PROBLEMS OF INTERIOR STRUCTURE, THE SOLAR DYNAMO
AND THE ROLE OF SCADM IN PROVIDING INTERIOR DIAGNOSTICS

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1. INTRODUCTION

The last ten years have seen an explosive increase in high-resolution observations of solar magnetic fields—from ground-based observatories and from space, in the visual, infra-red and X-ray ranges. Small scale magnetic fields, global oscillations, X-ray bright points and coronal holes have all been discovered. For the first time we are able to see the fine structure of magnetic fields at the surface of the sun and this tantalising wealth of information leaves me feeling that a decent understanding of solar magnetism can be attained within the next decade. Theory too has also made considerable advances, though it still lags behind the observations. As E. N. Parker has told us, "Nature is far more inventive than we are." Nevertheless, I remain optimistic. Turbulent behaviour is difficult to describe but I believe we shall discover how to pose questions that can be answered with sufficient precision to allow us to explain the weird behaviour of magnetic fields in the sun. It is reasonable to expect that the next ten to twenty years will produce an adequate theory of the solar cycle (which seems to me the principal problem of solar physics) and its relation to activity at the photosphere.

Dr. Noyes has already mentioned some aspects of our understanding of the sun's structure, of motion in its convective zone and of the solar cycle. In this review I shall attempt the difficult task of outlining what we know, what we do not know and what we would like to know. We naturally hope that SCADM will answer these last questions but I shall leave it to Dr. Brown to distinguish between those observations that are best made from the ground and those that must be made from space. In the time available I have necessarily to be selective in what I say; so I hope that nobody will be offended by omissions.

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2. **SOLAR VARIABILITY**

We seem to prefer to assume that the sun is immutable or if it varies, that the variations must be regular. Thus the variability of the solar cycle has only been accepted with reluctance. In fact one should expect the solar dynamo to oscillate irregularly; even simple nonlinear systems show aperiodic oscillations, characterized by the presence of "strange attractors" which are currently a fashionable topic for mathematicians to investigate. Looking back over sunspot numbers we can see a glitch around 1800 and, of course, the Maunder minimum in the seventeenth century. The record can be extended by using anomalies in C\textsuperscript{14} abundance, which are correlated with the envelope of solar activity. The Maunder minimum, the Spörer minimum of the sixteenth century and the grand medieval maximum are typical of a pattern of behaviour that has prevailed for the last 7000 years and so, presumably, for most of the sun's lifetime on the main sequence.

There is increasing evidence for fluctuations in the solar luminosity. On a timescale of days, the old APO measurements show increases and decreases in the solar constant corresponding to the appearances of faculae and sunspots. Rocket and satellite observations suggest that the solar constant increases from sunspot minimum to sunspot maximum (though the surface temperature apparently goes down). Long term changes, associated for instance with the Maunder minimum, have been suggested as causes of climatic change on earth.

The sun's rate of rotation also varies slightly with the solar cycle and analysis of early observations indicates that differential rotation was much less during the Maunder minimum. Eddy has recently presented yet more striking evidence for solar variability: measurements of the sun's diameter made at Greenwich from 1840 to 1950 show a slow decrease at a rate of about 0.1% per century. Observations at the Naval Observatory in Washington show a similar shrinking in radius, which is consistent with discrepancies in the description of a sixteenth century eclipse. There may be some different explanation for these results, and the rate of change certainly could not have been maintained for thousands of years. Nevertheless, we must accept that, over its history, the sun may have varied far more than we would surmise from contemporary observations.
3. SOLAR STRUCTURE

For reasons of simplicity nearly all solar models are spherically symmetrical. These models are obtained numerically by evolving a model star of one solar mass from the zero age main sequence for $4.75 \times 10^9$ years and requiring that the present radius and luminosity be reached. Fortunately there are just enough parameters to provide a consistent result. In these models energy is generated by burning hydrogen to form helium (the p-p reaction) at the centre of the sun. This energy is carried outward by radiation for about 70% of the solar radius but the outer part of the sun convects. Current estimates place the base of the convective zone at a depth of about 200,000 km, where the temperature is $2 \times 10^6$K, but this depth is poorly determined.

