Helioseismology, Dynamo, and Magnetic Helicity

Takashi Sakurai

National Astronomical Observatory of Japan
Mitaka, Tokyo 181-8588, Japan

Abstract. A brief review of the solar activity cycle and its dynamo models is given, with input from helioseismology. Recent new constraints on the dynamo models by the observations of torsional oscillations and magnetic helicity are discussed.

1. Introduction

The origin of the solar activity cycle is one of the fundamental and unresolved problems in solar and stellar physics. The difficulties in this research topic come from, among others, the following factors:

(1) The time scale of the phenomenon (11 or 22 years) is long and we need an accumulation of data over many years.

(2) The main process of the dynamo mechanism takes place in the invisible interior of the Sun.

(3) The Sun is the only star for which we can observe the activity cycle with spatial resolution, and our knowledge is limited to the current solar structure and solar rotation.

In this brief review article, we will summarize the available data sets (item 1). The information from helioseismology that has become available since 1970s gives the internal rotation of the Sun which was not accessible before (item 2). The formulation of the dynamo theory in the 1950s and its subsequent development, and recent progress in numerical simulations also have contributed to our understanding of the processes going on in the invisible interior (item 2). Observations of stellar activity cycles and theoretical studies show how the dynamo behaves in circumstances different from the Sun (different stellar structure and different rotation rates; item 3).

2. Solar Activity Cycle: Classical Observations

The first historical signature of the solar activity cycle dates from Galileo’s interpretation of sunspots published in 1612. Figure 1 (top panel) shows the variation of sunspot relative numbers in the last 80 years. The sunspot number varies in a period of 9 – 14 years, 11 years being the average period. The cycles are numbered according to Wolf, and the cycle that ended in 2009 was Cycle 23. The lower panel shows the so-called “butterfly diagram” in which the sunspots migrate from the mid latitudes toward the equator as the activity cycle progresses.
The sunspots generally appear as groups and are aligned in the east-west direction. Hale’s discovery of magnetic fields in sunspots (Harvey 1974) has later led to the establishment of the Hale-Nicholson law (Hale & Nicholson 1925); i.e., the bipolar nature of sunspot groups and its anti-symmetry with respect to the equator. Namely, the orientations of the poles are opposite in the two hemispheres, and they alternate in the 22-year cycle (Fig. 2). Figure 2 also vaguely indicates the so-called Joy’s law (Zirin 1988), namely the preceding spots appear closer to the equator than the following spots in a sunspot group. In addition, the preceding sunspots tend to be larger and have stronger magnetic fields, and live longer than the following sunspots. The following-polarity regions decay earlier, and they are seen to diffuse toward the respective (north or south) poles.

The development of sensitive magnetographs has made the measurement of magnetic fields outside sunspots possible. The discovery of the Sun’s polar field (Babcock & Babcock 1955) and its reversal at the epoch of sunspot number maximum (Babcock 1959) opened a new door to the understanding of the solar activity cycle. Figure 3 schematically shows how the sunspots and polar fields change in a 22-year cycle.

Another important player in the activity cycle is the differential rotation of the Sun which was discovered by Carrington in the 19th century. The sidereal rotation rate in deg/day is approximately expressed as a function of latitude $\theta$ as

$$\omega = A + B \sin^2 \theta + C \sin^4 \theta.$$  \hspace{1cm} (1)

The coefficients $A$ (equatorial rotation rate) and $B$ are, for example,

$$A = 14.38, \quad B = 2.96.$$  \hspace{1cm} (2)
Figure 2. Hale and Nicholson’s sunspot polarity law.

Figure 3. A schematic diagram showing the relationship between the sunspot magnetic fields and the polar magnetic fields.

according to Newton & Nunn (1951) who followed the rotation of long-lived single sunspots ($C = 0$ was assumed). Similar but differing results were obtained by Doppler measurements and by following magnetic structures other than sunspots (Schröter 1985).

