Proceedings of 12th Cambridge Workshop on Cool Stars, Stellar Systems, & The Sun, 2003 University of Colorado.

The Sun As A Guide To The Stars

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Abstract.

I review the "Sun as a guide to the stars" with emphasis on solar magnetism: its origins and effects. I do not present an in-depth review but instead try to highlight the current status of relevant solar physics. The first half of the discussion focuses on what we have learned about dynamo process on both large ($\ell \approx R_\odot$) and small ($\ell \ll R_\odot$) scales. The second half focuses on the observed effects of the emerging magnetic fields, especially the problem of atmospheric heating. I make no attempt to be complete in referencing, but instead try to point to some key references (mostly reviews) as appropriate. Some WWW resources are listed.

1. Introduction

At this early stage in the twenty-first century, it is instructive to look back and assess what we have learned during the century just past. By any measure, our understanding of the physics of the Sun has grown astonishingly, following the rapid developments in thermodynamics, spectroscopy and photography in the nineteen century. The first half of last century saw enormous growth in astrophysics in general and in solar physics in particular, as the theories of stellar structure and evolution and stellar atmospheres followed (or sometimes drove) developments in quantum mechanics and atomic and nuclear physics. Accompanying these theoretical developments were remarkable observational achievements in particular by Hale and associates and Lyot in solar physics. Many landmark studies addressing what can be considered to be fundamental problems in solar and stellar physics were completed, identifying the source of the Sun's energy and, throughout most of the Sun, its transport to the surface layers and beyond.

By comparison, solar physics during the second half of the last century has arguably seen relatively fewer results of such a fundamental nature, in part because only the hardest problems remained, which of course tended to be of a less tractable nature. It is not surprising that solar magnetic fields essentially define the most pressing outstanding problems today, namely: what is their origin and what are their effects? These are still problems today because of the difficult physical regimes in which stars and their magnetic fields exist: First, the stellar fluid is often strongly convective (Schwarzschild), and nonlinearities (in the Navier-Stokes equation) lead to fluid turbulence. Second, although the

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magnetic fields evolve linearly with a given fluid motion through the induction equation, the magnetic fields couple strongly (the fluid is highly conducting) and non-linearly back into the fluid's force and energy balance equations. These two kinds of non-linear coupling turn out to define (in part) further areas of current interest: fully non-linear dynamo models (force balance) and the heating problems of the chromosphere, transition region and corona (energy balance).

In case you need reminding of the importance of magnetic fields, table 1 compares qualitatively a star like the Sun both with and without magnetic fields[1].

Table 1. "Non-magnetic" vs. magnetic stars

Property	Consequence	further consequence
Non-magnetic star (fiction)		
radiative core		
radiative eqm. atmosphere		$I_\nu \lesssim B_\nu(T_{eff})$
convective envelope	granulation, and global oscillations	acoustic ("basal"?) heating: $I_\nu \gtrsim B_\nu(T_{eff})$ small amplitude, stochastic variability
differential rotation		
Magnetic star (non-fiction). All of the above, plus:		
seed field	"small" (convective) scale, turbulent dynamo	corona, X-rays (high-g)? massive cool winds (low-g)? "basal" heating?
multi-year *storage* of field	large scale, cyclic dynamo	flux emergence, spots Hale's, Joy's laws, polar field flip, active regions, flares, prominences, corona, X-rays, $I_\nu \gg B_\nu(T_{eff})$, wind, CMEs, spin down heliospheric influences

From an *ab-initio*, physical point of view, the problem of understanding the magnetic field of a rotating, electrically conducting star undergoing turbulent convection is too daunting (e.g. Moffatt 1978). However, there are many interesting observations – dating back to the time of Galileo and (of course) continuing today – whose implications continue to tease solar physicists into

[1]Non-magnetic stars are really fiction: magnetic fields almost certainly pervade the Universe, proto-stellar material contains far more magnetic flux than is accounted for in pre-main sequence phases (Mestel 1967), and the global dissipative decay of stellar magnetic fields takes $\approx 10^{9\rightarrow 10}$ years).

thinking that one day we might really understand what is going on. Some of the more painfully relevant observations will be discussed below. As a *leitmotif* for this paper, I adopt the notion that *ab-initio* solar physics really *is* hard, and I will therefore try to review what these interesting observations can tell us about what might be happening in the Sun. In this way I hope to provide a brief physical guide to the Sun as a typical late-type star.

