RELATIONSHIPS BETWEEN SOLAR AND STELLAR MAGNETIC FIELDS

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ABSTRACT

Observational and theoretical studies of solar and stellar magnetic fields are reviewed. The discussion draws together several themes that emerged during IAU Symposium 102 on "Solar and Stellar Magnetic Fields: Origins and Coronal Effects," and identifies a number of areas in which research over the next few years is likely to be fruitful.

1. INTRODUCTION

In July, 1908, George Ellery Hale, working at Mt. Wilson, demonstrated that the observed splitting of some of the spectral lines in sunspots is due to the Zeeman effect. This discovery represented a turning point in the study of solar physics, since it showed for the first time that magnetic fields played a role in solar activity.

Before Hale's discovery there had been many studies of the interrelations between the various manifestations of solar activity, but there was no unifying concept and theories were thus highly fanciful. Since the time of Hale's work it has become increasingly clear that magnetic fields play a dominant role in many solar phenomena, and much of contemporary solar physics is devoted to the observational and theoretical study of magnetic fields and their consequences.

One of Hale's reasons for founding the Mt. Wilson solar observatory was "the investigation of the Sun as a typical star". However, in the decades that have passed since the discovery of solar magnetic fields, the promise of a fruitful synergy between solar and stellar physics has never been fully realized. There has been a tendency for stellar studies to concentrate on abundances and evolution, while solar studies have tended to concentrate on activity and "meteorology." It was known that some stars possess magnetic fields, but these were thought to be somehow different from those of the Sun. On the other hand, while it was suspected that solar-like phenomena did occur on other stars, there was

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no way to study them, and consequently they were viewed as being unimportant. Recent observational studies of stellar chromospheres, particularly those undertaken by Olin Wilson at Mt. Wilson, have demonstrated the widespread occurrence in many stars of phenomena that were previously viewed as being of interest only to solar physicists. It is clear that a new phase of solar-stellar research has begun, in which the main unifying theme is the physics of magnetic fields in stars. This Symposium provided a timely opportunity to discuss what is known of this subject at present, and to define some of the important questions that remain to be answered.

This summary does not attempt to provide a detailed commentary on the previous contributions: they speak for themselves. Rather, it seeks to provide an account of the background research that has led to the present picture that we have of magnetic effects in the stars, with a special attempt to describe the logical (and not so logical) connections between key concepts. I believe that much can be learned by carefully following the development of "patterns of thought" in a discipline that is evolving as rapidly as the topic of this meeting.

The paper first reviews basic observational data for both the Sun and the stars. Then it discusses the two central theoretical problems that have been exposed during this Symposium: (i) the influence of magnetic fields on atmospheric structure, and (ii) the origins of solar and stellar magnetic fields. The paper concludes with an assessment of some promising directions for research over the next few years.

2. OBSERVATIONS OF SOLAR ACTIVITY AND MAGNETIC FIELDS

Prior to Hale's work at Mt. Wilson, there had already been a great deal of work done to characterize the nature of solar activity. Early work on sunspots had revealed their changeability, and the motion of sunspots across the solar disk had been used to determine the solar rotation rate and to demonstrate the presence of differential rotation. The existence of a solar cycle was recognized, and the systematic migration of the birthplaces of sunspots towards the equator during the progress of the cycle had been studied. Solar flares had been seen on a few occasions, and it was suspected that there was a connection between solar activity and terrestrial phenomena such as aurorae and magnetic disturbances. There was intense interest in expeditions to study the chromosphere and corona during solar eclipses.

In the latter part of the 19th century, advances in instrumental design led to a growing number of studies of the detailed structure of the solar atmosphere. The manufacture of superb high resolution gratings, combined with the application of photography to astronomical observations, led to remarkable advances in the quality and spectral purity of images of the Sun. These advances were particularly evident after the invention of the spectroheliograph, which allowed detailed studies to be made of the chromosphere, both on the disk and above the

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limb. It was apparently the observation of "vortices" in H-alpha with this instrument that led Hale to suspect that electrical or magnetic forces could be important in sunspots, and this prompted his Zeeman effect studies.

For three decades following Hale's work, observational studies of solar magnetic fields were devoted to discovering properties of the gross relationships between magnetic structure and activity. The polarity laws of active regions were discovered, and the basic 22-year cycle was identified. A great deal of effort was expended in attempts to measure the global (dipole) field of the Sun, apparantly in the belief that such a field would help to explain coronal structure (polar plumes) and possibly to establish a connection between solar and terrestrial magnetism. With hindsight, it can now be seen that that this effort was probably not focussed on a critical problem, and even today the significance of observations of solar magnetic fields made on a global scale is not clear.

