WHAT CAN WE LEARN ABOUT SOLAR CYCLE MECHANISMS FROM OBSERVED VELOCITY FIELDS?

PETER A. GILMAN
National Center for Atmospheric Research*, Boulder, CO 80307-3000

ABSTRACT I review the probable roles played by differential rotation, torsional oscillations, meridional flow, giant cells, supergranulation and granulation in determining the solar cycle. Strong radial gradients of angular velocity at the base of the convection zone of opposite sign in low and high latitudes are judged to be the primary determinant of the cycle. Radial gradients within the convection zone may be responsible for inclination angles of plage magnetic fields. These radial gradients also allow us to test the degree to which the sun tends toward a layer of constant angular momentum near the top of the convection zone, and toward angular velocity constant on cylinders near the equator in the lower part of the zone. Torsional oscillations are unlikely to be responsible for the solar cycle, but may be evidence of thermal and mechanical perturbations due to solar cycle magnetic fields. I raise questions about whether these oscillations represent a true pole-to-equator migration of a coherent signal, defining an “extended” solar cycle. Meridional flows as large as 20m/sec are shown to have enormous effects on migration speeds of dynamo waves, as well as on the mean differential rotation, raising doubts about the reality of such flow speeds. I also argue against the existence of megagauss magnetic fields at the base of the convection zone. In closing, I outline a scenario for how the solar dynamo really works, what is important and what is not. I also stress the need to test Parker’s “thermal shadow” concept, to examine mid-latitude “breaks” in torsional oscillation data, to use helioseismological techniques to infer as much as possible about the properties of the base of the convection zone, and to put more emphasis on the development of dynamo models of greater realism, applied to the base of the solar convection zone.

I. INTRODUCTION

Since flow of a conducting fluid in the presence of magnetic field will generate electric currents and thereby induce additional magnetic field, knowledge of such flows should help us understand how magnetic fields are maintained. If such flows maintain fields indefinitely against dissipation, then the fluid

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system constitutes a hydromagnetic dynamo. It is highly likely that the sun
(and other stars) are dynamos. Therefore, we should be able to improve our
understanding of the solar cycle, an intrinsically magnetic phenomenon, by
examining solar velocity fields. That is my assignment in this talk.

My strategy is to relate observed solar velocity fields to the solar cycle
via dynamo theory. The solar motions I focus on will be the mean differential
rotation, torsional oscillations, meridional flows, giant cells, and granules
and supergranules. Some aspects of these flows are observed directly, i.e.,
through the doppler shift of spectral lines, while others are seen through the
motions and shapes of surface magnetic structures. Still others are inferred
from solar acoustic oscillations through the techniques of helioseismology.
Such oscillations may also yield information about other properties of the solar
interior, such as magnetic field strength and structure.

After examining the possible role of various velocity fields in the solar
cycle, I will state a speculative scenario for how the solar dynamo works, which
can be tested, hopefully over the next decade or so. I will give my own opinions
of what will be found to be important in the solar dynamo and what will not,
as well as enumerate areas where I think work is particularly needed to test
dynamo ideas.

II. BRIEF QUALITATIVE REVIEW OF ELEMENTS OF DYNAMO
THEORY

In order to evaluate the role of particular velocity fields in the solar cycle,
I need to set a context by pointing out how velocities enter the theory of
dynamos, particularly periodically reversing dynamos. Other talks at this
meeting go into much more detail on the basics of dynamos, to which I direct
the reader's attention in these Proceedings.

There appear to be three types of motion that are of particular
importance in naturally occurring dynamos. The first is differential rotation.
The second is motions that have helicity, i.e., for which the scalar product
of velocity and vorticity is non-zero. In the well-known jargon of dynamo
theory, such motions give rise to the "α effect". An example on the sun would
be convection influenced by rotation. The third type are motions that cascade
magnetic energy down to dissipation scales.

In cyclic dynamos the motions and magnetic fields are linked as follows:

(a) Poloidal field (field in meridian planes in a spherical object like a star)
is produced from toroidal field (field wrapped around the axis of rotation) by
the action of helicity in the flow, or the "α effect".

(b) Toroidal field is produced from poloidal field by the differential
rotation and the α effect.

(c) The combination of (a) and (b), above, may produce propagating
dynamo waves in which both the toroidal and poloidal fields propagate
together in latitude and radius. These waves tend to propagate along lines
of constant rotation. For the sun, we interpret the movement of the sunspot belts
from mid-latitudes toward the equator as the solar cycle progresses, as dynamo
wave propagation in latitude.

