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Dynamos and magnetic fields of the Sun and other cool stars, and their role in the formation and evolution of stars and in the habitability of planets.

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Executive Summary.

A magnetic dynamo operates in all stars at least during some phases in their evolution. It regulates the formation of stars and their planetary systems, the habitability of planets, and the space weather around them. Dynamos also operate in objects including planets, accretion disks, and active galactic nuclei. Although we know that flows in rotating systems are essential to such dynamos, there is no comprehensive dynamo theory from which we can derive the strength, the patterns, or the temporal behavior of stellar magnetic fields.


Understanding the complex of non-linear couplings in a 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 stellar internal flows.

For cool stars like the Sun, dynamo action persists from the very formation of the star throughout its existence as a fusion reactor. The Sun's activity is modulated significantly from cycle to cycle, sometimes persistently for several decades. Activity decreased, for example, for decades in the 17th Century when Earth experienced the Little Ice Age. Observations of other cool stars are crucial to our understanding of solar/stellar dynamo action. This has taught us, for example, that convection is part of all solar-like dynamos, and that rotation regulates their strength. But we do not have a dynamo theory that explains why stars are as active as they are, why some show cycles and many do not, what causes the Sun's cycles to differ from one to the next, and how a cyclic dynamo can restart after a Maunder-like minimum. Hence, we cannot usefully forecast long-term space weather or reliably model the effects of stellar magnetism on the evolution of stars, planetary systems, and planetary atmospheres.

Numerical modeling has taught us valuable lessons about dynamos, including the fact that they are highly non-linear processes that couple scales across the full convection zones of stars down to the smallest convective scales. 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 new research opportunities to include high-fidelity numerical modeling, high-resolution helioseismic studies (such as enabled by SDO), comprehensive studies of the solar atmosphere and heliosphere (e.g., SDO, Hinode, STEREO, ATST, and other ground-based facilities), stellar global variability and internal structure (e.g., Kepler, COROT, ground-based observatories). We need to develop methods for monitoring hundreds of stars, and for direct observations of evolving patterns of activity on stellar surfaces and in stellar interiors (both by [Zeeman] Doppler imaging – only for fast rotators – and by UV/optical interferometry by, e.g., the Stellar Imager[20] or a similar mission). Together, these opportunities will rapidly advance our understanding of the impact of magnetism on stars and on the orbiting planets and their inhabitants.

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 to understand phenomena such as dynamo saturation in young, rapidly rotating stars or the apparent enhancement of activity in tidally interacting binaries[17]. Whereas several solar and heliospheric
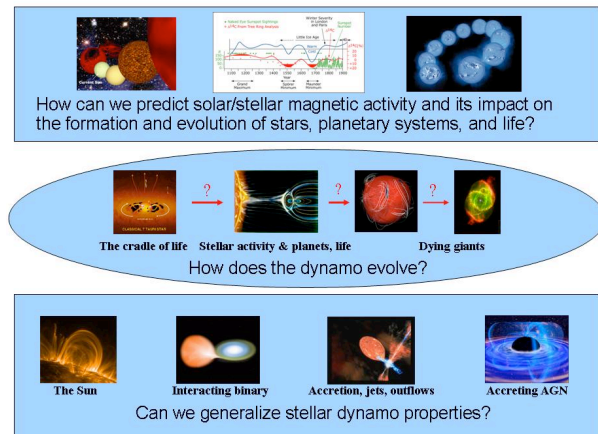
activity indices have been identified as somewhat useful to forecast the strength of subsequent magnetic cycles, these correlations are as poor as they are poorly understood; the wide range of forecasts for the next sunspot cycle clearly demonstrates the absence of predictive value of most or all of the methods[11]. A major problem is that *the validation of a successful cycle forecast would take decades if only the Sun were used as a benchmark: stellar constraints are essential!*

Stellar observations demonstrated that solar-like dynamos require a convective envelope immediately underneath 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. But observations show little change in stellar activity across the boundary where stars become fully convective (with activity continuing to depend on rotation and decreasing with age, and with activity saturating at comparable Rossby numbers), dynamos function in T Tauri stars and (tidally locked) rapidly rotating giants with very deep convective envelope; 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].
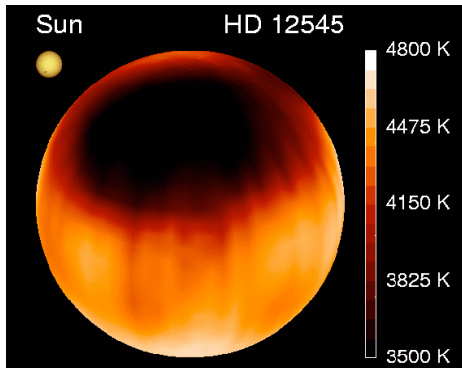

Fig. 2 Doppler-imaged temperature map of XX Tri (K0III). The 24-d tidally-locked binary component shows a large, persistent high-latitude starspot (or spot cluster) vastly larger than the entire Sun. Such high-latitude features are common among rapid rotators. [19]

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. 2), with at most 2% for the Sun. In inactive stars, the coverage by spots is too small to be measured by current instruments, but there the associated 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 the X-ray-dark coronal holes in the solar outer atmosphere[17].