There are some additional checks. Lithium, which burns at $2.4 \times 10^6$K, is largely depleted at the solar surface, though beryllium, which burns at $3.5 \times 10^6$K, is not. Thus the convective zone cannot be too deep. and must have beneath it a region with slow motions capable of providing some diffusion of Li and Be. In addition, there is the well-known neutrino problem: the lack of neutrinos shows that some part of the conventional picture is wrong, though it is hard to establish where the error lies.

The best prospect of improving our knowledge of solar structure comes from "solar seismology." Geophysicists have identified over one thousand normal modes of the earth, which are excited by earthquakes, and used their frequencies to determine the earth's internal structure. Similarly, the apparently irregular motion of the solar photosphere can be expressed in terms of the sun's normal modes of vibration. The 5-minute oscillations have indeed been shown to be global pulsations, corresponding to acoustic (or nonradial p) modes. Deubner's observations have established the structure of these modes in the $K-\omega$ plane (where horizontal wave-number is plotted against angular frequency) and distinguished between modes with differing numbers of radial nodes. The amplitude of a node peaks at a particular depth (roughly where $\omega/K$ is equal to the local sound velocity) and so the modes can be used to probe the sun's internal structure. Deubner, Ulrich and Rhodes have found excellent agreement between the observations and predicted values for a solar model. More refined observations will yield more precise information about the structure of the convective zone.
Longer period solar oscillations have also been reported, though they are more controversial. Periods up to about 60 minutes (which is the period of the fundamental p mode) have been detected by the SCLERA experiment and Hill has recently shown that phase is maintained for many days. A persistent oscillation with a period of 160 minutes was discovered at the Crimean Observatory and confirmed by groups from Birmingham and Stanford. The precise nature of these modes is unclear but they seem likely to be g-modes (corresponding to gravity or inertial waves). If their spatial variation were established such modes could provide valuable information on the structure of the sun's deep interior.

4. VELOCITY PATTERNS

The solar dynamo depends on the complex interaction between motion and magnetic fields, so a description of the velocity is a necessary preliminary to any understanding of the dynamo. Let me first summarize the observations of rotation and of convective motion. Rotation can be observed by Doppler shifts for photospheric plasma or by following surface tracers. The rate of rotation of magnetic features increases with their size: Sunspots rotate faster than photospheric gas and coronal holes rotate faster than the sunspots. A more precise method of probing subsurface rotation is to utilise the rotational splitting of normal modes. This splitting corresponds to the fact that each mode is localised at some depth (as described above) and reflects the angular velocity at that depth. If the oscillations are resolved into eastward and westward propagating waves, the slight difference in frequency between these waves reflects the variation in angular velocity with depth. Deubner et al. find that the angular velocity increases down to about 15000 km depth but better observations are needed to improve on this result.

At the photosphere we see two discrete scales of cellular convection, the granules (with a diameter of about 1500 km) and supergranules (with diameters of 30000 km). The interactions of magnetic fields with these patterns of motion can be directly observed. There is much evidence, principally from Mt. Wilson, suggesting the presence of larger scale patterns with velocities of order 10 m s\(^{-1}\) and length scales of several hundred thousand kilometres. It is, however, difficult to provide definite proof that such giant cells exist.
Theoretical studies of convection and rotation have made great strides forward recently, largely owing to the simulation of hydrodynamic flows on big computers. It is easy to explain the presence of granules in a boundary layer where all scale heights are small and the ionization of hydrogen takes place. Yet there is still no adequate explanation for the existence of supergranules. On the other hand, all studies indicate that there should be large-scale, energy-carrying convective cells that extend through the full depth of the convective zone, with a characteristic time-scale of the order of a month.

The effect of rotation on these cells has received much attention. The prevailing opinion is that in the equatorial regions cells should be roll-like with axes parallel to the rotation axis of the sun. The existence of such rolls has been demonstrated, both theoretically and experimentally, by Busse. Whether this "cartridge-belt" pattern has been observed in the sun is much more dubious.

