Solar-like Stellar Activity Cycles and the Mystery of the Maunder Minimum

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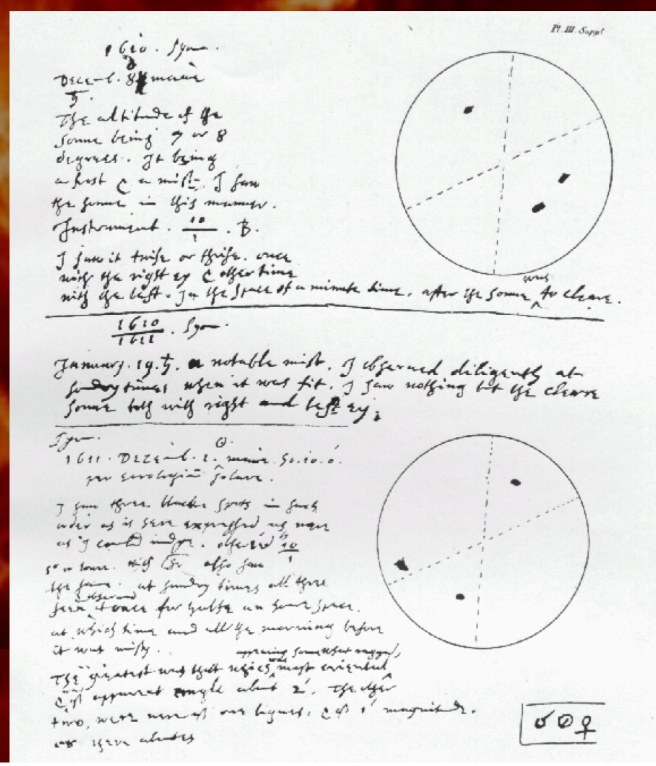
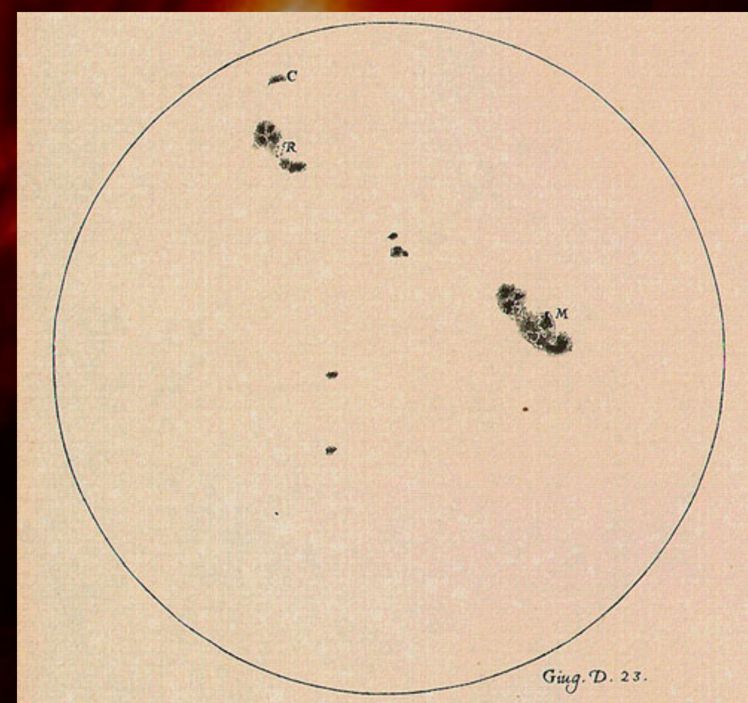
Discovery of the solar cycle

- The 11-year solar cycle is an obvious feature of solar activity
- But it was not discovered until the 19th century, over 200 years after Galileo and others began telescopically documenting sunspots.
- Why?

