The Stars as a Sun:
Secular Variations of Cycling and Non-Cycling Stars

A Science White Paper for the Astro 2010 Decadal Survey
Submitted for consideration by the Stars and Stellar Evolution Panel

Jeffrey C. Hall
Lowell Observatory
1400 West Mars Hill Road
Flagstaff, AZ 86001

(928) 233-3202
jch@lowell.edu

Mark S. Giampapa, NOAO / NSO

Gregory W. Henry, Tennessee State Univ.

Judith L. Lean, NRL

Steven H. Saar, CfA

David R. Soderblom, STScI

1. Introduction

The Sun's story is only half told because it lacks context. Only by listening to the stars can we understand the true nature of solar behavior. Stellar observations are inevitably sketchier than what we achieve for the Sun, but the great breadth of stellar data more than compensates, and we now have the means to go significantly deeper for stars as well.

The solar activity cycle is one of the most familiar astrophysical phenomena to professionals and laypersons alike, and is understood as the result of a self-sustaining magnetic dynamo generated through field shearing by differential rotation and turbulent convective motion and meridional transport below the solar surface. Less well understood is why the Sun and some Sun-like stars exhibit no (or at least greatly reduced) cyclic activity for perhaps 15-20% of their lifetimes, as well as the effects of these episodes on energy output.

This is a crucial time to investigate the solar-stellar connection with specific attention to the nature and effects of solar and stellar grand minima. The scientific motivations are:

1. The total solar irradiance (TSI) record of another solar minimum and cycle rise will soon be in place, adding an important datum to the record of secular evolution of the Sun in the absence of large-scale magnetic structures.
2. Current stellar synoptic data sets are both magnitude- and bandpass-limited. Extant programs have not found a statistically significant sample of genuine "solar twins," and after 40 years the venerable Ca II H&K proxy has likely revealed much of what it has to tell. However, new surveys are beginning to push the sample deeper, and important advances can emerge from other parts of the spectrum.
3. Activity modulates brightness. Solar effects are evident on Earth's surface temperature, accounting for globally averaged changes of 0.1°C. This change is much smaller than the projected global warming of ~2°C in the next century, but larger solar-induced changes are plausible on longer time scales and may have significant short-term effects (e.g., the harsh conditions of the Maunder Minimum). Understanding solar and stellar brightness excursions is of clear relevance to terrestrial climate change, and by inference, to life-sustaining exoplanet candidates.

2. Background

2.1. The Discovery of Stellar Activity Cycles

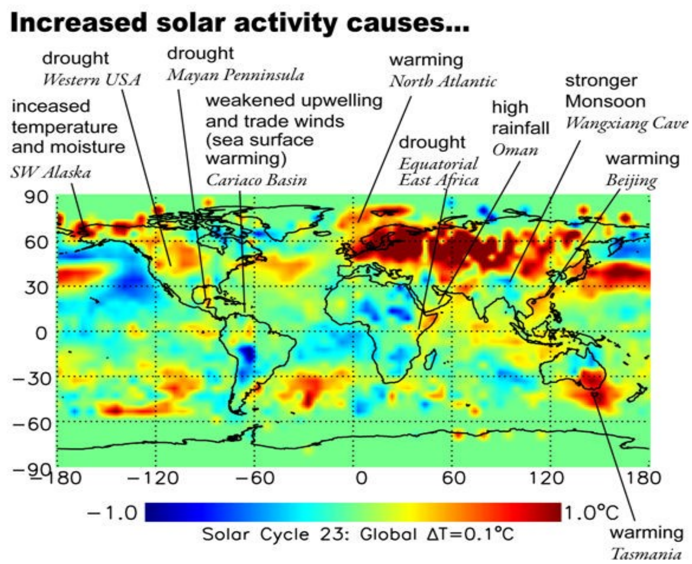
"Does the chromospheric activity of main-sequence stars vary, and if so, how?" Wilson (1978) posed this question in his classic paper detailing 11 years of observations of the activity of 91 stars at Mount Wilson Observatory (MWO). After another 30 years, the data set is larger but the results remain consistent: ~60% of Sun-like stars exhibit regular cycles akin to the Sun's (with the most well-defined cycles appearing typically in middle-aged stars as well as in K dwarfs with deep convective zones), ~25% vary irregularly (typically these are younger, faster rotators with presumably more vigorous dynamos), and ~15% are the so-called "flat activity" stars, which may be in periods analogous to the solar Maunder Minimum (e.g., Baliunas et al. 1995, Hall et al. 2007).

