HAMILTON ECHELLE SPECTROGRAPH OBSERVATIONS OF SOLAR ANALOG FIELD STARS

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- The start of an observing program to identify grand minimum stars.
  - Lubin, D., B. P. Holden, C. Stock, C. Melis, C., & D. Tytler, D., 2023: *Astronomical Journal*, in revision.
- Supported by NASA award 80NSSC21K1947, Solar Irradiance Science Team (SIST-3).
- Resources provided by UC Lick Observatory.

BRIEF PERSONAL INTRODUCTION

I'm a Research Physicist at Scripps Oceanography

- Working mostly in polar climate research, supported by NSF, DOE, NASA

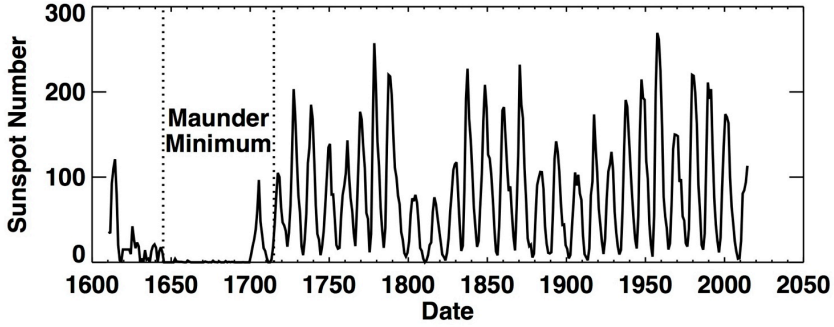
- But I've been "bootlegging" this research on solar analogs for about ten years.
- The NASA SIST-3 award (2021) is the first support I've had related to this topic.
- I made these observations back in 2013-2014.
- Then had three major awards to lead a big Antarctic field campaign (AWARE, 2015-2016).
- Then went back to reducing and analyzing the Lick Observatory data.
- Then had to go to Antarctica again (Siple Dome, 2019-2020).
- Then completed the Lick data analysis and started writing the paper.
- Will have to go to Antarctica again with another program called ALCINA (Palmer Station, 2025-2027), and these polar programs are very timely and rewarding. I'm not really complaining, but…
- The solar analog work keeps getting interrupted...*So why am I doing it?*

BRIEF PERSONAL INTRODUCTION

So why am I doing this solar analog research if it's so hard to keep going?

- Astronomical Observing is Fun.
  - At my age, telescopic observing is more fun than going to Antarctica, which is increasingly more of a young person's game.
- Sun-Climate Research Is Important.
  - Even though most of today's research relates to GHG-induced warming later this century, there needs to be adequate rigor on variability in the Sun's input to the climate system on century timescales and longer.
  - So here I'm an astronomer who really only cares about *one* planet.
- But This Work is Difficult to Fund.
  - This topic falls between disciplinary boundaries at the major funding agencies.
  - Not a major priority for most of the climate programs; also of less interest than other stellar astrophysical topics such as exoplanets.
- So I'm always looking for collaborators. It's hard to make progress alone!

MOTIVATION: THE MAUNDER MINIMUM



- A rapid climate change event induced by solar activity variability, with major climatic shifts primarily in Europe.
- Circa 1645-1715 CE, just after regular sunspot observations began.

ISSUES WITH SOLAR GRAND MINIMA

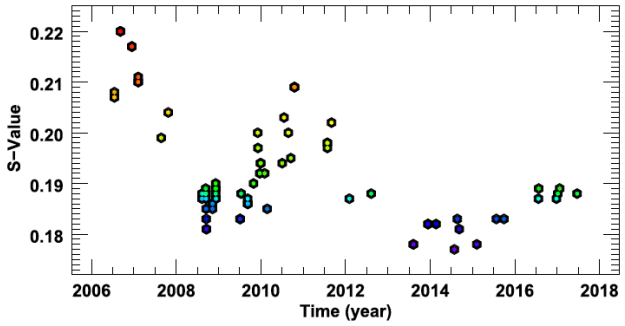
Though not as intense a shift in the Earth's radiant energy budget as contemporary GHG-induced climate warming, the historical Maunder minimum had some drastic effects throughout Europe, including:

- Widespread famines throughout northern Europe.
- Loss of Scotland's independence by 1707.
- Scandinavian wars bolstering the Swedish empire, ultimately leading to present-day national boundaries.
- Rise of the Netherlands as a major maritime power.

