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The Solar-Stellar Dynamo-Irradiance Connection

Ricky Egeland

High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, USA

Nearly everything that is known observationally about distant stars comes from their electromagnetic radiation. These observations are in limited bandpasses that form only part of the total solar irradiance that is observed for the Sun using space-based bolometers. Like the Sun, stellar spectral irradiance varies on multiple timescales, many of which are driven by surface magnetism. These time scales range from minutes (e.g. acoustic p-modes and surface granulation "flicker," (Cranmer *et al.* 2014) to a decade or more, analogous to the $\sim$11 year solar sunspot cycle. Long-term stellar variability is often not as regular or well-behaved as in our nearest star, for example the erratic "Var" class and multiple-period cycles of Baliunas *et al.* (1995).

The Sun's regular magnetic cycle is beautifully demonstrated in "butterfly diagrams" (e.g. Hathaway 2015) that reveal a remarkable level of order in a cycle that lasts $\sim$22 years when considering polarity. In these diagrams we observe that magnetic bipole regions have an opposite order of leading and following polarity across the equator, and this order changes in the same hemisphere from one sunspot cycle to the next (Hale's Law). The higher latitude following polarity (Joy's Law) is seen to be advected to the poles, which in turn flip their polarity some time after hemispheric sunspot maximum. There are three overarching questions when presented with this view of solar magnetism:

- What are the processes which generate and change the solar magnetic field?
- How do these processes depend on the solar structural and kinematic properties?
- How do these processes change on stellar evolutionary timescales?

Analogous questions may be asked of spectral irradiance. The first of these might be fruitfully explored with solar observations alone, but the second and third demand either observations of other stars or an unassailable dynamo theory, which nonetheless cannot be obtained without confirmation by stellar observations. Hence the interest in long-term synoptic observations of proxies for stellar magnetism that underlies the sub-field known as the "solar-stellar connection" and extends to studies of stellar spectral irradiance variability.

Figure 1 shows the bandpasses of six synoptic stellar surveys that capture variability of interest for studying stellar magnetism or spectral irradiance. The bandpasses are shown using the Kurucz *et al.* (1984) solar spectrum degraded to 1 Å resolution. The rough order of the number of target stars is indicated, which ranges from 10^2 to 10^9. Three of these are ground-based (HK Surveys, Fairborn APT Survey, and LSST) and three are space-based (*Kepler*, *TESS*, *Gaia*).

Four important parameters determine the science that can be obtained from a magnetic proxy or spectral irradiance variability program: duration, cadence, precision, and number of targets. In Figure 2 I plot each of the synoptic surveys with the duration of the program on the x-axis and the mean observation frequency on the y-axis. The marker size is scaled to the number of stars observed in the program. The Nyquist frequency

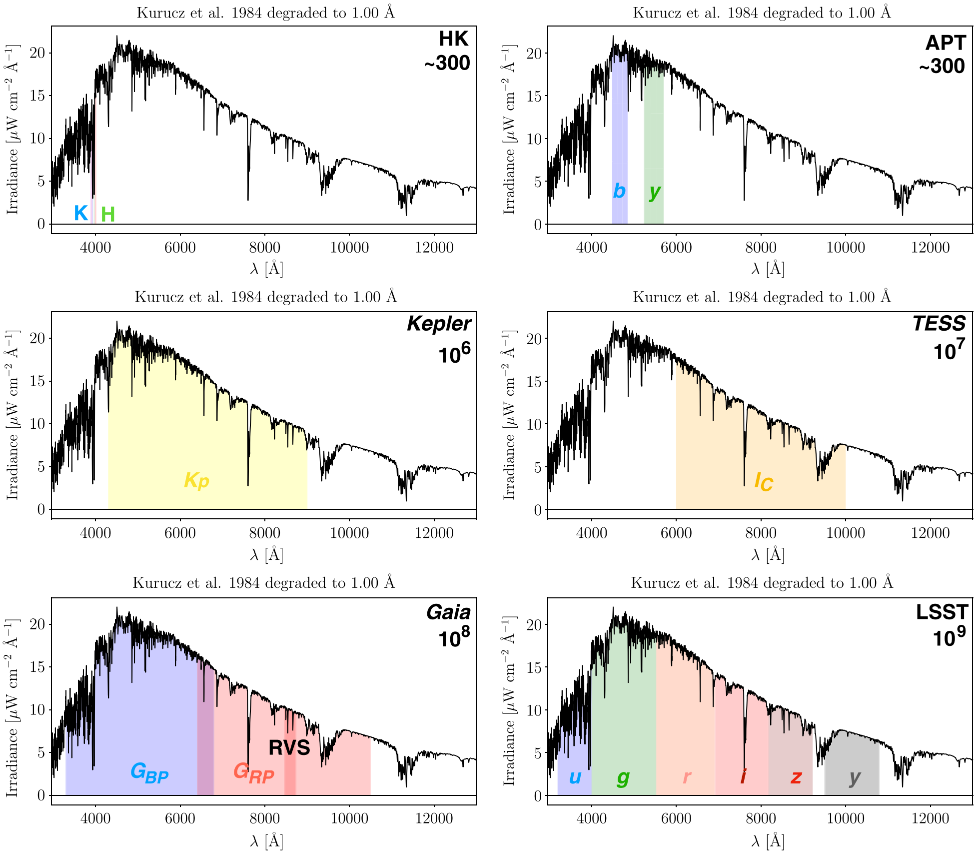

Figure 1. Synoptic stellar survey bandpasses.