Numerical models are rapidly advancing with computational capabilities. They provide insight in 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 very far from capturing the full range of MHD and plasma interactions from solar tachocline to atmosphere. The nonlinear differential equations that couple turbulent convection and magnetism to yield dynamo action cannot be solved analytically. Nor can the cyclic dynamo observed in 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 ~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. 3). 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. 2). 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].
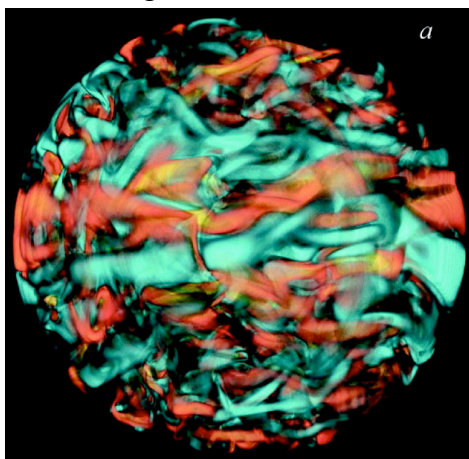

Fig. 3 Volume rendering of the toroidal magnetic field (red: eastward; blue: westward) from compressible MHD simulations of convection. This model lacks a tachocline and a realistic treatment of the near-surface layers. Strong, dynamic field is generated, but a cycling global dynamo is not excited in this simplified model. From Brun et al. (2004, ApJ 614, 1073).

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 random-walk dispersal quite well qualitatively, and even quantitatively on times 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], or to some as yet unimagined effect. Why the solar dipole and heliospheric field are currently only half as strong as during earlier cycle minima remains a puzzle, being neither understood nor predicted[16]. We also still do not understand the role of helicity in the dynamo; only continued detailed observations of the Sun can help us with that[12].

To understand dynamo evolution and the environments in which dynamos 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 giant stars also set valuable constraints.

2 Star formation, pre-main sequence stars, planetary systems and planetary atmospheres.
Magnetic dynamos are important also in pre-main sequence stars. 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, perpendicular to the disk. 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 stability, mass content and evolution. That, in turn, likely affects how many planets form, where they form, and what their masses and atmospheres are. The details of this hypothetical 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 accretion from the disk may be responsible for the very hot, energetic flares seen on these young stars[6].
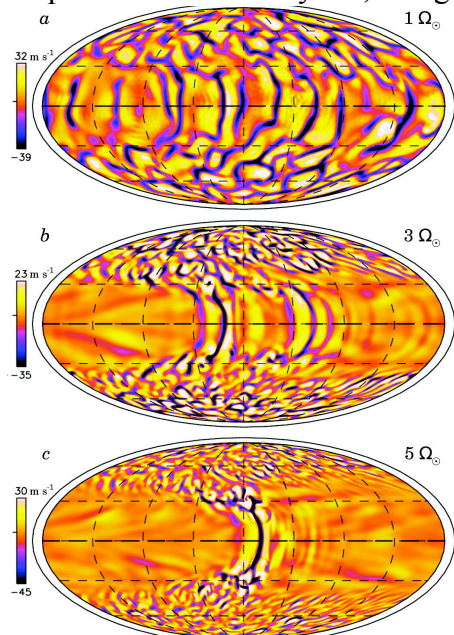

Fig. 4 Hydrodynamic models of envelope convection in a Sun-like star (Mollweide projection). The rapidly rotating model exhibits zones of enhanced convection in differentially-rotating nests. The model dependence of differential rotation on mean rotation rate appears inconsistent with observations, and the suggested strong decrease in meridional circulation appears inconsistent with other models (see text). These state-of-the-art simulations have a long way to go to achieve full realism, even though they already provide important insights. [3]

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 efficiency of the planetary 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 particle impacts energizing the topmost layers of the planet's atmosphere, and charge-transfer collisions allowing neutral particles to stream away, eventually resulting in very distinct atmospheres for planets as similar as Venus, Earth, and Mars. Understanding the evolution of planetary atmospheres in our solar system require an understanding of the magnetic activity of the host star over the ages.

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 the magnitudes of the differntial rotation 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, but that can be done for only very active stars (Sect. 4).

Numerical experiments show interesting trends (Fig. 4), 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[3], 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 (with, e.g., COROT and Kepler), which can be compared with their surface rotation; in a few cases even the depth of the convective envelope can be constrained[0]. A real breakthrough is expected 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 the realization that *we need a population study: we need to study the dynamo-driven activity in a sample of stars like the Sun, and compare it to observations of young stars, old stars, binary stars, etc*. The potential for a breakthrough in our understanding lies in spatially-resolved imaging of the dynamo-driven emission patterns on a variety of stars. These patterns, and how they depend on stellar properties (such as convection, (differential) rotation and helocity, meridional circulation, evolutionary stage/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.