2. The Solar Dynamos

2.1. Dynamos on Large and Small Scales

The clearest visible manifestation of the solar magnetic cycle is, of course, the sunspot cycle, which was noticed as early as 1842 by Schwabe. However, it was not until Babcock & Babcock (1952) invented the magnetograph that it was shown (Babcock 1959, Gillespie et al. 1973) that, roughly every 11 years, the magnetic fields in the polar regions of Sun reverse sign, with a particular phase in relation to the sunspot cycle. Figure 1 shows recent data compiled by K. Harvey and reproduced from Schrijver & Title (2001). We tend to take the 22 year solar cycle for granted, but it is useful to remind ourselves how remarkable an observation this is, by looking at the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{curl}\ (\mathbf{U} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}\ . \tag{1}$$

The decay time τ of a "fossil" magnetic field is controlled by the second term on the rhs of equation (1). For fields that permeate the whole star, this timescale is $\tau \approx |\mathbf{B}|/(|\eta\nabla^2\mathbf{B}|) \sim R_\odot^2/\eta \approx 10^{9\rightarrow 10}$ years. The remarkable thing is that the observations represented by Figure 1 show that the LHS of the equation evolves on global length scales on periods of 11 years! This fact points to the need for efficient inductive regeneration of magnetic fields by some kind of particular fluid motion $\mathbf{U}$ in the first term on the RHS of equation (1), in other words a "dynamo".

I deliberately used the plural form "dynamos[2]" to head this section because the data shown in Figure 1 are probably just part of the dynamo story, showing the evolution of surface fields on *large spatial and temporal scales.* Such large-scale, slow changes in surface magnetic fields have observable consequences that can and have been observed in other stars. Much of the "solar-stellar connection" that has been a central theme of the Cool Stars Meetings over the years has justifiably been concerned with understanding the nature of dynamos on these scales. However, observations from the stable vantage point of the MDI instrument on the *SOHO* spacecraft reveal that the surface magnetic fields exist in small concentrations of mixed polarity that continuously evolve and re-arrange themselves on relatively short timescales (as reviewed recently by Weiss 2001). Title & Schrijver (1998) and Schrijver et al. (1998) noted that at 1 arcsecond

[2]The fundamental physics of these "dynamos" is of course the same, determined by equation (1)– it's just the different time and length scales and forms of $\mathbf{U}$ and the non-linear influence of the Lorentz force that can be qualitatively different.

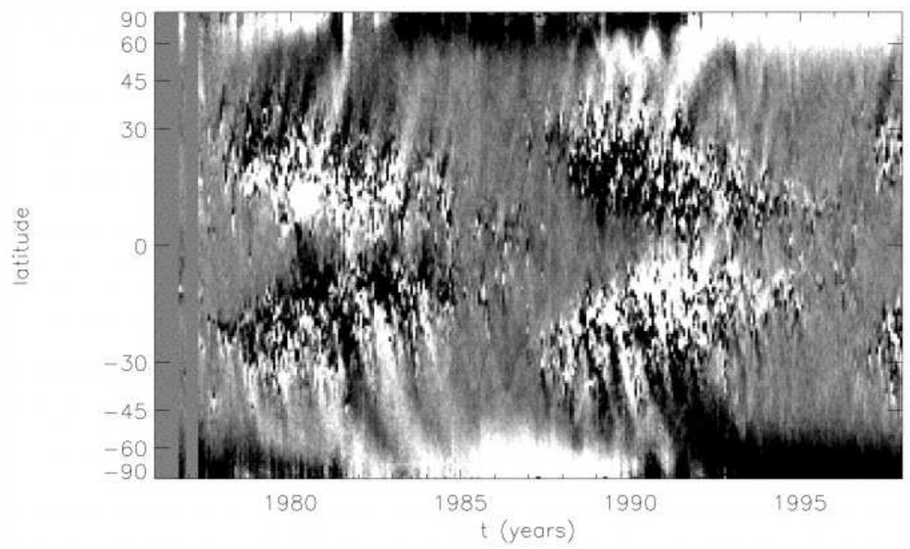

Figure 1. Maps of the longitudinally averaged field with time as observed for the Sun, showing one column for each Carrington rotation. The flux density measured for the Sun has been corrected for projection effects assuming a radial field (data from K. L. Harvey, image from Schrijver & Title 2001). The gray scales saturate at ± 4 Mx cm^{-2}.