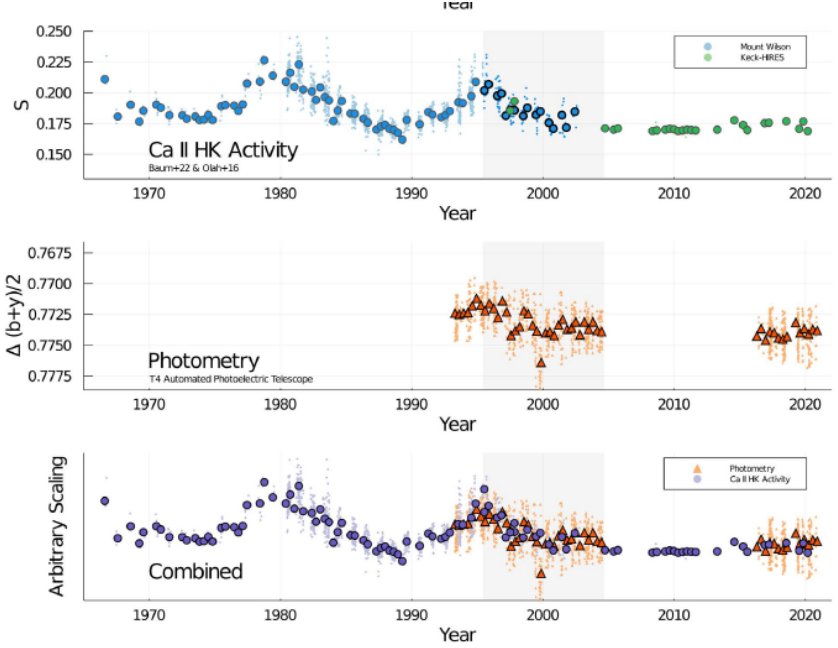
- How frequently to solar grand minimum events occur?
  - Are we possibly due for another MM later this century?
  - Less likely than believed about ten years ago (see Wang & Lean, *ApJ*, 2021).
  - But can we estimate grand minimum frequency from a large enough solar analog sample?
- How does a stellar dynamo behave during descent into and recovery from a grand minimum?
  - Would like to observe at least several stars in these phases.
  - So need multiyear observations, both spectroscopy and differential photometry (Hall et al., *AJ*, 2009)
- What is the precise SSI and TSI decrease from a typical solar minimum to a grand minimum?

IDENTIFYING GRAND MINIMA

- A few have been identified in activity time series derived from exoplanet search data sets.
- But we would like many more to constrain dynamo models and genuinely evaluate frequency of occurrence in nature.



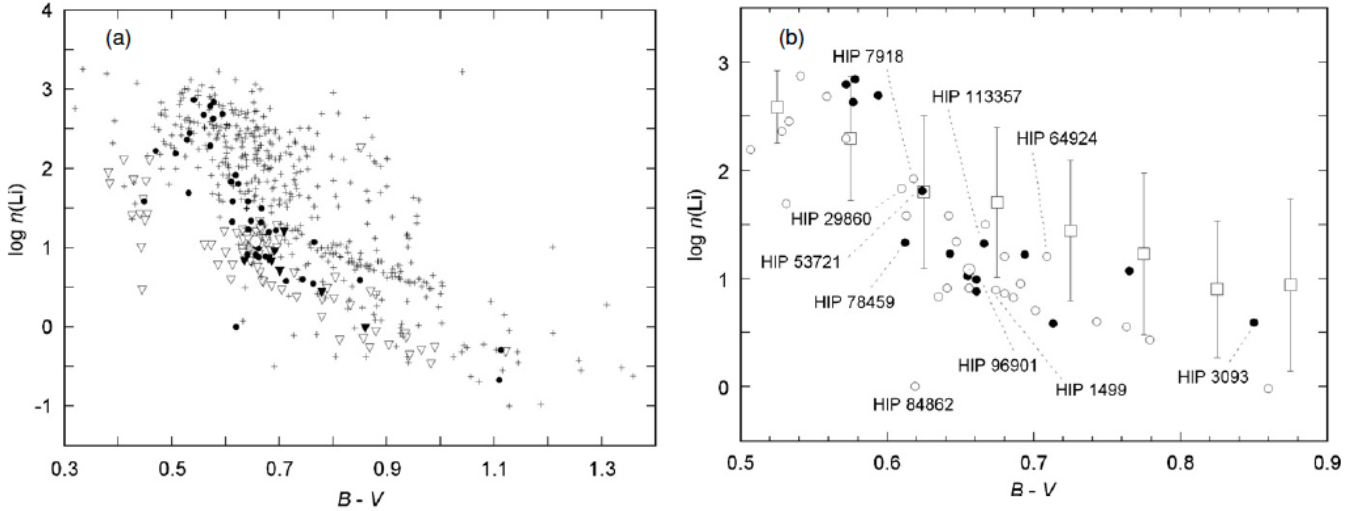
Shah et al., *ApJL*, 2018, for HD 4915



Luhn et al., *ApJL*, 2022, acquired some supplemental photometry for HD166620.