(d) The speed of dynamo wave propagation is proportional to the
differential rotation (the α^2ω dynamo case) unless the α effect is quite small.
In that case, the speed is proportional to the square root of the product of
differential rotation and $\alpha$. This is the so-called $\alpha \cdot \omega$ dynamo.

(e) The direction of propagation is determined by the sign of the
differential rotation and by $\alpha$. Angular velocity increasing inward and $\alpha > 0$
(helicity $< 0$) in the northern hemisphere results in dynamo wave propagation
toward the equator.

(f) Meridional flow, while not essential to the presence of a dynamo, can
affect the speed and direction of propagation of dynamo waves. This is simply
because the field patterns will be swept along by the flow.

The amplitudes of these dynamo waves will be limited by the cascade of
magnetic energy to dissipation scales, as well as by feedbacks of the induced
magnetic fields on the inducing flows.

III. MEAN DIFFERENTIAL ROTATION

Observations of the mean differential rotation of the sun are discussed in the
paper in these Proceedings by Snodgrass.

A. Implication from Mean Gradients for Dynamo Waves

Before anything was known about rotation in the solar convection zone
below the photosphere, mean field or $\alpha \cdot \omega$ dynamo theory, when applied to
the sun, treated the radial gradient of angular velocity as a free parameter.
To reproduce the migration of toroidal fields toward the equator that is
inferred from the sunspot “butterfly diagram” required that the angular
velocity increase substantially with depth (Stix 1976), given estimates of the
sign of the $\alpha$ effect from convection calculations. But now helioseismological
measurements are converging on the result that radial gradients within the
convection zone in low and middle latitudes are weak, with some decrease in
angular velocity with depth, except perhaps near the solar surface (Brown
would lead to toroidal field migration toward the poles, the opposite of what
is inferred for sunspot latitudes. Thus, mean field or $\alpha \cdot \omega$ dynamos do not
appear to apply to the bulk of the solar convection zone. This conclusion is
further supported by the full MHD dynamo calculations of Gilman (1983)
and Glatzmaier (1984, 1985a,b) that show that global convection that drives a
surface differential rotation similar to that observed on the sun also produces a
dynamo with poleward field migration. So dynamo theorists have turned their
attention to other regions of the sun, particularly the interface between the
convection zone and radiative interior below. I examine this possibility in the
next section.

Weak radial gradients of angular velocity in the convection zone imply
the mean latitudinal gradient seen at the surface, in the form of an equatorial
acceleration, is transmitted throughout the convecting layer. Since dynamo
waves, even those originating somewhere else, will tend to propagate along
surfaces of constant rotation, this latitudinal gradient could be responsible
for radial propagation toward the surface. However, the magnitude of the
observed latitudinal gradient is such that a dynamo wave would take of order
five years to cross the convection zone. Thus, it appears this process is too slow
to compete with either convection or magnetic buoyancy in bringing active region flux to the surface.

Helioseismology also seems to be converging on the result that radial angular velocity gradients are much larger at the bottom of the convection zone, and in the radiative core immediately below, than within the convection zone (Brown et al. 1989, Morrow 1988, Korzennik 1990). Furthermore, the rotation rate below the convection zone appears to be intermediate between the minimum surface rotation seen at the pole and maximum surface rate seen at the equator. This implies that at the base of the convection zone, the radial gradient must change sign at mid-latitudes. This raises the possibility of dynamo waves generated at the interface propagating both toward the equator and the poles.

Which branch produces which directions of propagation depends upon the sign of $\alpha$ at the base of the convection zone, rather than in the bulk of the zone. Global convection models (Glatzmaier 1984, 1985a,b, Gilman and Miller 1986) predict a sign change near the base, due to the particular structure of the convection there. Thus, a dynamo at the interface between the convection zone and the interior could produce dynamo waves propagating toward the equator in low latitudes, and toward the poles at higher latitudes. This scenario was first discussed in Gilman, Morrow and DeLuca (1989), and modeled in a more quantitative fashion by Belvedere, Proctor and LanzaFame (1991).

