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The solar magnetic dynamo and its role in the formation and evolution of the Sun, in the habitability of its planets, and in space weather around Earth.

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Summary

A magnetic dynamo will operate in the Sun throughout its lifetime. It regulated the formation of the Sun and our planetary system, it affects the habitability of the planets, and it determines the space weather around them. Dynamos also operate in objects such as planets, accretion disks, and active galactic nuclei. *At present, there is no comprehensive dynamo theory from which we can derive the strength, the patterns, or the temporal behavior of the Sun's magnetic field in past, present, or future.* Consequently, we cannot usefully forecast long-term space weather or reliably model the long-term effects of solar magnetic variability on the atmospheres of the planets, including Earth. *Understanding the complex of non-linear couplings in a stellar dynamo requires that we combine numerical studies and theory with observations of the evolving surface field of Sun and stars, of the average properties of magnetic fields in a large sample of stars, and of solar and stellar internal flows.*

Numerical modeling has taught us valuable lessons about dynamos, most importantly that they are highly non-linear processes that couple a vast range of scales within stellar convection zones. Our computer models are therefore of necessity simplified, and hence require observational guidance from stars with a variety of properties. Observations of light-curves and the application of (Zeeman) Doppler imaging continue to give us some of that information, but more is needed in the coming decade. We can expect exciting advances from high-fidelity numerical modeling, high-resolution helioseismic studies (with, e.g., SDO), comprehensive studies of the solar atmosphere (e.g., SDO, Hinode, STEREO, IRIS, and with ATST, FASR, and other ground-based facilities), and stellar global variability and internal structure (e.g., Kepler, COROT, ground-based observatories). We should also image surface activity and map interior flows for Sun-like stars. Together, these opportunities will rapidly advance our understanding of the impact of magnetism of the Sun on Earth and its inhabitants.

A strategy to understand the origins and effects of the solar dynamo is inherently interdisciplinary, and should include (1) continued solar observations of surface activity and interior flows, (2) utilization of long-term records that exist in, e.g., ice formations and other deposits on Earth, (3) high-performance numerical modeling using tens of thousands of processing cores, (4) observation and analysis of long-term variability in the magnetic activity of hundreds of stars, and (5) UV/optical interferometry (with, e.g., the Stellar Imager^[20] or Luciola^[21]) for surface activity mapping and resolved asteroseismology to measure internal differential rotation. Anticipating much input to the Decadal Survey on the solar aspects of this problem, we emphasize complementary stellar studies, realizing that solar constraints are critical.

1 The Sun and other cool main-sequence stars

We know that the mean solar activity level matches that of similar G2V stars, but we have yet to understand the observed dependence of stellar activity on rotation, and phenomena such as dynamo saturation in young, rapidly-rotating stars or the apparent enhancement of activity in tidally-interacting binary stars^[17]. Several solar and heliospheric activity indices have been identified as somewhat useful to forecast subsequent magnetic cycles, but these correlations are as poor as they are poorly understood; the wide range of forecasts for the present sunspot cycle demonstrates the lack of predictive value of most (or all) of the methods^[11]. A major problem is that *the validation of a successful cycle forecast would take decades if only the recent Sun were used as a benchmark: historical solar records and stellar constraints are essential!*

Stellar observations revealed that solar-like dynamos require convection immediately below the stellar surface, with rotation acting as a catalyst that strengthens the dynamo, at least up to a

point of saturation. The helioseismic determination of the solar rotation with depth and latitude guided theorists to models in which the rotational shear layer (the tachocline) below the convective envelope is crucial as a reservoir for field even as it is stretched and strengthened by latitudinal differential rotation. Observations reveal a pattern change in stellar activity across the boundary where stars become fully convective, but nonetheless activity continues to depend on rotation and decreasing with age, dynamos function in T Tauri stars and (tidally locked) rapidly rotating giants with very deep convective envelopes; recent models suggest that the buoyancy of the field can be countered by convective downdrafts^[2]. Dynamos appear also to function in brown dwarfs and may even aid global mixing in asymptotic and red giant branch stars^[5].

