SOLAR-STELLAR RESEARCH AND THE DYNAMO PROBLEM

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SUMMARY

Beginning in the late 1980s, helioseismology revealed the large scale rotation profile of the bulk of the solar interior. Almost at a stroke, entire classes of dynamo models – designed to explain the 22 year solar magnetic cycle – could be dismissed. Using the rotation data, kinematic models of the dynamo have met with some success, even demonstrating limited skill in forecasting properties of the solar cycle. However, more recent progress in numerical and observational studies have opened up new questions. Is the solar convection zone "essentially magnetized" in the sense that spatially intermittent but strong magnetic fields influence convection? What elementary process converts toroidal field, readily created by differential rotation, into poloidal field? What are the dominant modes of meridional circulation? Do flux transport models merely describe surface field evolution or do they genuinely contain essential physical processes at work? Do large – scale "wreaths" of magnetic field found in dynamical models exist purely within convection zones? How and why do the Sun and stars enter and exit global minima of their activity cycles (e.g., the Maunder Minimum)? These and longer standing questions, such as why the Sun/stars form spots at all, what drives the 11 year flip of global magnetic polarity, and what controls the diffusion of magnetism, require the acquisition and analysis of new and critical data. We argue that our understanding of the Sun and its enigmatic dynamo will be greatly complemented by more concerted comparisons with stars.

Our purpose is to summarize the case for "re-running the solar-stellar experiment" through a modest but concerted line of funding to allow the community to continue to and expand on studies of carefully selected stars and stellar ensembles on long time scales. Multi-decade observations are *essential,* given the 22-year global magnetic activity cycle of the Sun.

This cross-disciplinary activity is not new, but new reinvestment is timely. Results from KEPLER and other experiments have revealed accurate critical parameters for many Sun-like stars. Spectroscopy and photometry reflecting magnetically-induced variations now span several decades for the Sun and several well-observed stars. Continued and expanded observation programs will have broader impacts in stellar rotational evolution, the solar-terrestrial connection, space weather, and astrobiology, providing important constraints for diverse theoretical models.

Appendices summarize relationships to the astronomy and heliophysics decadal surveys, and reports on a community workshop held at the High Altitude Observatory at NCAR in March 2014.

UNDERSTANDING THE SOLAR DYNAMO – THE SUN IS NOT ENOUGH

Despite new ground-based observations, space missions, and improved numerical models, progress in the dynamo problem faces challenges:

1. The scientific returns from global helioseismology are diminishing. The primary axisymmetric shear layers that can generate toroidal field from poloidal field on large scales have been known for two decades; meridional circulation velocities at depth in the convection zone, a central component of certain solar dynamo models, remain near or below helioseismic detectability thresholds.

2. Recent work suggests that basic properties of (magneto)-convective energy and angular momentum transport across the convection zone are not yet well understood. The amplitude of convective velocities on large scales (supergranules and above) seems to have been seriously overestimated by present theory. The effective Rossby number is particularly uncertain, with significant implications for dynamo theories.

3. We do not yet know how the magnetic cycle of the Sun operates, in part because ab-initio global models remain far beyond the scope of modern computers. The poloidal → toroidal mechanism is generally assumed to occur within the shear layers found in 1. above. However, at least two challenges remain. First, 3D MHD convection simulations have shown that strong toroidal fields are significantly amplified by *non*-axisymmetric rotational shear. Second, identifying the toroidal → poloidal mechanism poses particularly difficult challenges involving small-scale helical turbulence and/or larger-scale nonlinear effects deep in the interior.

4. Semi-empirical solar dynamo models designed with ad-hoc parameters to match or assimilate data have demonstrated some predictive power. Prediction of the engine that generates radiative, magnetic and particulate variations at the earth is of importance to society. However, such methodologies beg important questions. Do they artificially tailor results to fit a single star? What is to be concluded by the agreement or disagreement of such model predictions with data?

Studies of the Sun *in its proper place as a star* can help constrain dynamos in several important ways:

1. Obviously but importantly, Sun-like stars allow us to study many realizations of “the solar experiment” under conditions of varying age, mass, metallicity, convection zone and rotational properties.