2.2. The Discovery of Grand Minima

"*The existence of the Maunder Minimum and the possibility of earlier fluctuations in solar behavior of similar magnitude imply that the present cycle of solar activity may be unusual, if not transitory.*" Eddy (1976), in his superb exposition of the absence of sunspots from 1643-1715, set the stage for extensive investigation of non-cycling episodes in the Sun and stars with this startling hypothesis, as well as through his connection of the Maunder Minimum to one of the severest episodes of cold weather during the Little Ice Age.

Similarly, the stellar Ca II H&K records reveal Sun-like stars in non-cycling states and, in a few tantalizing cases, evidence of stars that may be undergoing a transition from a cycling to a non-cycling state (or vice versa). Assuming G dwarfs exhibit some uniformity of phenomena, we may use them to look through the glass darkly to the Sun's past, inferring both the magnetic state of our star on millennial timescales, as well as its brightness excursions beyond the short (1978-present) span of continuous observations from space.

2.3. The Sun and Climate



That the Sun influences climate is not in dispute (Haigh 2007), but it does so in regionally complex ways, in concert with the modest globally averaged temperature change produced by the 0.1% solar cycle variation in TSI (Lean & Rind 2008). Irradiance measurements from space only extend back to 1978, long-term reconstructions rely on proxy records such as sunspots (e.g., Krivova et al. 2007) or physical models of the solar magnetic field (Wang et al. 2005). To complicate matters further, there is debate as to whether the baseline level of TSI has increased since 1978, due to zero-point shifts between the various radiometers. The effect of the Maunder Minimum on the Sun's brightness therefore remains an open question.

Brightness modulations by activity are ubiquitous among Sun-like stars (Radick et al. 1998), as is the increasing variability amplitude with decreasing wavelength, as seen, for example, in the coronal cycle of 61 Cygni (Hempelmann et al. 2006). However, the Sun's photometric variability appears to be sedate relative to similar stars (Lockwood et al. 2007). Is the Sun "special," or is this a precision or sample size issue? How might the variations of a typical Sun-like star affect its planets? Future synoptic programs can provide key data.

2.4. The Cycling and Non-Cycling Sun

Solar Cycle 24 will parallel the Astro 2010 decade and will be a fundamental datum in the record of solar activity. Predictions of the cycle's strength have ranged from very strong (Dikpati et al. 2006) to very weak (Svalgaard et al. 2005), with subsequent discussion as to whether the differences arise from the underlying assumptions or inherent unpredictability of the phenomenon (e.g., Cameron & Schüssler 2007, Bushby & Tobias 2007). Predictions of a cycle minimum in 2006 (Hathaway & Wilson 2004) have been successively revised (Biesecker 2009) as the minimum has dragged on. Recent work has argued that the Sun is near the end of a 95-year phase of high activity, and that either a full blown grand minimum or much weaker cycles are likely in upcoming decades (Abreu et al. 2009). If the Sun indeed is near a transition from a state of relatively vigorous to relatively low activity, a comprehensive observational record of Cycle 24 (both resolved and disk-integrated) is paramount. In any event, current observations (e.g, of the polar fields, solar wind and cosmic ray fluxes) suggest that Cycle 24 will be unlike any of the three prior cycles of the space era.

At the same time, essential questions remain about the variations of truly Sun-like stars, often called "solar twins." The solar twin 18 Sco (de Mello & da Silva 1997) is the only one with long-term activity and brightness measurements. It turns out to have cyclic photometric variations comparable to the Sun's (Hall, Henry, & Lockwood 2007), but although it is of near solar metallicity, its Li abundance is 3X solar (Meléndez & Ramirez 2007). This may be indicative of higher angular momentum (Takeda et al. 2007), with obvious implications for the dynamo and perhaps providing a clue to the relative brevity of its activity cycle (~7 yr). The few other solar twins identified thus far do not have long-term observational records.