The magnetic activity of cool stars spans an enormous range: the most active stars have more than half of a hemisphere covered by dark starspots (Fig. 1), with at most 2% for the Sun. In inactive stars, the coverage by spots is too small to be measured by current instruments, but the emissions from the hot outer atmosphere can be used as a measure of activity. At the extreme lower end of activity, entire coronae of inactive giant stars are dimmer than solar coronal holes^[17].

Numerical models are rapidly advancing with increasing computational capabilities. They provide insight into the magnetoconvective couplings near the surface^[18], multi-scale compressible convective envelopes^[9], and convection and dynamo action in fully convective stars, albeit thus far at low Reynolds numbers^[4]. These models are far from capturing the full range of MHD and plasma interactions from solar tachocline to atmosphere. The nonlinear

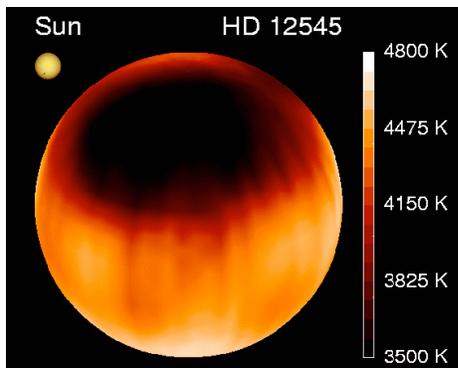


Fig. 1 Doppler-imaged temperature map of XX Tri (K0III). The 24-d tidally-locked binary component shows a large, persistent high-latitude starspot (or spot cluster) vastly larger than the entire Sun. Such high-latitude features are common among rapid rotators.^[19]

differential equations that couple turbulent convection and magnetism to yield dynamo action cannot be solved analytically. Nor can the dynamo of the Sun and other stars be simulated directly, as the solar convection zone is highly turbulent. In the high magnetic Reynolds number environment of the solar interior, the magnetic field is highly intermittent with length scales down to ~ 1 km. The volume of the solar convection zone would require $\sim 10^{18}$ gridpoints, evolved for millions of timesteps to achieve a full cycle of solar activity. This is more than a factor of a billion beyond present computational resources, and thus both analytical and numerical treatments must make approximations that simplify much of the physics.

Most dynamo concepts are kinematic in nature. A self-consistent model needs to include the interaction between the field and the flows. Some semi-analytical mean-field models have been tested that include this interaction (often captured by ad-hoc parameterizations), but comprehensive numerical experiments that include these couplings are in their infancy (Fig. 2). Thus observations are essential to validate the approximations made: comparisons of observed stellar dynamo patterns for different activity levels with those resulting from models is essential to guide dynamo research. Unfortunately, we know essentially nothing about these dynamo patterns, i.e., the stellar butterfly diagrams or - on smaller scales - the spectrum of emerging bipoles, their orientations, or their clustering properties for any star other than the Sun. For main-sequence stars with moderate to low rotation rates, activity tends to be cyclic, but no clear trend of cycle period with stellar parameters has been found, although there are hints of relationships between cycle period, rotation period, and the time scale for deep convection^[14]. For truly active stars, various variability patterns exist, but generally no unambiguous activity cycle is seen. In this context, it is interesting to add that the moderately and very active stars never reach low

states of activity, in contrast to the Sun during its cycle minima. Perhaps the dynamos of these active stars differ substantially from the solar dynamo, with either no organized butterfly diagram or with overlapping starspot cycles that combine to reduce the overall modulation.

Doppler images of rapidly rotating stars revealed other surprises: starspot clusters extending to the poles (Fig. 1). Surface-flux dispersal models need very strong meridional advection to produce mixed-polarity regions at high latitudes even if flux emerges at mid-latitudes under the influence of the Coriolis force^[8], yet state-of-the art models for convective envelopes suggest that these large-scale flows weaken rather than strengthen with increasing rotation rate^[3,9].