2. Asteroseismology yields the mean density, stellar age and depth of convection zone. This has recently been achieved for some two dozen stars. However, asteroseismic internal differential rotation profiles and meridional circulation remain ambiguous and unattainable respectively, for main sequence stars. Sub-giants (slightly evolved Suns) present more favorable prospects.

3. Traditional tools of spectroscopy and accurate photometry partly fill in these limitations, revealing stellar surface rotation rates, differential rotation properties, and activity cycles analogous to the 22-year solar cycle.

4. Stellar data also reveal the location of emergence and migration of magnetic fields across the surface (butterfly diagrams, active longitudes), as well as abundances and properties of surface convection.

These examples show that stellar data contain ingredients critical to probing mechanisms behind large-scale dynamo activity. For example, if activity cycles were confirmed in fully convective stars, then the entire class of models placing a central role on the tachocline and subadiabatic shear region would be called into question.

Other ingredients remain a real challenge: the unknown toroidal → poloidal field conversion mechanism is again not directly observable; the transport of energy and angular momentum across the convection zones presents difficult challenges. But the careful study of stellar properties and MHD models in relation to cycling magnetic activity ought to provide important clues.

Two separate decadal surveys have been recently conducted: Astronomy and Astrophysics (2010) and Heliophysics (also 2010). This separation is unfortunate, as solar-stellar work falls squarely across the boundary. We have written this white paper to point to the need to combine these sub-disciplines, which would enable meaningful support for genuine cross-disciplinary research on the needed long time scales.

Current status of solar-stellar datasets

Starting with Olin Wilson's Mt. Wilson survey in 1966, ending in 2003, several groups have continued the painstaking yet important work to acquire time-series data spanning decades. Lowell Observatory has since 1988 run the Solar Stellar Spectrograph, an instrument conceived by Dimitri Mihalas and others in the 1980s. These two datasets represent almost everything we know of the cycling behavior of stars like the Sun, based upon the modulation of chromospheric Ca II emission through the passage of active regions across stellar disks. Including the Sun, we now know of ~54 stars with identifiable “activity cycles”, some statistically of questionable significance.

Lockwood and Skiff at Lowell Observatory have performed milli-magnitude photometry of solar-like stars over three decades, the goal being to monitor photospheric modulation associated with spots and active regions. Far higher sensitivities are needed in such cases than in chromospheric features, but several stars show clear cyclic activity at the 0.1% level present on the Sun. The Fairborn Observatory, mostly devoted to finding extra-solar planets, now has 4 automated photoelectric telescopes dedicated to Sun-like stars, with 300 on the current program and durations of observation in the 10-20 year range. Unfortunately, the Fairborn observatory and its data currently operate in single point failure mode, relying on dedicated individuals in key positions. In Appendix B we list several unanticipated results of the Ca II and photometric long-term studies.

Significant NSF-supported research has continued at the National Solar Observatory and High Altitude Observatory through solar and stellar synoptic programs respectively. NSO solar data obtained by Livingston and colleagues extends from the mid 1970s, continuing through the present data through the SOLIS synoptic program. Metcalfe and colleagues at HAO and elsewhere obtained calcium line data from 2007 through the SMARTS consortium, until the prime instrument was decommissioned in February 2013. SMARTS targeted southern hemisphere stars including bright asteroseismic targets.

NASA, ESA and other agencies have flown important missions including solar irradiance variations since 1978, and spectral irradiances measured in more recent times, notably by the SORCE-SIM instrument. The KEPLER and other missions have provided invaluable asteroseismic and magnetic activity data for many stars, more results will become available as processing and analysis continues largely in Europe.

