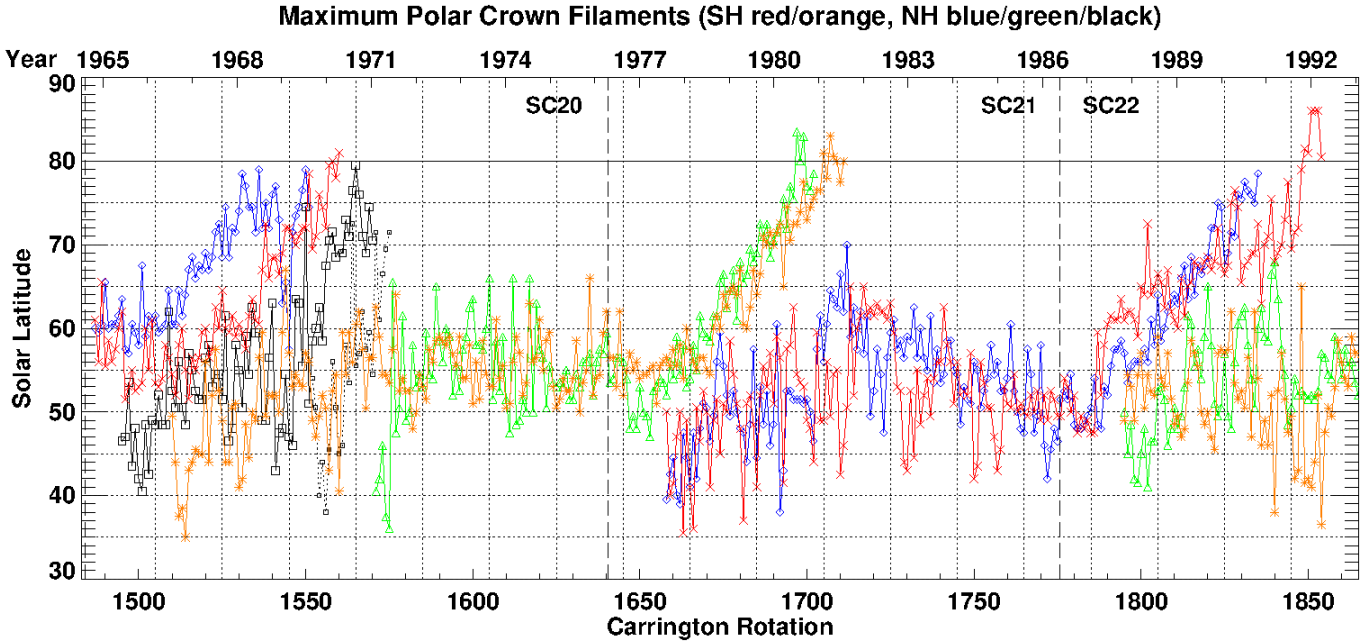


Maximum Filament Locations Similar Now to Previous Study by McIntosh (2003)



Secondary PCFs in RttP ~15° from Primary PCF and become primary after polarity change

3 RttPs in NH SC 20 (~1969-72)



Start/End latitudes ~same

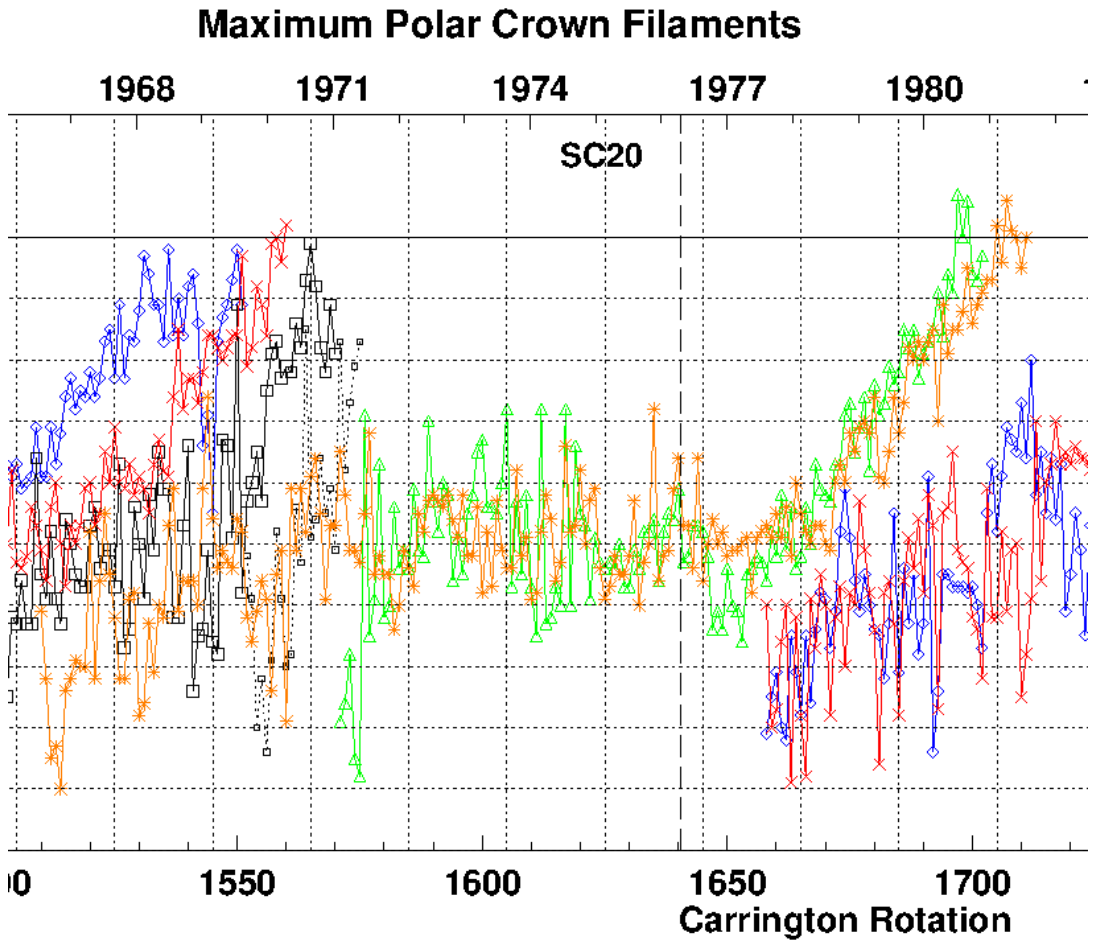
Dropout of 1st RttP ~1969 (polarity change, or 4 RttPs)

Primary-Secondary PCF ~10° start RttP and ~25° end RttP

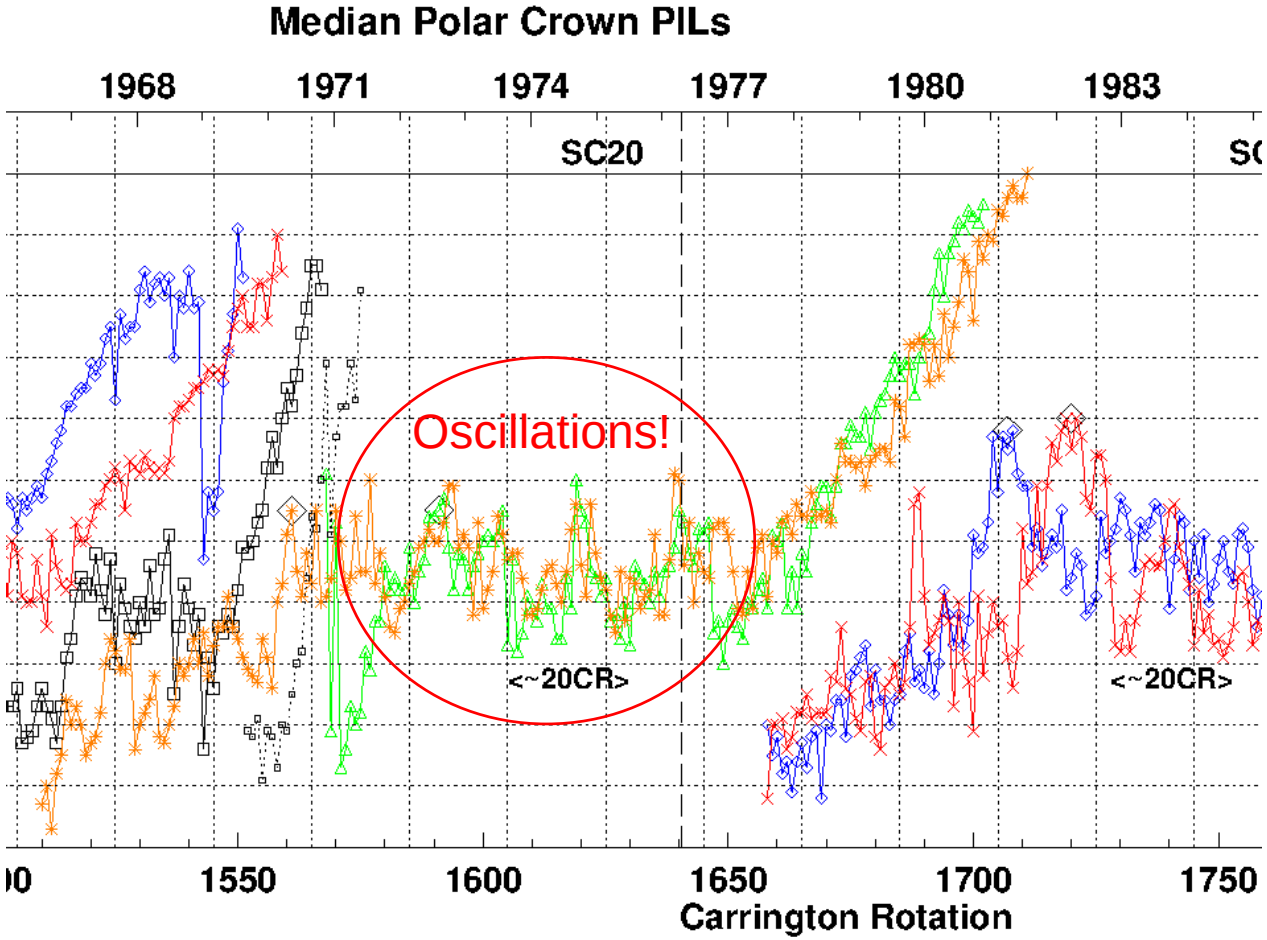
Median PILs a Cleaner, Better Story than Filaments

(~7.5° Equatorward)