resolution, the field patterns seem to evolve on timescales of ≈ 24 hours, comparable to the supergranulation timescale (e.g. Gibson 1973). They dubbed this the Sun's "magnetic carpet" (see Figure 2). Observations at similar angular resolution but with higher sensitivity to weak fields (Lin & Rimmele 1999) show that, away from these concentrations that tend to define the downdraft edges of supergranular cells and the chromospheric network, the Sun shows evolution of fields in association with the granulation and its evolution time of just 5-10 minutes (Figure 3). Thus, the *Sun's small-scale fields appear to evolve on the timescales of the convective dynamics.* This is also one consequence of a class of "fast dynamo" models that are discussed in section 2.4.. But does this fact constitute a dynamo? I return to this point shortly.

2.2. Large Scale ($\approx R_{\odot}$) Dynamo Action

Numerical dynamo models designed to explain global field variations required by solar and stellar observations differ in nature from those designed to study the smaller scale dynamo models. This is because dynamic calculations that are possible in small volumes of convecting fluid are not feasible for entire stellar envelopes. Most stellar dynamo work has therefore been performed kinematically where flow fields $\mathbf{U}$ are specified. Furthermore, because most flows of interest are turbulent ($R_m \gg 1$), mean field electrodynamics has been used to reduce physical variables into mean ($\langle \mathbf{B} \rangle$, $\langle \mathbf{U} \rangle$) and fluctuating ($\mathbf{b}$, $\mathbf{u}$) components according to appropriate spatial and temporal scales (e.g., Moffatt 1978). The induction equation is then solved for a "mean" field $\langle \mathbf{B} \rangle$ in terms of $\langle \mathbf{B} \rangle$, $\langle \mathbf{U} \rangle$ and a term which is the curl of the (non-zero) correlation $\langle \mathbf{u} \times \mathbf{b} \rangle$ between the

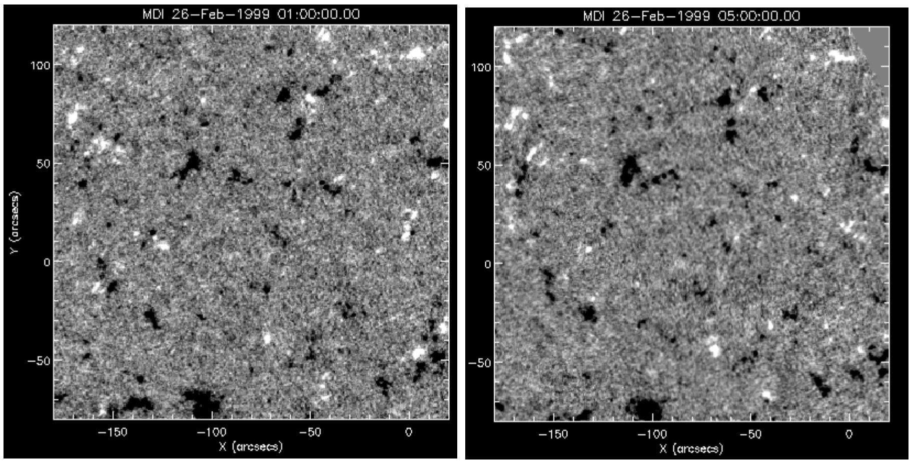

Figure 2. Evolution of the line of sight components of the magnetic fields of the quiet Sun as seen with the MDI instrument on *SOHO*. The two images, covering a 150 × 150 Mm^2 area, are separated by 4 hours. Schrijver et al. (1998) contend that the flux disappears in collisions between opposite polarities (here shown black and white) so fast that all field should disappear in a few days. New flux emerging in small ephemeral regions replaces the disappearing flux, resulting in this thoroughly mixed pattern. The gray scales saturate at ±30 Mx cm^{-2}.

fluctuating velocity and magnetic fields. The system is closed by approaching the limit of isotropic turbulence, and expanding the fluctuating quantities in terms of the mean values as $\langle \mathbf{u} \times \mathbf{b} \rangle_i = \alpha_{ij} \langle \mathbf{B}_j \rangle + \beta_{ijk} \frac{\partial \langle \mathbf{B}_j \rangle}{\partial x_k}$. Mathematically, the terms in α_{ij} and β_{ijk} enter as sources and sinks in the induction equation for the mean field. Such models are classified as turbulent or "mean field" dynamos, with names such as "$\alpha - \Omega$ dynamo".