STELLAR LITHIUM AS AGE INDICATOR

- Li abundance for a typical late-type dwarf begins at the local interstellar medium abundance.
- Over the main sequence lifetime Li is steadily depleted by convection at a rate dependent on details of the star's convection zone and mixing processes.

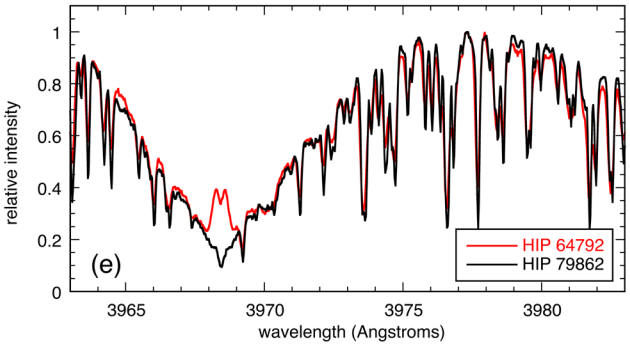


In a literature survey of published Li and HK activity data sets (Lubin et al., *ApJ*, 2010, we hypothesized that a combination of very low activity and relatively undepleted Li abundance may indicate a promising grand minimum candidate for future long-term observation.

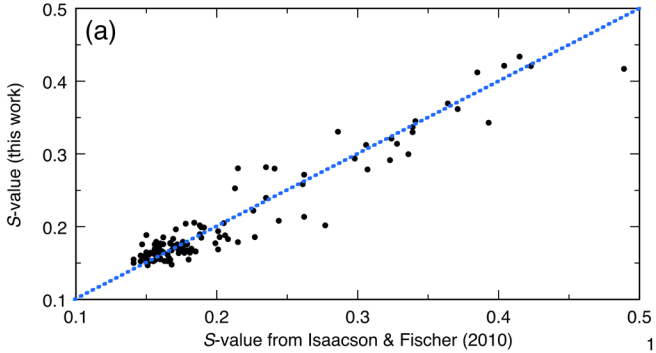
OBSERVING PROGRAM

- So we started an observing program specific to solar analogs to search for the most relevant candidates.
- T_{eff} within 500 K of solar, metallicity close to solar, verified on the main sequence with Hipparcos parallax data.

Over 22 nights during 2013-2014 we obtained high resolution observations of 211 solar analogs with R ~ 100,000 with the 3m telescope and Hamilton Echelle Spectrograph.

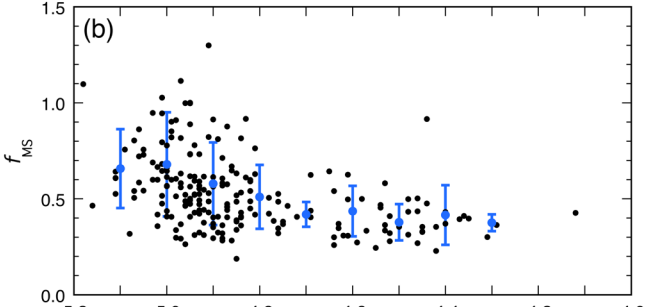


Examples of normalized order 144 spectra for a star in the normal solar cycling activity range, HIP 79862 (retrieved log R'_{HK} = -4.92; black), and an active star HIP 64792 (log R'_{HK} = -4.44; red)



(a) Activity retrieved following Wright et al. (*AJ*, 2004) and validated against a subset of our data having retrievals in Isaacson & Fischer (*ApJ*, 2010).

(b) The fraction of elapsed main sequence lifetime as a function of activity derived in this work; blue circles are averages over bins of width 0.1 and plotted at the bin's upper bound.



OBSERVING PROGRAM

- Li abundance detected in order 85 and retrieved using curves of growth in Soderblom et al. (*AJ*, 1993).
- We also correct for the small Fe line adjacent to the 6708 Angstrom Li absorption feature.