There are many additional arguments that favor a dynamo at the base of the convection zone (DeLuca and Gilman 1986; earlier references cited therein). More regular, smooth magnetic field structure is more likely near the base of the convection zone where the turbulence is weaker. This could lead to more dynamo action, even if the $\alpha$ effect is weaker there. Hale's polarity law would also be easier to sustain with more regular fields.

### B. Dynamical Considerations from Mean Differential Rotation

Gilman, Morrow and DeLuca (1989) demonstrated that the angular velocity profile with latitude near the base of the convection zone appears to be at or nearly at angular momentum balance with the interior below. That is, the torque exerted in the direction of rotation in low latitudes balances the torque opposite to the rotation at high latitudes, to within about 1%. Assuming the total system is in equilibrium, this result implies a cycling of angular momentum into the interior at low latitudes and out again at high latitudes. This cycle must be completed by flow of angular momentum from low latitudes to high in a layer below the convection zone. They argue that the most likely candidate to carry out this poleward transport is the electromagnetic body force from dynamo fields. If this picture is correct, then a dynamo at the base of the convection zone links convection zone dynamics, magnetic fields, and the angular momentum history together in important but subtle ways.

The global convection models of Gilman and Glatzmaier predict that a surface differential rotation profile like that of the sun should be accompanied by a profile within the convection zone of angular velocity constant or cylinders concentric with the rotation axis. This feature is particularly firm in the theory for low latitudes, outside the cylinder tangent to the interior boundary of the convection zone at the equator. This cylindrical profile would apply at depths in the convection zone where the influence of rotation upon the convection is strong.
Foukal (1972) and Foukal and Jokipii (1975) originally proposed that in a thin layer at the top of the convection zone, perhaps of the depth of supergranules, there is a layer whose angular velocity is tending toward a state in which the angular momentum per unit mass is constant with radius. This means the rotation increases inward as the inverse square of the radius. Foukal invoked this concept to explain the difference between sunspot and doppler rotation rates. Later, Gilman and Foukal (1979) tested this idea with a thin rotating spherical shell convection model, and found that convection did tend to build up such a layer. Helioseismology is now yielding rotation profiles that may allow tests of how closely the real sun approaches these limiting rotation patterns. A profile in the Ph.D. thesis of Korzennik (1990) (Figure 6.28) is particularly intriguing in that regard, shown here in Figure 1. This profile is for the solar equator, inferred from acoustic modes of spherical degree \( l \) between 5 and 600. It shows a peak angular velocity at about \( r = .93R_\odot \) falling off to the base of the convection zone at \( r = .72R_\odot \) by about 3.5\%, and by about the same amount to the solar surface, if extrapolated from .97\( R_\odot \) to the surface spectroscopic rate.

![Figure 6.28](image)

**Figure 6.28:** Equatorial rotation rate as a function of depth inferred from rotational frequency splittings, measured for degree 5 \( \leq l \leq 600 \). Measurements based on 1988 BBSO (5 \( \leq l \leq 60 \)) and on 1988 MWO (60 < \( l \leq 600 \)) observations have been combined to obtain this profile.

Fig. 1. Figure 6.28 from Ph.D. thesis by S. Korzennik, UCLA, 1990, illustrating the radial angular velocity profile at the solar equator, inferred from acoustic modes. Rotation units are in nano Hertz (vertical coordinate) and radius is in fractions of the solar radius (horizontal coordinate).

To test how close the lower part of the rotation profile approaches constancy on cylinders, we must project the surface angular velocity profile inward to .93\( R_\odot \), and then predict the rotation at the equator at convection

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zone base \((0.72R_\odot)\) from that at 39° latitude at \(0.93R_\odot\) since they are on the same tangent cylinder. This prediction indicates the angular velocity should drop from \(0.93\) to \(0.72R_\odot\) by about 7.4%. Since the actual drop is about 3.5%, about 47% of the drop predicted by constancy on cylinders is found. Thus the profile is a little less than half of the limiting case of constancy on cylinders.

In the thin layer at the top, for constant angular momentum, the angular velocity should increase from the surface to \(r = 0.93R_\odot\) by 14%. It is measured to increase by about 3.5%, so the profile is only 25% of that of a constant angular momentum layer.

We conclude that in low latitudes at least, the sun more closely approaches angular velocity constant on cylinders in the deep layers, than it does to constant angular momentum in the upper layers. But the tendency is of the correct sense in both cases.

