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The Solar-Stellar Connection: An Overview

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Abstract. The evolution of the solar-stellar connection is traced through the lens of two decades of Cool Stars Workshops. Six "themes" contrast our understanding twenty years ago at the time of Cool Stars 1 with current ideas at Cool Stars 12. These themes: magnetic cycles of activity and their evolution; atmospheric structure(s), heating processes, abundances, and the presence of planets around cool stars other than the Sun have developed dramatically (or even originated) during the two decades of meetings. Advances represented by new capabilities in observing facilities and computational power will make possible future discoveries, insights, and synthesis. New objects and relationships, new applications of physics, and horizons expanded beyond our local neighborhood will mark the exciting decades to come.

1. A Little History[2]

How did the "solar-stellar" connection originate? No less a scientific genius than George Ellery Hale remarked (1915), after reviewing a decade of solar work at the Mt Wilson Observatory, including his own discovery of magnetic fields in sunspots, that...."thousands of stars, in the same stage of evolution as the Sun doubtless exhibit similar phenomena, which are hidden from us by distance." A search for spectral variability similar to the Sun in other stars was reported briefly in a paper by Liller (1968) containing an acknowledgement to Leo Goldberg for suggesting the research and making the solar-stellar link through cyclic Calcium fluxes. Wilson (1968) submitted a manuscript 4 months later and also explicitly referred to "stellar analogues of the solar cycle."[3] Liller's photoelectric spectrophotometry suggested small random fluctuations might occur in a few cool stars, but Wilson's two-channel photometry revealed no "undoubted variations". It was decade later before Wilson (1978) could say definitively that

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[1] Harvard-Smithsonian Center for Astrophysics

[2] The SOC Co-Chairs for CS 12, Tom Ayres and Alex Brown kindly invited me to highlight topics of the solar-stellar connection as an introduction to the Boulder meeting and to pay particular attention to the state of our knowledge in 1980 when this series began as contrasted with the situation in the summer of 2001. Indeed this was a challenge! And so with apologies for omissions (including the displayed artefacts), this is a selective tour of the Solar-Stellar connection for two decades.

[3] Variations in the Ca II emission lines were originally sought by Wilson and Bappu (1957) ten years earlier, starting with first epoch plates in 1938; however they appear to have sought intrinsic stellar variability without reference to a "solar-stellar" analogue.

Figure 1. An obviously amateur photo-composite demonstrating the variety of tee shirts available at the Cool Stars Workshops... and the variety of attendees... who probably would prefer to remain anonymous, but I will identify them anyway: (*left to right; top to bottom:*) Carole Jordan, Jeffrey Linsky, Carol Schrijver, Jürgen Schmitt, Gaitee Hussain, and Scott Wolk with artefacts from CS2, CS3, CS4, CS5, CS8, and CS 10 respectively.

cyclic variations in stellar Ca II H and K fluxes were detected, and these were analogues of the solar cycle. Wilson's paper is generally thought to have inspired the subsequent work on the solar-stellar connection, at least in terms of magnetic activity.

As these early studies were underway, the solar physics community itself began to recognize that solar and stellar studies could profitably interact. In 1975, Bob Noyes as Chair of the Solar Physics Division of the American Astronomical Society established an *ad hoc* committee on the *Interaction Between Solar*

Physics and Astrophysics.[4] A year later the panel recommended expanded interdisciplinary ties between solar and stellar disciplines. Shortly thereafter two major NASA satellites were launched: the International Ultraviolet Explorer (*IUE*) and HEAO-2 (*Einstein*). Cool stars were frequent targets for these ultraviolet and X-ray instruments and it was natural to look to the Sun as a prototype to interpret the new data as they arrived. Thus, the *First Cambridge Workship on Cool Stars, Stellar Systems, and the Sun* was held in Cambridge Massachusetts in January 1980. The sequence has continued for more than two decades, and moved around the globe, arguably the longest running independent astronomy meeting in our profession! [5]

The Cambridge Cool Stars Workshops have continued a tradition of responding to the latest ideas and discoveries in cool stars research, including the meeting (CS9 in Florence) at which the first extra-solar planets were announced. A tabulation follows: of the meetings, their sites, and the Editors of each Proceedings.