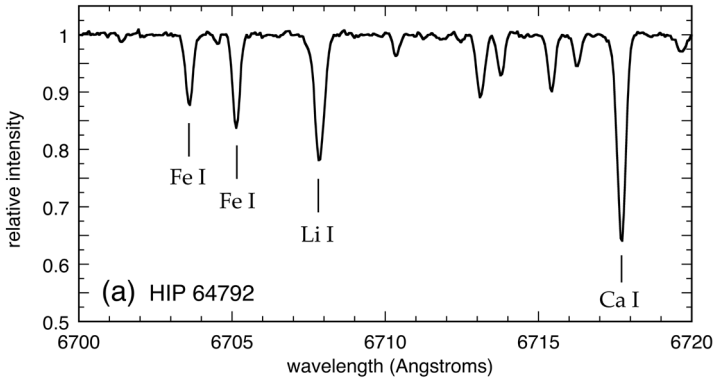
Examples of cubic spline-corrected echelle spectra from order 85 for stars with varying Li 6708 Å feature strength:

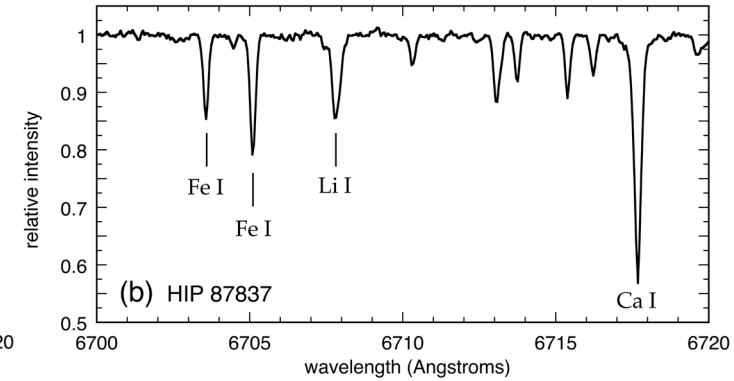
(a) HIP 64792 with retrieved log *N*(Li) = 2.77,

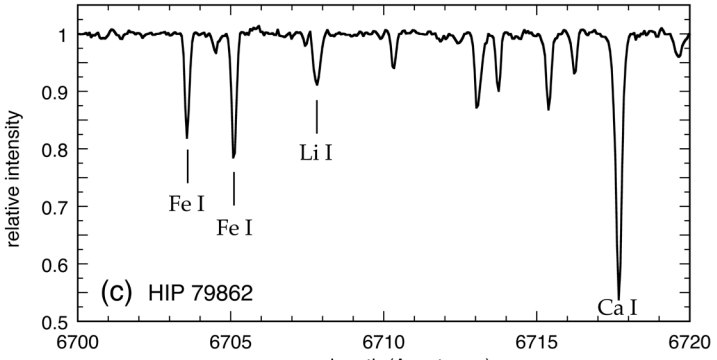
(b) (b) HIP 87837, retrieved log *N*(Li) = 2.38,

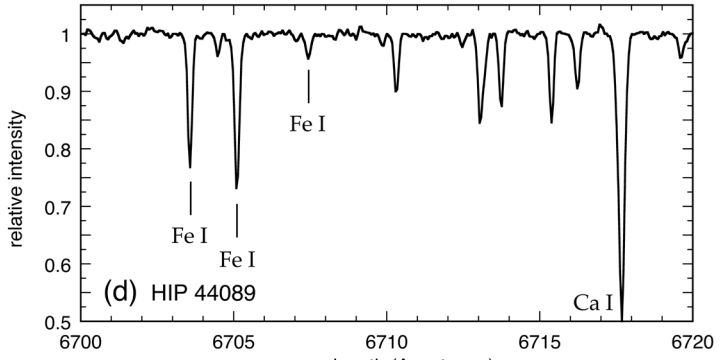
(c) HIP 79862, retrieved log *N*(Li) = 2.08,