It is worth noting that the main thrust of solar reseach in this period was not towards the study of magnetism and activity, but rather towards the study of gross photospheric structure and abundances (e.g. Minnaert 1953). The development of quantum mechanics, and a growing interest in the interpretation of the Hertzsprung-Russell diagram in terms of stellar evolution, seem to have been responsible for this particular focus of solar physics. A similar emphasis on photospheric structure and abundances has occupied stellar physics until very recently. One might suspect that this emphasis will be redirected over the next few years, into areas that lie closer to the central themes of contemporary solar physics. Instrumental capabilities naturally played an important part in determining the course of research in these areas. For example, the limited sensitivity and inconvenience of photographic techniques for measuring magnetic fields, combined with the poor resolving power of the solar telescopes of the time, retarded work on activity and magnetic fields in the first half of this century. Only now are the instruments becoming available to study the related phenomena in stars.

A new era of research on solar magnetic fields and activity was born in the 1940s, when narrow-band filters were applied to the study of evolutionary aspects of activity, and photoelectric methods were applied to the measurement of polarization in spectral lines. The seminal discovery in this period was the recognition of the extremely high temperature of the corona and chromosphere. This discovery revolutionised concepts regarding the basic physics of astronomical gases, and can be identified as the beginning of "high-energy astrophysics." Another important advance in this period was the introduction of "patrol" observations of solar activity. By the mid-1950s, the photoelectric magnetographs at Mt. Wilson had been developed into quite sensitive instruments, and they were used in studies of the detailed correlations between plages and magnetic fields, and of the large scale organisation of the solar magnetic field into bipolar and unipolar regions (e.g. Kiepenheuer 1953; Babcock and Babcock 1955; Howard 1959). The comprehensive review by de Jager (1959) summarizes the results of this

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work, and vividly illustrates the depth of knowledge 25 years ago.

The advent of space-borne instrumentation opened a new vista on solar activity. Gradually, this new way of exploring the outer parts of the solar atmosphere reinforced the belief that magnetic fields are the prime driving force behind most of the phenomena seen in the solar atmosphere. **Skylab** observations were particularly influential in triggering awareness of the importance of magnetic fields (see Vaiana and Rosner 1978). A singularly important observation from this era was the detection and study of coronal holes, since these provided new insight into the connections between solar magnetism and the solar wind (Zirker 1977). I must confess to the feeling that there has been an overemphasis in recent years on the magnetic aspects of solar atmospheric structure and heating. This has been prompted in particular by an almost universal chorus among space observers of the theme that the corona is composed of only two basic structures, loops and open-field regions. It is not clear to me that this kind of description of the corona focusses on a fundamentally important property (after all, it is hard to imagine a topology that contains other kinds of structures and still remains quasi-stationary), and such a description is probably so simplistic that it hinders the development of theoretical ideas.

A more illuminating description of coronal structure should add to the present emphasis on **global topology** (open versus closed) a characterisation of coronal structure using another parameter that measures the **local importance** of magnetic fields (a suitable parameter might be the ratio of magnetic to gas pressure, or a measure of the magnetic free energy). Such a parameter describing the local importance of the coronal magnetic field is not presently available because there is no way to measure accurately the coronal magnetic field. It is reasonable to expect that theoretical ideas regarding the role of magnetic fields in the corona will change when methods for measuring the field in situ become available and are widely applied. It will be interesting to discover whether there exist large volumes of the corona in which the magnetic field plays only a secondary role, just as it appears that magnetic fields are not particularly important in most parts of the photosphere.

Many important observational discoveries made over the past 20 years have resulted from major improvements in the spatial resolution of ground-based telescopes, combined with improvements in the stability and sensitivity of focal-plane instrumentation. As the sensitivity and spatial resolution of magnetographs has improved, the intimate correlation between photospheric magnetic fields and chromospheric fine structure has become ever clearer. A study of special significance in this connection was undertaken by Skumanich, Smythe, and Frazier (1975), who showed that there is a **linear** correlation (with some scatter) between the K-line intensity and the "magnetic field strength" on scales as small as 2.4x2.4 arc sec. This result represents a key link between solar and stellar observations, and it is important to note the caveat that the magnetic quantity measured in this study is an "equivalent field representing the total flux" and is **not** an actual field strength.

The discovery of supergranular velocity cells and their relation to magnetic fine structure and the chromospheric network provided the first evidence of a connection between convection and magnetic structure. The importance of this connection has been reinforced by studies of the filigree and other fine-scale structure discussed by Tarbell at this meeting. However, it must be emphasized that many of our concepts regarding the physics of the fine-scale magnetic structure are based on inferences and educated guesses about processes that occur on scales too small to be studied with contemporary instrumentation. For example, with only a few exceptions, the information that we have regarding the fine-scale structure of the solar magnetic fields is based on indirect methods that exploit low-noise observations made with magnetographs that do not resolve the magnetic structure (Stenflo 1973). It is inevitable that new telescopes (such as SOT) will show that the picture we have today is severely "blurred" by the observing methods we have been obliged to use.