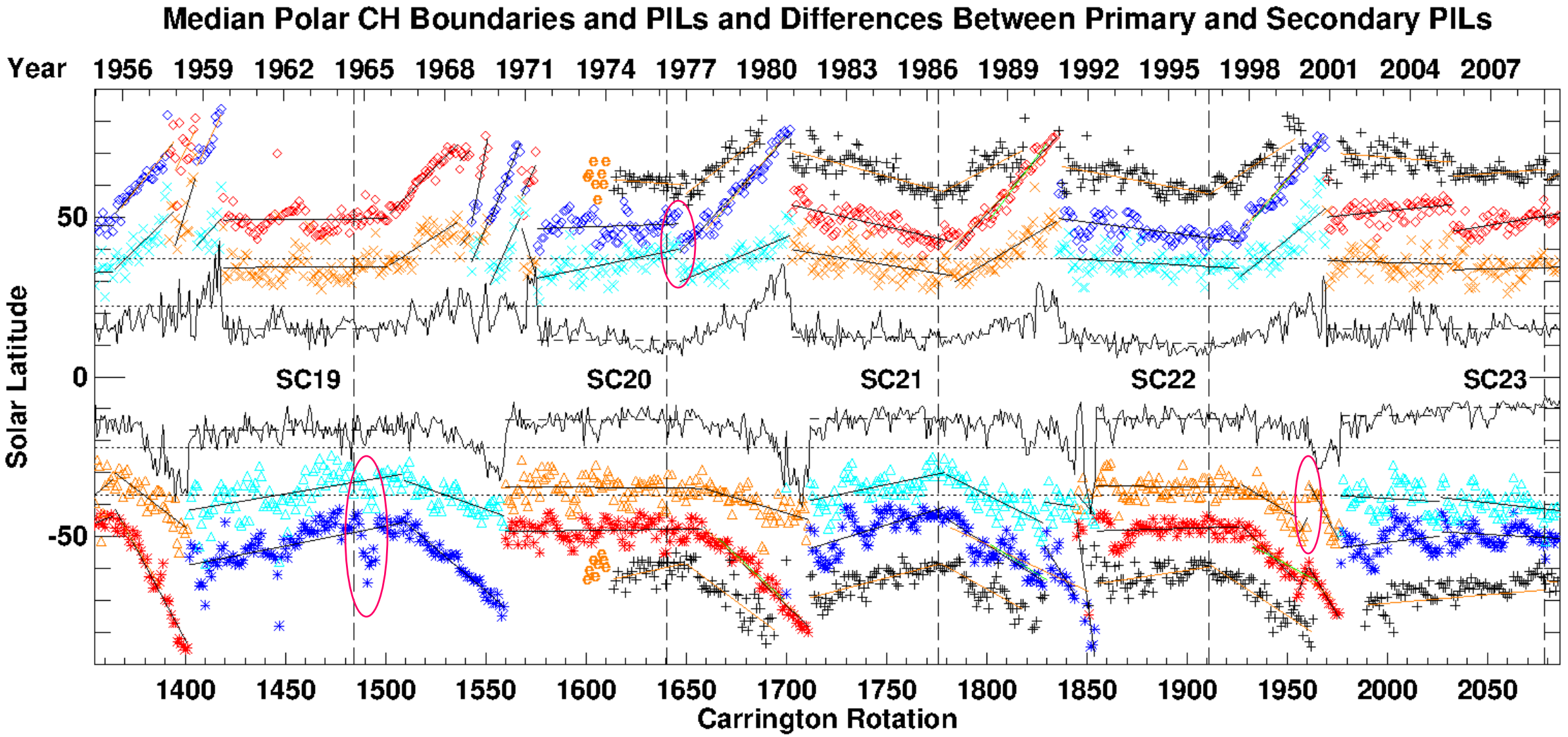
Diamonds at end RttP for Secondary PILs



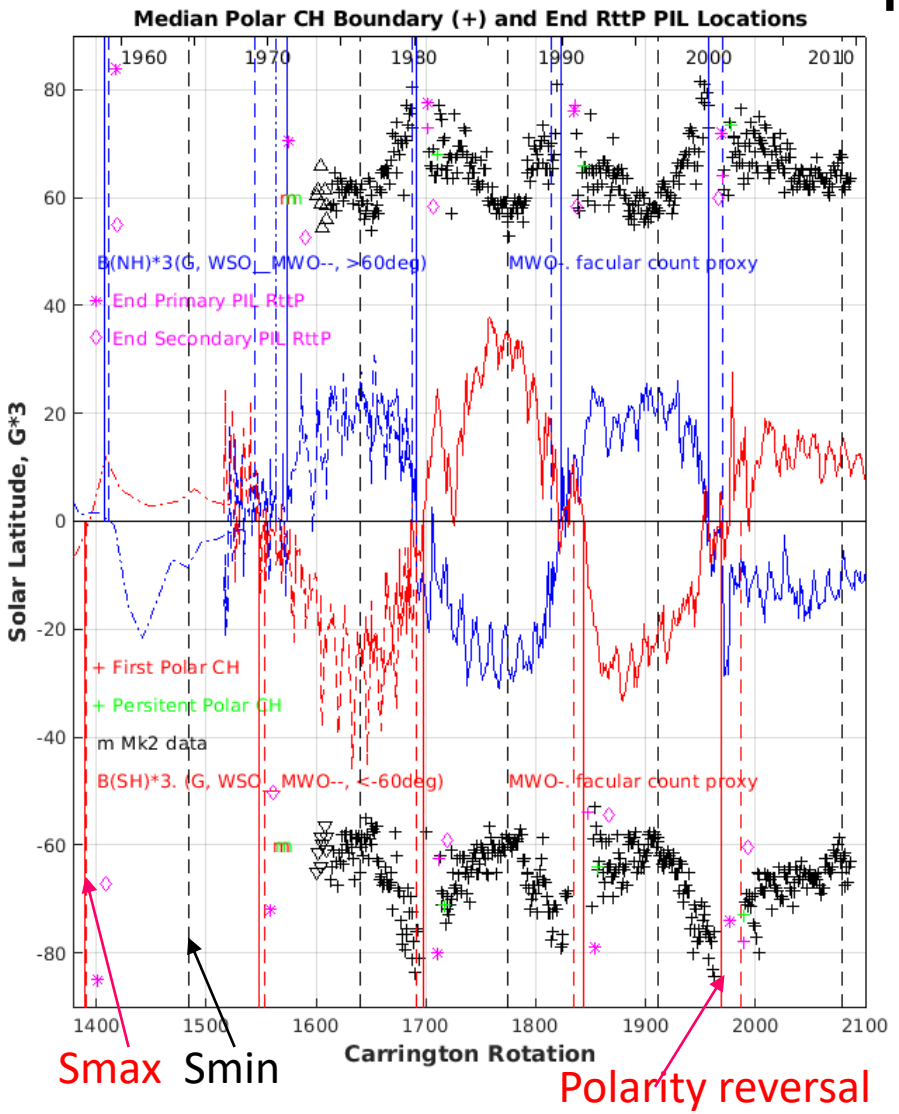
±55°



(Multiple) Rush-to-the-Poles (RttPs), non-Rush Periods (PILs 13-15°) and CH Boundaries (10830Å, max 32° SC 20-22) for SC 19-23



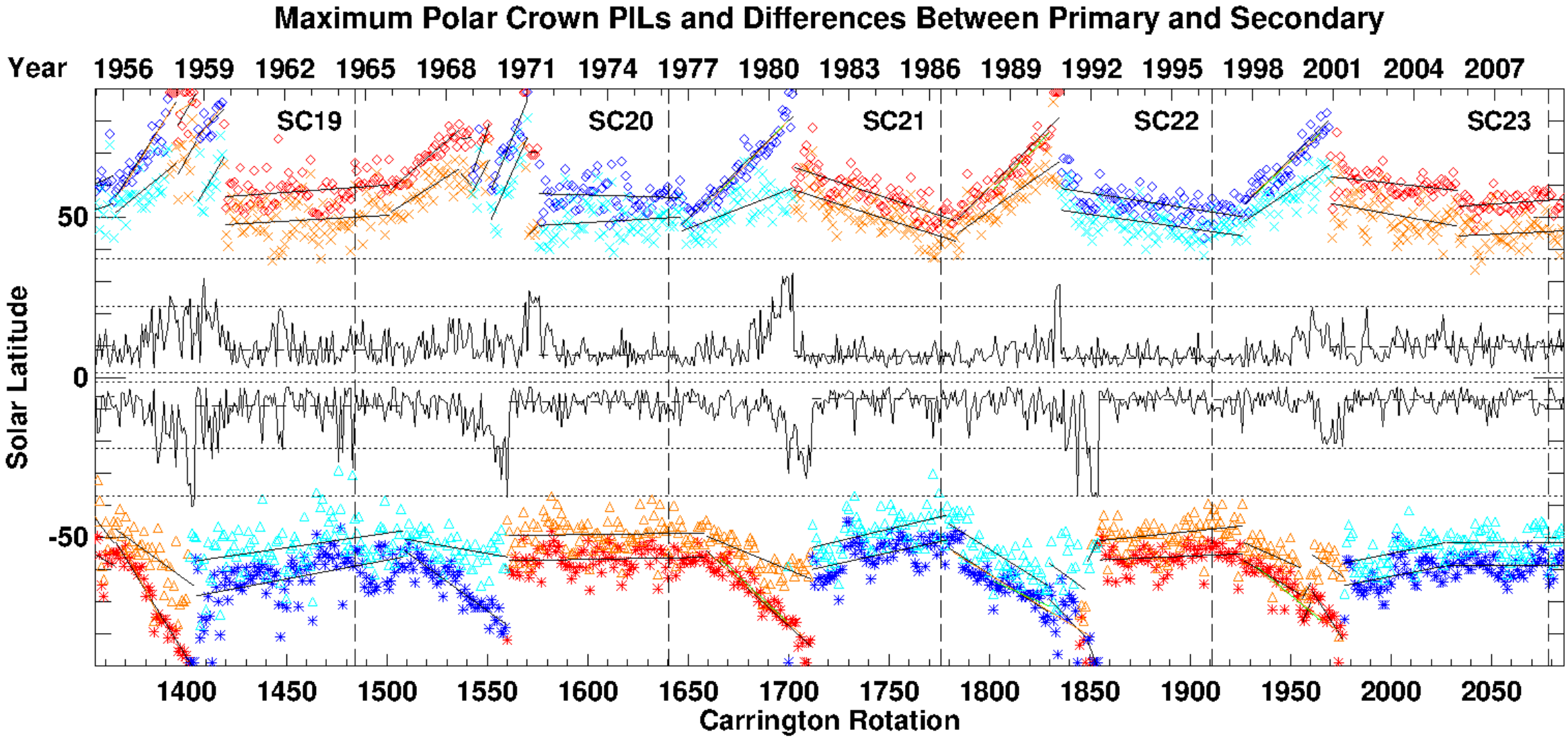
Polar CH Boundaries after Polarity Reversal and RttP PIL Endings