Given the complexity and non-linearity of dynamos, improved observational guidance is sorely needed. For example, detailed magnetographic observations over three sunspot cycles have given us much more insight into the behavior of the Sun's magnetic field at and above the solar surface: we understand the roles of differential rotation, meridional flow, and supergranular

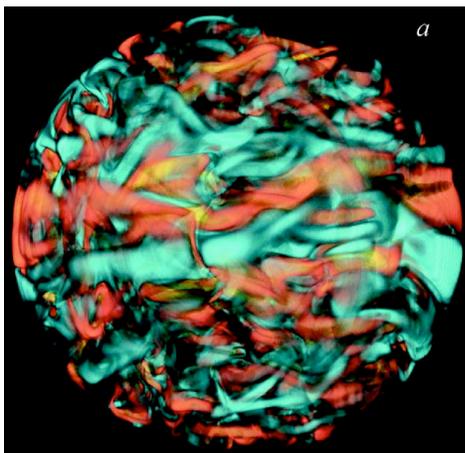


Fig. 2 Volume rendering of the toroidal magnetic field (red: eastward; blue: westward) from compressible MHD simulations of convection. This model lacks a tachocline and a realistic treatment of the near-surface layers. Strong, dynamic field is generated, but a cycling global dynamo is not excited in this simplified model. From Brun et al. (2004, ApJ 614, 1073).

dispersal quite well qualitatively, and even quantitatively on time scales up to several years. For longer time scales, understanding of the behavior of the large-scale solar field from cycle to cycle still eludes us: the global dipolar field, for example, does not show the anticipated hysteresis from one cycle to the next^[15], and we do not know if this is related to the modulated meridional flow^[7], to subsurface transport^[1], to variations in tilt angles of active regions, or to some as yet unimagined effect. Why the solar dipole and heliospheric field in the recent minimum are only half as strong as during earlier cycle minima remains a puzzle^[16]. We also still do not understand the role of helicity^[12].

To understand dynamos and the environments in which they operate, we must also study astrophysical dynamos that differ from the Sun. For example, close binaries should be studied because tidal interaction appears to strengthen dynamos. Fully convective dwarf stars, stars with shallow convective envelopes, and evolved stars also set valuable constraints.

2 Star formation, pre-main sequence stars, planetary systems and planetary atmospheres

In the initial phases of the contraction of the cloud out of which the Sun and the planets formed, magnetic fields were instrumental in transporting most of the angular momentum out of the core regions of the cloud. Without the expulsion of the bulk of that initial angular momentum, no star could have formed because centrifugal forces would have exceeded the pull of the gravitational field. Once a proto-star and a surrounding extended gaseous disk form, the star's strong magnetic field couples to the inner domains of the gaseous disk that surrounds a star for millions of years before the planets form. The star continues to accumulate mass from the disk for some time, but the disk cannot extend to the stellar surface: the magnetic field of the rapidly rotating star sweeps through the inner disk region, allowing matter to accrete only along the field. Accretion thus occurs in evolving columns connecting the disk to patches on the stellar surface. Where the material cannot reach the surface, the gas pressure aided by the magnetic field channels the material into jets of gas, shooting away from the poles of the star. More material is lost in a magnetically powered stellar wind. This balance in which matter moves toward and away from the star at different locations, affects the disk's properties. That, in turn, likely affects

how and where planets form, and what their masses and atmospheres are. The details of this scenario, and the precise role of the magnetic field in it, remain shrouded, because present-day telescopes cannot image the inner part of such disks around very young stars, and appropriate dynamo models are yet to be developed. The stellar magnetic field appears to be key to the rotational evolution of the system, however, as those stars with discs typically rotate more slowly than those without; moreover, the discs may modify coronal activity by truncating the stellar corona while disk accretion may be responsible for the large flares seen on these young stars^[6].

Stellar activity also affects the evolution of planetary atmospheres, both by (X)UV irradiation and through the interaction with the stellar wind^[10]. *The theories of stellar and planetary dynamos come together in the interaction of the magnetized stellar wind with the planetary magnetic field.* This determines the ablation of a planet’s atmosphere by setting the distance to within which the magnetopause can come down to the planet, with ‘auroral winds’ flowing down the open field around the magnetotail, with (X)UV radiation and energetic particles energizing the highest layers of the planet’s atmosphere, and charge-transfer collisions allowing neutral particles to stream away, eventually resulting in distinct atmospheres for planets as similar as Venus, Earth, and Mars.