New instruments are online or coming online: The Las Cumbres Observatory Global Telescope network (LCOGT, T. Brown science director) begins operations in 2015. LCOGT is a longitude-distributed network of telescopes dedicated to time-domain astronomy. The telescopes, instruments, scheduling, and data acquisition are robotic. The Danish-led SONG network of ground based telescopes is a similar independent effort, both projects having high resolution spectroscopic capabilities. The majority of these programs face significant budget reductions, in part because of the natural tendency for agencies to support projects promising more immediate returns. Studies of stellar activity cycles require a long-term funding commitment, but the expected return will be invaluable for a deep understanding of solar and stellar dynamos.

Recommendation

We recommend that agencies consider a new line of funding to permit the university community to engage seriously in solar-stellar work targeted toward understanding the mechanism(s) of large scale dynamo action. This might be part of a multi-national effort but we believe the US is well poised to lead this effort. Today, the community is strongly encouraged to pursue cross-disciplinary research and yet no line of funding exists for the community to pursue this essentially cross-disciplinary activity!

Compared with the expense of space missions, modest investments in supporting infrastructure of ground based telescopes, supporting the training of graduate students, post doctoral researchers, new tenure-track faculty, and support for current researchers and teachers in the community, would secure the continuous coverage of magnetically-induced stellar variations for posterity. Further, the science returns from short missions such as KEPLER and TESS, and new facilities such as the Daniel K. Inoue Solar Telescope (DKIST, formerly the ATST) will be strongly leveraged by supporting continuing and new decadal measurement programs and identifying new avenues for future research. The continuation and consolidation of extant data is vital to establish links between the decades of existing observations and the exciting programs and facilities noted above that are poised to take up a new set of expanded synoptic studies.

Consequences of a failure to act

We must consolidate and build on the decades of work on magnetically-induced variations of the Sun among the stars, if we are to understand how the Sun's dynamo operates. Even something as fundamental the 22-year Hale cycle – an established result that remains unexplained from the fundamental laws of physics – must be understood within the range of behavior, cycling or otherwise, of other stars. The Sun and the stars vary magnetically on time scales of decades, and require funding commitments, albeit modest ones, over similar time scales. The observations necessary for the study of these astonishing variations should not be passed over simply because the stars do not know about short-term local, or global, economies.

Failure to act will seriously retard progress in diverse areas, which are theory-rich but observation-poor, including: solar variability-climate connections; stellar angular momentum evolution; origins of space weather; exoplanetary atmospheres; habitability of planets orbiting stars on the lower main sequence.

APPENDIX A: RECENT DECADAL SURVEYS

The 2010 Decadal Study for Astronomy and Astrophysics, *New Worlds, New Horizon* (hereafter, *NWNH*) lists among nine "Science frontier questions related to understanding the cosmic order: How do rotation and magnetic fields affect stars?" (*NWNH, p. 57*). This is the first priority question of the Science Frontier Panel for Stars and Stellar Evolution, noting that Time-Domain Surveys in this area have "Unusual Discovery Potential" (*NWNH, p. 247, Table A.1*). *NWNH* expands further on this question:

To understand the lives of stars and the role they play in cosmic evolution we must understand the roles of mass loss, rotation, and magnetic fields in stellar evolution. Prospects are bright for the coming decade. All three phenomena can be assessed through high-dispersion spectroscopy. Rotational studies are possible with detailed long-term photometric monitoring. It is now becoming possible to study the structure and strength of magnetic fields on the surfaces of nearby stars, and changes in the magnetic fields can be diagnosed with X rays. At the same time, the major advance provided by the Advanced Technology Solar Telescope (ATST) will be an improved ability to observe and understand the rich array of magnetic activity exhibited by our nearest star, the Sun. (*NWNH, p. 64*).