Figure 4 shows two representative models of the rotation of the convection zone of the Sun which is consistent with the faster-rotating equator at the surface. As will be seen below, incompressible fast rotators favor Fig. 4b (by the TaylorProudman constraint), while classical dynamo theories preferred Fig. 4a which gives the correct (observed) migration of the generated magnetic field towards the equator. The results of helioseismology support neither of these, and the angular-velocity isocontours are close to radial, while a resemblance of Fig. 4b is seen in low-latitude regions (Howe 2009).
3. A Phenomenological Dynamo Model by Babcock

Babcock (1961) constructed a phenomenological model for the sunspot cycle (Fig. 5). Suppose the Sun has an initial dipole-like poloidal field (1). Because the plasma in the interior of the Sun is hot and has high electrical conductivity, the frozen-in condition is realized and the differential rotation stretches the field lines toward the east-west orientation (2). The amplified toroidal magnetic fields eventually float up and make sunspots, so that the sunspot groups are oriented east-west (3). Then the following polarity regions diffuse toward the poles, and reverse the polar field (4).

In step (3) the generated toroidal magnetic fields are supposed to more or less fill the whole convection zone initially, while sunspots are much smaller structures. Therefore, some mechanism must exist to transform a diffuse field into the form of flux tubes with amplified magnetic field, which experiences magnetic buoyancy and floats upwards (see Section 5).

In step (4), the following polarity preferentially diffuses toward the poles because of Joy’s law. Leighton’s dynamo model (Leighton 1969) also made use of this effect to maintain the dynamo. However, the tilt angles of sunspot groups show very large dispersion (Howard 1991), and how systematically the following polarity flux goes to the poles is not clear. This point has been investigated by Sheeley and his collaborators since the 1970s (see Section 6).

4. Classical MHD Dynamo Theory

Studies of the dynamo mechanisms were initiated as early as the foundation of magnetohydrodynamics (MHD), and a summary up to the 1970s can be found in Cowling (1981). In the following we will go through it briefly, with some interpretation contributed by the present author.
4.1. Taylor-Proudman Constraint and Differential Rotation

The equation of motion for a non-magnetic and inviscid fluid rotating with an angular velocity $\Omega$ as a whole is

$$\frac{dV}{dt} = -\nabla p - \rho \nabla \Phi + 2V \times \Omega,$$  

(3)

in the frame of reference rotating with $\Omega$. Here $\rho$, $V$, and $p$ stand for the density, velocity, and pressure of the fluid, and $\Phi$ is the gravitational potential.

By assuming that the motion is stationary ($\Omega \gg d/dt$), and the fluid is incompressible ($\rho=$const), then taking the curl of Eq. (3) we obtain

$$(\Omega \cdot \nabla) V = 0,$$  

(4)

namely, fluid motions must be invariant along the direction of the rotation axis. This constraint, valid for a rotating liquid ($\rho=$const.) in the steady state, is called the Taylor-Proudman constraint. The Sun is not a liquid and its density varies by more than six orders of magnitude between the surface and the bottom of the convection zone. However, the Taylor-Proudman constraint is still often invoked in order to understand the behavior of solar rotation law in a limited range of radial distance from the centre.

When convection occurs in a rotating fluid under the control of the Taylor-Proudman constraint, the convective velocity $V$ cannot change along the rotation axis (the $z$-axis), and the convective motion takes the form of cells elongated in the $z$-direction, like a beach-ball pattern. The fluid flows up in the middle of the cells and diverts horizontally in the direction parallel to the equator and then sinks. Because of the Coriolis force, the fluid diverted in the direction of rotation is bent toward the equator, while the fluid diverted in the direction opposite to the rotation is bent toward the...
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Figure 6. Under the Taylor-Proudman constraint, the convective cells are elongated in the direction of the rotation axis, and flows diverging in the azimuthal direction accelerate the equator.

poles. Therefore, faster-moving fluids are collected in the equatorial region and make the equator rotate faster than the high-latitude zones (Fig. 6). In other words this is the effect of Reynolds stress, \( \langle (V' \cdot \nabla) V' \rangle \), where \( \langle \cdot \rangle \) means statistical average and \( V' \) is the velocity field of convection in which the differential rotation is subtracted from \( V \).

4.2. Mean-field Dynamo Equation

Cowling (1933) showed that axisymmetric motion alone cannot maintain the magnetic field, and the magnetic field will decay by resistive diffusion. This is the so-called Cowling’s anti-dynamo theorem. Therefore, in order to consider a system that can maintain the magnetic field, one has to assume a fluid motion which is not axisymmetric. However, the most dominant motion in the Sun is its axisymmetric differential rotation. Therefore, we may divide the velocity \( V \) and magnetic \( B \) fields into main axisymmetric components and their residuals,

\[
V = \overline{V} + V', \quad B = \overline{B} + B',
\]

where \( \overline{\cdot} \) means averaging over the azimuthal direction. The differential rotation is given by \( \overline{V} \), and \( V' \) represents velocity fields in convective eddies.