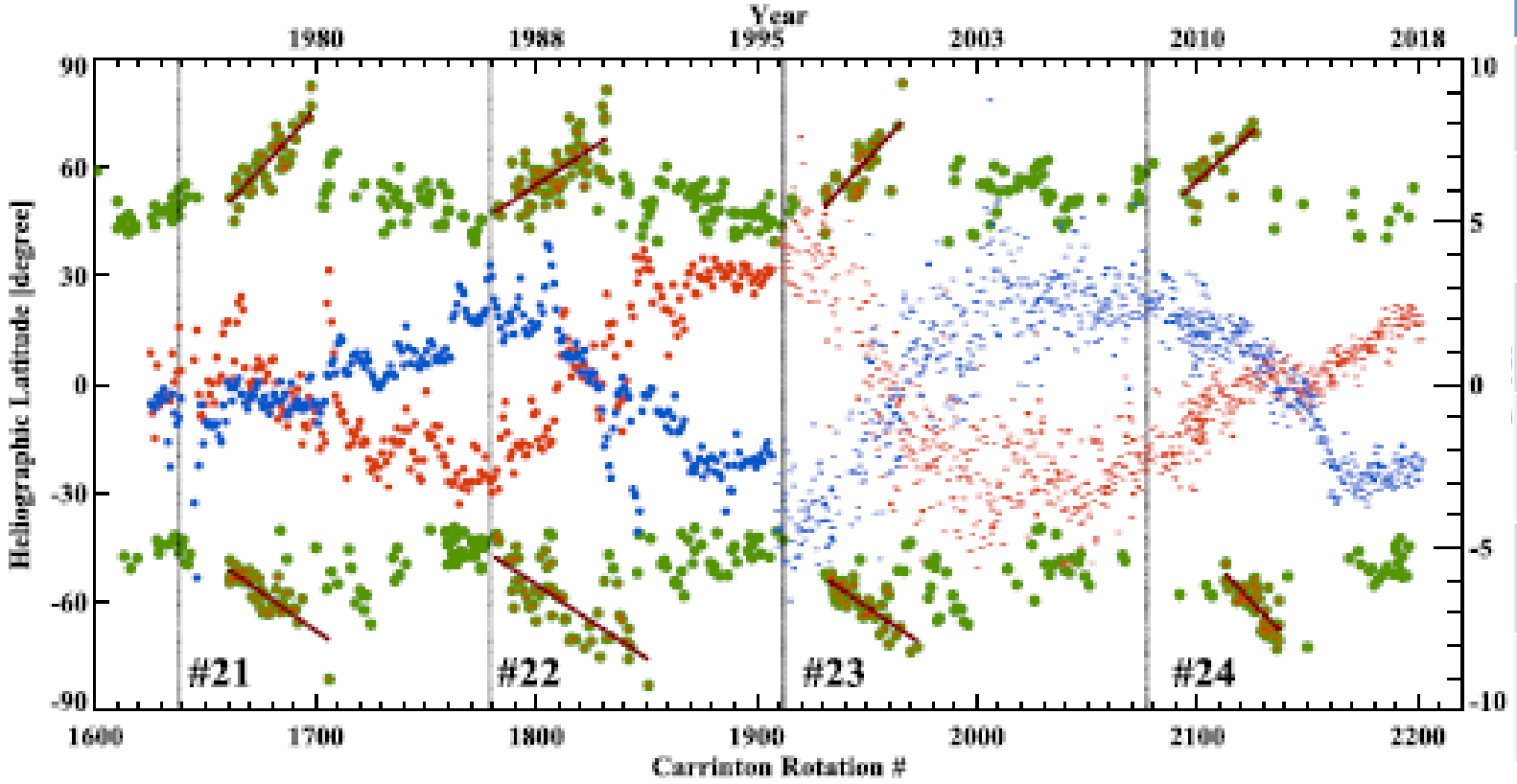
	Polarity Reversal >60° MWO SC20	Last Primary RttP	First Polar CH MK2 SC20	First Persistent Polar CH	End RttP Secondary PIL
SC 19 NH	1407Webb84	1418 (11)			1419 (12)
SC 19 SH	1385-9Webb	1401 (12)			1409 (20)
SC 20 NH	1525/1574	1575 (1)	1567 (-7)	(5) 1572 (-2)	(19) 1591 (17)
SC 20 SH	1548	1559 (11)	1560 (12)	(3) 1563 (15)	(-2) 1561 (13)
SC 21 NH	1691	1702 (11)	1702 (11)	(10) 1712 (21)	(-5) 1707 (16)
SC 21 SH	1698	1711 (13)	1712 (14)	(5) 1717 (19)	(3) 1720 (22)
SC 22 NH	1823	1835 (12)	1836 (13)	(7) 1843 (20)	(-6) 1837 (14)
SC 22 SH	1842	1854 (12)	1848 (6)	(9) 1857 (15)	(9) 1866 (24)
SC 23 NH	1957	1969 (12)	1970 (13)	(8) 1978 (21)	(-12) 1966 (9)
SC 23 SH	1969MWO	1976 (7)	1989 (20)	(1) 1990 (21)	(3) 1993 (24)
Medians CR lags	Lags prior col and reversal	11 NH 12 SH	11-13 NH 12-14 SH	7-8 NH 20-21 3-5 SH 15-19	-5--6 NH 14 3 SH 22

- The first polar CH (+) often occurs right after the last RttP primary PIL (*)
- First polar CH (+) ~1 year (11-14 CR) after polarity reversal >60°
- Persistent polar CHs (+) in the SH are 3-5 CR later, and are 7-8 CR later in the NH after the first polar CH
- The RttP end of the secondary PIL (◊) is ~22 CR past polarity change in the SH and only ~14 CR in the NH

Maximum PIL Locations are ~9° Poleward
primary RttP slope > secondary, but not as clean



Comparison Good with Xu et al. (2018) Filaments

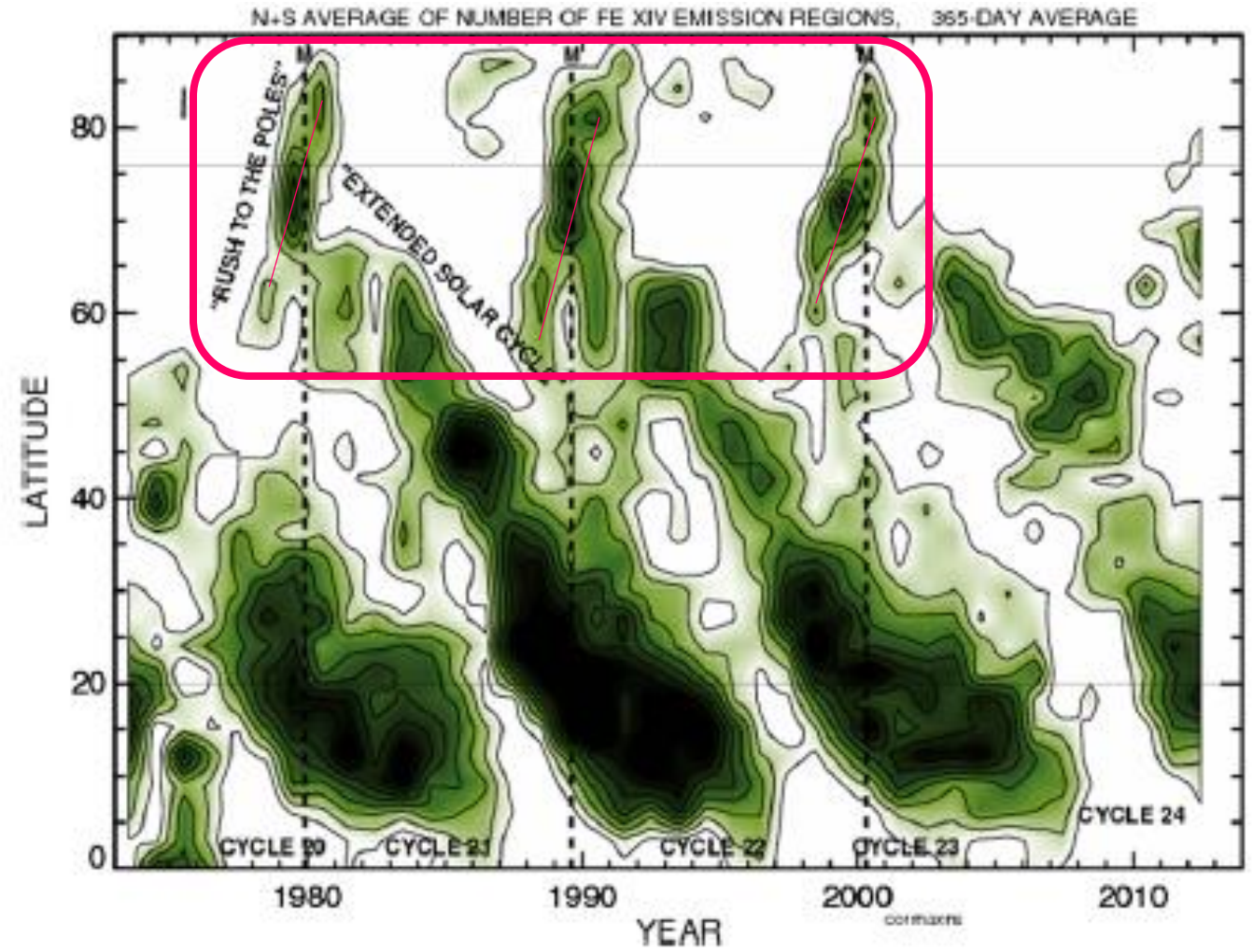


	NH slope °/CR, °Lat	|SH| slope °/CR, °Lat
SC 21 Xu	0.65 49-72	0.43 52-72
SC 21	0.75 46-75m 0.65 54-80x	0.59 48-75m 0.55 55-81x
Sc 22 Xu	0.40 47-68	0.41 49-77
SC 22	0.63 38-71m 0.51 49-75x	0.29 47-67m 0.38 55-81x
SC 23 Xu	0.67 49-72	0.42 53-71
SC 23	0.69 48-72m 0.56 56-76x	0.50 47-68m 0.46 56-76x

From Figure 3 of Xu et al. (2018) using Kanzelhöhe and Big Bear filaments (green) above 40° from Hα images where the RttP slopes are red lines. Magnetic fields are red (SH) and blue (NH) dots above 50° from Kitt Peak (1975-1995 l-o-s B so smaller), MDI/SOHO (1996-2010 radial B), and HMI/SDO (2010-2018 radial B).

Usually, RttP slopes for our study are faster for median (m) primary PIL locations than for maximum (x) . Xu's results are low or in-between. Better (faster) results with Xu et al. Kodaikanal (AGU poster).

Comparison Good with Altrock (2003, 2014)

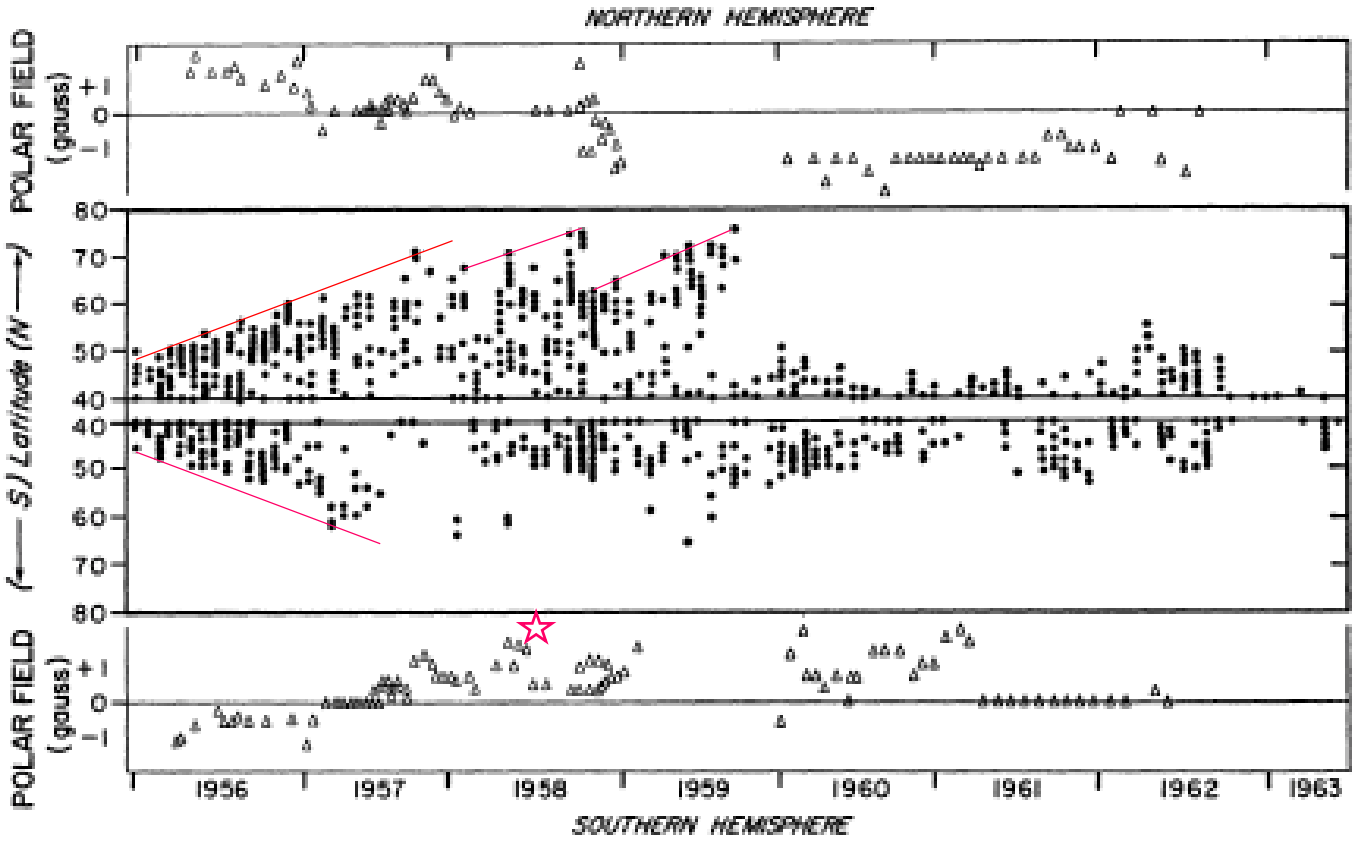


From Figure 1 of Altrock (2014) using Fe XIV 5303Å green corona line with yearly smoothing and NH and SH added together for SC 21-23.