The *NWNH* Decadal Survey also recognizes the critical importance of studying transient phenomena,

Since solar flares create many cosmic rays that can cause mutations of genetic material, understanding these flares is important for understanding the chances of a planet being habitable. Flares on the more numerous low-mass, cool stars may preclude some forms of life on orbiting planets already known and to be discovered. Studying flares from the Sun using optical techniques with ATST—and at radio frequencies by using the proposed Mid-Scale Innovations Program candidate, the Frequency Agile Solar Radiotelescope (FASR)—as well as studying stellar flares in far-off planetary systems…..could advance our understanding of planetary habitability. (NWNH, p. 202).

and also the power of seismology,

Stellar seismology is maturing rapidly. Analogous to Earth-based seismology, this technique enables astronomers to probe the deep interior regions of stars using the complex oscillations observed at the star's surface, much as the tone of a musical instrument reveals its internal construction. In the next decade, the rapidly increasing power of computers will allow us to take the known physical laws that are at play and synthesize them into detailed three-dimensional movies of the life and death of stars. (NWNH, p. 64).

All of these considerations, and more, lead to the following top-level recommendation (*NWNH, p. 34)*: **"NSF should work with the solar, heliospheric, stellar, planetary, and geospace communities to determine the best route to an effective and balanced ground-based solar astronomy program that maintains multidisciplinary ties. "**

The Heliophysics community conducted a separate decadal survey – *Solar and Space Physics: A Science for a Technological Society* (hereafter *STS*). The first among the four "Key Science Goals for a Decade" is, *determine the origins of the Sun's activity and predict the variations of the space environment (STS, p. I-8).* Closely related is overarching Goal 4, namely, *Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe (STS, p. I-12).* The first example given of a universal process that contributes to the control of the space environment is *Dynamos (STS, p. I-13).*

Specifically, under the proposed DRIVE initiative, the STS recommends that

NSF should ensure that funding is available for basic research in subjects that fall between sections, divisions, and directorates, such as planetary magnetospheres and ionospheres, the Sun as a star, and the outer heliosphere.

and

Solar and space physics has a clear home in NASA's Heliophysics Division. However, there remain important scientific links between Heliophysics and the Astrophysics, Planetary Sciences, and Earth Sciences divisions. The survey committee concluded that multidisciplinary collaborations between the solar, heliosphere, Earth science, and climate change communities are valuable, and it recognizes in particular the importance of collaborations between the NASA Heliophysics and Earth Science programs. Similarly, the survey committee endorses collaborations across the Heliophysics, Astrophysics, and Planetary Divisions.

APPENDIX B: Report from a community science meeting

On 19th and 20th March 2014, a group of interested parties from the US and Europe met to assess the current status of theory and solar and stellar datasets, of direct relevance to our understanding of dynamo action in stars like the Sun. Attendees included (those without affiliations are at HAO):

Tom Ayres (CU Boulder), Mausumi Dikpati, Tim Brown (CU Boulder), Ricky Egeland (Montana State), Sarah Gibson, Greg Kopp (CU), Jeff Hall (Lowell Observatory), Jerry Harder (CU), Philip Judge, Christoffer Karoff (U. Aarhus, Denmark), Michael Knoelker, Wes Lockwood (Lowell), Piet Martens (Montana State University), Savita Mathur (Space Science Institute), Scott McIntosh, Travis Metcalfe (Space Science Institute), Mark Miesch, Alexei Pevtsov (NSO), Joe Plowman, Rich Radick (USAF), Matthias Rempel, Steve Saar (Harvard Smithsonian CfA), Michael Thompson (NCAR directorate), Marty Snow (CU), Giuliana de Toma.