Substituting Eq. (5) into the induction equation (\( \eta \): magnetic diffusivity) gives

\[
\frac{\partial B}{\partial t} = \nabla \times (V \times B) + \eta \nabla^2 B,
\]

and taking the azimuthal average, one obtains

\[
\frac{\partial \overline{B}}{\partial t} = \nabla \times (\overline{V} \times \overline{B} + V' \times B') + \eta \nabla^2 \overline{B}.
\]

By subtracting Eq. (7) from Eq. (6), we obtain

\[
\frac{\partial B'}{\partial t} = \nabla \times (V' \times \overline{B}) + \overline{V} \times B' + V' \times B' - \overline{V} \times \overline{B}' + \eta \nabla^2 B'.
\]
We may further simplify Eq. (8) by assuming that
\[ B' \approx \tau \nabla \times (V' \times \mathbf{B}), \]
(9)
where \( \tau \) is the eddy turnover time. The second term on the right-hand side of Eq. (7), \( \mathbf{V}' \times \mathbf{B}' \), will then become some function of the components of \( \mathbf{B} \) and their spatial derivatives. Under the condition of spatial isotropy (no special directions), this quantity can only depend on \( \mathbf{B} \) and \( \nabla \times \mathbf{B} \), and we can write
\[ \mathbf{V}' \times \mathbf{B}' = a\mathbf{B} - \eta_t \nabla \times \mathbf{B} \]
(10)
and
\[ \alpha \approx -\frac{\tau}{3} \mathbf{V}' \cdot \nabla \times \mathbf{V}'. \]
(11)
Here \( \mathbf{V}' \cdot \nabla \times \mathbf{V}' \) is called the (kinetic) helicity, and
\[ \eta_t \approx \frac{\tau}{3} \mathbf{V}'^2 \]
(12)
is called the eddy diffusivity. Finally we arrive at the mean-field dynamo equation,
\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B} + a\mathbf{B}) + \eta_t \nabla^2 \mathbf{B}. \]
(13)
This formulation was established by the so-called Potsdam school (Steenbeck & Krause 1969). The notable difference between the original induction equation and the mean-field dynamo equation is the appearance of additional electromotive force \( a\mathbf{B} \) and enhanced magnetic diffusivity \( \eta_t \).

Let us introduce the spherical-polar coordinates \((r, \theta, \phi)\). The \((r, \theta)\)-component is also called the poloidal component (subscript \( p \)), and the \( \phi \) component is the toroidal component. We can write
\[ \mathbf{B}_\phi = B, \quad \mathbf{B}_p = \nabla \times (Ae_\phi). \]
(14)
The mean-field dynamo equation is now split into two equations. When the velocity has only the \( \phi \)-component (differential rotation),
\[ \mathbf{V} = \Omega s \mathbf{e}_\phi, \quad s \equiv r \sin \theta, \]
(15)
we obtain
\[ \frac{\partial B}{\partial t} = s (\nabla \Omega \times \nabla A)_\phi + \eta_t (\nabla^2 - \frac{1}{s^2}) B + \left[ \nabla \times (a \mathbf{B}_p) \right]_\phi, \]
\[ \frac{\partial A}{\partial t} = a B + \eta_t (\nabla^2 - \frac{1}{s^2}) A. \]
(16)
(17)
Here the “\( \Omega \)-effect” means the stretching of field lines by differential rotation. The “\( \alpha \)-effect” in Eq. (17) describes the feedback from the toroidal field to the poloidal field. The dynamo in which the toroidal field is generated by differential rotation, and the poloidal field by the \( \alpha \)-effect, is called the \( a\Omega \)-dynamo. The dynamo in which the toroidal field is generated also by the \( \alpha \)-effect from the third term in the right-hand-side of Eq. (16) is called the \( \alpha^2 \)-dynamo. If \( \alpha = 0 \), then \( A \) decays according to Eq. (17), and eventually \( B \) also decays by Eq. (16); this is Cowling’s anti-dynamo theorem.
4.3. Dynamo Wave

