DYNAMICS OF THE SOLAR INTERIOR AND THE SOLAR DYNAMO
Background paper for symposium on the Solar Cycle
and Dynamics Mission
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I. Introduction and Goals

The solar convection zone is the origin of most of the variations in solar output observed or suspected to occur. The sun's magnetic field is rooted there, and solar activity and the solar cycle are generated and maintained there. Changes in the magnetic fields which reach into the solar atmosphere and beyond to interplanetary space are largely determined by the dynamo action of velocity fields in the convection zone. If changes in solar luminosity occur on time scales of months to millenia, such changes probably have their origin in the changing dynamics of the convection zone, either as cause of or in response to long term changes in the level of solar activity. Fluctuations would occur in the rate at which energy is brought to the surface by convection, and the solar diameter would be slightly modified.

To describe and ultimately understand the global workings of the solar dynamo requires simultaneous high quality photospheric observations of solar velocities, magnetic fields, intensity patterns, luminosity and various radiative outputs. The observations must be nearly continuous in time and of long duration--most or all of a solar cycle. Such a measurement program should be a major part of the proposed Solar Cycle and Dynamics Mission. It would be more ambitious than ever attempted before, but the potential now exists to make it successful.

Now is a particularly appropriate time to develop such a measurement program, for at least two reasons. First, recent evidence for a solar
signal in terrestrial proxy records such as carbon 14 in tree rings, together with more sensitive dating techniques being developed, indicate we may soon be able to reconstruct solar history over the past several thousand years in some detail. We need a more detailed template of actual solar observations from which to extrapolate back. Second, theoretical and computational tools and models have now reached the point that quantitative modeling of the global circulation of the sun and its dynamo action is within reach, so that much better information than now exists on global solar velocities, magnetic field and intensity patterns is needed for comparisons with such models.

Beyond answering important questions concerning the solar dynamo itself, which we discuss in detail below, such an observing program offers a unique opportunity for insights into the behavior of dynamos occurring anywhere in the universe. The solar dynamo is the only one which offers the prospect of observing directly some of the primary motions responsible for the induction of magnetic fields. This is not possible for the planetary interiors or other stars.

II. Solar Questions to Answer

There are many aspects of the global behavior of the sun which we need to observe in detail before we can really understand the solar dynamo. Central is the need to observe the global circulation of the solar surface—differential rotation, global eddies or convection, and their variations in time over a solar cycle. This is needed because such circulation should be characteristic of the global flow within the convection zone, which in turn should be responsible for much of the amplification and maintenance of the sun's magnetic field. The velocity
patterns of individual global eddies must be resolved, so that their interaction with the differential rotation and the magnetic field can be determined. We need to know how much the basic rotation of the sun influences the eddy structure, and which eddy sizes dominate in the flow pattern. We also need to know how persistent the eddies are in time—over one rotation to the next, and over a substantial part of the solar cycle. Are different kinds of eddies characteristic of different phases of the magnetic cycle?

Ground based measurements of global circulation of the sun using the Doppler effect have up to now defined rather well the average differential rotation of the sun. They have also given hints of time variations on a variety of time scales, but have told us practically nothing about global scale eddy motions. Global velocity measurements from different ground based observatories have been difficult to compare, because of contamination in the signal by short time scale solar noise, interference by the atmosphere, and instrumental effects. We mention below how space observations may overcome these difficulties.

Knowledge of how the eddies and differential rotation vary with depth is also of great importance because the sun's magnetic field is rooted beneath the photosphere, and most of the induction of the field takes place there. The radial angular velocity gradient plays a key role in many current solar dynamo theories. Extrapolations downward from the surface measurements must be made with the aid of theory. In this regard, it has recently been demonstrated that frequency splitting due to rotation in solar oscillations near 5 minute periods may tell us how the angular velocity varies with depth to 15-25 thousand kilometers below the sun's surface and perhaps deeper. This is because different modes of oscillation peak at different depths in the convection
zone, and respond mostly to the rotation at that depth. In principle, these oscillations will also indicate how the differential rotation varies with time at these depths. The potential for global oscillations to reveal global convective eddy structure remains to be explored. Frequency splitting in those 5 minute oscillations with peak amplitudes very close to the surface can also be compared directly with the surface doppler rotation values.