Harriot 1610



Galileo, 1613



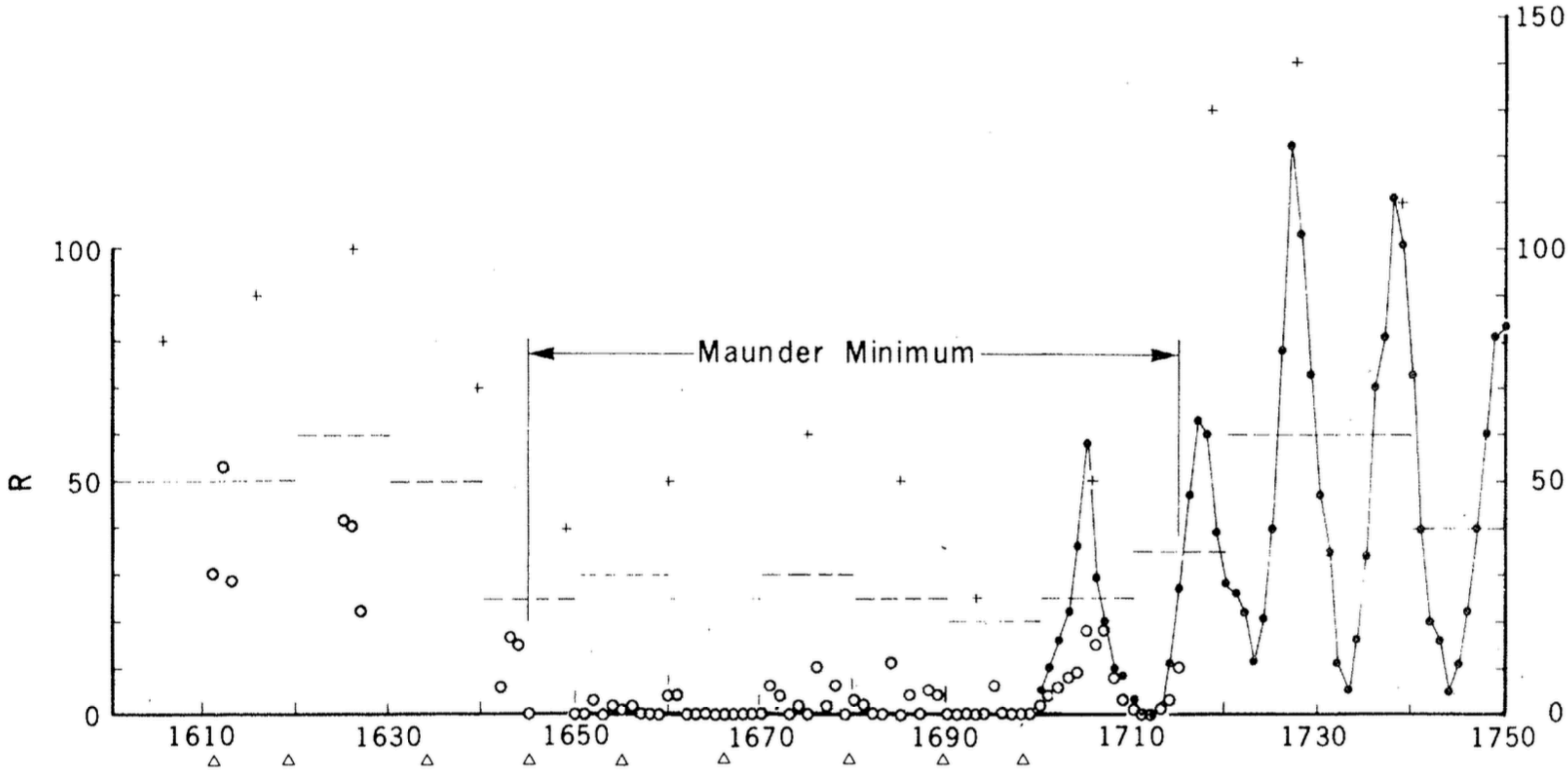


Fig. 9. Estimated annual mean sunspot numbers, from 1610 to 1750: open circles are data from Table 1; connected, closed circles are from Waldmeier (*3*); dashed lines (decade estimates) and crosses (peak estimates) are from Schove (*8–11*); triangles are Wolf's estimated dates of maxima for an assumed 11.1-year solar cycle (*3, 6*).

Eddy (1976)

Maunder supported these claims with quotations from the scientific literature of the period in question. The editor of the *Philosophical Transactions of the Royal Society*, in reporting the discovery of a sunspot in 1671 (in the middle of the "prolonged sunspot minimum"), had written that (*15*, p. 173) ". . . at Paris the Excellent Signior Cassini hath lately detected again Spots in the Sun, of which none have been seen these many years that we know of." (Following this, the editor went on to describe the last sunspot seen, 11 years before, for those who might have forgotten what one looked like.)

Cassini's own description of his 1671 sighting reads as follows (*15*, p. 174): "... it is now about 20 years since astronomers have seen any considerable spots on the sun, though before that time, since the invention of the telescopes they have from time to time observed them." Cassini also reported that another French astronomer, Picard, "... was pleased at the discovery of a sunspot since it was ten whole years since he had seen one, no matter how great the care which he had taken from time to time to watch for them" (*16*, pp. 141–142). And when the Astronomer Royal, Flamsteed, sighted a spot on the sun at Greenwich in 1684, he reported that "[t]hese appearances, however frequent in the days of *Scheiner* and *Galileo*, have been so rare of late that this is the only one I have seen in his face since *December* 1676" (*15*, p. 174).

Eddy (1976)

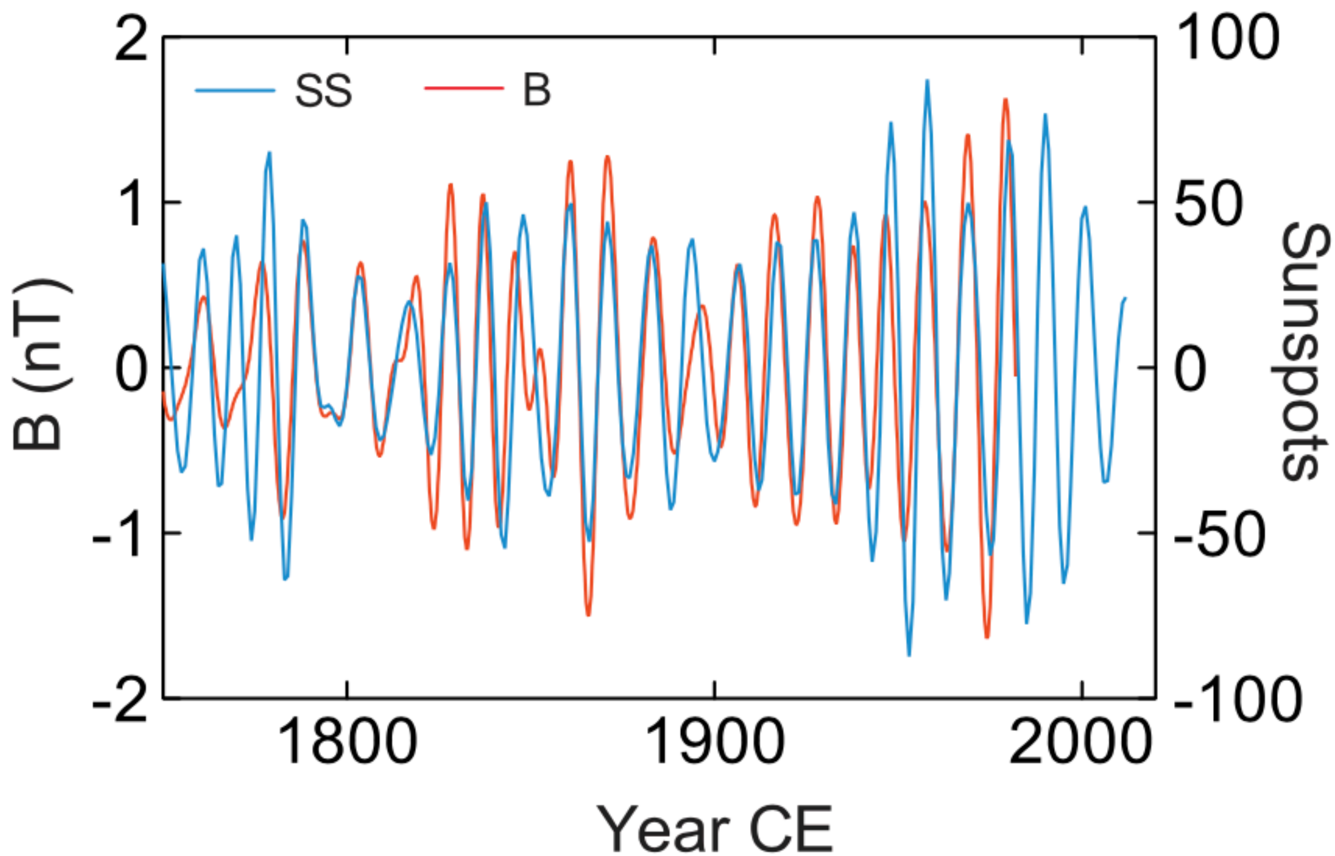


Figure 2. Comparison between monthly sunspot numbers (in blue) and values of the solar interplanetary magnetic field derived from a combination of the NGRIP and Dye 3 ^{10}Be records from Greenland (shown in red) for the interval from 1750 CE to the present (McCracken & Beer 2015). Both data sets were processed the same way by applying a band-pass filter (7.46–15.75 yr).