The Rossby number $\mathcal{R}\mathrm{o}$, the ratio of the rotation period P_{rot} to the turnover time τ_{c} at the base of the convection zone, measures the amount of helicity introduced into the turbulence via the Coriolis force. Fluid helicity is a simple measure of the breaking of reflectional symmetry, which is necessary for the regeneration of large scale magnetic fields. Turbulent dynamos, with assumptions of slow rotation, weak stratification, and differential rotation proportional to rotation, yield well-known scalings for dynamo efficiencies measured by dynamo number $N_{\mathrm{D}} \propto \mathcal{R}\mathrm{o}^{-2}$. Such scalings have been shown to be broadly compatible with stellar data (e.g., Noyes et al. 1984).

Several observations critically constrain the properties that a large-scale dynamo must have. First, some qualitative conclusions can be inferred from simple properties of the observed emerging magnetic flux:

- Sunspots mostly emerge according to a specific time-latitude pattern- the butterfly diagram (cf. Figure 1),

- Sunspot groups emerge with opposite polarities oriented nearly E-W; in a given hemisphere the leading polarity is nearly always the same, and

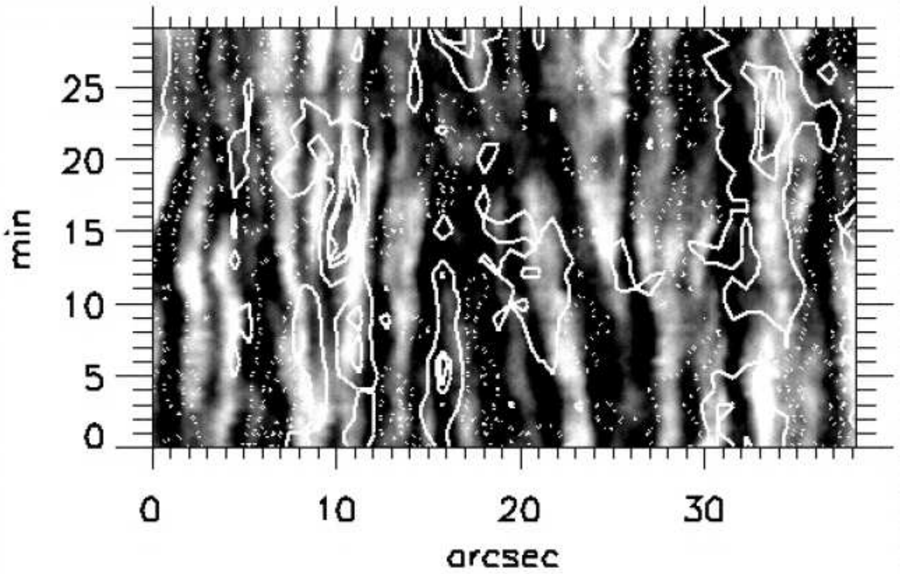

Figure 3. Time slice of IR continuum intensity with the magnetic flux ϕ_B overlaid as contours, with positive and negative polarities shown as solid and dashed lines. These "granular" magnetic fields, i.e. those away from the network, evolve along with the granulation (from Lin & Rimmele 1999).

opposite to the other hemisphere; and the leading polarity switches as the "new cycle" begins with the emergence of opposite polarity leaders at the tips of the "butterfly's wings" (Hale's polarity laws),

- The emerging sunspot groups or bipoles are systematically tilted wrt the E-W direction, the tilt is typically 10° (4°) for groups emerging near 35° (10°) latitudes (Joy's law),
- There was at least one epoch when sunspots were rare (the Maunder Minimum) for several cycle periods, but indirect indices have shown that the Sun maintained a well-defined, phase-locked cycle, throughout this period (Beer et al. 1998, their figs. 1, 2).