Detailed interactions between the sun's velocity and magnetic fields are undoubtedly complex and occur on a wide range of spatial scales, but are not well measured. In order to examine interactions between velocities and magnetic fields in the photosphere, we need to measure the magnetic field to at least the same resolution as the velocity field, and at certain times to much higher resolution, since we already know much of the magnetic flux emerging at the surface is in the form of intense flux tubes. Solar dynamo theory demands answers to such questions as--Is the large scale movement of magnetic flux across the solar surface due to transport by the observed large scale velocity field, or are small scale interactions important, producing more of a "random walk"? Are large scale velocity patterns near active regions different than elsewhere? Are there certain velocity patterns which tend to be found in the neighborhood of coronal holes? Can horizontal divergence in the velocity field be found where new magnetic flux is emerging, indicating a region of upwelling which might have brought up the flux?

Global convection patterns on the sun should have associated small amplitude but persistent surface spatial variations in radiative flux. If large enough, these flux intensity patterns should also contribute to changes in solar luminosity. Slightly warmer fluid should be found
where upwelling occurs. Changes in these patterns with time should be associated with detectable changes in the global velocity and magnetic field patterns. If the variations in the radiative flux could be detected, then they could yield information about the temperature structure with depth in the eddies, as well as provide another measure of subsurface rotation. The global oscillations can also yield information on the mean temperature structure with depth, as well as the depth of the whole convection zone.

III. Why Make These Observations from Space?

There are several reasons why the measurements need to be made from an orbiting platform. A prime reason is that the combination of bad weather and night time prevent us from getting the needed continuity of measurements from the ground. We argue this point in more detail below. In addition, differences in local seeing and atmospheric transparency as well as scattered light and short time scale noise of solar origin have made it extremely difficult to intercompare the ground-based observations which have been made, as well as making it difficult to separate what is solar in origin and what is not. This is particularly true of global velocity observations, but is also a serious problem in comparing magnetograph measurements. Luminosity measurements are clearly best made from space, to escape atmospheric scattering and absorption. We discuss the problem with respect to velocity measurements in greater detail, to illustrate the need for intense observations from space.

Progress in making global velocity measurements from the ground has been slow partly because of instrumental difficulties and atmospheric effects, and partly because there is a great deal of noise on the
sun in the form of small scale motions (so called granulation, 5 minute oscillations, and supergranulation) which have larger amplitude than the global motions. Some of these difficulties may be overcome by improvements in ground based instrumentation, but others can be surmounted only by making frequent measurements from an orbiting platform.

We estimate that to resolve the velocities of global eddies, we need a basic measurement accuracy of between 1 and 10m/sec (a Doppler shift $\Delta \lambda$ of $2 \times 10^{-5}$ to $2 \times 10^{-4}$ $\AA$ at $\lambda = 6000$ $\AA$). This precision can be obtained only by use of a wavelength reference against which to measure the doppler shift of the solar spectral line chosen. Otherwise various instrumental drifts mask the solar signal. Such reference techniques are currently being developed but have not been proven yet.

To reduce the small scale solar noise, the whole disk of the sun must be observed much more rapidly than is done by current systems. We estimate the time interval between observations should be no more than about 1 minute and preferably much less in order to average out the well-known 5 minute solar oscillations, requiring the use of some sort of "panoramic detector" which views the whole sun essentially at one time.

Averaging together observations made at 1 minute intervals over periods of 30 minutes to 1 hour should reduce the short time scale noise to the point that more persistent velocity patterns are evident. However even this is not enough, because the resulting patterns will probably be dominated by supergranules which last up to a day or two. To suppress these patterns and highlight the global eddies, we can average spatially, or take advantage of the fact that due to solar rotation supergranules move a distance equal to their own diameter across the solar disk in a few hours (4 hrs at the equator, longer at
higher latitudes). Thus by averaging over a few consecutive orbits supergranule velocities can also be reduced, though not eliminated. Then by comparing successive averaging periods, we can pick out the global velocities, which should not be cancelled out by the averaging process.