Beer (2017)

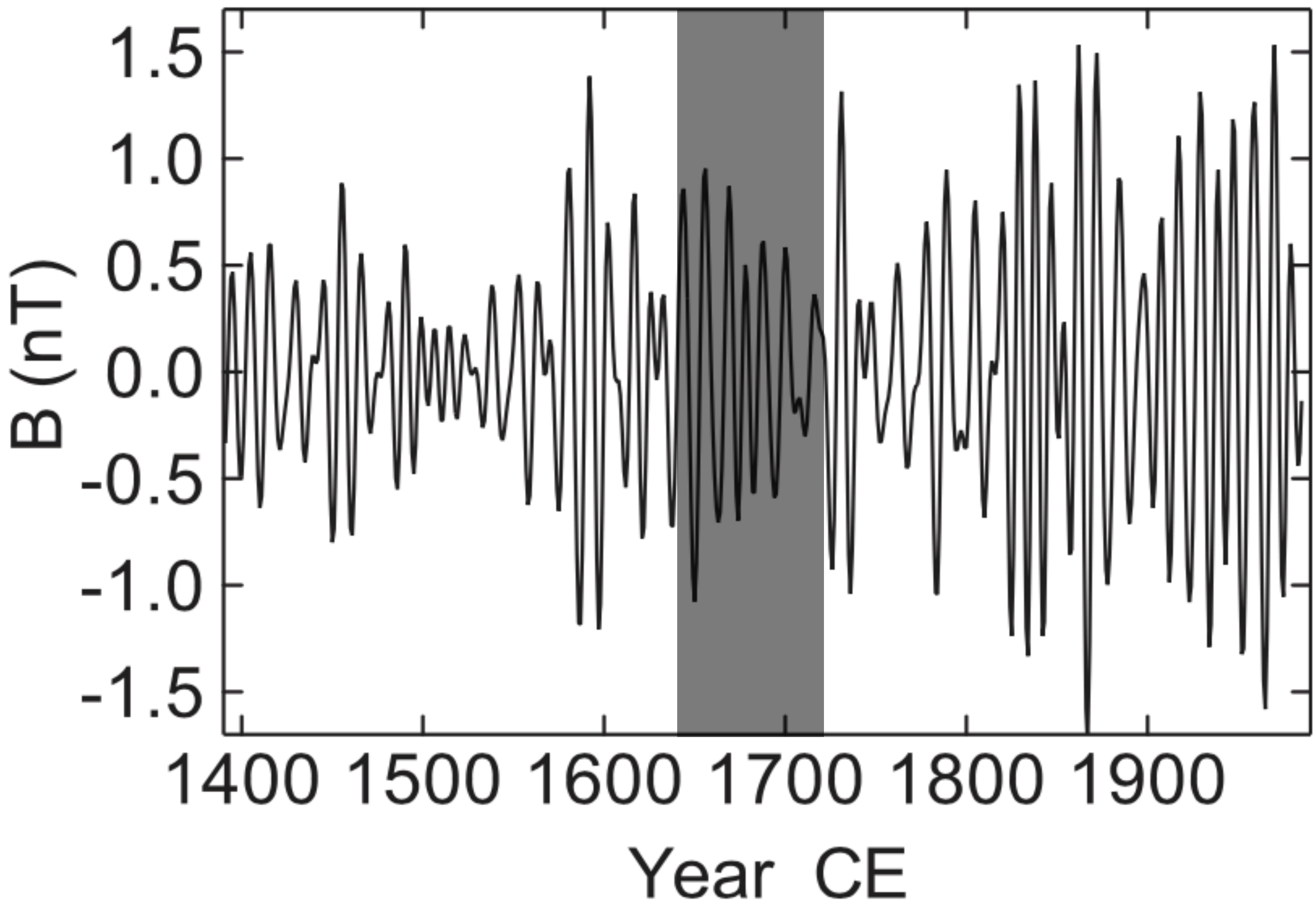


Figure 3. As Fig. 2 but showing only the interplanetary magnetic field derived from the two ^{10}Be records, now for the full available range from 1391 CE to the present. A band filter (7.46–15.75 yr) has again been applied.

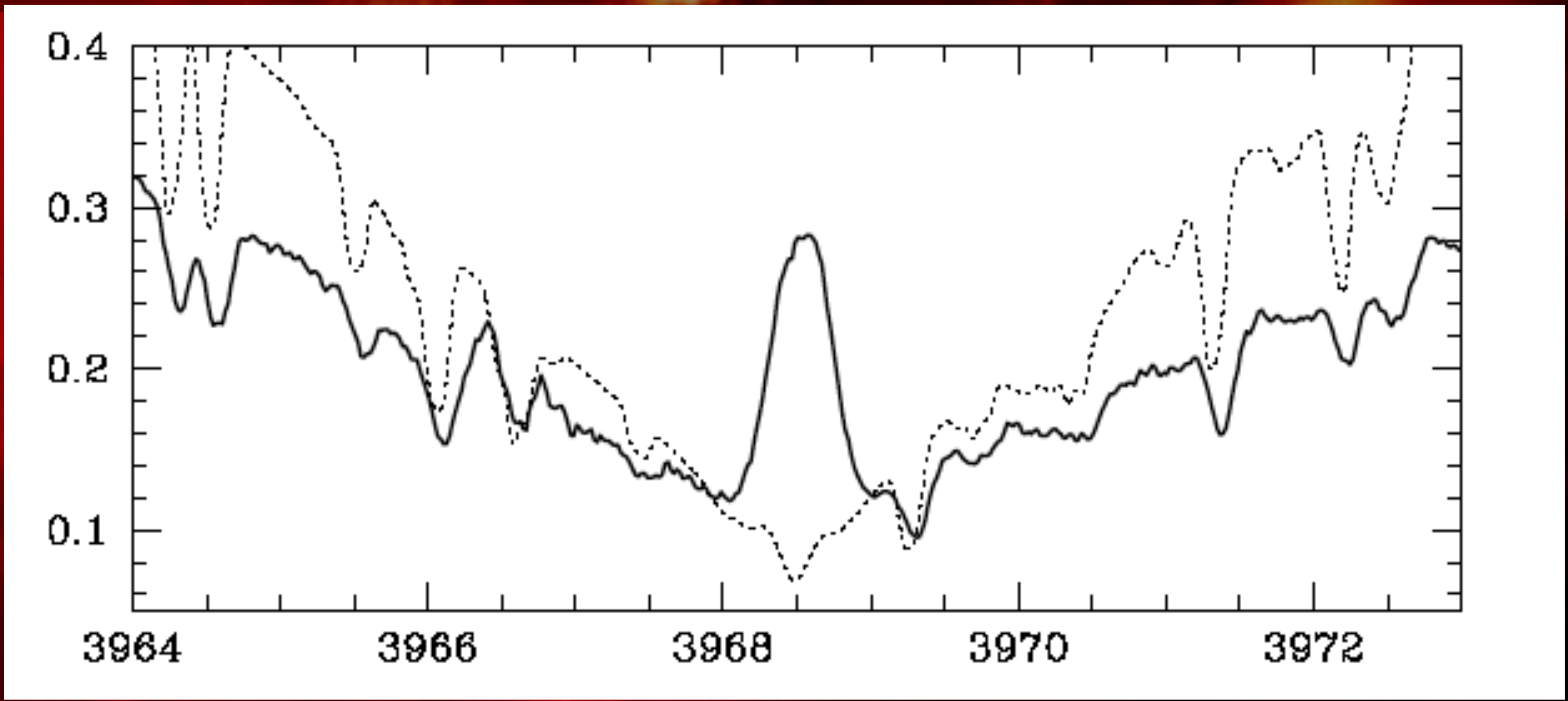
Beer (2017)

The Mount Wilson H & K Project

- Begun in 1966 by Olin Wilson on the 100-inch telescope at Mount Wilson
- 91 stars observed monthly
- Later moved to the 60-inch, cadence increased.
- Produced measurements of stellar rotation
- Provided global activity distribution
- Helped establish age-activity relation

Ca II H&K lines

- The Ca II H & K lines form from magnetic heating in the chromosphere.
- S is essentially an equivalent width of the emission reversals
- R'HK, a function of S and (B-V), is the fraction of a star's luminosity emitted in the H & K lines.