Perhaps, it should not be surprising that the asymptotic limits are not reached in either upper or lower layers, because the transition is not sharp. We should expect that penetration and mixing will work to reduce the angular velocity maximum. Eddies crossing from below will try to increase the speed of the upper layer, and eddies crossing from above will try to speed up the lower layer. In addition, radial magnetic fields may work against the peak angular velocity.

What is needed to explore this problem further is an angular momentum mixing model that captures the effects of both weak and strong rotation on convective eddies, or, alternatively, a global convection model of sufficient resolution that it resolves eddies both above and below the angular velocity peak.

C. Other Effects of Differential Rotation on Magnetic Fields

Even if the solar dynamo is concentrated at the base of the solar convection zone rather than throughout its bulk, the differential rotation within the convection zone may have observable effects on magnetic fields seen at the surface. Some evidence of this may be present in the inclination angles of magnetic fields of growing and decaying plage regions, as estimated by Howard (1991). These are summarized in Figure 2. The forward inclination of growing plages might be explained by angular velocity that decreases with depth (such as in Korzennik’s profile) acting on a flux tube rising from the bottom of the convection zone. For the Korzennik profile, the average forward inclination of 24° seen in Figure 2 could be generated in about 5 days.

Figure 3 gives a schematic of how differential rotation would act on a rising flux tube.

Once this inclined flux reaches the photosphere, it would also be acted upon by the angular velocity increasing with depth above \(r = 0.93R_\odot\). In time, this could also produce the reverse inclination seen in decaying plages. Howard (1992) has also demonstrated a backward inclination of 5° for sunspot fields which could have the same origin. A quantitative testing of this explanation obviously requires detailed calculation, with assumptions about the form of interaction of the flux tube and the surrounding flow, as well as a calculation of the role of Maxwell stresses associated with the curved fields in limiting the growth in inclination angle.
INCLINATION ANGLES OF PLAGE MAGNETIC FIELDS

Growing Plages

\[ 28° \]
\[ 10° \]

Average inclination of growing plages = 24°

Decaying Plages

\[ 3° \]
\[ 13° \]

Fig. 2. Average inclination angle to the local vertical of plage magnetic fields, as measured by Howard (1991).

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- Average rotational velocity on loop moves it forward.
- Differential rotation tilts loop forward.

Fig. 3. Schematic illustrating effects of a radial differential rotation on a rising flux loop that is part of a toroidal field at the base of the solar convection zone.
IV. TORSIONAL OSCILLATIONS

The so-called "torsional oscillations" on the sun were originally discovered by Howard and LaBonte (1980) and since have been extensively analyzed by these authors, as well as Snodgrass and others. The accompanying paper in these Proceedings by Snodgrass reviews these flows extensively. The basic effect is seen as small perturbations on the mean differential rotation, of amplitude ±5-10 meters/second, that appear to migrate toward the equator from very high latitudes. The largest latitudinal "shears" in these perturbations occur near the peak of solar activity in low latitude. The migration of these waves appears to be synchronized with the solar cycle, but with a new wave seen in high latitudes several years before the start of a new sunspot cycle. The wave then reaches sunspot latitudes and migrates to the equator by the time that sunspot cycle is ended.

To understand what torsional oscillations might be telling us about mechanisms of the solar cycle, we must speculate on their origins. There are several possibilities.

1. The oscillations result from a false doppler signal from the magnetograph measurements, or from some artifact of the analysis technique. The former seems now to be ruled out by various arguments. The latter is not so easily dismissed. The various analyses do yield somewhat variable results, with problems of "cross talk" between data in low and high latitudes, when fitted with low order spherical harmonics. But my biggest concern about the data is whether they demonstrate a truly coherent pattern that migrates all the way from polar latitudes to the equator, in a time several years longer than the canonical 11-year sunspot cycle. Examination of the various plots of velocity vs. latitude reveal persistent "gaps" in the patterns in mid-latitudes. These gaps seem to appear no matter what analysis method is used. They raise the possibility there are distinct low latitude and high latitude rotation perturbations associated with each sunspot cycle, but without a true migration of a single "pulse" from high to low latitudes over a much longer time period. The distinction is important, because the different interpretations would relate to different dynamo behavior near the base of the solar convection zone.