Nonlinear convection in a Boussinesq fluid, confined between two rotating spherical shells, has been studied by Gilman in a series of numerical experiments. There is a tendency to form elongated cells in these computations, and the sun's equatorial acceleration can be reproduced. However, the effect of turbulence in mixing angular momentum and angular velocity remains uncertain. Moreover, compressible convection has yet to be properly investigated.

5. MAGNETIC FIELDS

The range of fields observed in the sun has advanced considerably since the time of Hale. As well as sunspots there are active regions and complexes of activity. As resolution has improved smaller and smaller features have been discovered. Over all this range it seems that flux emerging from the photosphere is concentrated into discrete tubes (or ropes) and there is as yet no evidence for the existence of a weaker background field.

Active regions are the best known magnetic features. Their systematic behaviour (emergence in sunspot zones that migrate towards the equator, opposite polarity in northern and southern hemispheres, reversing every 11 years) defines
the solar cycle. Outside active regions, almost all the magnetic flux is contained in the network, which outlines the boundaries of supergranules. When viewed with sufficient resolution, the network itself is composed of small flux concentrations (typically around $3 \times 10^{-17}$ mx, where a maxwell is the unit of magnetic flux and $1 \text{ mx} = 10^{-4}$ Wb). These small scale fields are typically intergranular and make up the filigree which can be observed from the ground only when seeing conditions are exceptionally good.

The above refers only to the instantaneous field configuration. It is important also to follow the emergence of flux through the photosphere and into the corona. Here again there is apparently a continuous spectrum, from active regions ($10^{22}$ mx) down to the limits that can be seen. Smaller concentrations of flux, called ephemeral active regions (EARs), are seen in magnetograms but it is difficult to identify them unambiguously without synoptic coverage. Soft X-ray observations provide a less subjective means of noting flux as it emerges, for the expanding field lines produce enhanced X-ray emission from the corona. These X-ray bright points (XBP) were systematically observed from Skylab and have substantially enhanced our understanding of magnetic fields in the sun. The spectrum of emerging flux peaks towards small scales (the rate of emergence is greatest at $10^{19}$ mx, the limit set by resolution) and more flux emerges on small scales than as active regions. The Harvard/AS and E group finds XBP at all latitudes, with a greater concentration at the equator. Moreover the rate of emergence of flux (as shown by XBP) is greatest at sunspot minimum, as Dr. Davis will explain. The Skylab period included a single event, over the whole solar surface, with XBP associated with the emergence of vigorous activity (this will be described by Dr. Golub). Although magnetograms are essential for any study of solar magnetic fields, soft X-ray images provide important extra information.

Finally, we have learnt more about large-scale fields since 1970. Decaying active regions can form large unipolar regions. Within these regions some field lines are open, extending into interplanetary space. Coronal holes are found to coincide with open field lines, and their relation to interplanetary fields has been intensively studied. In particular, Levine has shown that the magnetic sector pattern can be derived from the large scale structure of smoothed-out photospheric fields.
6. **DYNAMO THEORY**

Despite some attempts to revive the oscillator theory, it is generally agreed that the solar cycle must be driven by a hydromagnetic dynamo in the convection zone. The basic concept of the dynamo has not changed since Parker's original paper. An initial poloidal field is drawn out azimuthally by differential rotation (so producing the field that erupts in active regions). This process is easy to grasp; the next stage, producing a reversed poloidal field from the azimuthal flux, is more subtle. Parker proposed that this be effected by cyclonic eddies with a preferred sense of helicity. Since then, the developments of mean field electrodynamics has yielded a variety of so-called $\alpha \omega$ dynamos based on the combination of helicity (the $\alpha$-effect) with differential rotation. These models reproduce the main features of the solar cycle: the formation of strong toroidal fields that migrate towards the equator and then reverse for the latter half of the cycle. With suitable timing, a plausible butterfly diagram can generally be obtained.