Maunder Minimum analogs?

- Baliunas & Jastrow (1990) identified low-activity, sun-like dwarfs as "Maunder minimum" ("Grand Minimum") candidates. Almost all are "flat activity stars".
- Implication is ~tens of % of Sun-like stars are in persistent and extraordinarily low activity states

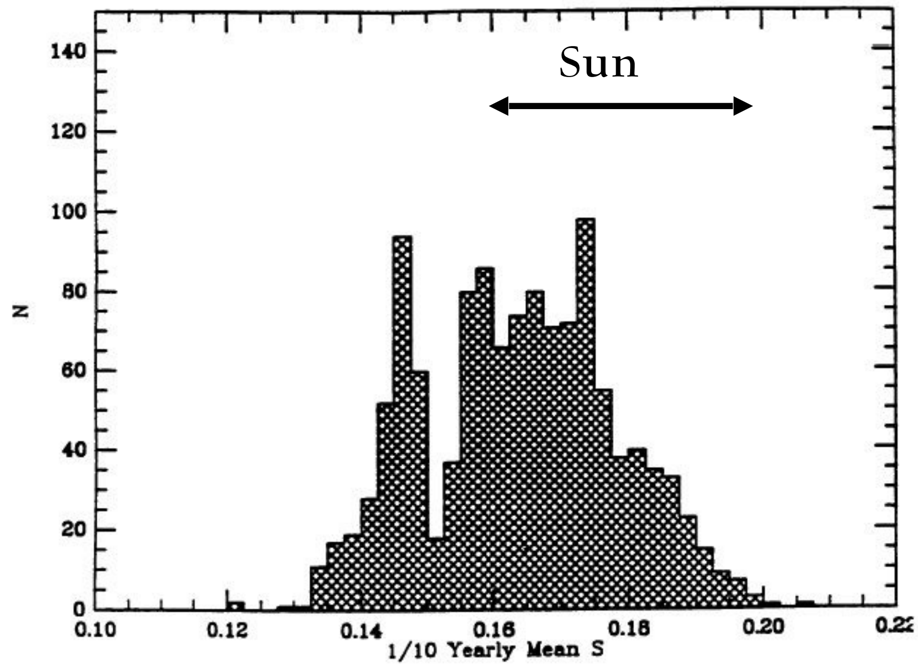
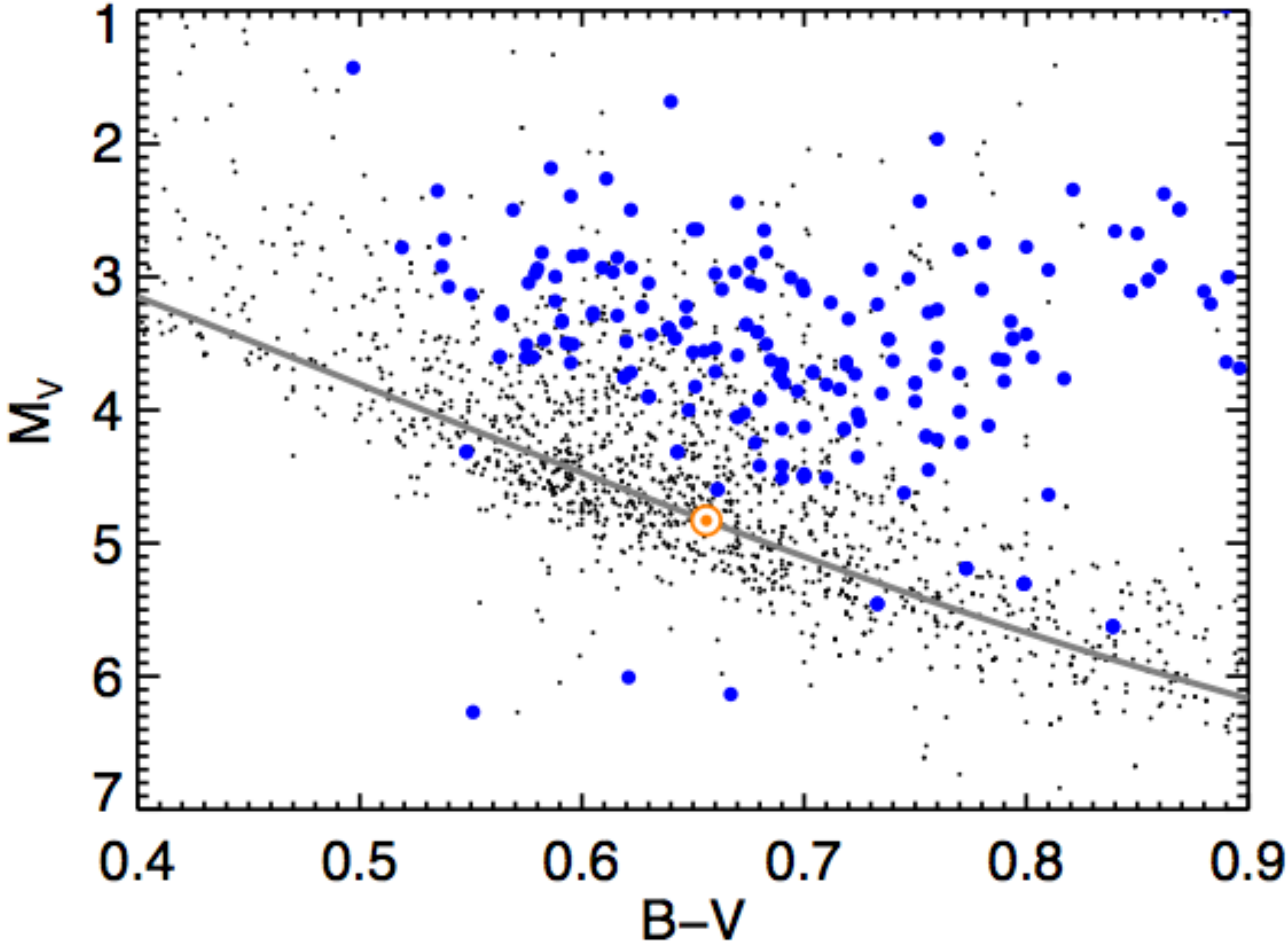


Fig. 18: Frequency distribution of the S index (0.1 year averages) for inactive ($0.13 \leq \langle S \rangle \leq 0.20$) solar-like ($0.60 \leq$ (B-V) ≤ 0.76) dwarfs (from Baliunas and Jastrow 1990).