2. The oscillations are an intrinsic velocity pattern on the sun of nonmagnetic origin, that perhaps even drives the solar cycle and determines its period. There are several arguments against this possibility. First, there is no known nonmagnetic mechanism to produce that long a period on the sun. Second, the axisymmetric mode represented by the torsional oscillation is not a favored mode of convection under the influence of rotation. Third, the motions are very small in amplitude compared to the mean differential rotation and convection. Fourth, axisymmetric meridional flow and differential rotation cannot produce poloidal field from toroidal, and so can not complete a dynamo cycle.

3. The oscillations are a direct response of the rotation to the electromagnetic body force of the dynamo fields (Yoshimura 1981, Schussler 1981). This possibility is, at best, oversimplified because one should assess the impact of this force on the mechanism for maintaining the mean differential rotation. For example, this force could change, or produce, mean meridional flow which, in turn, would change the differential rotation through coriolis forces. Without considering these effects, predicting from the models that
the maximum shear in the torsional oscillation should occur at the latitude of maximum solar activity is probably fortuitous. Progress on a more consistent approach has been made by Kleeorin and Ruzmaikin (1991).

All of the above cited calculations assume, implicitly or explicitly, that the dynamo is distributed throughout the depth of the convection zone. If, instead, the dynamo is concentrated at the base of the zone, then a different argument must be made, because the electromagnetic body force will look much different.

Given that candidates 1 - 3, above, appear unlikely, what, then, is the origin of the torsional oscillations? We believe the most likely is:

4. The oscillations are a secondary flow arising from the thermal and mechanical disturbance caused by solar activity and the subsurface toroidal field at certain latitudes. Several candidate processes could contribute:

(a) alteration and partial suppression of convection due to the magnetic fields of active regions;
(b) downflows due to rising flux tubes;
(c) Parker's "thermal shadow" effect.

With this origin, the torsional oscillation need not be purely axisymmetric, but might include low, non-zero longitudinal wave numbers as well, particularly from the longitudinal variations in solar activity.

This possibility is essentially unexplored from a theoretical point of view. In this paper, I look only briefly at one possibility, namely Parker's "thermal shadow" concept (Parker 1987). In this concept, there is a strong toroidal magnetic field of rather broad latitudinal extent at or near the base of the convection zone (presumably maintained by dynamo action). This field partially blocks the radial heat transport by convection. This blocking induces secondary circulations above and below the field that are responding to the induced horizontal density and temperature perturbations. In addition, a smaller scale, sporadic instability of the toroidal field produces loops that rise to the photosphere as new active region flux.

In Figure 4, I have adapted Parker's scheme and added rotation. The important point is that a toroidal field near the convection zone base should induce a pair of meridional flows above, which share a downflow that occurs near the central latitude of the toroidal field. Coriolis forces acting on the horizontal branch of these flows near the surface would produce a perturbation in the mean differential rotation, such that the maximum shear would occur near the latitude of expected maximum in solar activity, as is observed.

It is intriguing to consider reversing the logic and arguing that the existence of torsional oscillations could be taken as evidence for thermal shadowing.

It is important to stress that these meridional flows are not responsible for the solar cycle itself, nor would they contribute much, if at all, to bringing the flux to the surface, and they certainly would not be responsible for driving the mean differential rotation, but only a small perturbation on that mean.

Grand roles have been postulated for meridional flows, e.g., Snodgrass and Wilson (1987), but these seem unlikely since, to be true "drivers" of the cycle, they must ultimately have a nonmagnetic origin, whence they encounter the difficulties outlined under item 2 of this section.
Fig. 4. Schematic of possible relationship between a toroidal magnetic field near the base of the solar convective zone, meridional circulations induced by "thermal shadowing", and the position of the torsional oscillations in latitude. Concept derived from Parker's (1987) proposal of "thermal shadows".

V. MERIDIONAL FLOWS

The most remarkable aspect of meridional flows on the sun are the wide variations in the estimates of their amplitudes. From sunspot drifts, 1 - 2 m/sec are common (Howard and Gilman 1986) while the average doppler rate is close to 20 m/sec, with flow toward the poles in low latitudes (Duvall 1979, Howard 1979). Short term spot rates as large as 100 m/sec have been claimed (Ribes et al. 1985).

A. Implications for Dynamo Waves
Since meridional flow can sweep the magnetic field patterns of dynamo waves along, the rate of sweeping will vary enormously, depending upon which flow estimates are used. A second problem is that the meridional flows are estimated only at the solar surface. What sweeping effect is produced depends upon the meridional flow at the depth of origin of the dynamo. If this is at the base of the convection zone, then it is the meridional flow at the base that counts.