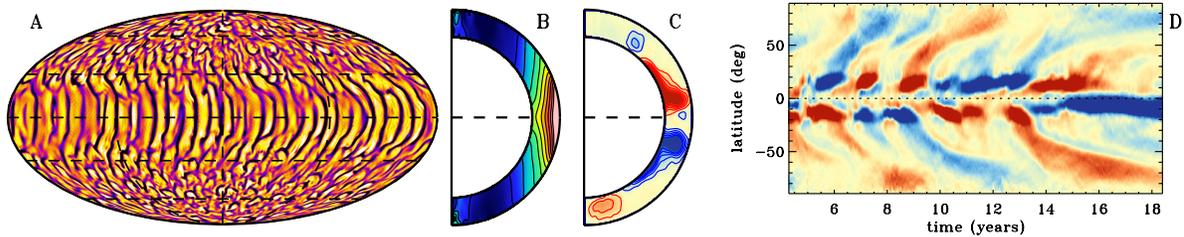


Fig. 3 Dynamo simulation of a Sun-like star rotating 5x faster than the Sun [3]. Rotationally-influenced convection (A: radial velocity near the surface: upflows bright, downflows dark) establishes a strong rotational shear (B: mean angular velocity; pink faster, blue slower) which generates coherent bands of toroidal field (C: red eastward, blue westward). These toroidal bands undergo quasi-periodic magnetic cycles with polarity reversals on a 4-year time scale (D: mean toroidal field at the base of the convection zone, of order 10kG). Such simulations have yet to achieve full realism, but already provide important insights.

3 Flows in the interior of stars

Our detailed knowledge of the stellar internal stratification stands in stark contrast to the simplified models of the large-scale flows. Solar data suggest that the magnetic field affects the large-scale flows, at least in the phenomenon of the torsional oscillation. But the observed variations in the surface meridional flow remain to be understood: are they associated with the magnetic field or are they a consequence of fluctuations in convection?

The situation is a little better for the differential rotation, because several techniques already help constrain it for some stars by using the fact that the periodicity of the disk-integrated signal depends on the latitude at which active regions preferentially emerge. Thus, as the sunspot cycle progresses, the rotation period changes with the mean active latitude. Stellar astronomers have assumed that the spread in observed rotation periods for a given star over the years is a measure of at least the magnitude of the surface differential rotation of a star, although with the caveat that there is no clear matching of the measured rotation period with the rotation period of the corresponding mean emergence latitude for the Sun. We infer that for Sun-like stars the differential rotation is comparable to that of the Sun, and are learning about the variation in differential rotation with spectral type along the main sequence^[13]. Observations with, e.g., COROT and Kepler can be expected to provide much more information on stellar surface differential rotation. For fairly rapidly rotating stars for which a series of Doppler images is available, an even better constraint on differential rotation may be achieved (Sect. 4).

Numerical experiments show interesting trends (Fig. 3), but whether these are consistent with stellar behavior remains to be established. Recent models of much of the solar convective envelope at different rotation rates, for example, suggest a decrease in relative differential rotation with increasing rotation rate that is not supported by the limited available observations, associated with a marked decrease in meridional flow that is inconsistent with the strong increase suggested by flux transport modeling to explain polar spots^[8]. Here, too, *observational guidance is essential to validate our approximating models of the flows of matter, energy, and field within the interiors of Sun and stars*. Estimates of internal rotation rates of stars should become available with the growth of stellar seismology, which can be compared with their surface rotation; in a few cases even the depth of the convective envelope can be constrained^[9]. *A real breakthrough is anticipated once stellar surfaces are resolved, and asteroseismic determinations of latitude and depth dependences of the flows become available.*

4 Observations: possibilities and limitations

Key to successfully developing a predictive dynamo theory is *a population study to compare the dynamo-driven activity in the Sun to that in a diverse sample of stars*.