Saar & Baliunas (1992)



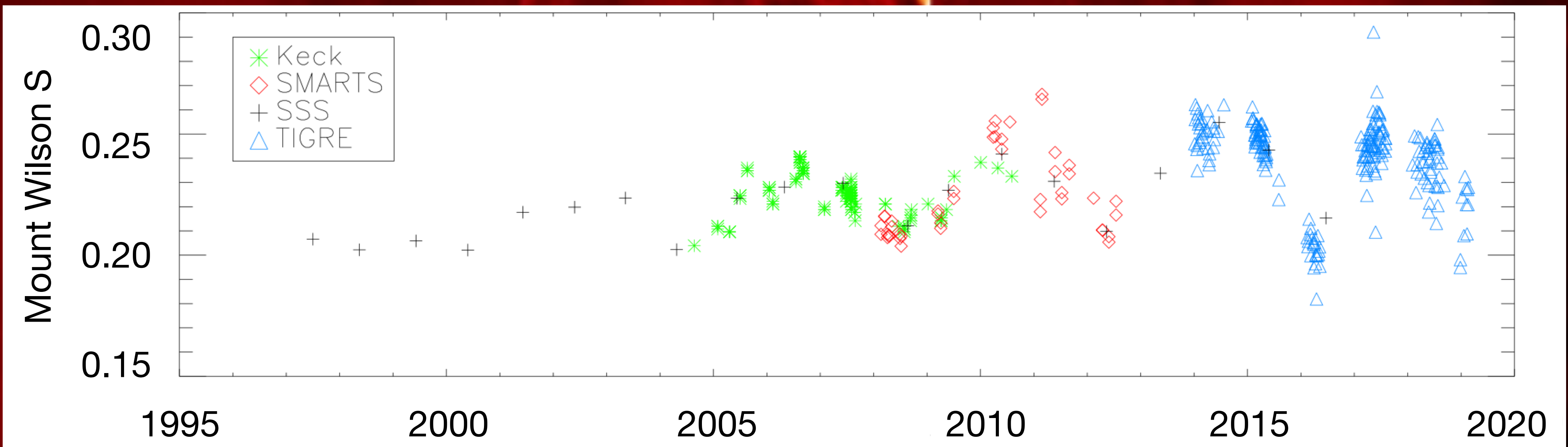
Wright (2004)

Enter exoplanets!

- Mount Wilson ceased its observations in the 2000's.
- RV planet searches take dozens of high resolution spectra of thousands of stars over decades
- Some spectra, like those from Keck/HIRES, include the Ca II H&K lines
- Planet hunters are extending the Mount Wilson time series into the 2020's and beyond!

A star exiting a Grand Minimum?

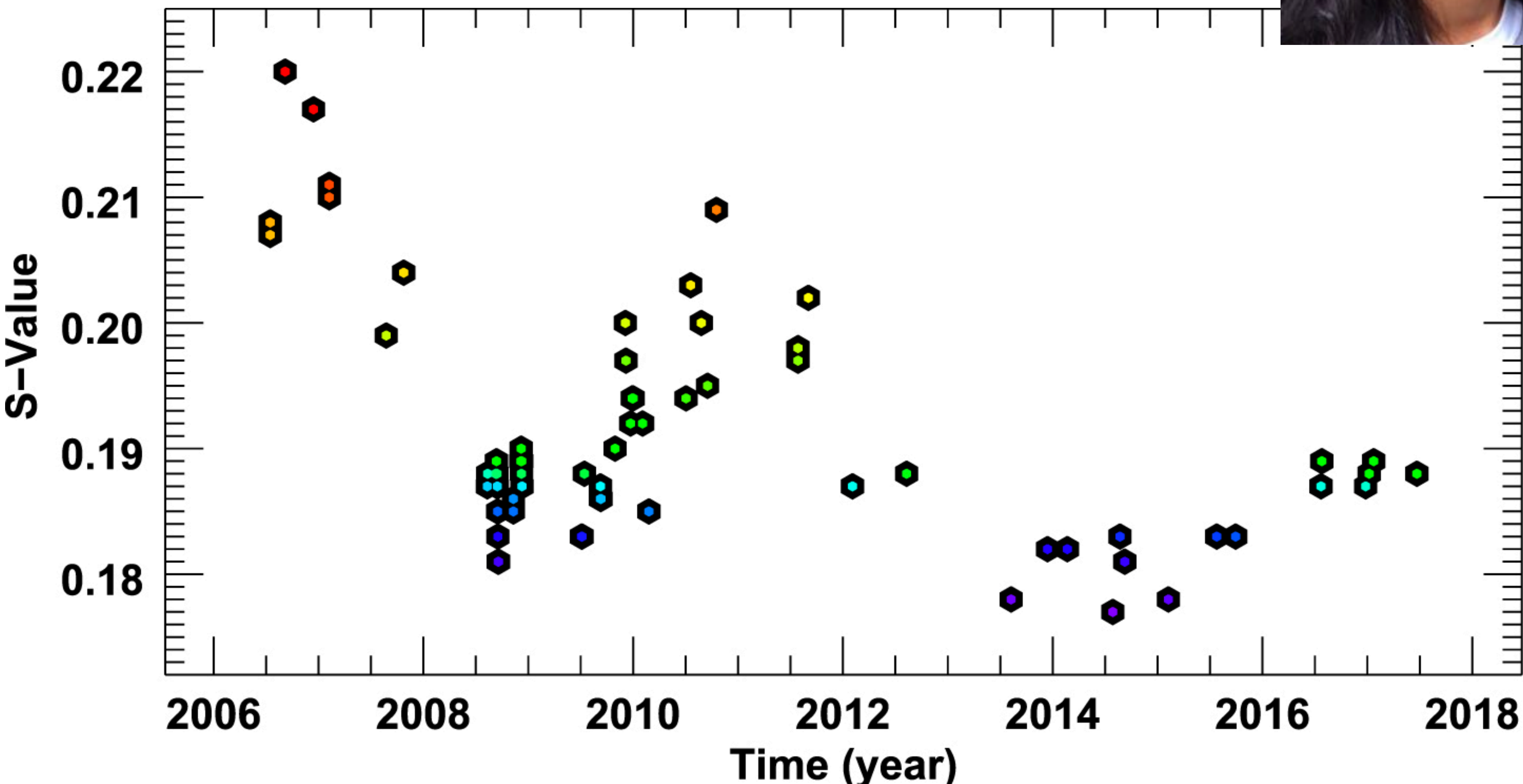
HD 140538



Mittag (2019)