2. Themes of the Solar-Stellar Connection

Six topics clearly illustrate examples of the solar–stellar connection and recent progress, generally driven by new observations and accompanying theoretical interpretations. For each area, the concepts and ideas in place at the first Cambridge Cool Stars Workshop in 1980 are contrasted with the state of our understanding as this talk was prepared in July 2001. I suspect that contributions in these Proceedings will make this manuscript "history" very soon!

2.1. Cycles of Activity

Because Calcium emission in the Sun can be linked directly to the photospheric magnetic field strength, a similar relationship is expected to occur in cool stars. Stellar studies can identify not only the cyclic behavior of magnetic activity in cool stars, but the activity level and its decay, and offers a direct measurement of the rotational period. At the time of the first Cool Stars Workshop, Olin Wilson had measured the flux in the centers of the Calcium II, H and K lines, of 91 main-sequence stars for a period of 9 to 11 years at Mt. Wilson Observatory (Wilson 1978). He found a cycle of variation in about 12 of these stars but could not detect short period flux modulation caused by rotation of features on and off the stellar disk.[6] This program was extended enormously by Baliunas and other colleagues who have found cyclic variation in 111 main sequence stars, and rotational modulation in dwarfs, giants, and supergiants (Choi et al. 1995; Rao

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[4] This panel comprised: Jacques Beckers; Andrea Dupree, Chair; Lawrence Fredrick; Jack Harvey; Jeffrey Linsky; Larry Peterson; Art Walker.

[5] To clarify this assertion, "independent" means free of affiliation with, or support from, the American Astronomical Society or the International Astrophysical Union. The subject, astronomy, distinguishes Cool Stars from the "Texas Symposia" which principally attract physicists.

[6] These necessarily few sentences do not do justice to Wilson's scientific motivation and fundamental first observations which motivated so much subsequent research. These are discussed in detail by Noyes (1996).

COOL STARS MEETINGS

Mtg.	Year	Site	Proceedings Editors
CS 1	1980	Cambridge, MA	A. Dupree
CS 1.5	1980	Bonas, France	R. Bonnet & A. Dupree
CS 2	1981	Cambridge, MA	M. Giampapa & L. Golub
CS 3	1983	Cambridge, MA	S. Baliunas & L. Hartmann
CS 4	1985	Sante Fe, NM	M. Zeilik & D. Gibson
CS 5	1987	Boulder, CO	J. Linsky & R. Stencel
CS 6	1989	Seattle, WA	G. Wallerstein
CS 7	1991	Tucson, AZ	M. Giampapa & J. Bookbinder
CS 8	1993	Athens, GA	J.-P. Caillault
CS 9	1995	Florence, Italy	R. Pallavicini & A. Dupree
CS 10	1997	Cambridge, MA	R. Donahue & J. Bookbinder
CS 11	1999	Tenerife, Spain	R. Garcia Lopez, R. Rebolo & R. Zapatero Osorio
CS 12	2001	Boulder, CO	T. Ayres & A. Brown

et al. 1993; Baliunas et al. 1995, 1998) with coverage extending up to 30 years in some objects. Surveys of 800 solar dwarfs in the Ca II H and K lines (Henry et al. 1996) enabled identification of the very inactive stars suggesting that our Sun will be in a Maunder minimum phase for about 10% of its remaining main sequence life. Additionally, specific solar-like stars have been examined (Radick et al. 1998) in both Ca II H and K and photometrically to identify an the equivalent of an 11-year solar activity cycle. Radick et al. were able to demonstrate that long-term brightness and magnetic activity increase (or decrease) together for old solar-like stars (faculae-dominated) whereas young active stars display the reverse correlation because they are spot-dominated.

The level of emission has been related to the interior structure of the star through an empirical correlation with the Rossby number (Noyes et al. 1984). Thus within the framework of these theoretical assumptions, constraints can be placed on dynamo models both for level of activity and its decay. Luminous stars frequently exhibit multiple periods suggesting that pulsation is present that can modulate the Ca II H and K emissions. Particularly interesting has been the identification of Ca H and K modulation in evolved stars such as the He-burning clump giants in the Hyades (Baliunas et al. 1998) suggesting that a dynamo resurgence occurs after evolution on the red giant branch. Ages of individual stars can be determined via the Ca emission level (Soderblom et al. 1991) which have particular relevance in dating stars with planets.