	Av NH+|SH| Slope °/CR	Av NH+|SH| °Lat Begin/End
SC 21 Xu	0.54±0.11	52-74
SC 21 CR1666-1699	0.70±0.09 0.61±0.05	50-73 median 57-78 max
SC 21 Altrock	0.63	62-82
SC 22 Xu	0.41±0.01	52-70
SC 22 CR1802-1830	0.63±0.21 0.46±0.18	51-68 median 61-74 max
SC 22 Altrock	0.85	57-81
SC 23 Xu	0.55±0.13	51-70
SC 23 CR1933-1965	0.54±0.20 0.56±0.18	51-68 median 58-76 max
SC 23 Altrock	0.65	60-81

The RttP slopes for Altrock are in range of Xu et al. (2018) and this study, except for SC 22 where they are a bit larger. The latitudes start and end a bit higher.

Comparison Good with Hyder (1965)



From Figure 1 of Hyder (1965) using filaments from 40-80° from Meudon Hα images with estimated RttP slopes in red, with a red star in the SH with fewer observations where the median primary PIL RttP ended.

SC 19 CR range	°/CR °lat range NH or |SH|
NH RttP#1 Hyder	0.89 49-73 (24/27)
NH RttP#1 1367-1394	0.79 53-73m 1.03 58-85x
NH RttP#2 Hyder	0.90 68-77 (9/10)
NH RttP#2 1395-1405	1.25 65-77m 0.40 83-87x
NH RttP#3 Hyder	1.17 63-77 (14/12)
NH RttP#3 1406-1418	1.34 66-82m 0.82 75-85x
SH RttP Hyder	0.90 45-64 (19/21)
SH RttP 1367-1388	1.05 45-66m 1.21 52-76x

Slopes ~0.9°/CR from Hyder Figure 1, about same as our study.

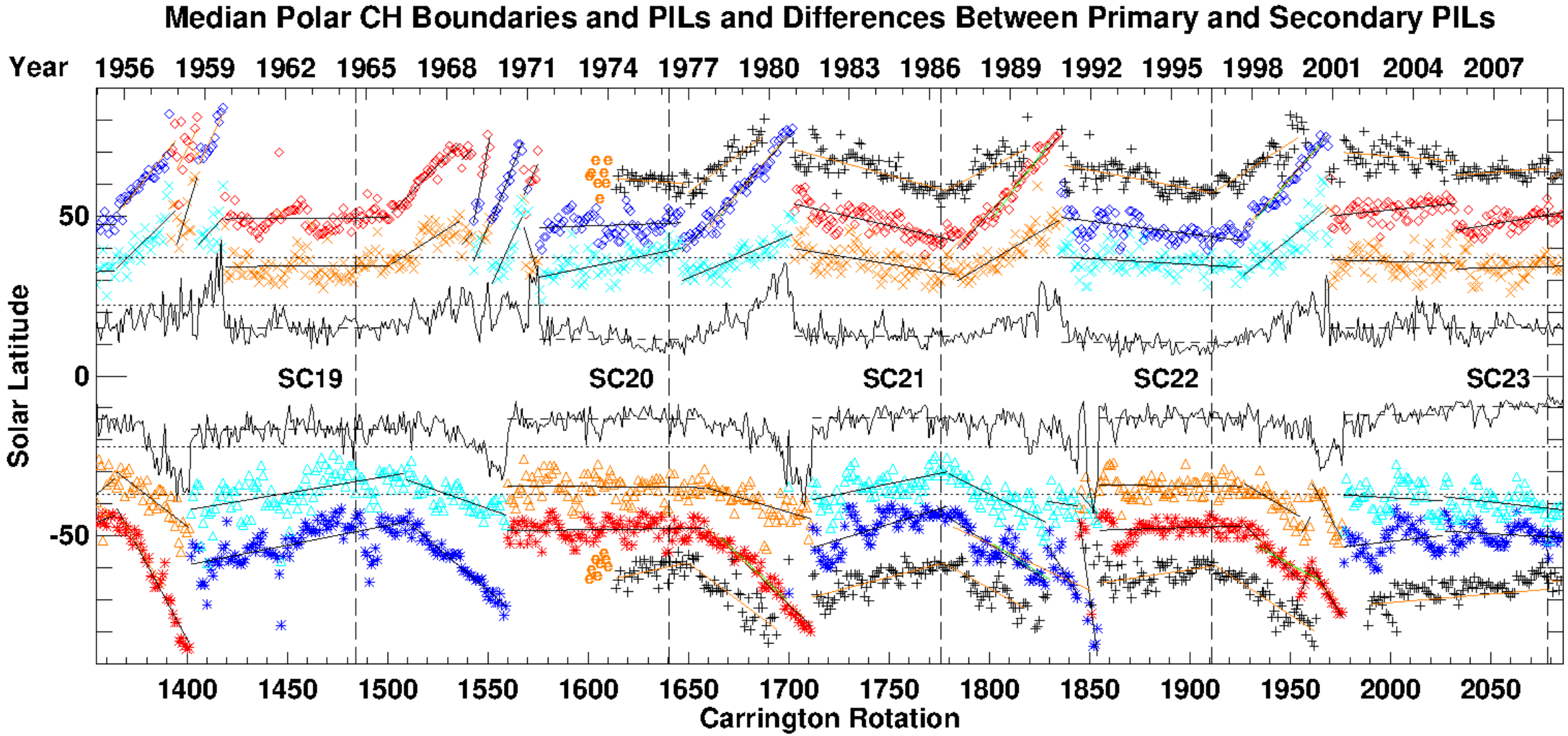
Comparison Good with Xu et al. (2020)

SC## NH, SH	CR range	Lat begin/end median	Lat begin/end max	Lat/CR slope Med max Xu 2020 (2018)	
19 NH Xu 2020	1365- 1406	53.4 to 75.8±0.5	59.2 to 89.4	0.55±0.04 0.51±0.09	0.74±0.05max
SH	1365- 1428late	-56.8 to -64.3±0.9	-65.1 to -75.1	-0.12±0.02 -0.88±0.04	-0.16±0.02max
20 NH Xu 2020	1502- 1521early	50.6 to 63.9±0.7	58.6 to 69.1	0.70±0.06 0.29±0.06	0.55±0.08 max
SH	1509- 1548early	-45.7 to -64.9±0.7	-54.9 to -70.8	-0.49±0.03 -0.39±0.08	-0.41±0.05 max
21 NH Xu 2020	1660- 1698	46.0 to 75.1±0.7	54.3 to 79.5±0.9	0.75±0.03 0.67±0.05	0.65±0.04 max (0.65±0.07)
SH	1660- 1706	-47.7 to -75.2±0.7	-55.0 to -80.6±0.9	-0.59±0.02 -0.57±0.07	-0.55±0.03 max (-0.43±0.05)
22 NH Xu 2020	1779- 1832	38.3 to 70.5±0.6	48.6 to 74.8±0.9	0.63±0.02 0.59±0.08	0.51±0.03 max (0.40±0.06)
SH	1782- 1851	-47.2 to -67.2±0.5	-54.6 to -81.1±0.7	-0.29±0.02 -0.57±0.07	-0.38±0.02 max (-0.41±0.05)
23 NH Xu 2020	1930- 1965	48.0 to 72.0±0.7	56.4 to 76.0±1.0	0.69±0.04 0.77±0.09	0.56±0.05 max (0.67±0.10)
SH	1932- 1973	-50.2 to -69.5±0.6	-59.6 to -78.8±1.0	-0.47±0.02 -0.50±0.04	-0.47±0.04 max (-0.42±0.05)

Xu et al. 'Migration of Polar Crown Filaments in the Past 100 Years' (SH002-0024 Fall AGU 2020 and accepted Astrophysical Journal article 2021) uses Kodaikanal Hα images (and from BBSO and KSO later years) to find filaments and the slopes for the Rush-to-the-Poles.

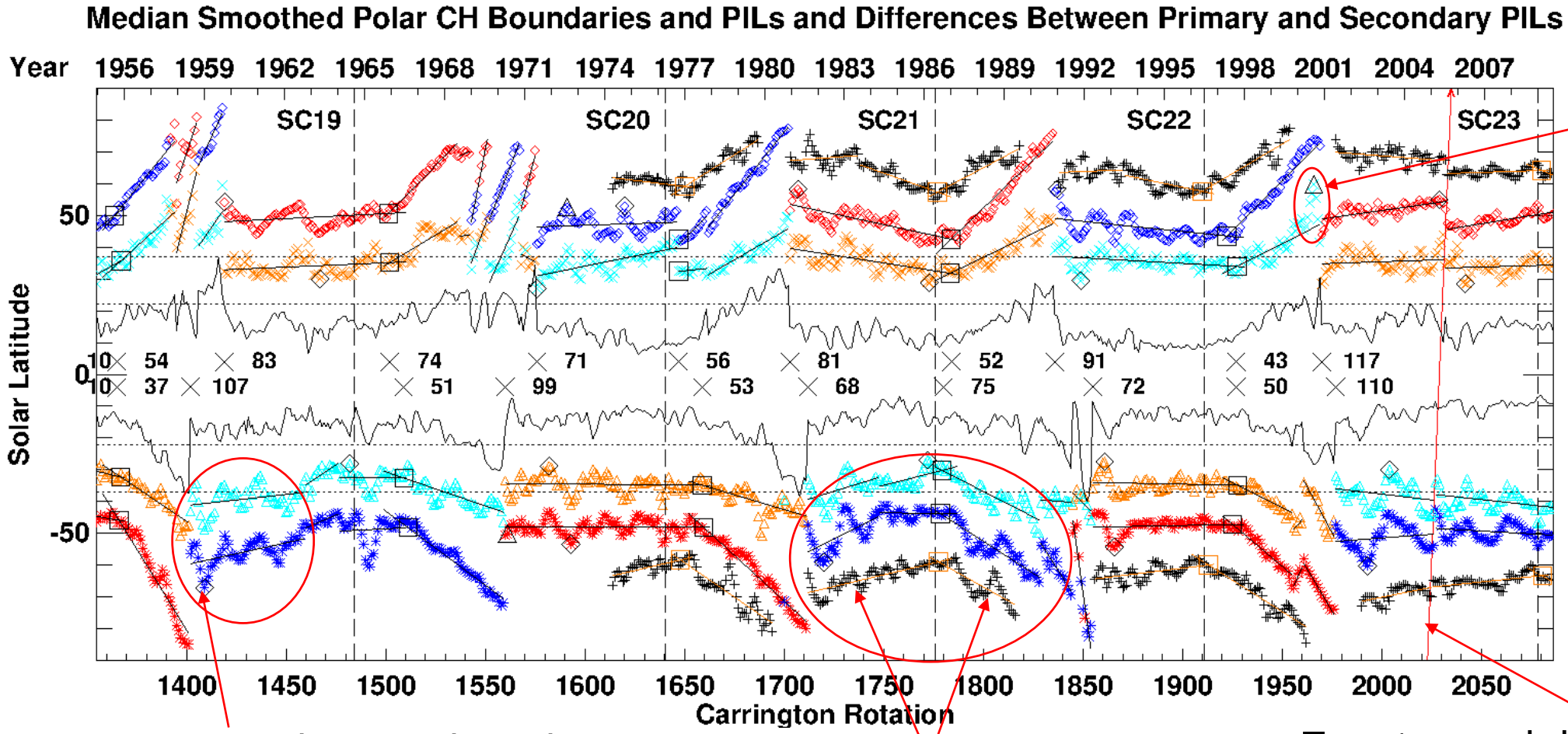
- Slopes are larger than for the filaments found in Xu et al. (2018), and in better agreement with the present study.