The success of these kinematic models, where the velocities are prescribed, has led to some exaggerated claims. The fully magnetohydrodynamic dynamo problem, including the forces exerted by the fields themselves, is much more difficult and work on it has only just begun. Within the last few months Gilman has included magnetic fields in his numerical experiments and obtained dynamo action—but the details are very different from those envisaged in mean field electrodynamics. That theory relies on approximations which cannot be justified for motion in the sun; so the results, though qualitatively valuable, are not reliable in detail.

Theoretical studies of vigorous convection in a magnetic field show that magnetic flux ends up confined to ropes at the boundaries of convection cells and this result accords with the discrete flux ropes found at the surface of the sun. Any accurate treatment of the solar dynamo therefore involves the interaction between these flux ropes and the convective motion. This poses a formidable theoretical problem, where observations can offer valuable guidance.

An alternative picture of the solar dynamo is that the main effects occur at the base of the convective zone, where convection is less vigorous and the fields...
can be more diffuse. There the interaction depends critically on the effects of magnetic buoyancy, which has not yet been incorporated in any nonlinear calculation. From the theoretician's point of view, the dynamo problem remains as difficult as ever. We need guidance from observations, as well as access to Crays and other large computers. Still, I am confident that the problem can eventually be cracked.

7. WHAT WE NEED TO KNOW

The observations we need are listed below. Some of these may be made from the ground but many, as Dr. Brown will show, can only be obtained from space.

Global properties: The solar luminosity ($L_\odot$) and radius ($R_\odot$) must be measured precisely, so that variations of order $10^{-3} L_\odot$ over a period of 11 years can be detected. Experimental checks on the apparent shrinking of the solar radius are also needed.

Oscillations (p and g modes): Precise measurements are needed for periods from 1 minute to at least 160 minutes. We need enough precision to resolve individual modes of the 5-minute oscillations and to confirm (hopefully) the reality of the long period oscillations. For the latter it is also essential to establish spatial structure so that the modes can be properly identified.

Velocities: Variation of rotation with time can be observed directly; variation with depth must be derived from the 5-minute oscillations. Large scale meridional circulations (reported by Beckers) and patterns corresponding to giant cells require observations with an accuracy of at least $10$ m s$^{-1}$, extending over several months.

Magnetic fields: The fields in active regions and the network must be mapped in detail and related to the patterns of large scale motion. (For this purpose it is not necessary to resolve the fine structure of intergranular fields.) This requires synoptic coverage from magnetograms. At the same time, X-ray observations are needed to detect emerging flux and large scale structures.
In summary, continuous observations with sufficiently high resolution are needed in order to reveal the relationship between magnetic and convective structures. Such a program requires a combination of ground-based observations with others made from space. This overall program should cover a whole 11-year cycle. In particular, it is important to be ready by sunspot minimum (not later than 1985). Experience from Skylab shows that much more can be learnt when fields are relatively simple—for instance, the famous coronal hole could never have appeared at sunspot maximum. Further, the Skylab period covered a unique event which lasted for six months. In order to establish whether this behaviour is typical it would be necessary to maintain magnetograph and X-ray observations for about two years.

So we need to have a grand collaborative program. Theoreticians and observers must work together to define objectives and understand results. Careful planning is needed to isolate those observations that must be made from space with SCADM. Moreover, a sustained commitment from the whole solar physics community is needed to ensure success. I believe that the scientific gains would amply justify this effort and I hope it will be made.
QUESTIONS AND COMMENTS

COMMENT BY:  J. H. Thomas, University of Rochester

DIRECTED TO:  N. Weiss

You mentioned the importance of possible variations of the Sun's radius. In addition to the long-term decrease in solar radius discussed by Jack Eddy, there is the possibility of a cyclic change in solar radius over the solar cycle which I discussed in my paper yesterday (session on Solar and Stellar Variability - see abstract in these proceedings). SCADM offers an excellent opportunity to determine whether such a variation of radius with solar cycle does occur. Ground-based measurements of the absolute solar diameter are plagued by differential refraction, seasonal variations, and other atmospheric effects; thus, space measurements are particularly desirable. The solar luminosity, radius, and surface temperature are intimately related; it seems to me we need to monitor all three quantities to understand solar variability.