If progress is to be made in quantitative magnetic studies, futher work must be done in the area of spectroscopic diagnostics. There is an extremely complex relationship between the structure of three-dimensional solar magnetic fields and the polarisation signature they impress on spectral lines. Methods used today to unravel this relationship are crude, and lead to major errors in interpretation. For example, several discussions at this meeting have confused the terms "magnetic flux" and "magnetic field strength." The main reason for this probably lies in the inability of modern magnetographs to provide unambiguous measures of one or other of these quantities. Clarification of the relations between these two properties would represent a valuable contribution to the understanding of solar magnetism, and it is disappointing to note how little is being done in this area.

The development of extremely sensitive and stable magnetographs has led to new discoveries and clarifications of the nature of the large-scale structure of solar magnetic fields. In particular, the torsional oscillation discussed in this volume by Howard and LaBonte is evidently a manifestation of a fundamentally important process in the solar cycle. Observations of this kind, concentrated on the large-scale, slowly evolving aspects of solar magnetism and activity, require a dedicated, synoptic observing program. The astronomical community must support programs of this kind, despite pressures for rapid results and limited efforts. A related kind of research program involves the investigation of the evolution of solar activity over very long time scales. In this field, Eddy's work on the Maunder Minimum has provided a strong stimulus to attempts to determine the variation of solar activity over many cycles. The remarkable historical survey by Xu and Jiang (1982) which recovered 32 previously "lost" sunspot sightings during the years 1603-1665, combined with their arguments concerning the destruction of records during the Boxer rebellion, throws open the entire question of the reality of the Maunder Minimum. It is clear that painstaking work will be required to characterize the nature of solar variability on time scales longer than those covered by reliable historical records.

3. OBSERVATIONS OF STELLAR ACTIVITY AND MAGNETIC FIELDS

The observational search for stellar analogues of solar magnetic activity is extremely challenging. Direct observations of stellar magnetic fields are hard to make, and until very recently most detections referred to A and F stars. At the present Symposium, the physics of such "magnetic A stars" has not been discussed (see Cameron 1967 for a review), apparently because it is generally felt that there are fundamental differences between the magnetic fields in these objects and those in solar-type stars. However, it might be unwise to view the magnetic A stars as a distinctly different class of objects. The basic difference between the magnetic fields of these stars and those of "solar-type" stars is that the magnetic A stars possess a marked global magnetic field, while the solar-type stars are characterised by strongly inhomogeneous fields. However, it is quite possible that the magnetic A stars do have an inhomogeneous field that is hidden from current observing methods by the global field, and on the other hand it is well known that the Sun exhibits large unipolar magnetic structures reflecting organization on a global scale. There are some intriguing similarities between the two kinds of stellar magnetism (including irregular variability, changes in photospheric structure, and possibly coronal effects), and a closer examination of the magnetic A stars might provide some important insight into the possible forms of stellar magnetic activity. If the evidence for a rapidly rotating magnetic solar core continues to accumulate, the connection between solar magnetism and the magnetic A stars will assume even greater importance.

The magnetic fields of magnetic A stars can be studied directly by analysing the circular polarisation of Zeeman-sensitive lines, since the global fields impose a strong signature on the line profiles. The magnetic fields of solar-type stars are much harder to study, because the mixture of almost equal areas of positive and negative polarity in relatively small active regions implies that the Zeeman splitting of magnetically sensitive lines cannot be detected by an analysis of circular polarization. Recently, however, the measuring techniques reviewed by Marcy in these proceedings have been applied to late-type stars, and some direct detections of magnetic fields have been reported. While the importance of such direct detections of stellar magnetic fields must not be underestimated, the method will not yield much reliable quantitative data without a breakthrough in instrumental sensitivity and (possibly) in basic technique. It is important that the observers who are applying this method constantly remind the theoreticians who use their data that the measurements do not provide reliable quantitative information.

Because of the limited possibilites for direct measurements of magnetic fields on cool stars, almost all of the information that we have regarding stellar magnetic activity on such stars is based on observations of "activity indicators," such as those reviewed by Zwaan in this

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volume. The principal indicator in use at present is the H and K flux parameter, which was used by Olin Wilson at Mt. Wilson in his pioneering studies of stellar chromospheres. In an early paper on this technique, Wilson (1968) justifed his research on the grounds that "it is a reasonable supposition that if analogous cycles could be detected in other stars with different values of the fundamental stellar parameters, the results would be of considerable value in sharpening the theoretical attack on the whole problem". Without the dedication and foresight displayed by Wilson, some of the critical data that is used today would not yet be available.