SC 19-23 Median PIL and CH Boundary Locations
Adjusted before 3-CR Smoothing



SC 19-23 Oscillations after Secondary PIL Rush-to-the-Pole End Peaks

The end of the Rush-to-the-Pole (RttP) of the secondary PIL (diamonds or triangles) is usually later than the RttP end of the primary PIL marking the polarity change at the pole at Solar maximum (Smax), red=negative and blue=positive



Early end ~60°N in the Rush-to-the-Pole (RttP) Secondary PIL

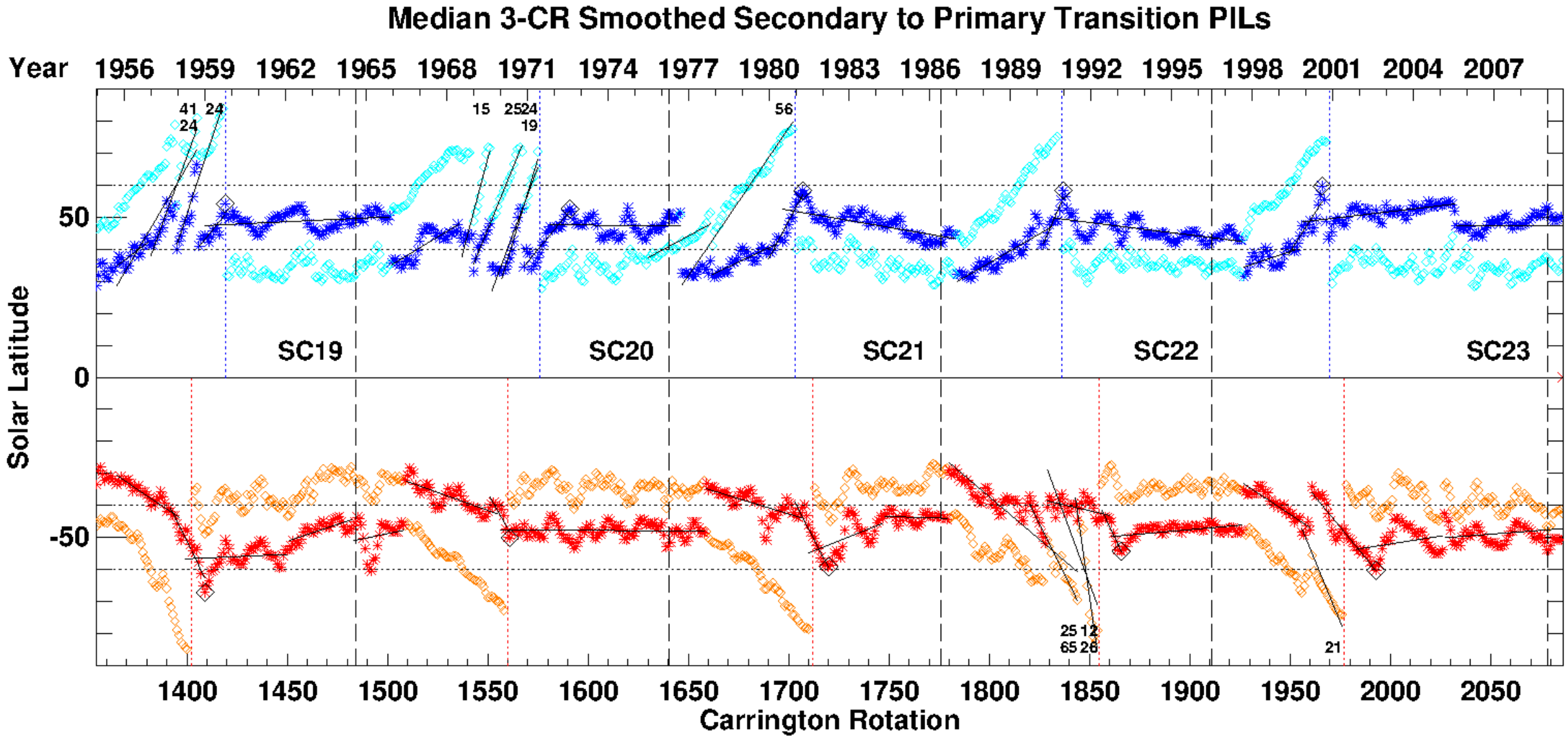
Smax Secondary Rush-to-the Pole (RttP) PIL ends in Primary non-Rush PIL ~67°S

Oscillations also in CH boundary

Equatorward drop in latitude from South to North ~15°/CR (CR=Carrington Rotation)

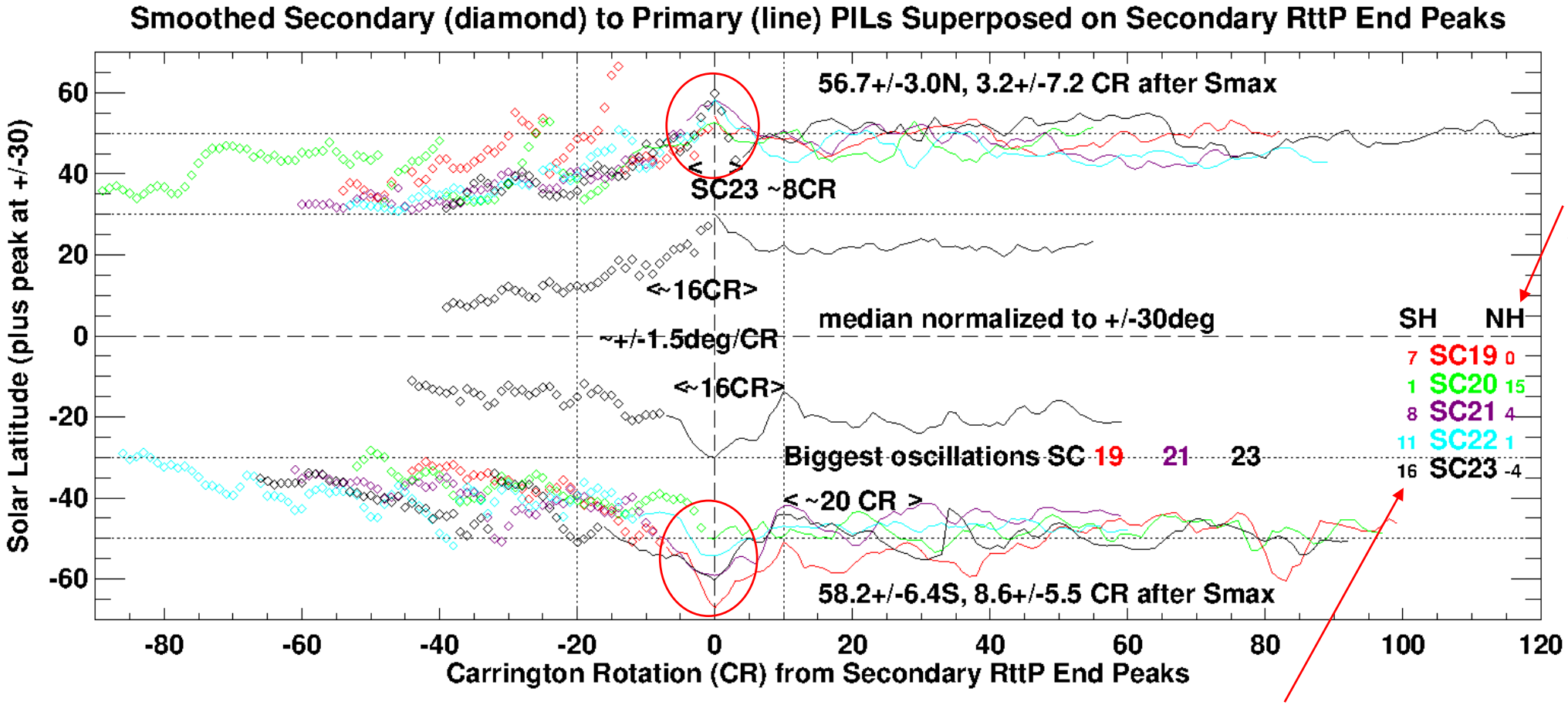
Transition PILs are Secondary RttP (◊ peaks) to non-rush Primary

Slopes found for full (secondary plus primary) multiple RttPs



Secondary PIL Ends Its RttP ~57°N (~58°S) in the Primary non-Rush PIL ~3 CR (~9 CR) after Solar Maximum Polarity Change

Superposed Epoch Plot with the end of the Secondary PIL's RttP at Zero



Northern Hemisphere (NH) secondary PIL RttP end is ~3 CR (1 CR median) after the Solar maximum (Smax) polarity change

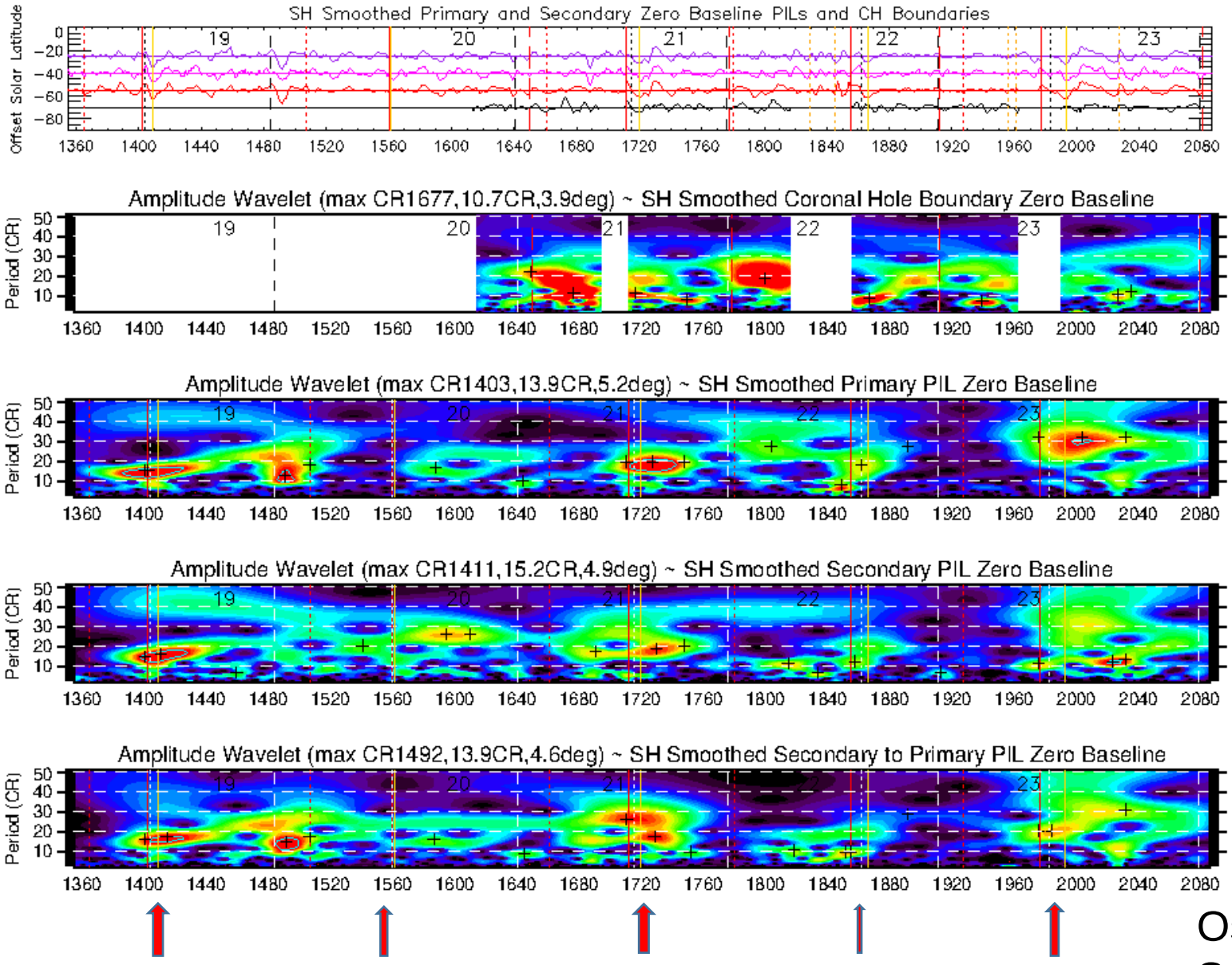
Southern Hemisphere (SH) secondary PIL RttP end is ~9 CR (8 CR median) after the solar maximum polarity change