(d) HIP 44089, with inferred log *N*(Li) < 0.91





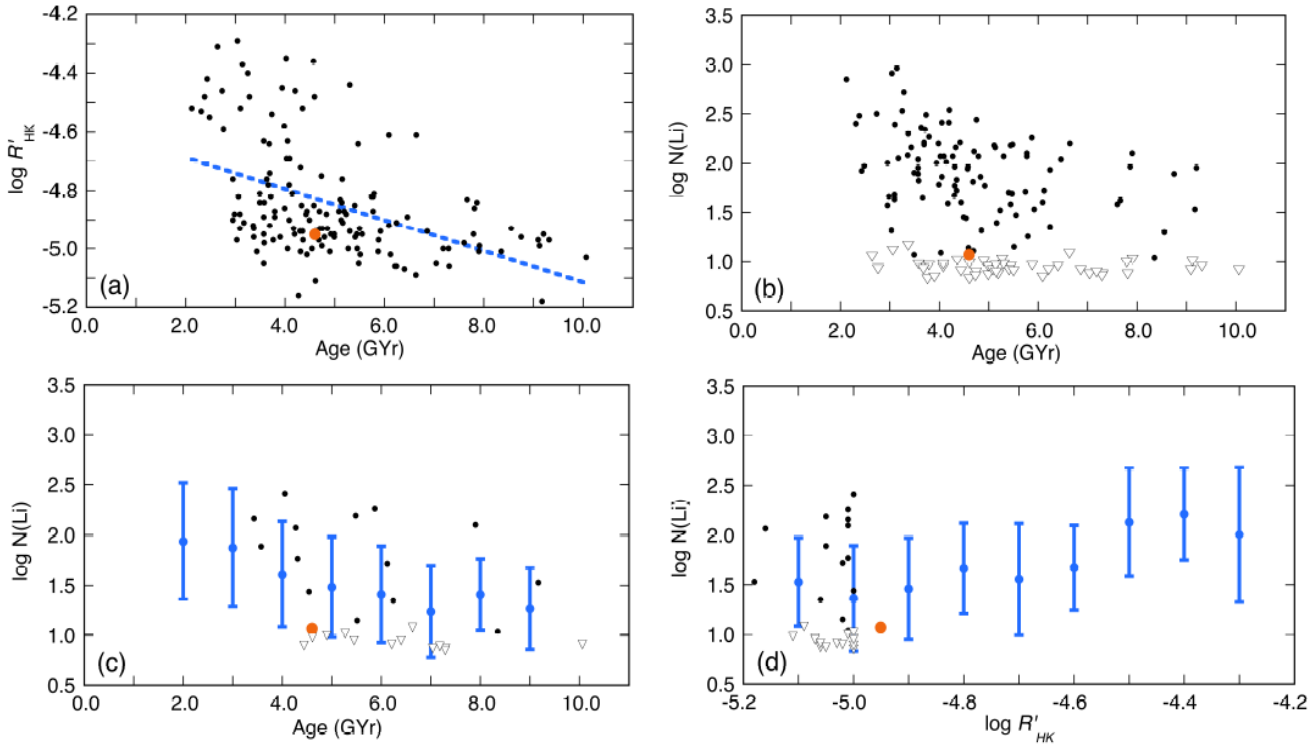




APPLICATION TO GRAND MINIMA

- Examine the subset of 148 stars having T_{eff} within 500 K of solar.
- As in 2010 literature data survey, identify stars with very low activity and relatively undepleted Li abundance.

(a) activity versus isochrone expectation age from Casagrande et al. (*A&A*, 2011);
(b) our retrieved log *N*(Li) versus isochrone age;
(c) versus isochrone age with Li abundances averaged over age bins of width 1 Gyr and plotted at the bin's lower bound, with error bars representing ±1σ standard deviation;
(d) versus log R'_{HK} with the Li abundances averaged over log R'_{HK} of width 0.1 and plotted at the bin's upper bound.
Sun is depicted by orange dot.



CONCLUSIONS

- Our data are publicly available the the UCSD Library Research Data Collections; just search on my last name or go to (https://doi.org/10.6075/J0X34XN2).
- In future work we will retrieve photospheric abundances and other stellar properties, to identify the most Sun-like.
- And we plan to keep observing with Hamilton and the APF.

- From the above we suggest that 24 stars in our sample may be promising candidates for further long-term activity observation and monitoring with differential photometry.
  - If we imagine that ***every*** one of these stars with very low activity and normal-range Li abundance is an example of a grand minimum, this gives an upper limit on grand minimum frequency occurrence in our sample of ~16.2%.
  - From extreme value theory, the probability *P* of the Sun entering another grand minimum at present is 0.51, and this increases to 0.54 by the year 2050 and to 0.59 by 2100.
- These estimates from extreme value theory should be regarded only as upper limits:
  (1) There is no guarantee that all 24 stars would emerge as example grand minima after several years of observation. We really need the multiyear or multidecadal observations (Hall et al., *AJ*, 2009)
  (2) Current understanding of solar variability (Wang & Lean, *ApJ*, 2021) suggests that grand minima do not occur with any regular periodicity on century timescales.