2.2. Evolution of Magnetic Activity

Taking the chromospheric Ca HK emission as a tracer of magnetic activity, our understanding of its evolution was extremely simplistic in the late 70's. The most frequently displayed graph in the early days came from Skumanich's (1972) short paper showing that the decay of Calcium emission, rotational braking, and Lithium depletion (as far as the Hyades age) in dwarf stars as a function of time followed a square root law.[7] However now it is clear that simple "square-root" scaling relations do not always apply.

Studies of clusters have shown that ultra fast rotators exist, and these stars must spin down differently from the predictions of a simple square-root law (cf. Stauffer et al. 1997; Krishnamurthi et al. 1997; Sills et al. 2000 and references therein). Many people including Soderblom, King, Stauffer, Hartmann, Pinsonneault and others who study clusters remark that "each cluster has its own story to tell" but after rotation convergence, the activity-age relation appears to hold for dwarfs older than the Hyades.

Giant stars display a decay in Ca HK activity as these stars move up the red giant branch (Beasley & Cram 1993; Dupree et al. 1999; Pasquini et al. 2000) and their rotation decreases (Melo et al. 2001). This is expected, but the surprising fact is that activity returns in the form of increase in Ca emission, and even X-rays are detected in the He-burning giants –the "clump" stars (Stern et al. 1981; Dupree et al. 1999).

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[7] It is noteworthy that this 2.2 page paper is in the 99.9 percentile of high numbers of citations (385) of any in the NASA Astrophysics Data System data base, and ranks second in the ApJ Letters archives in citations/page of text! The principal figure from this paper was voted the "most popular in show" at CS1.5.

2.3. Atmospheric Structure(s)

It was during the 60's and early 70's that the *Orbiting Solar Observatory* series of satellites began to reveal the complex structure of the outer solar atmosphere. The chromosphere and corona of the Sun were generally divided into 3 structural elements: the Quiet Sun, Active Regions, and Coronal Holes.[8] The SKYLAB experiments in 1973, because of their higher spatial resolution and, in particular, the American Science and Engineering soft X-ray images, confronted us with the overwhelming dominance of the magnetic field in structuring the corona. The coronal loop model devised by Rosner, Tucker, and Vaiana (1978; the 'RTV–models') suggested that magnetic loop structures formed a fundamental building block of the solar corona. These models with constant pressure, uniform heating, and recipes for relationships among physical parameters in coronal loops became influential in subsequent years and were adopted by the stellar community too.

Observations of outer atmospheres of stars were in a very primitive stage. A few rocket flights (Moos and Rottman 1972; Catura et al. 1975; Weinstein et al. 1977) and the *Copernicus* satellite (Dupree 1975, Evans et al. 1975; McClintock et al. 1978) gave hints of far ultraviolet chromospheric emissions. Early results from IUE and the Einstein satellite, made possible a broad-brush overview of cool star atmospheres. 'Sharp dividing lines' were conjectured (Linsky & Haisch 1979; Ayres et al. 1981) to exist in the Hertzprung-Russell diagram separating solar-like stars from non-solar stars or the presence of X-rays or not. Stellar coronas were thought to be isothermal, or, to have two temperature (2-T models) components (Holt et al. 1979).

The next two decades have dramatically changed these simple views. Studies with TRACE and SOHO/EIT demonstrate that solar coronal loops can not be reconciled with simple assumptions of RTV models (Aschwanden et al. 2001). In fact, only 30% of the loops studied could be accommodated by RTV models, and the brightest EUV loops exhibit scale heights far in excess of their hydrostatic values. The ULYSSES spacecraft passing directly over the solar poles dramatically confirmed *in situ* the origin of the fast solar wind (Phillips et al. 1995) which now appears to be accelerated and reach several hundred km/s velocities deep within the corona at $2R_\odot$ judging by the SOHO/UVCS measures (Miralles et al. 2001).