~16 CR Oscillations from Solar Maximum Transition Peaks

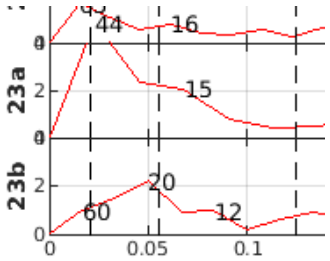
Red lines Smax polarity change when primary PIL ends its RttP

Gold lines transition peaks or secondary PIL RttP endings

SH



Fast Fourier Transform (FFT) Amplitudes (°Lat) and Periods (CR)
SC 23a ~5° ~35CR
SC 23b ~2° ~20+CR



~10-35 CR period of oscillations →

Largest SH (Southern Hemisphere) oscillations in odd SCs 19, 21, 23

Oscillations ~16 CR Smax Transition Peaks

FFT

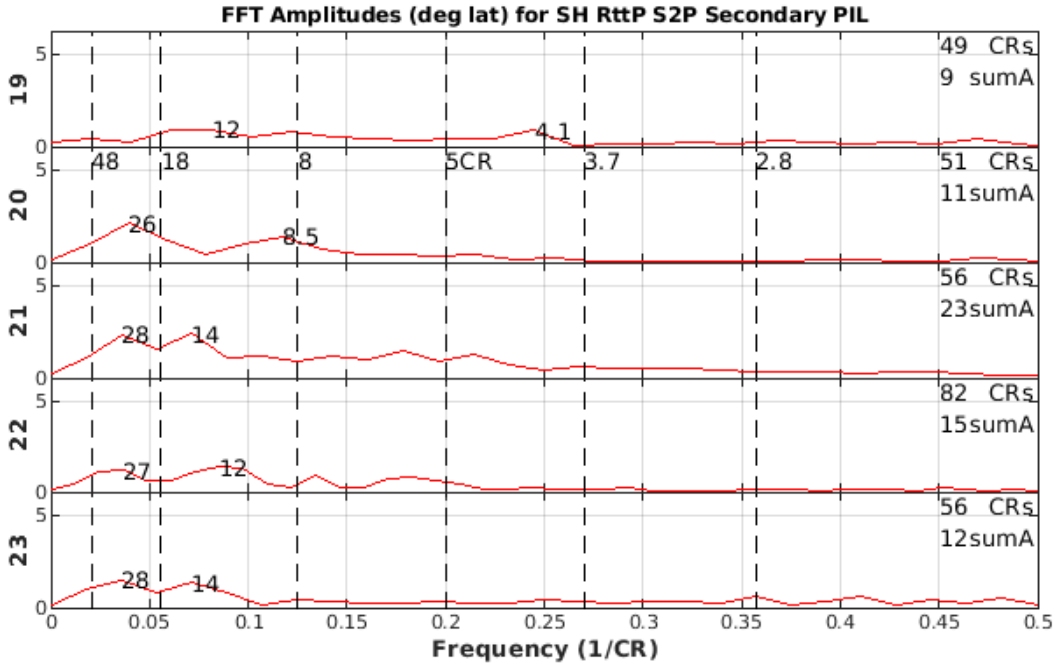
SH NH

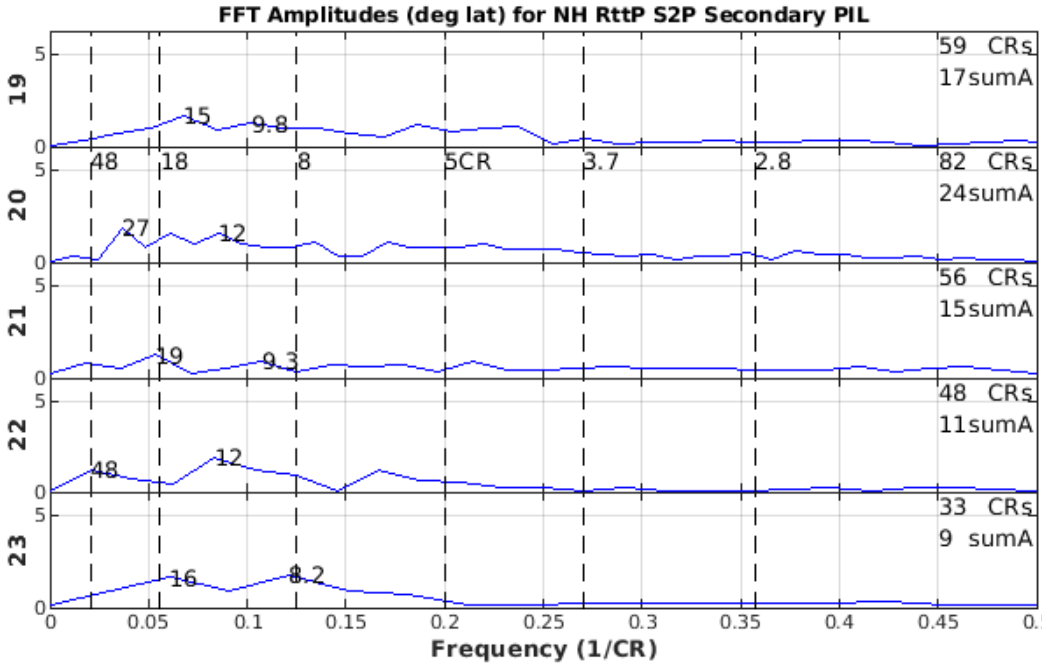
Small CR

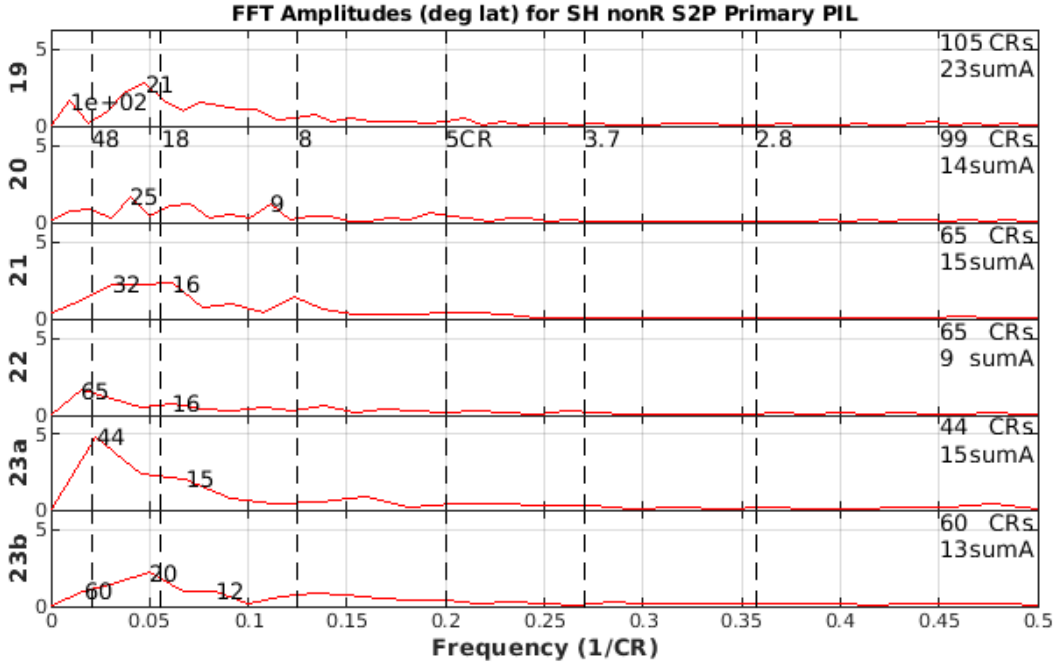