Taken together, these observations (the first three were already cataloged by Hale and associates in 1919) indicate a significant degree of spatial order in the dynamo "source regions" of the solar interior, that these regions must be able to store flux for a decade, and that the cycle has stochastic properties. These data still present some of the most critical constraints for models of the solar dynamo. To be consistent with observed latitudes and tilts of emerging bipolar regions over the solar cycle, the field has to be considered as a coherent structure originating from a "source region" of well-ordered toroidal flux in the interior (e.g. Schüssler 1996).

To make a stronger statement we must appeal to interior models that have been confirmed or derived from helioseismology, which show that the source region is most naturally identified as the sub-adiabatically stratified, convectively stable layer lying directly beneath the convection zone. The differential rotation in this "tachocline" region inferred from helioseismic work leads to conversion of poloidal to toroidal field (the "ω-effect") on suitable timescales. Furthermore it naturally produces toroidal field of different signs in different hemispheres, as required by Hale's observational constraints. If the field were stored deeper where differential rotation is weak, the ω-effect is diminished. If higher, the flux tubes are buoyant in the super-adiabatically stratified convection zone, and canonical wisdom holds that the tubes will rise in $\lesssim 1$ month, much less than the period of the solar cycle (although see below). Dynamic models strongly suggest that coherent flux ropes cannot be stored for 11 years within the convection zone. The dynamic models that examine the balance of buoyancy, drag and Coriolis forces show that field strengths of $\approx 10^5$ Gauss must be present just below the base of the convection zone. It is important to note that, even at this juncture, there are important unresolved issues that will be mentioned below.

The conversion of toroidal to poloidal field, completing the "dynamo cycle", is a more challenging problem (e.g., Parker 1955). Early mean-field models were developed based upon Parker's (1955) physical picture: to overcome Cowling's "anti-dynamo theorem" the Coriolis force induces asymmetries in the convective eddies (e.g. Moffatt 1978). An important crossroads was reached in the late 1980s when the internal rotation profile in the convection zone was accurately constrained by helioseismic data (e.g., Brown et al. 1989), showing that the α-effect, which converts toroidal to poloidal field, cannot be distributed throughout the convection zone as in earlier mean field models (e.g., Stix 1976). The convection zone rotates with very little radial shear. This implies that one must look to one of two alternatives for a suitable large-scale solar dynamo. The first is the radiative-convection zone interface class of models (proposed by Parker 1993). In these models, it is supposed that the quite different physical conditions across the interface lead to very different diffusivities, which under suitable conditions lead to cyclic solutions to mean field equations. All the "action" in these models takes place in the neighborhood of the core/ convection zone interface, and the surface fields simply emerge from this region and play no role in completing the dynamo cycle. This is quite different from the second class of models, which instead appeal to the decay of the systematically tilted bipolar sunspot "sources" of poloidal field at the solar surface (with "large cell" meridional circulation) for completion of the dynamo cycle ("flux transport" or "*B-L*" dynamos, e.g. Dikpati & Charbonneau 1999). The *B-L* class of models therefore is a truly global model which relies on meridional circulation to advect the surface fields down to the interior where the reversal of the poloidal field component can take place. The proposed meridional flows have been detected half way down the convection zone (Braun & Fan 1998).

2.3. Current Issues

Given the helioseismic data, it turns out to be difficult to make a mean-field dynamo model that can reproduce the spatial distribution of emerging sunspot groups over the solar cycle. Nevertheless, both interface and *B-L* dynamos are currently considered as viable models. Our inability to discriminate between such different models arises because, in spite of our relatively detailed knowledge of the Sun, there remain several (well-known but) open questions:

- Is enough known about the solar interior kinematics? For example, does the meridional flow needed for the B-L models extend fully down to the base of the convection zone?

- Are the [anisotropic] "eddy diffusivities" (values of η adopted in the mean-field equations based on equation 1) adopted in current models reasonable? Both the B-L and interface models depend *critically* on this parameterization, but there is no direct way to determine these diffusivities (at least those used below the surface).

- Schüssler (1996) argued that there is 2 orders of magnitude less energy in the differential rotation to account for the magnetic energy in the toroidal field associated with the solar cycle. Furthermore, unless the toroidal field is concentrated into many thin ($r < 100$km) "fibrils", individually having much smaller fluxes than observed in active regions, the tension force limits ω-effect amplification by stretching to much smaller field strengths. How then are the 10^5 Gauss tachocline fields generated, as required by current flux emergence models and Hale's and Joy's laws? Are the toroidal flux ropes quite homogeneous or split into many fibrils? Is a quite different magnetic intensification process needed (e.g. the flux tube "explosion" model of Rempel & Sch ü ssler 2001)?