The diffusion terms do not affect the periodic property of the solution, and for simplicity we may drop them and we obtain the following

$$\frac{\partial^2 A}{\partial t^2} = \alpha s \, (\nabla \Omega \times \nabla A)_\phi.$$  \hspace{1cm} (18)

This equation has a propagating solution, the dynamo wave as discovered by Parker (1955). The wave propagates in the direction of $\alpha \nabla \Omega \times e_\phi$, along the $\Omega=$constant surface (Yoshimura 1975). This property is called the Parker-Yoshimura rule (Cowling 1981). If the dynamo wave were to be identified with the migration of the sunspot belts towards the equator, $\alpha(\partial \Omega/\partial r) < 0$ in the northern hemisphere.

These properties can be qualitatively understood as in Fig. 7. Among the two models shown in Fig. 4, here we assume Fig. 4a. The volume distribution of kinetic helicity can be inferred by considering the effect of Coriolis force on the convective flows (Fig. 7b). In the northern hemisphere, the kinetic helicity will be negative in the upper part and positive in the lower part of the convection zone. The sign of $\alpha$ is opposite to these. Because of the density stratification, the velocity is larger in the upper part and it will dictate the $\alpha$-effect. Therefore the Parker-Yoshimura rule expects the migration of the field towards the equator because $\alpha > 0$ and $\partial \Omega/\partial r < 0$ in the northern hemisphere.
The direction of the propagation of the dynamo wave can be understood graphically as shown in Figs. 7(c)–(f). Suppose the toroidal field is already generated (Fig. 7c) which is indicated by ⊗ (northern hemisphere) and ⊙ (southern hemisphere) in the meridional cross section. The flux tube will rise as Ω-shaped loops, and they will be rotated clockwise by the Coriolis force in the northern hemisphere (Fig. 7d). In the meridional plane poloidal field-line loops are generated, which may merge and make large-scale poloidal fields. Because of the differential rotation of Fig. 7a, a poloidal loop in the northern hemisphere will be tilted and generate new toroidal fields, which are indicated by ⊗ and ⊙ (Fig. 7e). By comparing Fig. 7c and Fig. 7e, we can conclude that the original toroidal flux tubes have moved towards the equator. If we adopt Fig. 4b as the internal rotation, we obtain the poleward migration of sunspot belts.

The period of the cycle $T$ is roughly given by

$$T \approx |\alpha \nabla \Omega|^{-1/2}.$$  

(19)

Because the value of $\alpha$ is not well estimated, Eq. (19) may not be a strong proof of the theory; $\alpha$ of the order of 5 cm s$^{-1}$ gives roughly $T = 10$ years.

5. Criticisms and New Developments

The classical dynamo theory described above was established already in the early 1970s. On the other hand, numerical MHD simulations started to show controversial results in the 1980s. Helioseismology started in late 1970s when the oscillations were identified as global eigenmodes of acoustic waves. Inversion methods using helioseismology as a diagnostic tool have been developed, and in the 1990s the internal rotation was beginning to be inferred. The most recent results (Howe 2009) show that the constant-\Omega surfaces in the convection zone are almost radial with a possible exception of the low-latitude regions; in the low-latitude regions the angular velocity is nearly cylindrical and generally increases with $r$ (i.e., the dynamo wave propagates poleward) and decreases with $r$ near the surface. There is a region of strong rotational velocity shear at the bottom of the convection zone, called the tachocline. (The radiative core shows rigid-body rotation, in spite of the continuing contraction of the core as the star evolves. The only possible way of keeping the rigid rotation would be for the magnetic field to permeate the core.)

How to generate such a differential rotation in the convection zone is another challenge (Miesch 2005), but suppose the rotation is as observed, how can we understand the dynamo process? Apparently the classical dynamo theory predicts poleward migration of sunspot belts, and it is clear that the basic framework of the theory has to be reconstructed.

5.1. Magnetic Buoyancy

It is a general tendency that magnetic fields put into a convective fluid are swept to the boundary of convective eddies and turn into flux tubes with amplified field strength, and at convective cell centers the magnetic fields are dissipated by being folded many times (Galloway & Weiss 1981). Therefore, even if the dynamo-generated toroidal fields are global scale initially, they tend to be bundled into flux tubes. This looks consistent with the appearance of sunspots which occupy 1% or less of the solar surface. However, the flux tubes experience magnetic buoyancy (Parker 1975). Because of the magnetic
pressure and the pressure balance with the external non-magnetic medium, the pressure in the flux tube is lower than the surroundings. If the temperature is the same (i.e. heat exchange is efficient), the flux tube is less dense and will float up. Its speed is roughly the local Alfvén speed, and the flux tubes will escape from the convection zone quickly; no time for them to participate in the $\alpha$ effect.