Comparison of velocities on successive days even with all of the averaging will be difficult because of residual noise and the rotation of the sun—more frequent samples are necessary. We need an essentially continuous record of averaged velocities, either as a succession of averages, or as a running average. In either case, this is achievable only from orbit, since night and bad weather prevent it from the ground. From the ground, observing runs long enough to largely cancel out supergranules would be achieved only occasionally.

Of course, new difficulties are introduced by going to space. For example, the velocity of the orbiting platform must be known to within a few meters per second, so it may be subtracted out, and stability of the instruments must be achieved.

Why a long term mission or series of missions?

The obvious answer to this question is that we are looking at the global dynamics of the sun over the course of a solar cycle, so we need to observe the sun that long. On the short time scale end, we expect changes on a time scale of a month or two, since that is a reasonable estimate for the turnover time for the entire convection zone. Furthermore, the basic rotation rate of the sun can be defined unambiguously only by averaging over at least one rotation (about 27 days). Over shorter times, a doppler rotation signal can not be distinguished unambiguously from other east-west motions of broad longitudinal extent. It is the changes in rotation, global eddies, magnetic fields, and intensity patterns from
one rotation to the next, over the solar cycle, which are crucial to gaining an understanding of the workings of the solar dynamo. Therefore the space shuttle would be an inappropriate platform on which to make synoptic measurements, since observing would be limited to at most a few periods of one to two weeks per year. A free flying satellite, perhaps serviced periodically from the shuttle, would be far more appropriate. However, the shuttle could be very useful for test flights of some instruments, as well as for certain supporting measurements.

Observational requirements

As already indicated, we would like to achieve 1-10 m/sec accuracy in doppler velocities, with sampling rate fast enough to average out 5 min oscillations. Horizontal resolution should be \( \approx 15 \) arc sec. But to study the oscillations themselves, we need to use all the data at a sampling rate of every 10 seconds or so. Ideally, we would like continuous observing runs of several days (possible with a high inclination orbit) in order to resolve finer differences in frequencies between waves. However, by suitable use of "apodizing functions" on data which is periodic gaps due to the orbit, such long strings can be put together with only modest loss of accuracy.

Magnetic fields need not be measured quite as often as velocities, but certainly at least once per orbit, to an accuracy of a few gauss, with spatial resolution of less than 10 arc sec if possible, since the magnetic field has so much fine structure. For intensity and luminosity measurements, we should aim for relative accuracy of .1%.

Supporting observations and theory

There are several observations related to those above, some to be made from space and some from the ground, which also need to be made. A
particularly important one is the measurement of correlations between velocity and intensity, to very high spatial resolution (∼1 arc sec). Such a correlation is known to exist on the scale of granules, and may vary with time. It is relevant to the global velocity problem because such a correlation, particularly if it is time dependent, can appear like a large scale velocity. Such measurements are possible only from orbit with a high resolution telescope--these might be done periodically on Spacelab using the Solar Orbiting Telescope (SOT).

X-ray measurements of coronal structure, including particularly coronal holes are important for relating the surface magnetic and velocity fields. These are discussed more in the companion SCADM background paper by Holzer.

Both velocity and magnetic field observations should be done from the ground, for purposes of comparison for accuracy, as well as providing coverage if the satellite measurement system should malfunction at certain times.

To compare with solar velocity, oscillations, magnetic field and intensity measurements discussed above the relevant theory must be developed much further than it has so far. In particular, global convection and dynamo modeling must take into account compressibility, as well as small scale turbulence. Dynamo interactions between velocity and magnetic fields on smaller spatial scales will also need special attention. Global oscillations theory should be pushed to its limits, to see how deep into the convection zone information can be obtained, and to see how local the diagnostic inferences can be made.