The Mt. Wilson H and K flux program, described in this volume by Vaughan, has made important discoveries in several areas, including (i) the delineation of the star-to-star variation in H and K fluxes across the cool part of the H-R diagram, (ii) the detection of stellar activity cycles, and (iii) the determination of stellar rotation rates and the gross structure of stellar active regions. Some aspects of these discoveries will be discussed below.

A number of important effects combine to produce the observed star-to-star differences in H and K fluxes. Some of the differences are undoubtedly due to variations in the degree of chromospheric activity. It is important that extensive, long-term studies be made in an effort to characterise the maximum amplitude and time scale of variations of this kind. Another component of the star-to-star variation is due to the fact that the Mt. Wilson H and K photometer measures a quantity that is not a "pure" indicator of the degree of chromospheric activity. In the hotter stars, for example, there will be an important "photospheric" contribution to the line fluxes: the precise calibration of this factor will require a dialogue between theoreticians who construct radiative equilibrium models of stellar photospheres, and theoreticians who carry out non-LTE diagnostics of the H and K lines. In the cooler stars, the calibration of the H and K index in terms of the adjacent continuum bands becomes uncertain, since the continuum becomes heavily blanketed by spectral lines. In intrinsically luminous stars, the H and K emission width exceeds the pass-band of the Mt. Wilson spectrophotometer, and the measured fluxes are thus less reliable indicators of the degree of chromospheric activity.

Despite these diagnostic difficulties, observations of stellar H and K fluxes exhibit a number of intriguing tendencies. Among the main sequence stars, there is a wide range in H and K flux for a given spectral type. It is observed that the emission strength depends on the age of the star, or its rotation rate, or both (Wilson 1963). It would be a particularly valuable contribution to theoretical work in this field if observational desiderata were available to separate the age and rotation factors. This is not easy, since indicators of stellar age are not very accurate. Moreover, there is a clear correlation between age and rotation period, and it may be impossible in practice to separate cleanly their respective influences on the H and K line fluxes. Among the giant stars, H and K emission is widespread, but more work is required to quantify the star-to-star variation in terms of stellar type, class, and evolutionary status. The study of H and K fluxes in binary systems is also instructive, since the stars presumably have identical ages. The relation between H and K strengths and evolutionary stage can thus be studied, although one must always be suspicious of the possibility that the chromosphere of the star in question is somehow influenced by the companion star.

Wilson's (1978) report on the nature of stellar activity cycles provides a fascinating first glimpse into the range and possible forms of variability of stellar chromospheres. The connection between these stellar cycles and the solar cycle is immediately clear, but we should be cautious in reading too much into the very limited information we have on the activity of the stars and of the Sun. For example, it is quite possible that over relatively short (in cosmic terms) time scales, the range of cycle morphology exhibited by the stars in Wilson's sample is duplicated by variations in the form of the solar cycle (one has only to review the evidence of palaeomagnetic variations to be struck by the absence of stable patterns in magnetic cycles). It is not known whether or not there are episodes of intensified activity in the past history of the Sun that could be related to a changed cycle morphology such as that seen in the stars above the "Vaughan gap." Furthermore, there is a distinct possibility (discussed below) that there is not a linear, or even a one-to-one relation between the measured H and K flux and the presumably more fundamental parameter -- the total magnetic flux. Attempts to reproduce quantitatively the forms of the cycles seen in the K-line fluxes may fail unless the possibility of a non-linear and perhaps multi-valued relation between K-line flux and magnetic flux (or field) is included in the theory.

The detection of rotational modulation of the H and K fluxes in a number of cool main sequence stars provides a reliable new method for measuring stellar rotation periods. This will provide important data for studies of the rotation-activity connection. Furthermore, detailed studies of flux changes made with adequate time resolution will reveal important properties of the physical organization of active regions on the stellar surface. This kind of study will prove to be particularly rewarding if it finds that different kinds of stellar active regions (depending on size, magnetic configuration, and degree of maturity) have different spectrophotometric signatures. If these can be measured, and calibrated by solar observations, we will be able to learn a great deal about the influence of magnetic fields on the structure of stellar active regions. Noyes has discussed these possibilities further in his contribution to these proceedings.

In fact, observations of other signatures of stellar activity already provide some insight into the structure of stellar active regions. At the present time, the main signatures that have been exploited (in addition to H and K) are (i) starspots and related variations of broad-band fluxes; (ii) He 10830 and to some extent H-alpha , both observed from the ground; (iii) the UV spectrum from Ly-alpha to the Mg II resonance lines, observed mainly with IUE; and (iv) the X-ray spectrum from 0.2 to 3.0 keV, observed mainly with the Einstein satellite. Other instruments and other parts of the electromagnetic spectrum have also been used.

Starspots have long been recognised by the presence of rather regular modulation of the light-curve of BY Draconis and RS CVn stars. Observations of stars with spots provide important data on the size, life-time, and physical properties of the dark regions. New techniques reviewed by Vogt (1981) can reveal details of the shape and position of spots on the stellar surface.