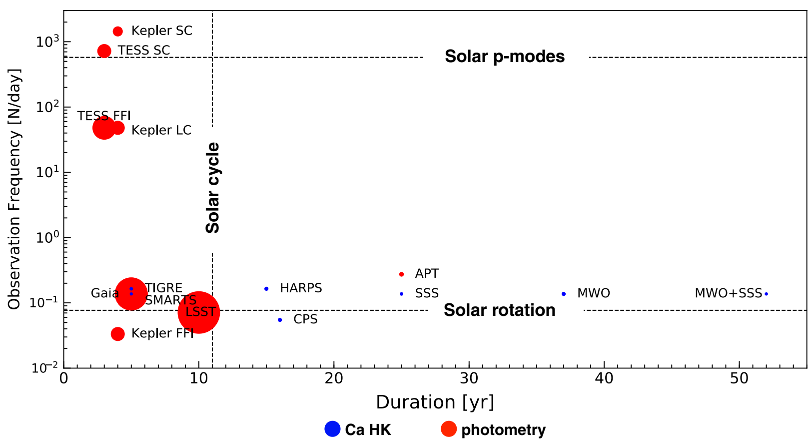

Figure 2. Synoptic stellar survey duration and mean cadence.

required to capture solar p-modes and rotation is indicated, as well as the solar cycle duration.

The ground-based Ca II HK surveys are the current champions of duration, and will remain so for quite some time. Prominent among these are the Mount Wilson Observatory

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HK Project (MWO; 1966–2003; Baliunas *et al.* 1995) and the Lowell Observatory Solar-Stellar Spectrograph (SSS; 1994–present; Hall *et al.* 2007). Only these have sufficient duration to reveal Sun-like stellar activity cycles, and when combined they produce time series exceeding 50 years (Egeland 2017). Other stellar HK surveys include SMARTS and TIGRE, as well as radial velocity exoplanet surveys CPS and HARPS with irregular cadence. The Fairborn Observatory Automated Photometric Telescope program (APT; 1993–present; Henry *et al.* 1995) is the longest running photometric survey sensitive enough to detect the $\sim$1 mmag cycle-scale variation of the Sun. Recently, Radick *et al.* (2018) compares SSS HK activity to APT photometry to reveal the patterns of their correlation as well as the trend for more active stars to have larger amplitude variability.

The space-based exoplanet missions *Kepler* (2009–2018) and *TESS* (Ricker *et al.* (2014); launched April 2018) lead in cadence and precision. Lightcurves from the short-cadence (SC) targets of these missions can detect the p-mode oscillations and characterize stellar structure using asteroseismology. The 30 minute cadence of the long cadence (LC) targets is more than sufficient to detect stellar rotation, with over 34,000 rotation periods reported in McQuillan *et al.* (2014) and revealing a curious upper limit that may be a signal that magnetic braking stops operating when the dynamo becomes sufficiently weak (van Saders *et al.* 2018). The remarkable technique of exoplanet spot-transit photometry has revealed the location and size distribution of spots on another star (Morris *et al.* 2017). *Kepler* full-frame images (FFI) have recently been calibrated to remove instrument systematics allowing them to be used to study medium-term (4 year) photometric variability at a monthly cadence (Montet *et al.* 2017). *TESS* will provide similar FFIs at a 30 minute cadence and 27 day duration for the majority of the sky over its nominal 2 year mission. Overlapping observation sectors will have coverage for up to 1 year duration, and mission extension combined with plentiful fuel reserves could potentially extend *TESS* time series to the decade scale (G. Ricker; this meeting). The *Gaia* stellar astrometry mission obtains photometry with sufficient precision and cadence to detect variability and rotation. Lanzafame *et al.* (2018) reports on over 8×10^8 sources with > 20 observations, $\sim 5 \times 10^5$ classified as "variable", and over 15,000 with rotation period detected.

The Large Synoptic Survey Telescope (LSST; LSST Science Collaboration 2009) will regularly observe an unprecedented $\sim 2 \times 10^{10}$ targets over a nominal 10 year period starting in 2021. Each target will be "visited" approximately 80 times per year, with observations spread among its 6 bandpasses. The target 5 mmag zeropoint precision, combined with bandpass and seasonal averaging, should yield seasonal means at $\sim$1 mmag precision. While this is just at the threshold of detecting a weak Sun-like photometric cycle, many millions of more variable active stars will be detected by LSST (Hawley *et al.* 2016). Furthermore, actual zeropoint precision may reach the 2 mmag level (Ž. Ivezić, this meeting), and even more precise *relative* photometry may be obtained with additional processing, enabline LSST to detect Sun-like photometric cycles.

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