HD 4915

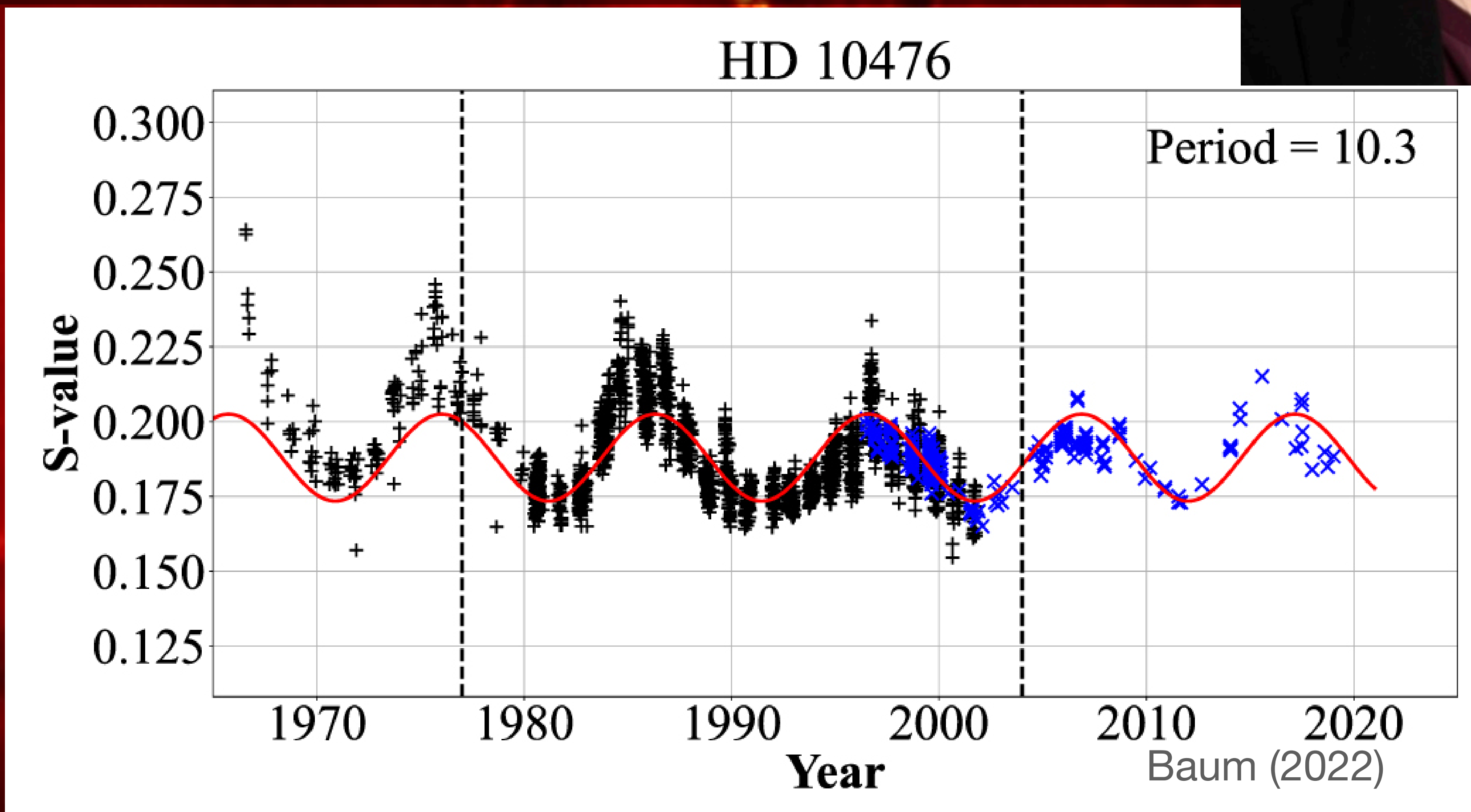
A star entering a Grand Minimum?

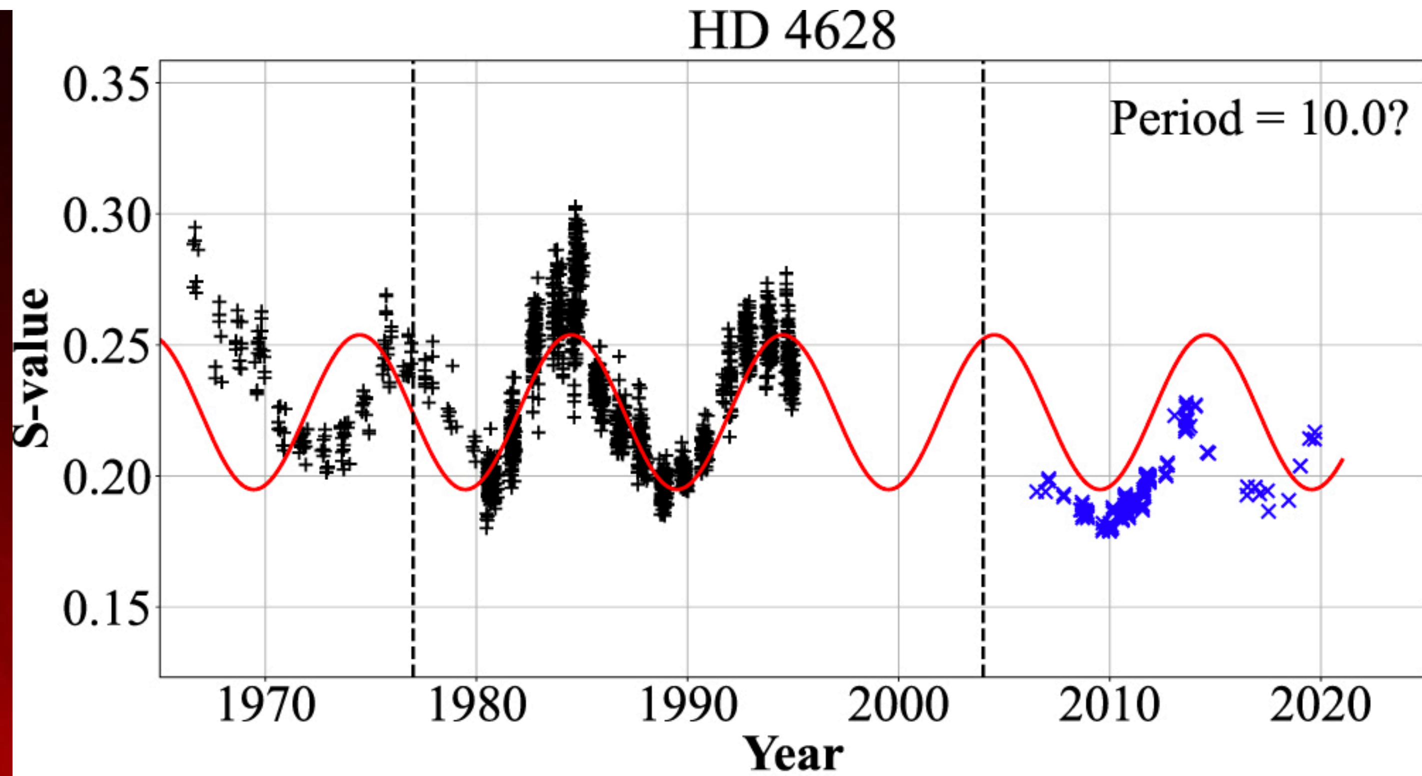


Shah (2018)