And what of stellar analogs of the Maunder Minimum (MM)? We are hindered by the substantial – and generally difficult to quantify – amount of light in the Ca II H&K line cores arising from non-dynamo-related sources, and this problem is at its worst for inactive or evolved stars, both for activity expressed in terms of the MWO *S* index (Judge & Saar 2007) as well as the chromospheric fractional flux R' (Schröder, Reiners, & Schmitt 2009). Wright (2004) has argued that we do not know of any MM stars, but the effects of metallicity and gravity on R' were not included in its calibration by Noyes et al. (1984), and further work is required. The fraction of solar analogs in the cluster M67 lying below the present solar minimum is ~17% (Giampapa et al. 2006), in accord with the statistics of the MWO sample, but we do not have a clear picture of their variability (or lack thereof). There is no difference in Ca II H&K activity between the cycling and flat activity stars (Hall & Lockwood 2004), but as Judge & Saar (2007) have pointed out, the HK proxy, whose variations generally trace modulation of large scale magnetic structures associated with the dynamo, is a poor tracer of surface magnetic fields that are the likely determinants of the true nature of a grand minimum. These authors identify two stars that do appear to be bona fide MM candidates, but which exhibited UV and X-ray emission comparable to the modern solar minimum. Thus there is evidence that the MM Sun may not have been much different from the modern Sun, but it remains indirect and lacking time-series corroboration.

The Sun's photometric quiescence, as well as the seemingly small solar twin phase space, have led to discussion of whether or not the Sun is an atypical star. Gustafsson (2008) argues the Sun is not unusual, but Böhm-Vitense (2007) writes: "*Clearly the Sun is not a good* *standard star for the discussion of stellar activity."* Perhaps our familiar "Sun as a Star" paradigm is indeed better expressed as examining "the Stars as a Sun," both in the sense of identifying what really constitutes "sun-ness," as well as understanding whether our star's time domain behavior is in any way exceptional. In Section 3 below, we discuss the observations and instrumentation that will help us address these issues.

3. Science Requirements, 2010-2020

3.1. Facility and Instrument Needs

To make progress in this area, we must support three key efforts over the next decade.

Continued solar irradiance observations. The 30-year TSI record began in 1978 with the HF radiometer aboard Nimbus-7 and continues today with instruments aboard SOHO and SORCE. The SORCE mission has been extended until January 2012, and on June 15, 2009, Glory will join the "A-Train" to begin a new, complementary record of solar irradiance measurements, followed by TSIS on NPOESS in 2013. Acknowledging the finite physical and financial lifetimes of solar irradiance missions with inexorably degrading radiometers, we emphasize the critical importance of maintaining an *unbroken* record of TSI measurements. Creating an unambiguous composite record is difficult in any event (Fröhlich & Lean 2004, Willson 1997), and overlapping radiometer records are vital. The Sun is the only star for which we have any observations at all at the precision and accuracy level of the TSI measurements. The Kepler mission will, we hope, be revealing of similar behavior, but the long-term precision of its data is problematic, and that mission is short-lived.

Dedicated, preferably automated ground-based facilities. Henry (1999) has discussed the benefits and extremely high (sub-millimag) precision of automated photometric observing, and in the Astro 2010 decade, we need to dedicate sufficient resources, both photometrically and spectroscopically, to achieve the required science. Stellar as well as Sun-as-a-star facilities (e.g., Livingston et al. 2006) are needed. Due to the heavy observing requirements, the more these facilities can be automated, the better. Contemporaneous spectroscopy and photometry are not merely desirable, but necessary. For compatibility with the large existing data sets, straightforward standard filters (*BVR* and *by*) are recommended. The science drivers (see section 3.2 below) demand echelle spectroscopy to reach the resolution and wavelength coverage required.

Time domain space-based observations. The Sun and Sun-like stars are far more variable in the UV and X-ray than in the optical; solar UV radiation varies by tens of percent, and X-rays by a factor of 10, over the course of an activity cycle. Such observations are both unambiguous indicators of magnetic activity as well as important discriminants of genuinely low-activity stars (Judge & Saar 2007). For example, the CoRoT satellite observatory has been making new discoveries about stellar activity during the course of its search for extrasolar planets; the power spectrum of intensity fluctuations suggests a level of granulation noise that is significantly higher than that seen in the Sun but in stars that are ostensibly more quiet than the Sun. While a given space-based observatory of course cannot be wholly devoted to one program, excellent progress has been made in detecting coronal activity cycles using XMM/Newton (Favata et al. 2008; Robrade, Schmitt, & Hempelmann 2007). Support of time-domain space-based observations with acceptable observing burdens will provide an essential multiwavelength perspective for the more densely sampled ground-based programs.

3.2. Science Needs

For $V \leq 7$, we know of one solar twin (18 Sco), and perhaps 2-3 stars for which 40 years of observations have revealed evidence of cycling to non-cycling transitions. Key questions can be addressed by pushing the sample deeper along both the magnitude and wavelength axes.