Ground-based observations of He 10830 show a remarkable variety of line profiles, and some perplexing time variations (e.g. Zirin 1975; O'Brien and Lambert 1979). Although controversy surrounds the interpretation of He absorption or emission, it seems probable that in main sequence stars, at least, the He spectrum is photo-excited by soft X rays from a corona. In this case, the He observations can be used to infer the presence of a corona, and to study the coronal evolution by proxy. In luminous stars it is not clear at present how the He absorption is formed, although it is evident that it requires temperatures in excess of radiative equilibrium values. Unfortunately, He 10830 lies in a heavily blended part of the spectrum, but despite this the greater flux at this wavelength favours He over H and K as a chromospheric-coronal diagnostic in cool stars. H-alpha has provided a good deal of the information we have on the solar chromosphere, and it is likely that a concerted study of this line in other cool stars would give valuable information on stellar chromospheres.

The IUE satellite has revealed a number of important properties of chromospheres of late-type stars. As emphasized by Linsky in this volume, a vital clue to the structure of stellar active regions is provided by the studies that show that the ratio of two line fluxes (say, Mg II to C IV) depends on the absolute level of activity measured, for example, by the surface flux in one of the lines. This result shows that active regions exhibit collective effects, and cannot be regarded as composed of a conglomeration of "elementary" active structures with a universal spectral signature. This result is not surprising, since solar studies show that the "activity" in network regions, in plages, and in sunspots, is not characterized only by a linear superposition of elementary structures. This discovery has the unfortunate consequence that it complicates the procedures that might be used to unravel the various factors that control the strength of activity indicators in flux spectra. These factors include (i) the area covered by the active regions, and (ii) the "intensity" of the active regions. Moreover, it strongly implies that there is not necessarily a simple correlation between the H and K flux and quantitative measures (such as flux or field strength) of the magnetic field.

The detection of X-ray emission in a large sample of late-type stars by the Einstein satellite represents an important step in the study of stellar activity. The results and implications of this work have been reviewed in this volume by Vaiana. There is a widely held view that stellar X-ray emission provides very firm evidence not only for the existence of a stellar corona, but also for a **magnetic** origin of the emission. Presumably, this view has been reinforced by the growing acceptance of the idea that magnetic processes determine the energy balance of the solar corona. However, while such an agument is appealing in the context of main sequence stars, I find it less compelling in intrinsically luminous stars. Perhaps such stars have magnetic fields that can excite stellar coronae, or play a role in mass loss, but one would be more comfortable if the theoretical edifice being erected on this hypothesis were based on firmer foundations. A direct detection of magnetic fields in such stars would be extremely convincing, but this is a remote possibility. It seems more probable that observations of flare-like events, or time dependent phenomena that could be related to active region changes, will provide the kind of evidence that we seek. Observations in X rays or at radio frequencies would be useful in this context, since they are more sensitive to transient activity than are the usual chromospheric indicators.

This brief review of the observational aspects of stellar activity would be incomplete without a mention of the "transition locus" in the H-R diagram between solar-type stars with a hot corona and low-mass winds, and luminous stars with cooler outer atmospheres and high-mass winds. The exact nature of the dividing line between these two classes of stars is not yet clear, and in fact, there are "hybrid" stars that fall between them. The analogy between this division of stellar types and an apparently similar difference between solar active regions and coronal holes suggests an explanation of the dichotomy in terms of differences in stellar magnetic field configuration. Several theoretical papers at this meeting have explored this question. Again, however, one would feel more secure if there were firmer evidence for the existence of significant magnetic fields in the atmospheres of late-type giant stars.

4. THEORIES OF MAGNETIC EFFECTS IN STELLAR ATMOSPHERES

Magnetic fields influence the structure of stellar atmospheres in many ways. One crude classification of these influences divides them into those that change the mass distribution in the atmosphere (pressure and velocity) and those that change the energy distribution (temperature). Of course, these two aspects cannot be clearly separated, but it is nevertheless convenient to discuss their physics from these two points of view.

4.1 Mass Balance

Magnetic fields in the solar photosphere appear almost always to exist in a form of magnetostatic equilibrium, as described in the contribution by Spruit in this volume. Essentially, the gas pressure inside the almost vertical magnetic structures is reduced, and the horizontal pressure of the surrounding non-magnetic region is partially balanced by

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magnetic pressure. An important question regarding this configuration is why the gas pressure inside the magnetic structure is lowered. The answer is not known, although a plausible suggestion involves the inhibition of heat flux into the magnetic region, with a consequent lowering of the temperature and decrease of the pressure scale height. However, there are several arguments suggesting that such a configuration is unstable. If the degree of inhibition depends on the size of the magnetic structure, it would be possible to explain the observation of the existence of an ordered sequence of photospheric magnetic structures, characterized by one dominant parameter, the total flux in the structure (Frazier 1978).