Figure 5 shows two simple forms of meridional flow of 20 m/sec at the surface which differ according to the level at which the return horizontal flow
occurs. Obviously, the sweeping of field patterns produced at the convection zone base by those patterns would differ by an order of magnitude.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{two_limiting_cases}
\caption{Schematic of examples of meridional flow in the solar convection zone that could complete the circulation associated with a poleward flow in the photosphere of 20 m/sec.}
\end{figure}

A 20 m/sec meridional flow toward the poles will carry a particle across the sunspot zone (30° latitude) in only six months! This is 20 times faster than the observed migration, and in the opposite direction! So either the surface doppler flow must not be doing this to the solar dynamo waves, or it must be counterbalanced (rather finely) by another process, resulting in the much lower net migration rate. A 2 m/sec meridional flow would still have a significant, but not nearly so profound, effect. The above considerations suggest that the amplitude of meridional flows must be quite limited in dynamo regions, unless the actual field structure is quite resistant to being displaced in latitude. Figure 6 shows how this resistance might occur. A toroidal field at the base of the convection zone puts up a loop that is acted upon by a meridional flow that increases with height. This loop is pulled in latitude by the strong flow above, but movement is resisted by the Maxwell stresses built up along the curved field lines. Near the solar surface, this could result in seeing doppler meridional flow that is much larger than that for the sunspots tied to this flux tube.

B. Dynamical Considerations
Meridional flow is a very efficient transporter angular momentum in latitude, so even small flows can make a difference. This transport, by itself, will always tend to produce an equatorial deceleration, the opposite of what is observed. So it, perforce, can not be the dominant mechanism of angular momentum transport.

Global convection models predict equatorial acceleration driven by the Reynolds stresses of global convection. The convergence of latitudinal angular momentum transport in the models needed to maintain the observed equatorial peak in angular velocity is itself in approximate agreement with estimates from sunspot motions (Gilman and Miller 1986, Gilman and Howard 1984). These models predict meridional flow of magnitude 2 m/sec. or less, also similar
EFFECTS OF MERIDIONAL MOTION ON TOROIDAL FIELD LINES

Meridional flow pulls all parts of loop out of plane of the loop, to higher latitudes.

Fig. 6. Schematic of effect of meridional flow with radial shear on a rising toroidal flux loop anchored to a toroidal field at or near the base of the solar convection zone.

to estimates from spots. But a meridional flow of 20 m/sec would result in 10 times as much angular momentum transport, unbalanced by any other mechanism, which would surely destroy the equatorial acceleration. Clearly, even larger transient meridional flows, as reported by some, would cause even more profound dynamical effects.

We conclude that, both from the point of view of angular momentum balance and from dynamo wave considerations, meridional flows of 1 - 2 m/sec are much more plausible than are flows of 20 m/sec and larger.

VI. GIANT CELLS, SUPERGRANULES AND GRANULES

Giant cells, or convection patterns on a global scale, have not been convincingly observed, so we cannot infer much about the solar cycle from the observations. They are still the most likely driver of the observed equatorial acceleration. If the seat of the solar dynamo is at the base of the convection zone, then their potential dynamo effects in the bulk of the convection zone are less important than previously thought. But knowing how much helicity or α effect giant cells generate at the base of the convection zone becomes more important. To figure that out requires a boundary layer approach to the interaction of convection above with the radiative zone below. Supergranules and granules are well observed, but it is not clear that details of their observation tells us anything about how the solar cycle works. Obviously these flows are responsible for much local concentration of magnetic flux, and participate in a cascade of magnetic energy to scales small enough for ohmic dissipation to occur (~1 km.) But there will never be a way to observe
such small scales directly. These flows also disperse magnetic flux across the solar surface, and thereby participate in determining large scale surface flux patterns. The relationship between this process and the solar dynamo is unclear – and a matter of active debate at this meeting.

VII. MEGAGAUSS FIELDS AT THE BASE OF THE CONVECTION ZONE?

Dziembowski and Goode (preprint) have suggested that certain helioseimological measurements indicate there may be very large amplitude magnetic fields at the base of the convection zone, perhaps of order $10^6$ gauss. From the point of view of magnetohydrodynamic processes likely to be working there, this seems unlikely. The upper boundary of this layer of field would be extremely unstable to magnetic buoyancy, which should drive flux through the convection zone to the surface. The larger the field, the more flux should appear at the photosphere. But the magnetic flux observed to reach the surface is well known, so the larger the field, the smaller the fraction of it that can be allowed to reach the surface, which is counter to the expected effects of magnetic buoyancy. Parker (1984) has argued that even at $3 \times 10^4$ gauss, only a small fraction is ever seen at the surface. Megagauss fields should also severely inhibit convection, and surely stop the dynamo driver locally.