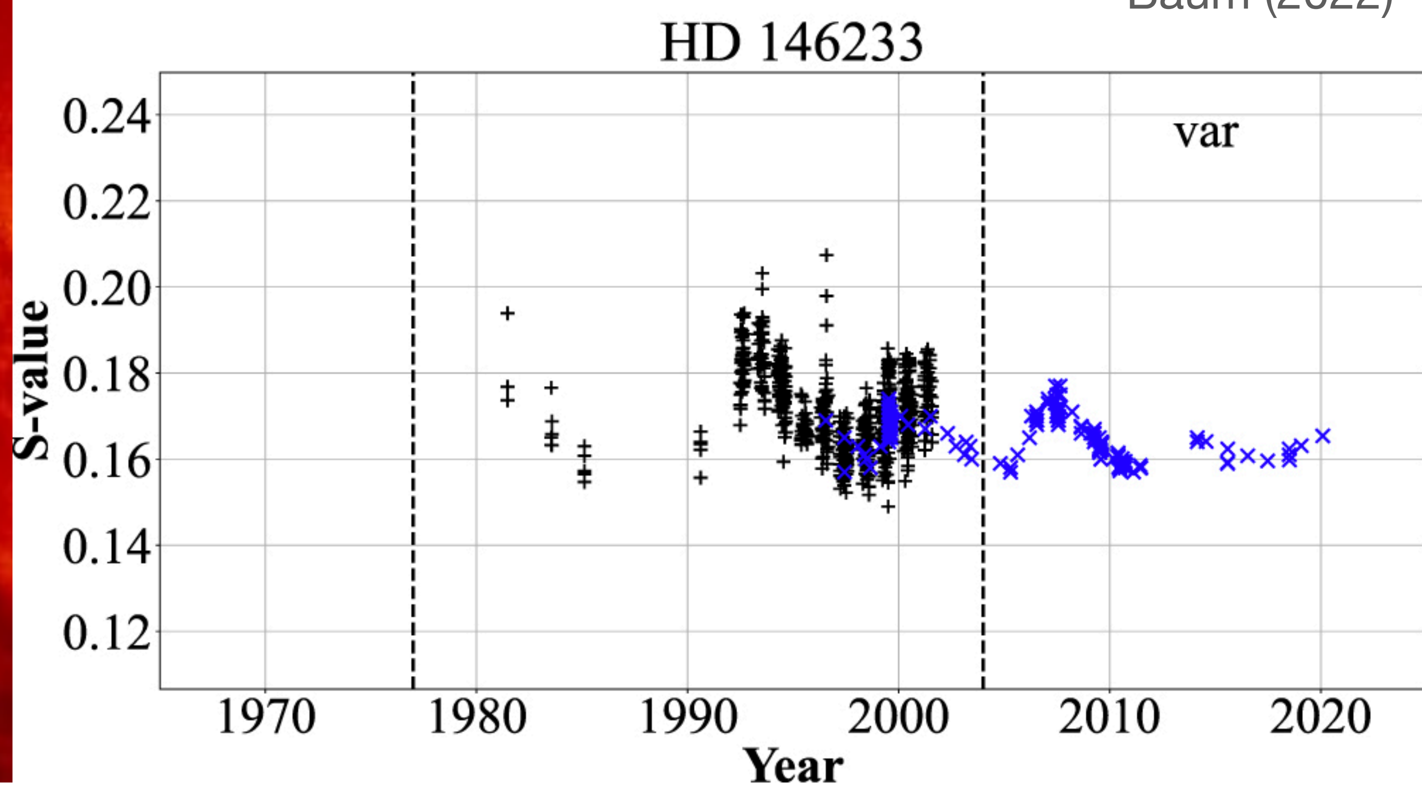
Combining Mount Wilson and the California Planet Survey