In the solar chromosphere the filamentary structure seen in H-alpha, Ly-alpha, and other lines strongly suggests the existence of a filamentary magnetic field. It is tempting to postulate that the chromospheric filaments (or fibrils) are individually connected to a discrete magnetic "knot" in the photosphere, but this is probably not the case. Attempts to discover such a connection have been unsuccessful (e.g. Dunn and Zirker 1973), and it is likely that the filamentary appearance of the chromosphere is due to the fact that the chromospheric magnetic field guides the velocity patterns, without necessarily being composed of discrete tubes.

The existence of loops in the solar corona points to magnetic control of the distribution of matter. Presumably, much of the corona lies in a configuration close to magnetostatic equilibrium, so that the sum of gas pressure and magnetic pressure is approximately constant. In this case, since the loops are regions of high pressure (high temperature and possibly high density), they will be regions with relatively low magnetic field. This conclusion is perhaps counter-intuitive, and it is important to make accurate measurements of coronal magnetic fields, both inside and outside loops. It is also of considerable importance to study the velocity field in coronal loops, to test whether dynamical forces can be important in controlling the mass distribution. Magnetic fields are obviously involved in the difference between closed regions and coronal holes, but it is not yet clear whether the main effect of the magnetic field in a hole is to force the outflow to diverge, or to modify the local energy budget through changes in the heating mechanism or heat transfer processes. As emphasized by Hartmann in this volume, this is an exciting area of research, since there is a growing body of evidence that suggests that magnetic fields play an essential role in the winds from a large variety of stars.

It seems reasonable to conjecture that processes akin to the solar phenomena described above are operative in stellar atmospheres, and that similar magnetic distortions of the mass distribution do occur. If this is the case, we can infer that photospheric field strengths will increase down the main sequence, in parallel with the increase in photospheric pressure, while any fields in the photospheres of low gravity stars will be much weaker than those on the Sun. The latter fact suggests that convective motions (which are more vigorous in luminous stars) will have a very strong influence on any magnetic structures existing in giant stars. Note that while it might be possible to make some reasonable suggestions about the field strengths encountered in stars other than the Sun, it is impossible to make corresponding statements about the total fluxes that might be found in magnetic elements on such stars. It is thus not possible at this time to discuss important questions such as the relative importance of sunspot-like and plage-like structures in other stars.

Since we have such a limited understanding of the factors influencing the magnetic field configuration of the solar chromosphere and corona, it is hard to make plausible suggestions regarding field configurations in other stars. For main sequence stars, there is some evidence that the more active objects have plage-like chromospheric components that essentially cover the entire star, and inferences based on scaling laws for magnetic loops (see the contribution by Golub in this volume) suggest a similar blanketing by coronal loops in very active stars. It seems clear that once the surface coverage by magnetic fields becomes larger than, say, 50%, the entire stellar atmosphere will have to adjust to this fact, and extrapolation from the Sun may then give a false picture. In stars with low surface gravity, the pressure scale height can be as large as the stellar radius, and in this case a magnetostatic structure will be enormously extended.

4.2 Energy Balance

As discussed above, the inhibition of energy transport in the deeper layers of a photospheric magnetic element seems to be an important factor in intensifying the field strength. Spectroscopic studies of sunspots and pores show that the photospheric velocity field corresponding to granulation in the quiet photosphere is indeed suppressed, in accord with the theory, although it is not clear that motions on unresolved spatial scales are similarly inhibited. In fact, there are many unsolved problems regarding the nature of the processes that modify energy transport in and near sunspots (Wilson 1981).

While it appears that magnetic fields act to inhibit the flow of energy in the deepest parts of the photosphere, this tendency yields rapidly to the extra heating evident in the magnetic parts of the upper photosphere (bright points, network) and in the chromosphere. The connection between magnetic fields and chromospheric heating is of vital concern to this Symposium, since it forms the basis of the supposition that the H and K fluxes of stars provide a quantitative estimate of some parameter associated with the magnetic field. Given the importance of this connection it is sobering to note that despite a great deal of work we have no real understanding of the mechanisms responsible for the extra heating that occurs in magnetic regions of the solar chromosphere.

A view that remains popular is that the magnetic regions are heated by "waves" that are generated by turbulent buffeting of flux tubes in the convection zone, and which dissipate their energy in the chromosphere by shock formation. A similar idea has been studied by several workers as a model for heating the non-magnetic chromosphere, but there are many unsatisfactory assumptions and approximations in these models. It seems likely that the heating results from the dissipation of electric currents generated locally by interactions between magnetic elements and waves of various kinds. A satisfactory theoretical study of this process would require the developement of a detailed multi-fluid model for the partially ionized chromospheric plasma. This model should include the possibility of drift and diffusion of several of the dominant components of the plasma (e.g. electrons, neutral hydrogen, protons, etc.), and should describe the electron-ion components as an ambipolar fluid. This fluid model could be used to describe the behaviour of the plasma in the neighbourhood of magnetic structures, including a consistent description of the external "exciting" processes. Such an ambitious program may lie many years in the future, so that the important question of the connection between magnetic fields and H and K emission will remain unanswered.