The fact that sunspots are aligned nicely in the east-west direction indicates that sunspot flux tubes were not created from weak and tangled toroidal fields but were born as flux tubes oriented in the east-west direction. Although flux tubes easily float up in the convection zone, they may stay for a long time at the bottom of the convection zone (i.e. tachocline) where the super-adiabatic temperature gradient is modest. The existence of strong velocity shear there also looks favorable for magnetic field amplification. Starting at the 1980s theoretical studies have been carried out to investigate the stability of flux tubes at the bottom of the convection zone and how they will travel through it (Moreno-Insertis 1992). At the bottom of the convection zone, the equipartition field strength $B_{\text{eq}}$ (magnetic energy $=$ convective kinetic energy) is about $10^4$ gauss (G). A flux tube with $10^4$ G fields will be destroyed during its ascent through the convection zone by turbulent convection. Fields far exceeding $10^5$ G would float entirely as a ring and are not consistent with observations. The most favorable field strength has turned out to be around $10^5$ G. Such flux tubes will keep their entity and their east-west orientation during their ascent. However, it is not clear how the field strength ten times $B_{\text{eq}}$ can be created, and flux tubes with such a field strength may not be able to harbor the $\alpha$-effect.

Modern dynamo models assume that the $\Omega$-effect works in the tachocline with large velocity shear, and flux tubes with $10^5$ G field strength are created. The flux tubes rise through the convection zone in a few months, maintaining their entity against destructive convective motions surrounding them. They do not participate in the $\alpha$-effect: The $\alpha$-effect is supposed to work either near the surface [the so-called Leighton mechanism, as depicted in Fig. 5, step (4)], or in the tachocline. The former is called the flux-transport dynamo, and the latter is called the interface dynamo (Charbonneau 2010). The migration of sunspot belts is still by the dynamo wave in the interface dynamo. In the flux-transport dynamo the migration of sunspot belts is not ascribed to the dynamo wave but is explained by the meridional circulation.

The meridional circulation at the surface is a slow (10–20 m s$^{-1}$) poleward flow. Its detection has long been controversial (Bogart 1987), but recent results tend to converge as the poleward flow, and the same results were obtained by helioseismology as well (Gizon & Rempel 2008). To generate the meridional flow is as challenging as the generation of differential rotation, however.

In addition to the information on the internal rotation and flows by helioseismology, we have another two constraints on the property of the dynamo mechanism: They are the torsional oscillations and magnetic helicity.

6. Meridional Circulation and Torsional Oscillations

In Babcock’s model, the reversal of the polar fields is by diffusion of the following polarity of active region magnetic fields. However, it is not clear how diffusion can systematically transport one part of active region magnetic flux to the poles. In the 1980s Sheeley and his colleagues started to simulate the behavior of the observed magnetic flux with a model including diffusion, laminar meridional flow, and magnetic flux injec-
tion from observation (which is now called the data assimilation). They concluded that a poleward flow is required to explain the behavior of surface magnetic flux (Sheeley 2005).

This surface poleward flow must sink and return to low-latitude regions in the convection zone. Such a signature was found in the Doppler measurements of solar rotation as torsional oscillations (Howard 1996). Torsional oscillations are residuals of the differential rotation after the smooth functional form as Eq. (1) is subtracted, and appear as bands of faster or slower rotation. They were observed to migrate from the mid latitude to both high and low latitudes in a time scale longer than 11 years.

The torsional oscillations were interpreted as a nonlinear feedback (by the $\mathbf{J} \times \mathbf{B}$ force) from the dynamo-generated magnetic field to the differential rotation, while recently other interpretations are also proposed (Rempel 1996). If the nonlinear feedback is in action, it implies that the magnetic field and gas are coupled at least in the upper convection zone. The concept of isolated flux tubes is therefore too idealistic. The coupling also implies the existence of the $B_p$ component in the dynamo-generated flux tubes, which is consistent with the $\Omega$-shaped flux tubes rising through the convection zone.