For the Sun, we need (1) continued observations of surface activity and interior flows and (2) utilization of long-term records that exist in, e.g. ice formations and other deposits on Earth. In particular, frontiers of relevance to the dynamo appear to include (a) investigations into the structure and evolution of the solar differential rotation and meridional circulation, particularly at high latitudes, including how such flows couple to magnetism; (b) investigation of the distribution and evolution of magnetic flux on all scales in the photosphere and investigations of the characteristics of emerging flux from photospheric, chromospheric, coronal, and heliospheric observations, including the energy and flux budgets, the fibril nature of the field, the photospheric evolution of emerged flux (fragmentation, coalescence, emergence, submergence), pole-equator differences in fields and flows, helicity flux, multipolar components of the global poloidal field, dipolar tilt, etc.; and (c) study of comparative solar minima and maxima.

A breakthrough in our understanding of dynamos can also come from spatially-resolved imaging of the dynamo-driven emission patterns on a variety of stars. How these patterns depend on stellar properties (such as convection, rotation, meridional circulation, age, ...), are crucial for dynamo theorists to explore the sensitive dependences on many poorly known parameters, to investigate bifurcations in a non-linear 3D dynamo, and to ultimately validate a model.

For other stars, magnetic fields can be mapped by

- *Rotational modulation*. Brightness variations caused by structures rotating across the visible hemisphere can yield longitude maps of activity if the intrinsic evolution of the source regions is slow compared to the stellar rotation, which is not the case for slow rotators like the Sun.

- *Eclipse mapping*. The crossing of one star in front of its companion allows some low-resolution recovery of atmospheric structure. But there are very few Sun-like eclipsing systems with orbits wide enough to ignore tidal coupling.

- *Doppler imaging*. Inhomogeneities on the surface of a rotating star cause line-profile distortions that can be used to map these inhomogeneities. Some latitude information can be recovered from the velocity amplitudes. The technique is limited to stars that rotate at least 5 times faster than the Sun, but not so fast that Doppler and thermal broadening are comparable. Thus, the method is not useful for stars of Sun-like activity. The use of Zeeman-sensitive lines enables access to slower rotators, but only for the largest-scale magnetic field, leaving active region scale structures well out of reach.

- *Interferometric imaging* is currently most frequently used at radio wavelengths. Only a few

optical interferometric imaging studies have been performed on stars. New ground-based instrumentation will boost the potential. However, UV/optical interferometry from space (as with the Stellar Imager) is essential for a breakthrough in dynamo modeling.

- *Direct imaging* is possible for very few stars. The star α Ori is one of the largest in the night sky, and UV/optical imaging that star with 30 elements across the photospheric diameter would require a telescope 10 times larger than HST. Nearby dwarf stars would require diameters of several hundred meters (see Sect. 5 and Fig. 65

For stars with rotation periods of less than about a week, useful information can be gathered by (combinations of) these methods. *But only large-baseline interferometers can provide latitude and longitude maps of the magnetic fields of stars that rotate as slowly as the Sun* (Fig. 4).

The principal unknowns about stellar interiors that need to be established in order to understand stellar magnetic activity are the large-scale transport mechanisms for the magnetic field, i.e., the internal differential rotation and meridional flow. The Sun's internal differential rotation is measured using helioseismic means: the higher-order acoustic modes that resonate within the Sun are slightly altered in frequency because of the Doppler effects associated with the Sun's rotation. Modes with degrees $\ell = 0-3$, measured in integrated starlight, provide the mean rotation period. Measurement of differential rotation within the convective envelopes necessarily requires spatial resolution to measure modes well above $\ell \sim 10$. Using the differential paths probed by modes of different order and degree, the latitude and depth dependence of the internal differential rotation can be determined. For stars, the acoustic signature of meridional circulation will remain out of reach, but the internal differential rotation can be determined by observing the p -modes in the intensity signal at stellar surfaces. This signal can be determined from measurements taken well within the period of the modes; for main-sequence stars, a 1-min spacing between measurements is required to measure p modes with 3-8 minute periods; a lower cadence suffices for evolved stars.