As reviewed by Chiuderi in this volume, there has been a major conceptual breakthrough in the related problem of coronal heating, provided by the "electrodynamic coupling" model of Ionson (1982). This is not an entirely new approach to problems in cosmic electrodynamics, since "circuit models" have been used widely in magnetospheric studies for several decades (e.g. Alfven 1979). The application of this approach to coronal heating is new, however, and the explicit derivation of the equivalent circuit is more firmly based on physical principles than the picturesque models that are sometimes used in these studies.

Since several heated debates regarding this model arose, both inside and outside the Symposium, it is appropriate to make a few comments at this point. First, it may be noted that the existing theories of coronal heating were unfruitful. These theories focussed on specific processes that might transport and dissipate energy in the corona, but they could not be tested because either (i) the theories were too abstract to be applicable to the solar atmosphere (which is highly inhomogeneous on all scales), or (ii) the crucial tests could not be made because of observational constraints (e.g. the coronal magnetic field cannot be measured accurately). In addition to these objections, the existing theories have generally assumed that the problem could be divided into one part dealing with the propagation and dissipation of energy, and another dealing with the generation of the necessary Poynting flux. This approach could never explain the coupling between coronal heating and the primary energy source in the convection zone.

It is important to judge Ionson's model in the spirit of its objectives, and not in terms of the older, failed approaches. For example, by focussing on the global electrodynamic coupling, Ionson cannot answer questions regarding the details of specific generation, propagation, or dissipation modes. This is seen as a shortcoming by many commentators, but future work within the spirit of the global model will be able to make specific predictions that may prove to be more readily tested than those made by previous workers. Finally, Ionson's model provides a close analogy between the electrodynamic behaviour of the solar atmosphere and the physics of electrical circuits, and thus provides a new way of looking at several old problems. It is quite enlightening to reverse the analogy, and to seek parallels in the solar atmosphere for several processes that are familiar in electrical circuit theory (the reader might speculate on the parallels between open transmission lines and coronal holes, or electrical discharges and solar flares, or analogies to feedback processes).

Most of the theoretical ideas discussed above in the solar context may be readily modified to produce speculations regarding corresponding processes in other stars. However, it seems that so little is **understood** (as opposed to believed!) about the role of magnetic fields in the mass and energy balance of the solar atmosphere that such speculations are premature. It is evident that while studies of the stars offer us new insights into the possible range of behaviour of stellar magnetic fields, it is only by studies of the detailed phenomena occurring on the Sun that we will develop an understanding of the fundamental processes at work. I share strongly the view expressed by Linsky, that we must study the Sun much more if we are to understand the stars.

5. THEORIES OF THE ORIGINS OF STELLAR MAGNETIC FIELDS

The structure and evolution of magnetic fields in stellar atmospheres are controlled by processes occurring beneath the visible layers of the atmosphere. We have only rudimentary ideas regarding the physical conditions in these sub-atmospheric layers, and consequently the theoretical investigation of the behaviour of magnetic fields in stellar interiors is severely hampered. It is convenient to separate the theoretical problem into two parts, one addressing the question of the factors that determine the large-scale, long-term behaviour of the magnetic field, and the other dealing with the processes responsible for the small-scale structure. Some workers believe that these two aspects cannot be separated, and that both are tied directly to the existence of discrete magnetic elements (flux ropes of various sizes) in the stellar interior.

Most attempts to explain the large-scale, long-term aspects of solar (and stellar) magnetism are based on the theory of the turbulent dynamo, reviewed in this volume by Schuessler. The essential features of dynamo theory are (i) the generation of toroidal magnetic fields from poloidal fields by differential rotation, (ii) the expulsion of this field from the solar interior under the influence of convective motions and buoyancy, with a Coriolis-induced helical motion leading to the generation of a poloidal field with reversed polarity, (iii) dispersal of the magnetic flux by eddy diffusion, concentrating the residual poloidal field near the poles, and (iv) repetition of this process to yield the full 22-year cycle.

Each part of this explanation contains questionable theoretical arguments. For example, it is by no means clear what causes solar differential rotation, so that it is difficult to estimate the distribution of rotation rate within the interior, and hence to estimate the rate of shearing of the magnetic fields. The role of buoyancy is poorly understood, and a critical problem of dynamo theory concerns the mechanisms that are responsible for holding the magnetic field down for a sufficiently long time against the strong buoyancy forces. The concept of turbulent diffusion of magnetic fields also contains a number of questionable features. A comparison of the monographs by Piddington (1981) and Parker (1979) provides complementary pictures of many of the important issues.