7. Magnetic Helicity

Helical nature of solar structures (Fig. 8) has long been known; whirl patterns around sunspots, sigmoidal coronal loops, and chirality of prominences (Pevtsov 2005). Magnetic helicity is a quantitative measure of how the magnetic flux systems are intertwined with each other. It is defined as

$$H = \int_V \mathbf{A} \cdot \mathbf{B} \, dV, \quad \mathbf{B} = \nabla \times \mathbf{A}$$

(20)

for a closed volume $V$, and is a conserved quantity in a fluid of infinite conductivity. For a semi-infinite space bounded by the solar surface from below, a modification to
Eq. (20) was introduced (Berger & Field 1984). Since we cannot directly measure the vector potential \( \mathbf{A} \) and hence \( H \), a proxy (current helicity) such as

\[
H_c = \int_V B_z J_z \, dV \quad (J_z = (\nabla \times B)_z)
\]

or

\[
\alpha_{av} = \frac{\int_V B_z J_z \, dV}{\int_V B_z^2 \, dV}
\]

has been used. Figure 9 shows the latitude distribution of \( \alpha_{av} \) (Hagino & Sakurai 2004). Although scatter is large, there is a statistical tendency that the current helicity is negative in the northern hemisphere and positive in the southern hemisphere. This “hemispheric sign rule of helicity” was discovered by Seehafer (1990) and subsequently confirmed by several groups.

Figure 9. A proxy to the current helicity [\( \alpha_{av} \) defined by Eq. (22)] as a function of latitude, obtained at the National Astronomical Observatory of Japan (Hagino & Sakurai 2004).

8. Discussion

Figure 10 shows the change in \( d\alpha_{av}/d\theta \) for 15 years (Hagino & Sakurai 2005). Some dynamo models predicted such variation of magnetic helicity within an activity cycle (Choudhuri, Chatterjee, & Nandy 2004). Zhang et al. (2010) proposed that some regions do not follow this rule, particularly in activity minimum. These facts may give clues as to the origin of magnetic helicity. In one model, the flux tubes are generated without twist and they get twisted statistically by helical turbulence during the ascent (the sigma effect, Longcope, Fisher, & Pevtsov 1998). However, in seeing the changes in magnetic helicity with time, it is more likely that the magnetic flux is born (or amplified) with initial twist. In any case the observation of magnetic helicity will give further constraint on the dynamo models. We need helicity measurements with higher accuracy which would give the helicity of weak field regions (background fields) and the long-term variation of helicity.
Figure 10. Time variations of the slope of the current helicity parameter $\alpha_{av}$ in terms of latitude, derived from the magnetographs at Okayama (left, 1983–1994) and Mitaka (right, 1992–2001) of the National Astronomical Observatory of Japan (Hagino & Sakurai 2005).

Since the difficulties and discrepancies in the classical dynamo models were recognized, efforts have been put into several directions; theoretical studies, simplified numerical studies, and full three-dimensional simulations. Yet we are not at the goal and our picture of the dynamo mechanism is still made of ‘cut and paste’.

For a breakthrough, one would need multiple steps:

1. Further development in helioseismology to diagnose the structure of the tachocline and meridional flow.
2. High-accuracy measurements of magnetic helicity and its long-term time variation.
3. Theoretical studies and numerical simulations on
   (a) the origin of differential rotation and meridional circulation,
   (b) the role of the tachocline in the dynamo mechanism, and
   (c) the location of the alpha effect.
4. Input from stellar observations.

As far as the numerical simulations are concerned, we may point out the recent (partial) completion of the so-called K-computer (10 petaflops) of RIKEN.\textsuperscript{1} Astrophysics and elementary particle physics are one of the five main strategic research areas of this facility.

The observations of stellar activity cycles need a very long time span, but yield information which is not obtainable from only looking at the Sun (Saar 2002). The evolution of stellar activity levels is not a simple function of age or rotation velocity, and suggests the existence of multiple modes and complicated mode changes in the operation of the dynamo in different situations. Stars later than spectral type M3.5 are believed to be fully-convective, and a possible change in dynamo action (across M3.5) has been detected (Jackson & Jeffries 2010).

In conclusion, we would anticipate a ten- or twenty-year endeavor to fully disentangle the mystery of solar and stellar activity.

\textsuperscript{1}http://www.aics.riken.jp/en/
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