- If interface models are appropriate, can we identify a physical reason why the α-effect must be confined to low latitudes to produce reasonable butterfly diagrams?

- Is there a dynamical problem in generating the needed 10^5 Gauss fields with the traditional α-effect in the interface class of models (the "α-quenching problem", reviewed by Cattaneo 1997)?

- Does a sufficiently large fraction of the surface fields that result from the tilted, decaying active regions in the B-L models get dragged down into the interior, or is much lost into the heliosphere?

- Long-term indirect indices of solar cycles, sensitive primarily to the poloidal magnetic field component in the heliosphere, have shown that the Sun maintained a well-defined, phase-locked cycle, throughout the sunspot-poor "Maunder Minimum" period (Beer et al. 1998, figs. 1, 2). What does this imply for the dynamo models?

- Recent work suggests that long-term flux storage might in fact be efficient *within* the convection zone (Dorch & Nordlund 2001). While apparently contradicting the simple arguments listed above, the new calculations are fully dynamic and include the effects of the strong down-flowing plumes associated with the convection. The plumes serve to keep the buoyant flux ropes within the convection zone. Should we then reconsider the tachocline as a fundamental element of the solar dynamo? If so, how do we account for the systematic behavior of emerging sunspot groups over the solar cycle?

These issues present challenging but different problems for the turbulent and B-L models. In section 4. we review some stellar observations that might be used to help answer some of the difficult questions listed above.

2.4. Small-scale Dynamo Action

The magnetic Reynolds number R_m measures the relative importance of the first to the second term on the rhs of equation (1). It is $\approx U\ell/\eta$, where ℓ is a characteristic length scale of the flow, η the magnetic diffusivity and U the fluid speed. MHD simulations of convecting, non-rotating magneto-fluid indicate that any 3D turbulent flow with a large magnetic Reynolds number is extremely likely to be a dynamo (e.g., Cattaneo & Hughes 2001), in the sense that seed magnetic energy is readily amplified. It appears unavoidable that even non-rotating convecting stellar envelopes will amplify existing fields and thereby act as dynamos. Dynamic 3D calculations of the kind presented by Cattaneo & Hughes (2001) produce amplification via chaotic fluid trajectories in the first term of eq. (1), producing accordingly small scale, chaotic magnetic structures. The calculations are possible only in small "computational boxes" which do not, for example, feel the effects of rotation, and therefore cannot produce "large scale" fields of order the box size. Existing calculations show that seed magnetic fields increase until the Lorentz force equals hydrodynamic forces. The magnetic energy density evolves in a few convective turnover times to reach a steady state which is typically 1/5 of the value which would be in equipartition with the kinetic energy density. Perhaps the most salient feature is that *magnetic fields are generated on the scale of the driving motions.*

The computed dynamic behavior, when viewed appropriately (i.e. assuming the computed convection cells correspond in scale to solar granules) and degraded to the resolution obtained by current observations, is reminiscent of the solar atmosphere, and it is tempting to identify the magnetic fields observed on granular scales (e.g., Lin & Rimmele 1999, Figure 3) as resulting from such dynamics. Perhaps the "magnetic carpet" seen on supergranular scales (Figure 2) is also simply the result of magnetic fields being generated on the larger scale of the supergranular driving motions, and thus correspond to the same basic phenomenon. While suggestive of small-scale dynamo action, the qualitative agreement between the numerical experiments and available observations does not prove that small scale dynamo action is responsible for the solar behavior. It is possible that what we observe is simply a surface re-arrangement of fields generated elsewhere, with no significant increase in magnetic energy density. But given the turbulent regime of the solar convective motions, field amplification seems inevitable as a result of this re-arrangement.