It is important to realize that there are a number of hotly debated questions that touch at the heart of attempts to explain the gross behavior of stellar magnetic fields. One of these concerns the role played by turbulent diffusion. Another concerns the question of modelling the effects of turbulent convection. In the model discussed by Gilman, for example, the behaviour of the magnetic field is explained in terms of the properties of large-scale "global convection" flow patterns, and smaller scales of turbulence are described by parameters that are isotropic. Another approach to the problem (e.g. Durney and Spruit 1979) identifies the primary factor in the theory as anisotropic turbulence. Some aspects of these alternatives might be tested when very accurate synoptic observations of large-scale solar velocity fields are available, but this is not certain.

Another important question concerns the properties of the solar core, in particular whether it is rotating rapidly, and whether it posesses a strong, primordial magnetic field. A related problem concerns the behavior of the overshooting region between the radiative core and the convective envelope. A number of theoreticians believe that this region plays a central role in the physics of solar magnetic fields. A cloud hangs over all of these questions, since the persistent failure of attempts to account for the solar neutrino deficit may indicate that there are fundamental processes occurring in the solar core about which we presently know nothing.

Given these problems with solar dynamo theory, it is not surprising to find that applications of the theory to other stars can not be made with confidence. One might expect that stars with properties similar to those of the Sun would behave as the Sun does, but this expectation would not be met if stellar magnetism has a long "memory" of the history of the star. Given the rudimentary state of the theory, the kind of taxonomical approach discussed in this volume by Rosner is particularly appropriate. We need more information on the **empirical** connections between rotation, activity, age, and so on, to assist the development of reliable models. It is especially difficult to extend the solar analogy to stars with internal structures and evolutionary histories that may differ greatly from those of the Sun, without much more insight into the factors controlling the operation of the solar magnetic generator.

The existence of discrete magnetic structures of various sizes in the solar atmosphere presumably results from the interaction between convection and magnetic fields in the interior, but the mechanisms responsible for this intermittency of magnetic flux are unknown. However, the question of the relationship between the global aspects of magnetic fields in the Sun, and the relatively fine-scale structure seen in its atmosphere is an important one, for two reasons. First, it is possible that an essential part of the theory of magnetic generation is the existence of discrete magnetic structures: an example of this would be the "flux-rope dynamo" mentioned by Schuessler. Second, the structural aspects of atmospheric fields clearly play a central role in controlling the gross properties of the atmosphere. Since a key link in the rotation-activity connection is the problem of the loss of angular momentum and spin-down, and since these processes depend on the structure of atmospheric winds and magnetic fields, there is an intimate connection between the evolution of stellar magnetism on a long time scale and the detailed atmospheric structure of the star. Aspects of this link have been discussed by Roxburgh in this volume. However, it is premature to attempt to formulate a detailed explanation of the interconnections between interior and exterior processes insofar as they influence the long-term evolution of stellar magnetic fields.

6. CONCLUSION

This review has identified a number of important areas where productive research should be possible. Solar observations should be afforded high priority, since they offer a unique opportunity to study the relevant processes in action on astrophysical scales. It is important to study both the global solar properties and the fine scale structure. An area where much more work should be done involves the measurement of vector magnetic fields, and the development of adequate diagnostic methods to interpret such measurements.

Stellar observations, particularly the Mt. Wilson H and K flux program, have rekindled interest in Hale's vision of the solar-stellar connection. There is a multitude of observational problems that should be pursued in connection with this observing technique. Supplementary spectrophotometric data should be obtained in lines such as H-alpha and He 10830. Attempts to refine the measurement of magnetic fields in late-type stars should be encouraged. The wealth of knowledge added by satellites such as IUE and Einstein will require several years to be thoroughly digested, but thought must be given now to the next generation of even more powerful instruments.

Theoretical work in the area of solar and stellar magnetism will continue to be very challenging, since it will be necessary to treat complex interactions between physical processes that are not understood well at present. The problem of atmospheric heating will be solved only when present approaches to the problem are revised to provide a much more realistic description of the atmospheric plasma (see Alfven 1979). Basic assumptions (such as ideal MHD) are simply not adequate to account for the important processes. Ionson's model might provide a vital ingredient in this revision. Dynamo theory is in a rudimentary state, with increasingly complicated models being constructed on the basis of assumptions that are clearly suspect. Unfortunately, this Symposium did not reveal a new conceptual approach to the dynamo problem, and progress is likely to be slow. It seems inevitable that the explosion of new observational data on stars of diverse characteristics will generate new theoretical ideas regarding the generation of stellar magnetic fields, and the effects of these fields on atmospheric structure.

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