Materials from this meeting are available at

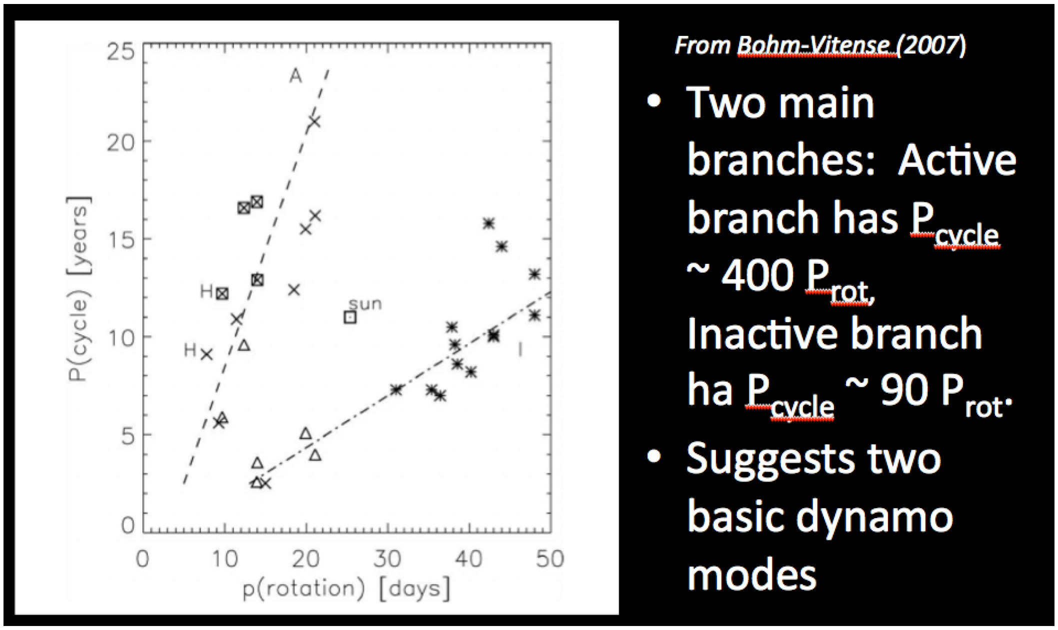
http://workshop.solar-stellar.org/

The discussion proceeded with the following points in mind:

- The origins of large-scale dynamo action are not adequately constrained on the basis of mere solar data alone. By “large scale” we mean that there is a flux imbalance on large scales – comparable to the solar radius – bigger than convection. Stellar data are necessary to probe large-scale dynamo activity.
- The effects of large-scale dynamo action – variations in radiative and particulate output and the conversion of the Sun's flux to high energies (UV/X ray) on decadal and longer time scales – are neither well measured nor understood.

The group arrived at some striking conclusions:

- The coupling between differential rotation and convection in the Sun is fundamentally not understood.
- The ensemble of sun-like stars indicates a far richer behavior that might have been anticipated on the basis of solar data
    - stars appear to have multiple cycle periods (including the Sun),
    - cycles may temporarily lose phase coherence,
    - stars can lie in different regimes, the Sun may be anomalous (see the figure below)



- at least two stars appear to suggest evolution from cycling to Grand Minima (analogous to the solar Maunder Minimum).

- space-borne measurements of solar variability from SORCE-SIM appear at variance with stellar observations (even in the *sign*!). If real, they will have significant implications for solar-terrestrial physics.
- Long timeseries of stellar and solar data in milli-magnitude photometry, and activity indices, are critical, given the 22 year solar cycle, yet
- stellar work in this area remains dangerously under-funded, almost entirely privately funded. In the case of the important APT program, operates in single point failure mode due to lack of funding.
- Data are physically scattered widely. A new homogeneous database of solar-stellar observations will provide an invaluable research tool.
- The NSO solar “Integrated Sunlight Spectrometer” (ISS) instrument has 10 channels of 0.5-1 nm width and a spectral resolution of around $5x10^5$, but much of this spectral diversity has barely been explored owing to lack of resources.
- Some stars are “special”:
  - having been “sounded” by Kepler (C. Karoff's 20 Sun-like stars)
  - being especially solar-like (18 Sco, although this star has a 7 year vs 11 year solar period for calcium variations)
  - they are entering or leaving grand minima, for example.

  These cases should serve as targets for individual study.
- Phase two of the Kepler mission (“Kepler II”) will obtain important data on various Mt Wilson stars and cluster stars such as Hyades and M67 stars.
- About 12 Kepler II target stars coincide with the Mt. Wilson survey.
- The new Lowell DCT, LCOGT and SONG telescopes are well suited to continued solar-stellar studies should competition for time allow. NASA's Transiting Exoplanet Survey Satellite (TESS), scheduled for launch in 2017, is well suited to solar-stellar research by targeting the brightest main sequence stars in an all-sky survey.