5 Feasibility of interferometric imaging

An interferometric imager should provide sub-milliarcsecond images for a significant sample of stars similar to the Sun, as well for other cool stars with very different characteristics. The Stellar Imager (SI^[20]) is one such proposed UV/optical observatory. SI would have access to an exciting array of distinct stars and stellar systems (Fig. 5). For a resolution comparable to a medium-sized solar active region, a maximum baseline of ~ 500 m is needed when observing a dwarf star with an angular diameter of 2 milliarcseconds in the mid-UV. In addition to single F-through M-type dwarf stars, a variety of other target stars is accessible to such an observatory, including wide binaries, stars with planetary systems, and stars that probe the Sun's activity over time. Such an observatory will, for the first time, enable imaging of magnetic activity of a variety of Sun-like stars, and of stars with shallow convective envelopes, fully-convective cool, close

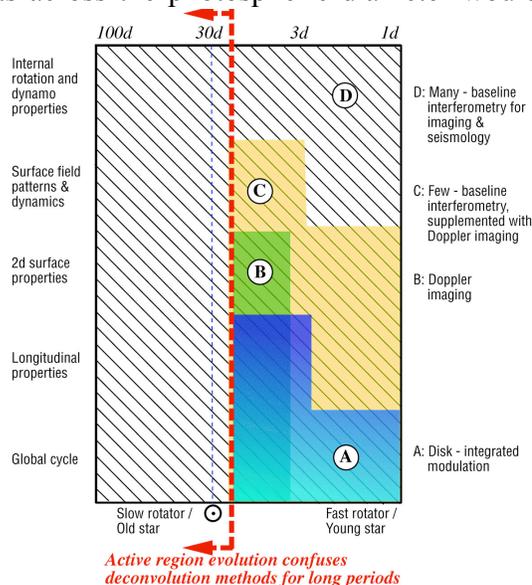


Fig. 4 Many questions regarding geometrical information on surface flows and surface magnetic fields on cool stars like the Sun require some form of imaging. Spectroscopic Doppler imaging can help in this area only by coarse mapping of stars that rotate neither too slowly nor too rapidly. Rotational modulation provides no latitudinal differentiation within the visible hemisphere. Space-based UV/optical interferometric imaging opens up the entire range of rotation periods to determination of patterns in flux emergence and migration.

binary systems with dual active components magnetically coupled at a few stellar radii, compact RS-CvN-type binaries, mass-transferring Algol-type systems, and red (super-)giant stars.

6 Needs and opportunities for dynamo-related studies in the coming decade(s)

Development and validation of a predictive solar dynamo model requires advances in solar and stellar modeling and observations. Improved MHD modeling of the Sun combined with helioseismic measurements of subsurface flows and field-induced perturbations by will improve our understanding of the stellar internal dynamics. Disk-integrated observations of stars will provide low-resolution views of their internal structure and mean internal and surface rotation, and will constrain differential rotation and modulated starspot activity for many types of stars. Imaging of stars and helioseismic mapping of internal flows opens up

entirely new sets of constraints to the development and testing of dynamo models for stars, including the Sun in the past, present, and future. And long-term solar activity variations can be studied in geological records, provided all transport processes involved in their deposition from Sun to Earth are understood. An interdisciplinary research approach is outlined in the Summary.

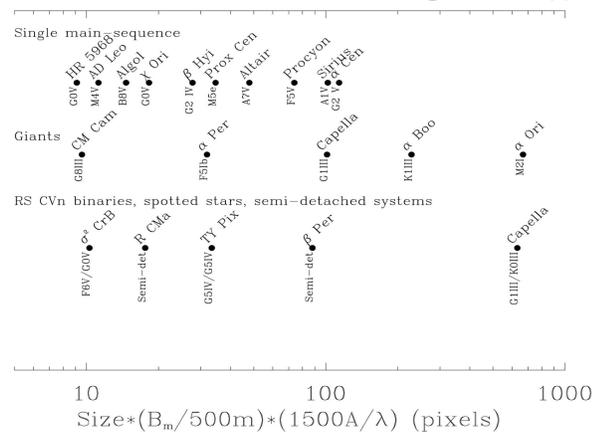


Fig. 5 Sample targets for the study of stellar dynamos. The horizontal axis shows the number of resolution elements across the equator for single stars or across the system at quadrature for binaries, assuming a baseline of 500m observing at 1,500Å.

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