- ~55 years of data for ~60 stars
- Extends Mount Wilson data set by x1.5–2



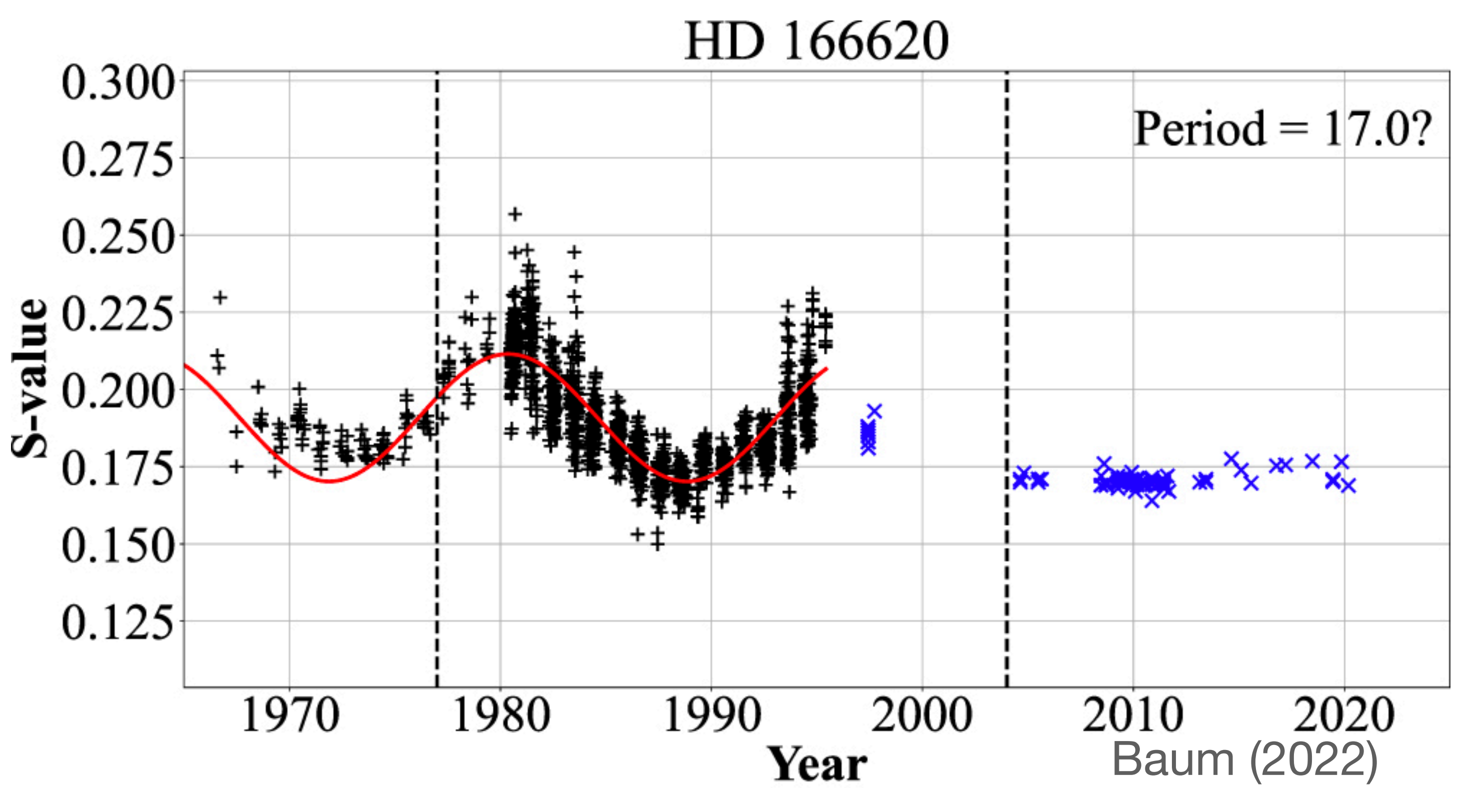

HD 4628
Period = 10.0?
S-value
0.35
0.30
0.25
0.20
0.15
1970
1980
1990
2000
2010
2020
Year

Baum (2022)


HD 146233
var
S-value
0.24
0.22
0.20
0.18
0.16
0.14
0.12
1970
1980
1990
2000
2010
2020
Year

HD 166620

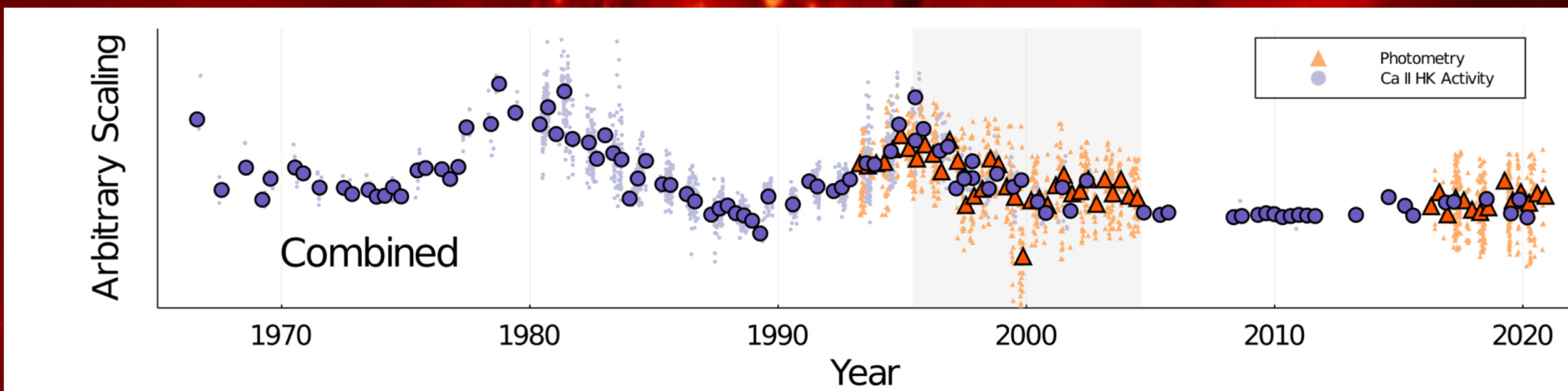
A star entering a Maunder Minimum?



Baum (2022)

Or a different star?

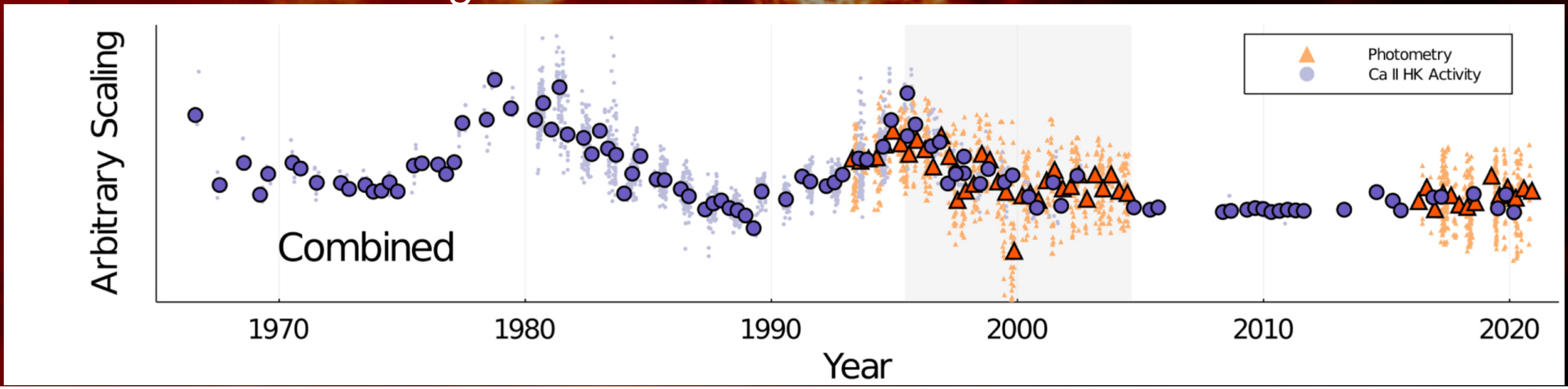
HD 166620



Luhn (2022)

HD 166620

- Minimum activity level (S=0.171) is very similar to last cycle minimum (S=0.172) but lower than previous minimum (S=0.181)
- Photometric and S-index variability during grand minimum is lower than previous minima
- Suggests that the grand minimum is not a new state of extraordinarily low activity, but more like an extended minimum.
- Lower variability is consistent with the lower sunspot numbers during the Maunder Minimum.
- Suggests that variability, but not mean S level, could identify other stars in a grand minimum



Summary

- We can expand our study of solar/stellar dynamos by looking at solar analogs to “extend” the historical record of sunspots.
- Mount Wilson + Planet Search surveys provide >50 years of history for dozens of stars
- One in ~dozens of cycling stars has entered a clear Maunder-minimum-like state in ~a few decades. This implies the duty cycle is ~few percent or so.
- Still need a theory that unifies sunspot numbers, Ca II H&K levels, and radioisotope data for behavior during a grand minimum