Spectroscopy of stars in the far and extreme ultraviolet regions coupled with X-ray spectroscopy has suggested different coronal structures too. Like the Sun, temperatures are continuous, smoothly varying from chromospheric to coronal values (Dupree et al. 1993; Griffiths & Jordan 1998; Sanz-Forcada et al. 2001); moreover the maximum temperatures in cool star binaries are easily more than an order of magnitude higher than found in the quiet sun. The emission measure distribution shows features that differ from the solar case. A stable enhancement of the emission measure distribution over a small temperature range appears in

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[8] My recollection of the discovery and naming of these holes in the corona is that it occurred one morning in the early 70's. George Withbroe, Bob Noyes, and I were at the CfA studying the latest numerical printouts from the Harvard experiment on the OSO-6 satellite. Leo Goldberg walked in the room, looked over our shoulders at these crudely colored Mg X images, and said "My goodness, there is a hole in the corona today." The name stuck, and only later did we appreciate the solar significance of these features.

a wide range of active stars. Evidence is accumulating that this enhancement may be associated with high latitude or polar regions of the stars (cf. Brickhouse & Dupree 1998; Jeffries 1998; Schmitt & Favata 1999; Brickhouse et al. 2001).

Densities as measured from diagnostic lines of highly ionized iron are high with values from $10^{12} - 10^{13}$ cm^{-3} at temperatures near 10^7 K. Pressures implied by these densities are higher than observed in solar active regions. Reproduction of the emission measure distributions for stars is proving to be a challenge for it is hard to match the small sizes and high densities implied by the spectra (Schrijver et al. 1989; Griffiths 1999; van den Oord et al. 1997).

Just as the 2-T coronas have vanished, a 2-flavor characterization of cool star outer atmospheres is no longer applicable (Hartmann et al. 1980; Reimers et al. 1996; Ayres et al. 1997). The "hybrid" stars represented the connection between solar-type and Alpha-Ori type atmospheres, exhibiting hot outer atmospheres and a massive wind, and appear to be ubiquitous (Schröder et al. 1998). Results from the FUSE satellite are just beginning to appear, but it is already clear that O VI emission occurs from F0 II to K5 III demonstrating the prevalence of warm ($3{\times}10^5$K) atmospheres across the H-R diagram. Evidence for extended atmospheres comes from the narrow fluorescent lines first noted in ORFEUS spectra (Dupree & Brickhouse 1998) of luminous cool stars that appear to result from Lyman-alpha pumping of Fe II (Hartman & Johansson 2000; Harper et al. 2001).

Optical techniques have identified extremes of activity in some well-studied rapidly rotating stars. Photometric measures suggested the existence of dark polar spots which are particularly well-documented in the decade long study of HR 1099 (Vogt et al. 1999). Zeeman-Doppler imaging confirms circumpolar spots and reveals also the nature of the azimuthal magnetic field (Donati 1999). AB Dor is a particularly well-studied pre-main sequence rapid rotator, and the magnetic field extends from the equator to above a latitude of 60° (Donati et al. 1999). Although the differential rotation of AB Dor is similar to the Sun, the azimuthal field is comparable in strength to the radial field, and displays a high latitude band encircling the pole (Jardine et al. 1999). Such behavior is markedly different from the solar case, and indicates that rapidly rotating cool stars are not simply fast rotating suns. Magnetic field emergence may preferentially occur at high latitudes from Coriolis forces in rapidly rotating stars (Schüssler et al. 1996) and stripping of extended coronal loops could result from centrifugal forces (Jardine and Unruh 1999). These two processes could conspire to produce dense loop structures at the poles. Clearly, the solar-stellar connection may be more tenuous as magnetic activity approaches extreme values. The extent of "(super)saturation" in the coronal fluxes in stars of extreme rotational velocities has been measured (Vilhu and Rucinski 1983, Randich 1998, James et al. 2000) but an explanation for this is lacking.

As a sample of future possibilities, the first direct image of a stellar surface other than the Sun was obtained of the M supergiant Betelgeuse by the HST/FOC in a broad ultraviolet band (Gilliland & Dupree 1996). The chromosphere of the star is extended by more than a factor of 2 in diameter beyond the photosphere, and displays a hot spot in its chromosphere. This low gravity star marks a clear break with the solar-stellar connection, and objects in intermediate stages would be extremely informative. Spectra obtained of restricted regions of the star have been interpreted (Lobel & Dupree 2001) to infer the complex dynamics of the outer atmosphere.