Magnetic field patterns of stars can be mapped by

• *Rotational modulation.* Brightness variations caused by structures rotating across the visible hemisphere can yield longitude maps of activity, provided that 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
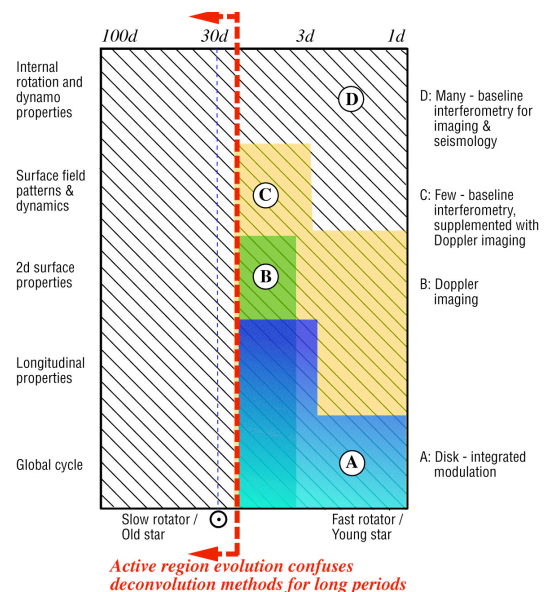

Fig. 5 Many questions regarding geometrical information on surface flows and surface magnetic fields on cool stars like the Sun require some form of imaging. Spectroscopic Doppler imaging can help in this area only by coarse mapping of stars that rotate neither too slowly nor too rapidly. Rotational 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.

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 studies have been performed on some cool supergiants to date, but new instrumentation will boost the potential. The ESO Very Large Telescope promises to resolve several hundred cool stars with at least a dozen pixels on their disks. UV/optical space-based interferometry (such as proposed for the Stellar Imager) is needed for a breakthrough in understanding dynamos.

• *Direct imaging* is possible for very few stars, which tend to be giant stars rather than main-sequence stars. The star α Ori is one of the largest in the night sky, and 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. 6).

For stars with rotation periods of less than about a week, useful information can be gathered by (combinations of) these methods. *Only large-baseline interferometers can provide latitude and longitude maps of the magnetic fields of stars that rotate as slowly as the Sun* (cf. Fig. 5).

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 ℓ = 0, 1, 2, 3 can be measured in integrated starlight; these provide access to the mean rotation period (as measured by precursor missions such as COROT and Kepler). 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 min periods; a lower cadence suffices for evolved stars.

5 Feasibility of interferometric imaging.

An interferometric imager would have to be able to 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 NASA Stellar Imager (SI[20]) is one such proposed UV/optical observatory. This interferometer would have access to an exciting array of
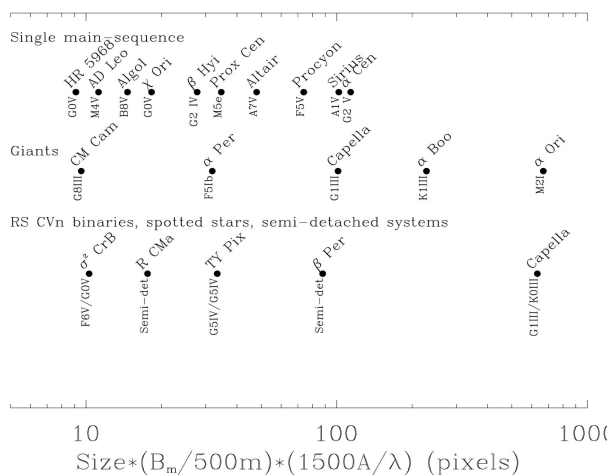
Fig. 6 Sample targets for the study of stellar dynamos. The horizontal axis shows the number of resolution elements across the equator for single stars or across the system at quadrature for binaries, assuming a baseline of 500m observing at 1,500Å.

distinct stars and stellar systems (Fig. 6). 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 binary systems with dual active components magnetically coupled at a few stellar radii, compact RS-CvN-type binaries, mass-transferring Algol-type systems, red giant stars, and red supergiant stars.

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

Understanding the highly non-linear stellar magnetoconvection that drives dynamo action requires advances in modeling and observations, for both Sun and stars. The next decade promises to see remarkable progress on these fronts, with current and planned space- and ground-based observatories. Improved MHD modeling of the Sun combined with helioseismic measurements of subsurface flows and perturbations caused by magnetic fields by the Solar Dynamics Observatory will improve our understanding of the stellar internal dynamics. Disk-integrated observations of stars by COROT and Kepler will provide low-resolution measurements of their internal structure and mean internal and surface rotation rates, and will constrain differential rotation and modulated starspot activity for many types of stars. *A strategy to understand the origins and effects of stellar dynamos should also include (1) long-term observations of the activity of hundreds of stars, (2) UV/optical interferometry (with, e.g., the Stellar Imager[20] or Luciola[21]) for surface mapping and resolved asteroseismology to map the internal structure and the internal differential rotation, and (3) advanced numerical modeling with high-performance computers with tens of thousands of processing cores.* All of these are essential for a comprehensive understanding of the dynamo process powering stellar variability.

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