For all these reasons, such field strengths seem implausible. Unfortunately, it is difficult to see a magnetic signature in acoustic oscillations at the base of the convection zone for fields much less than $10^6$ gauss (Dziembowski and Goode, preprint).

VIII. SOLAR DYNAMO SCENARIO

Based on the arguments above and other considerations, I offer the following outline of how the solar dynamo works, what is important and what is not. I fully expect not all of it will prove to be true, but gives a good “target” for observers and theoreticians alike to aim for and at.

1. The seat of the dynamo is near the base of the convection zone and is of an $\alpha - \omega$ or $\alpha^2 - \omega$ type. The change of sign of the radial gradient at mid-latitudes is crucial. Helicity is pumped in from above. Torques from differential rotation are balanced by dynamo induced electromagnetic body forces in the layer immediately below the convection zone.

2. Magnetic flux rises to the photosphere due to buoyancy and convection. Flux comes out at low latitudes despite coriolis forces because of exchange of angular momentum between flux tubes and surroundings (D’Silva and Chaudhuri, preprint). Inclination angles (relative to the vertical) of flux at surface (as measured by Howard) are due to action of radial differential rotation. Magnetic axis tilt angles (from east-west direction) in bipolar spot groups are due to Coriolis forces acting on rising tubes. Both angles are bounded by electromagnetic body force resistance.

3. Most of flux reaching the surface is pulled back down (Parker 1984) but some reconnects at the surface and escapes. Much reconnection must occur at depth, to allow dynamo wave to progress, and bound toroidal field build-up.
4. Surface dispersion of magnetic flux occurs by various mechanisms, but this is cosmetic, not fundamental to the dynamo.

5. Torsional oscillations arise from meridional circulation induced by the thermal shadow from toroidal field near the base of the convection zone, plus aggregate effects of the presence of solar activity throughout the zone.

6. Low latitude and high latitude parts of the torsional oscillation are not smoothly connected. Instead, they are different parts of a single (not extended) solar cycle phenomena.

7. The toroidal field is large enough to produce spots only in low latitudes because of some combinations of:
   (a) weaker \( \alpha \) effect at high latitudes;
   (b) toroidal field in high latitudes weaker, also has more curvature, more resistant to radial displacement of loops, and to latitudinal dynamo wave propagation.

8. Details of the maintenance of differential rotation in the convection zone is relatively unimportant for the dynamo. The point is that angular momentum from high latitudes is deposited near the equator until a balance is struck, which ensures torque balance, and a sign change in the radial rotation gradient in mid-latitudes at the convection zone base.

9. Peak rotation rate within convection zone is a real feature, especially at low latitudes. Profile is determined by interpenetration of small eddies weakly influenced by rotation, from above, and large eddies, strongly influenced by rotation, from below.

10. Meridional circulation turns out to be near the low end of estimates, and does not play a dominant role in either the dynamo or the differential rotation profile.

11. Dynamo action due to differential rotation and the \( \alpha \)-effect are minimized in the bulk of the convection zone due to the filamentary nature of the field there, as well as the short residence time of rising flux tubes.

12. There are no megagauss fields at the base of the solar convection zone.

IX. IMPORTANT AREAS FOR FUTURE EMPHASIS

Based on the above, I offer several areas that need and warrant particular emphasis for future study. I am sure the reader will think of others, too.

A. Confirm or refute Parker’s thermal shadow concept.

B. Look carefully at the connection between torsional oscillation signal in sunspot latitudes, and the high latitude signal. Is this really a “pole-to-equator” phenomenon? Breaks keep appearing in mid-latitudes in the data. The reality of the extended solar cycle is really the same question. I note that coronal “butterfly diagrams” do not seem to show evidence of an extended cycle (Hundhausen, private communication).

C. Push helioseismology to the limit to deduce properties of the interface between the convection zone and the interior. How sharp is the boundary layer? Does the low latitude interface differ from the high latitude interface?

D. Develop interface dynamo models of greater realism.
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