2.4. Heating

The ongoing quest for the source of heating for solar/stellar chromospheres and coronas has been driven to enlarge its options as observations narrow the viable possibilities. The early volumes of *Cool Stars Workshops* show the unmistakable influence of the SKYLAB missions, and the overwhelming impression of the dominance of the magnetic fields structuring the solar corona and hence the heating. Preferences for coronal heating mechanisms focussed on current-driven instabilities and Alfvén waves.

Buttressed by solar measurements with high spatial resolution, some proposed mechanisms such as traveling waves with sufficient energy to heat the corona have not been detected (Bruner 1981), and while there is a remaining panoply of processes (including Alfvèn waves, slow and fast magneto-acoustic waves and reconnection processes), different heating processes are believed to operate in different parts of the corona. Regions of high magnetic field could be subject to heating by small-scale reconnection processes – so-called nanoflare heating (Parker 1988; Klimchuk & Cargill 2001). Observations of solar line profiles (Dere & Mason 1993) were believed to signal these processes. However recent SOHO/SUMER measurements of profiles from the transition region suggest that the geometry of the emitting regions, shaped by the magnetic field, is dominant in forming the multi-components of emission profiles (Peter 2001).

Coronal holes have received careful scrutiny with the SOHO/UVCS experiment where coronal line profiles can be used to infer particle velocity distribution functions. Here it is believed that ion-cyclotron resonant Alfvèn waves heat and accelerate the high speed solar wind throughout the open field corona (Cranmer 2000).

Stellar observations are providing similar challenges. Emission from the low chromospheres of dwarf stars appears to be in harmony with acoustic wave heating models (Ulmschneider et al. 2001). Two components have been identified in the ultraviolet line profiles of other cool stars including giants and supergiants (Wood et al. 1997) and ascribed to heating processes. Demands placed on the coronal heating sources are severe and remain to be identified, if the high coronal densities indicated by the extreme ultraviolet and X-ray emission line diagnostics in active stars prevail.

2.5. Abundances

The dependence of solar elemental abundances in the corona upon the First Ionization Potential (FIP effect) was first discovered in the composition of solar energetic particles following flares. Crawford et al. (1972) noted that a similar correlation had been found earlier in cosmic ray abundances (Havnes 1971). Three decades of solar observations show that the pattern of enhancements is not simple. The FIP effect can depend on magnetic configuration and arguably the age of the solar feature. Abundances in coronal mass ejections into the solar wind can differ from the in-ecliptic coronal hole solar wind. And particle events can have a compositional bias dependent on charge to mass ratios. Moreover gravitational settling may alter the abundances in certain features.

The situation is even more confused with respect to stellar coronae. Claims of a similar FIP effect in some stars (α Cen, for instance: Drake et al. 1997) are confronted by different patterns in other stars; Metal Abundance Deficiency (MAD) (Schmitt et al. 1996, CF Tuc), a Noble Gas Enhancement (Drake et al. 2001), an Inverse FIP effect (Brinkman et al. 2001, HR 1099), Flaring Enhancements, and here at CS 12, there is a paper on "Crazy" Coronal Abundances (Linsky et al. 2001). The CS10 Meeting provided a balanced perspective in a major Discussion Session chaired by C. Jordan (cf. Jordan et al. 1998) which identified also puzzling anomalies remaining in both solar and stellar atmospheres. Hopefully the rich Chandra and XMM-Newton spectra of cool stars will begin to show a pattern as these are further analyzed. And in many cases, better photospheric abundances should be obtained.