RttP Secondaries

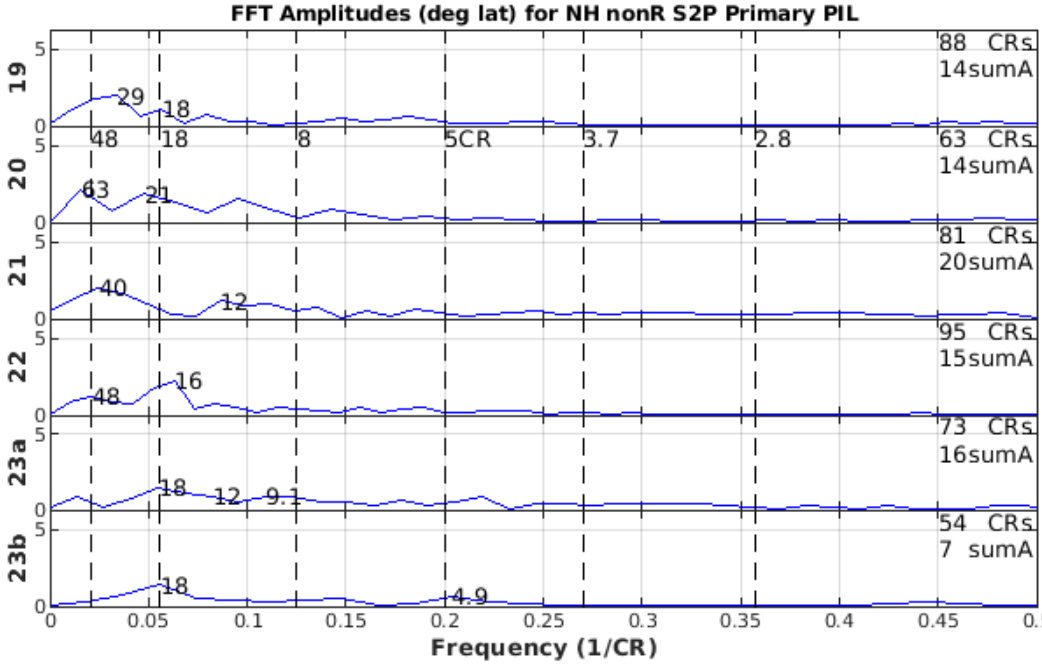
Large CR

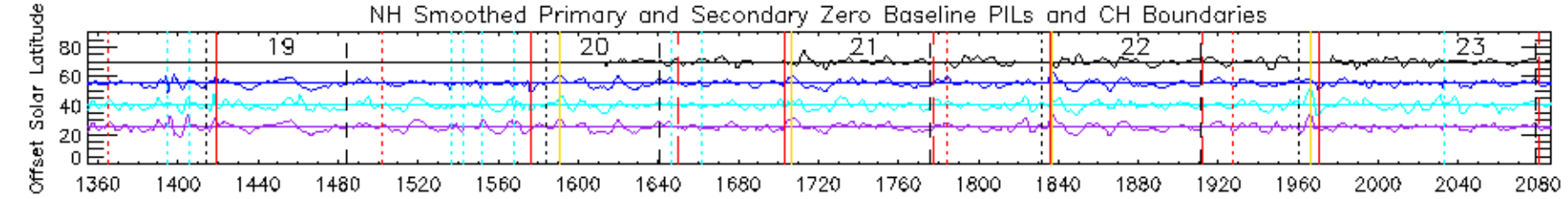
Non-Rush Primaries

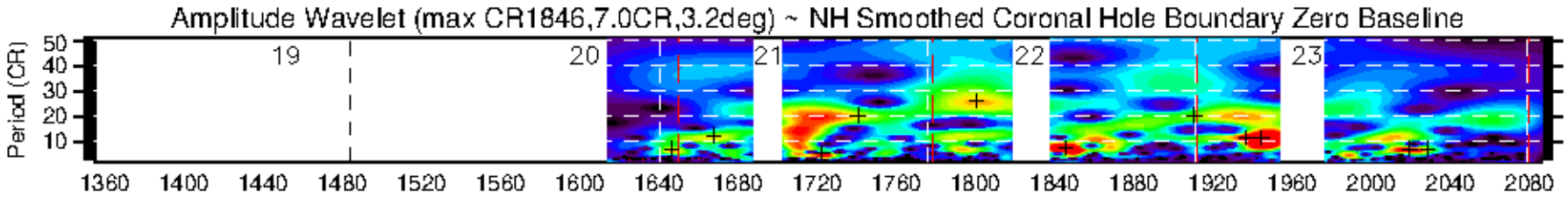


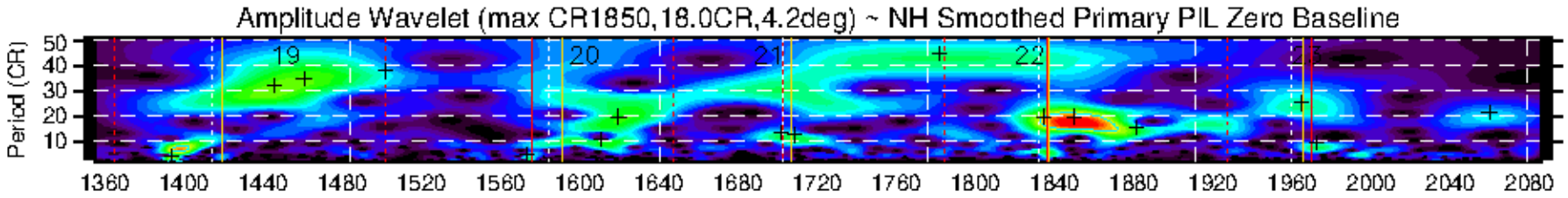


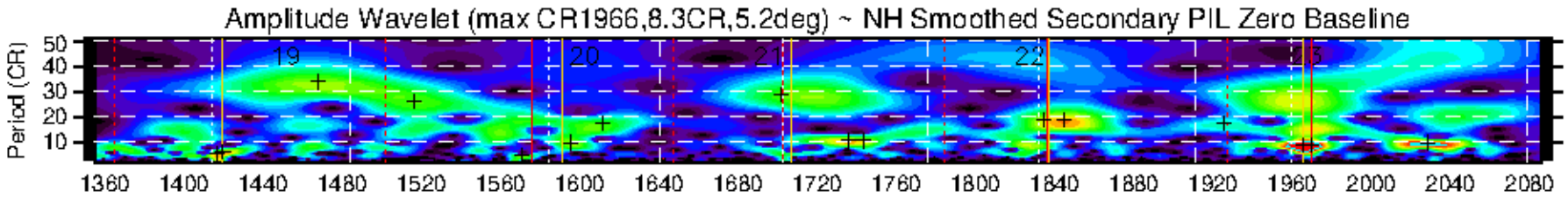


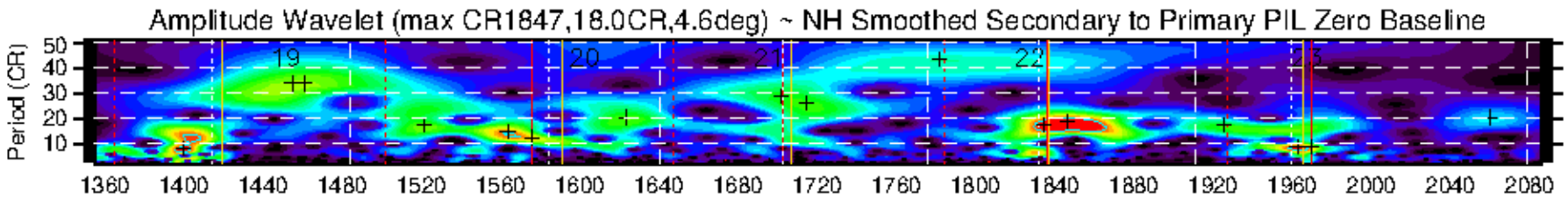












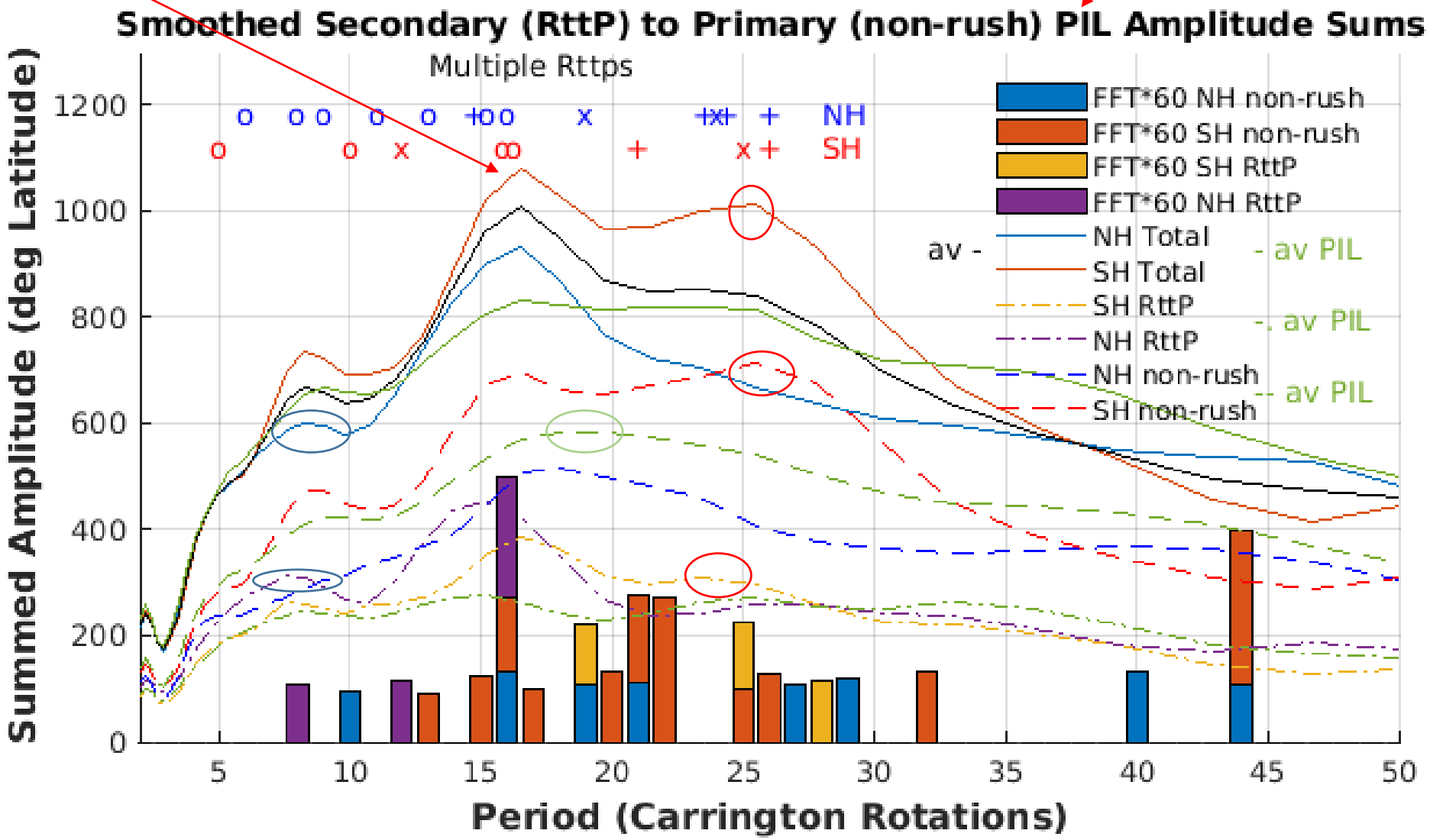
NH

NH amplitudes < SH except for RttP <18 CR

Secondary PIL amplitudes > Primary PIL

~16 CR PIL Peak Period from FFT Bars and Wavelet Amplitude Sums

Purple curve from previous slide



Av PIL = primary + secondary PIL (av NH + SH)