The magnitude axis. With facilities that can conduct surveys to, say, $V \approx 11$, we can survey solar analogous G dwarfs out to ~300 pc, increasing the sample volume by a factor of several hundred. Which parts of the dauntingly vast steradians do we target? Kepler fields are an obvious starting point, and attention to survey and follow-up observations of known planet hosting stars, as well as the many that will undoubtedly turn up over the next few years, is a logical first step. However, a carefully considered set of additional Galactic plane survey areas to match the anticipated observing resources is warranted in the early part of the Astro 2010 survey period.

The wavelength axis. Synoptic spectroscopic observations to date have focused narrowly on the Ca II H&K chromospheric activity proxy. This is neither unjustified nor careless, as the relatively large excursions in HK emission clearly reveal the basic nature of a star's variations. However, lines formed throughout the solar photosphere show clear signatures of the cycle, sometimes in odd ways. The solar cycle 21/22 minimum is plainly apparent in various photospheric lines such as Mg I *b*, but the cycle 22/23 minimum is not (Livingston et al. 2006), and Schüssler et al. (2003) have demonstrated that the CH λ4300 G band sensitively traces photospheric magnetic flux. These features, rather than HK, will reveal the behavior in non-cycling stars of the small-scale magnetic features that not only were likely present during the Maunder Minimum, but which play an essential role in modulating the brightness of grand minima.

Ca II HK observations can usefully continue, especially in the neglected southern sky (Metcalfe et al. 2006), to facilitate comparison with the existing data sets, but these observations alone will be insufficient to advance our understanding of inactive star variations significantly in the next decade. There are no long-term observations of Sun-like stars of the G band and the myriad other photospheric lines between λλ4000-5000, and the ideal instrument for future solar stellar studies will span at least ~λλ3800-6000 at sufficient resolution for both solar twin identification and time-series work (at least ~30,000). While the variability of the photospheric lines is considerably lower than that of the HK lines (often fractions of a percent), there are also many more photons in this part of the G star spectrum than in the dark cores of the near-UV HK lines.

Finally, the differing behavior of the photospheric proxies, combined with HK observations, may relieve us from the unpleasant prospect of having to wait 10 (or 70!) years to be sure we really have seen a grand minimum. Differences in *short-term* behavior of these features in cycling and non-cycling stars, combined with confirming variability or non-variability of the HK emission on timescales of 2-5 years, may be sufficient to identify the genuine analogs of the elusive Maunder Minimum.

4. Summary

The Sun has recently completed a relatively modest solar cycle (Cycle 23, ranked 10th in strength of the cycles since 1700), characterized by a long decrease to the current minimum. Although active regions have emerged with the next-cycle polarity, the sluggish onset of Cycle 24 raises a good possibility that it will also be rather weak, with a slow rise to maximum. Multiple studies have suggested that Sun is near the end of a roughly century-long period of vigorous activity, and that either weak variability or a grand minimum may be forthcoming in the next few decades.

The modulation of solar brightness by grand minima is a critical question for understanding the secular evolution of its irradiance on century and millennial timescales. Observations of Sun-like stars in cycling and non-cycling states are essential to help answer this question, and the existing data sets show that both deeper surveys and time-domain observations, as well as exploration of previously neglected parts of the spectrum, are required to make progress.

This science has fundamental astrophysical relevance, elucidating the nature of solar and stellar dynamos, as well as the processes that cause extreme modulation of their large scale manifestations. For example, is there a chaotic component to the solar dynamo that leads to excursions from cyclic variation? What is the range of excursions of the solar cycle, in both amplitude and period, in strict solar twins? **The science also has practical import regarding the Sun's contribution to climate change**, both globally and in its likely more important localized effect during lulls in activity.

As exoplanet discoveries march steadily down the mass scale toward Earths (already to 1.7 Earth masses as very recently announced by CoRoT), **an improved understanding of the luminosity excursions of the host stars has important implications for Origins and SETI work**.

To make these discoveries happen during the Astro 2010 survey period, the community must support

- continued, unbroken TSI observations from space;
- ground-based solar facilities (such as the SOLIS Integrated Sunlight Spectrometer) making full disk and resolved observations of Cycle 24 in key diagnostic features;
- observations of Sun-like stars in survey and time-series modes, automated to the degree possible, both photometric and spectroscopic, via facilities that can dedicate sufficient resources filling the requirements of
    - imaging and spectroscopy to $V \sim 11$-12;
    - wavelength coverage greatly expanded from Ca II H&K, from at least the near UV to mid optical.

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