2.6. Planetary Systems

There is no "Then" and "Now" contrasting CS 1 with the present, because the first planetary system, 51 Peg was announced at the Ninth Cambridge Cool Stars Workshop in Florence, Italy in 1995. As *The Washington Post* noted in its issue of 8 October 1995:

> **Italian[sic] Astronomers say a Jupiter-Like Planet Circles a Star in Pegasus**... Two Swiss scientists say they have discovered the first planet outside Earth's solar systen, revolving around a star in the constellation Pegasus. ....If verified, the unnamed planet would be the first found in a "live" solar system. The astronomers, Michel Mayor and Didier Queloz, made the claim at a conference entitled, "Cool Stars, Stellar Systems, and the Sun", held Friday in Florence to discuss the possible existence of planets revolving around other suns, and maybe even one like Earth that harbors life...[9]

We have come a long way since 1995 and the discovery of 51 Peg (Mayor & Queloz 1995). Now (25 July 2001), the Marcy-Butler web site notes there are 67 planets discovered orbiting 60 parent stars (see *http://exoplanets.org/*). About 1000 stars have been surveyed representing a nearly complete sample of solar-type stars within 30 pc. Upsilon And contains the first multiple planetary system and 6 stars have 2 or more planets.

Perhaps the most surprising characteristic of these new planets is that they are unlike our own solar system in that massive, Jupiter-size objects are within 1 AU of the parent star. Information is also rapidly accumulating on the parameters of the stars harboring planets. They appear to be chromospherically inactive and may have (Santos et al. 2001) higher metal abundances than the Sun – topics discussed here at CS 12. When the full title of the Cambridge Cool Star Workshops was constructed back in 1979, we have every right to claim we were prescient about these exciting new developments!

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[9] An erratum was published later by The Washington Post changing 'Italian' to 'Swiss' in the title.

3. Future of Cool Star Physics

Many promising areas of cool star physics are developing, largely driven by technical advances. My personal list would contain the following seven topics where substantial advances will happen:

- **Time and Large Formats as new dimensions:** A rich data base of wide field photometry is becoming available as a result of monitoring programs for gravitational lensing and supernovae events. OGLE is but one example, with a public archive of about 50,000 variable stars. Variables, many of which are cool stars, are the flotsam of these surveys, but a treasure to studies of the presence and character of stellar variability.

- **Spatial Resolution/Imaging Interferometry:** Phase-closure is beginning to be achieved in cool star studies as the COAST images of Capella have demonstrated (Baldwin et al. 1996). Plans are being made to achieve even larger baselines in space than on the ground. We may hope to actually image active regions on other stars and witness the results of dynamos in detail. Clearly these accomplishments will establish a whole new field of stellar physics.

- **New Wavelength Regimes:** The far ultraviolet is now open with the FUSE satellite; the infrared and submillimeter regions will be available for imaging and spectroscopy with detailed analysis of line profiles. These regions offer unique and powerful access to cool stars and star forming regions, and will finally allow a complete probe of a variety of temperatures and conditions.

- **Higher Sensitivity (everywhere!):** Larger samples will be possible, and a movement away from the so-called "Alpha-Beta" programs of bright objects will enable homogeneous samples of similar (fainter) stars such as stars in clusters.

- **High Resolution Spectroscopy:** Spectra with decent resolution in conjunction with higher sensitivity will enable new problems in addition to the traditional abundance and modeling studies. Issues of cluster self-pollution, and planetary cannibalism (including isotope detection) can be addressed. I believe "a spectrum is worth one thousand images," and we can not even imagine the discoveries to emerge.

- **Computational Astrophysics:** Here enormous advances in computational capability make possible the modeling and spectral synthesis necessary to interpret the interferometric measures or even the resolved disk spectra such as reported first for Betelgeuse. Stellar line profiles contain vast amounts of information, and require sophisticated modeling – which is only beginning. And ambitious plans for "star in a box" calculations, tracing a star from its core to outer atmosphere, will soon produce results for detailed comparison with observations.

- **Theory:** Cool Stars Workshops have been driven by observational advances over the past two decades, and I believe more theoretical work is

> needed to understand these results. Many very basic problems are still with us: What heats the solar corona in its various regions? What creates even hotter stellar coronae? What are those strange magnetic structaures inferred from euv and x-ray observations of stellar coronae? Why are densities so high? What drives stellar winds? Why are exoplanetary systems so different from ours?

Let us hope that two decades from now (optimistically planning for Cool Stars ∼22!), there will be a review of answers to our current puzzles. Or at least we will have made the valiant effort and learned a lot along the way!

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