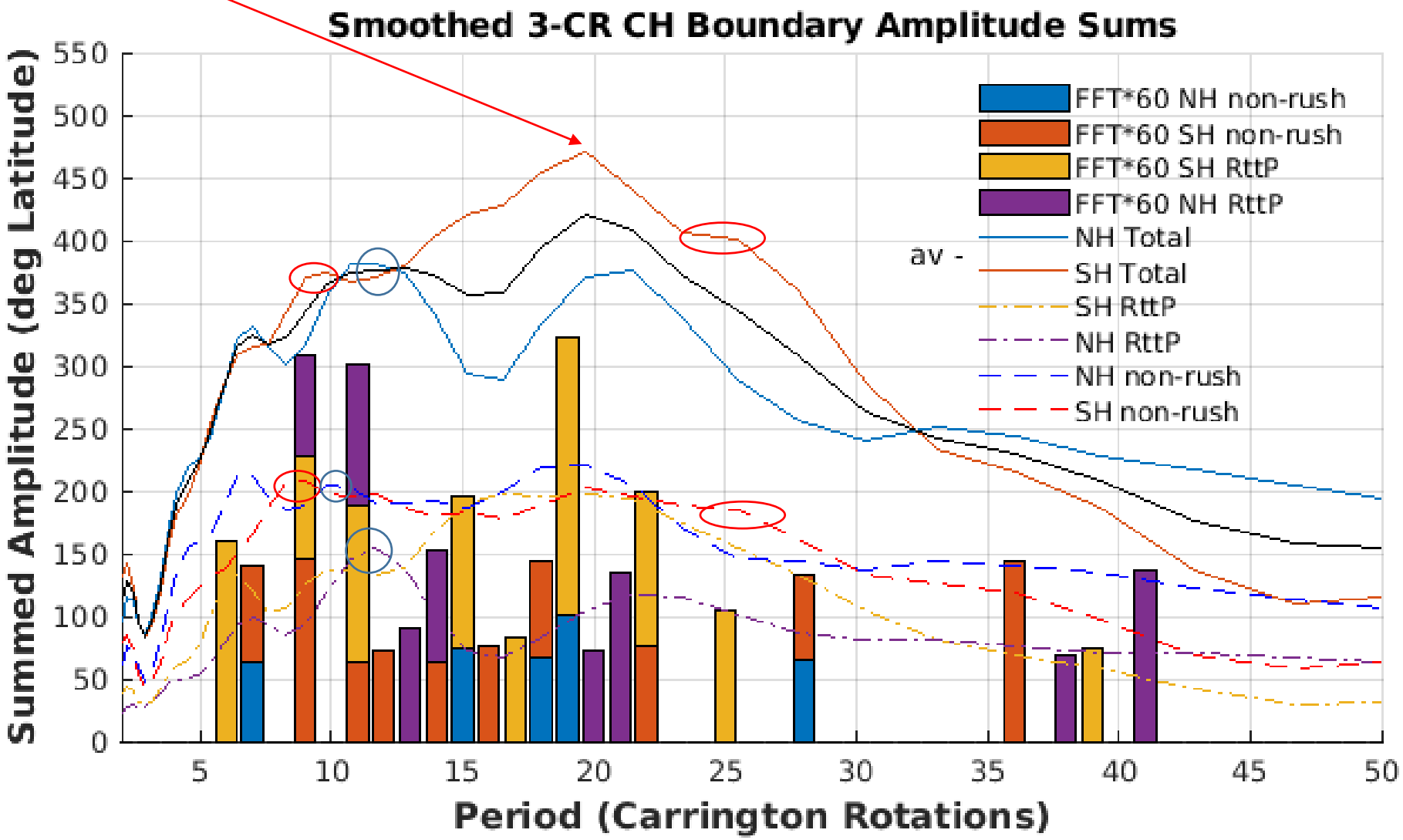
SH peak ~25 CR, non-Rush

NH peak ~8 CR, RttP

Av PIL non-Rush peak ~20 CR

~20 CR Period for CH Boundary from FFT Bars and Wavelet Sums

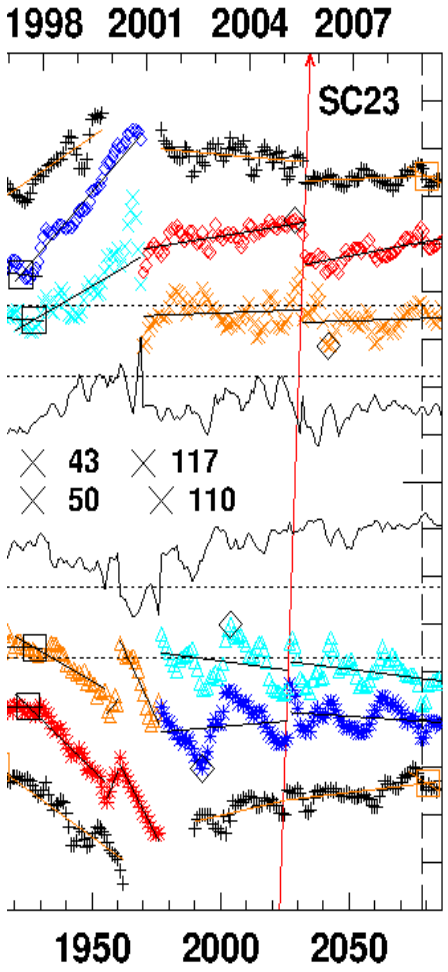
No major ~16 CR period because have only one CH Boundary



SH peak
~25, ~9 CR
- Similar to PIL

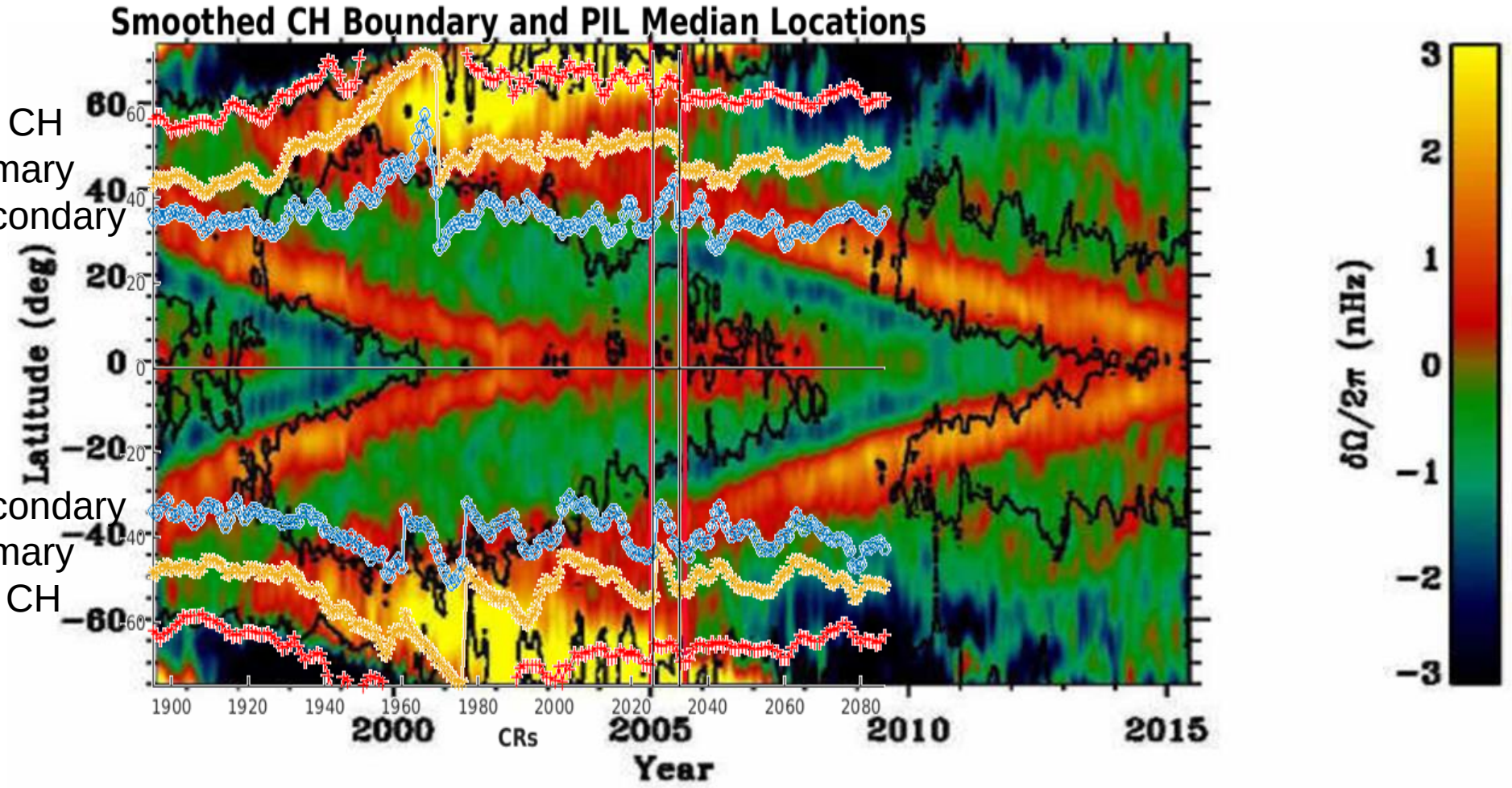
NH peak
~11, ~7 CR
- Similar to PIL

~15°/CR Disturbance Expands Polar Coronal Holes ~50% from South to North in 2005 CR2023-35



NH CH
Primary
Secondary

Secondary
Primary
SH CH



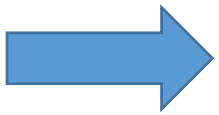
Southern PIL wavelets ~30 CR before, ~22 CR after and smaller amplitudes

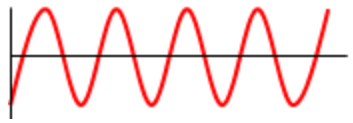
From Howe (2016) meridional flows and 5 G unsigned magnetic flux.
Overplot SC 23 PILs and Coronal Hole boundaries.

~±57° Latitude

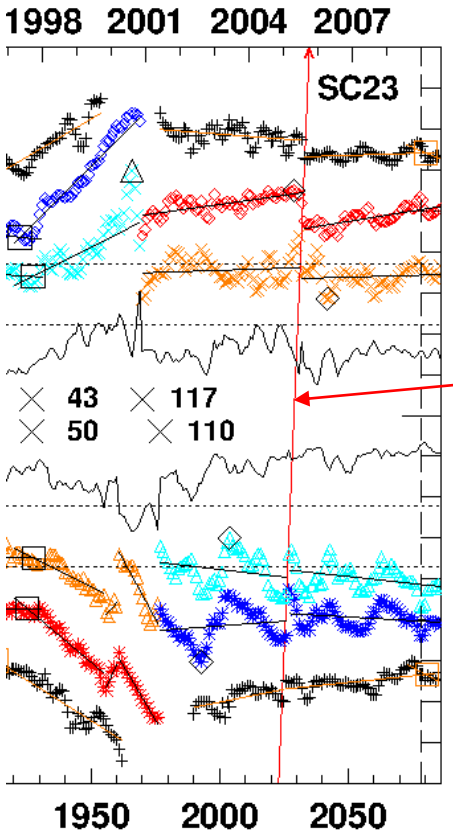
CONCLUSIONS

The RttP End of the Secondary PIL in the Transition to the non-rush Primary PIL





~16 CR Oscillations in Solar Latitude!



CH (NH)
Primary
Secondary

Secondary
Primary
CH (SH)

Other periods shared with Coronal Hole (CH) boundaries of ~25 (SH), ~20 (non-rush), ~7-12 CR (mostly NH)

DISTINCT ~15°/CR Disturbance from Southern Hemisphere (SH) to Northern Hemisphere (NH) in 2005 SC 23 solar minimum!

What do modelers think happened here?

What solar interior explains B, CHs, and RttP PILs in Smax?

https://www2.hao.ucar.edu/mcintosh-archive/four-cycles-solar-synoptic-maps

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Differences in the Solar B Field from Various Sources

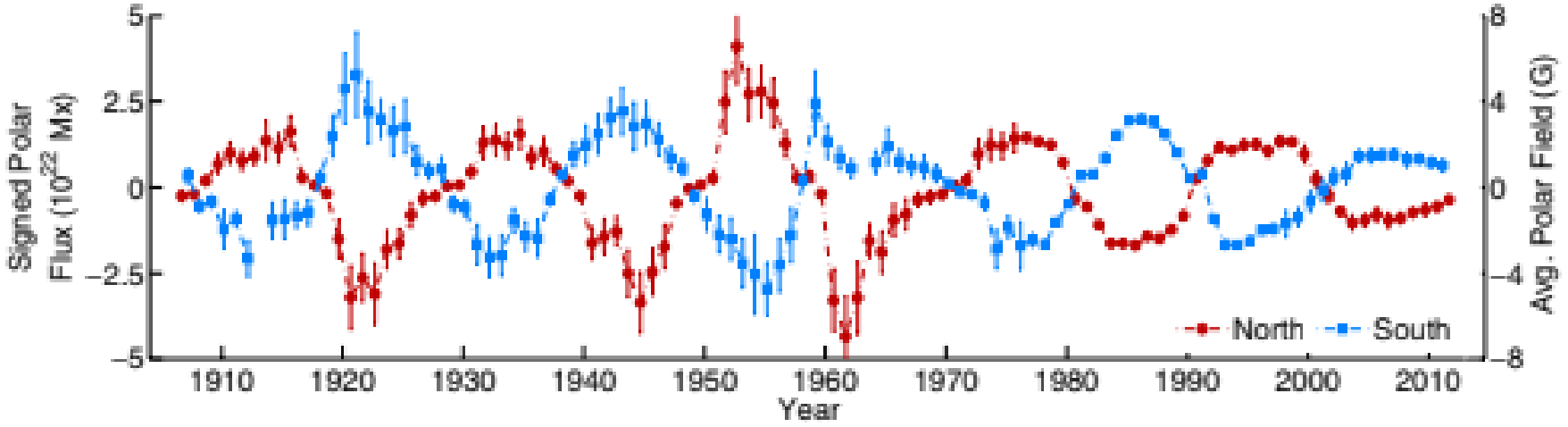

Figure 14. Consolidated signed polar flux database referenced to MDI measurements. Data points were taken from MDI (1996–2010), WSO (1975–1996), and MWO (1906–1975). The second axis shows the equivalent values of average polar field strength referenced to WSO measurements.

Figure 14 from Muñoz-Jaramillo et al. (2018) from facular counts and used from 1955-1968 in slide 9 (times 3), but is ~3 times smaller than polar field of Y-M Wang in slide 9, and ~3 times smaller than MDI and HMI radial fields in slide 11. KSO LOS (line-of-sight) field in slide 11 is (naturally) smaller in SC 21-22, unlike this proxy field or the polar field of Y-M Wang from MWO and WSO, which shows the smallest magnitudes in SC23 at the end.