I note in passing that such "small-scale" dynamos, in which magnetic fields are generated on the scale of the convective motions, might lead to the generation of stochastic magnetic fields on very large (stellar) scales, in very low gravity stars. Not only are the stars rotating very slowly, but if Schwarzschild's (1975) speculations are correct[3], these stars have fewer, larger convective cells (relative to the stellar radius). Recent numerical simulations seem to confirm

[3] It may be that granulation is a pure surface effect, not related to the fundamental scales of convection: see Rast (1999) for this perspective.

the enormous scales of convection in M supergiants (Freytag 2001). Such fields might help explain the origins of the massive stellar winds and some peculiar dynamic properties of the chromospheres.

3. Surface Effects

3.1. Importance of Flux Emergence

The emergence of new magnetic flux into the atmosphere has many important effects. In very general terms, when the flux is advected (or equivalently diffused by turbulent eddies) and buffeted by the surface motions (a combination of granules, gravity waves and global oscillatory motions), several interesting effects occur. As noted above, systematically tilted sunspot fields can become a source term in the mean field B-L dynamo models. All emerging magnetic fields can inject and store magnetic free energy throughout the photosphere--corona domain. The free energy is the source of heating (dissipation on small scales), large-scale energy storage in magnetically sheared structures (e.g. filament channels) and current systems, loss of equilibrium (flares, coronal mass ejections, spicules, micro-flares...), the solar wind, spin-down (part of long-term dynamo problem), irradiance (luminosity?) variations, and other phenomena. In other words, the free energy associated with the emergence of new field and its interaction with the convective motions and pre-existing field leads directly to much of the phenomena that solar physics is currently concerned with, as summarized in the lower section of Table 1.

3.2. Surface Magnetic Field Properties

I place emphasis here on quiet Sun conditions, but will discuss active regions to illustrate physical points of interest when needed. The magnetic flux observed in quiet regions is currently classified into two components which are only crudely understood. First, there are the "flux tubes" (sometimes called "fibrils"), which

- have 1-2kG ($\approx$ equipartition) field strengths, are oriented nearly vertically,
- are 100-200 km in diameter,
- are long-lived and stable over many granular lifetimes,
- individually are at or below the angular resolution limit of current instruments,
- are almost always found in the lanes between super-granule cells, and are believed to be the building blocks of the magnetic network whose structure is essentially unresolved in Figure 2,
- form the "roots" of the chromospheric network,
- can intertwine and potentially lead to chromospheric/coronal heating (Parker 1972).

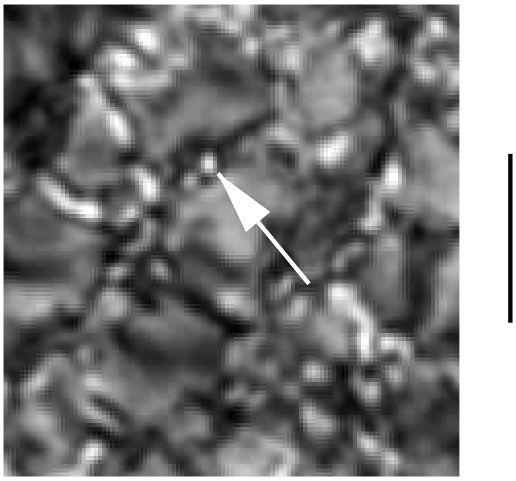

Figure 4. "G-band" image of a small area of the quiet Sun including network, obtained on the Swedish Vacuum Solar Telescope. This is part of one frame of a "G-band", phase-diversity corrected movie. The "G-band" is sensitive to small but intense magnetic flux concentrations in the photosphere. The arrow indicates what might be considered to be a single flux tube sitting in an inter-granular lane. The figure is part of a movie kindly provided by G. Scharmer and colleagues.

Figure 4 indicates what might be considered as an individual "flux tube" sitting in an inter-granular lane. These structures lie mostly below the resolution limit of current instruments, so their basic properties are actually poorly understood. Magneto-convective simulations suggest that they are stable structures, formed by the "convective collapse" process which amplifies weaker surface fields that are advected to strong convective down-drafts. In the traditional picture (e.g. Spruit et al. 1991), a strong enough flux concentration collapses because convection is suppressed within it, leading to a steeper vertical temperature profile and lower gas pressures within the flux element compared with the surroundings. Hence the external photospheric gas compresses the flux concentration until a new equilibrium is reached for field strengths near equipartition with the external photosphere, ≈ 1300 G. Before the collapse process, newly emerged flux should evolve along the lines of the numerical results presented in section 2.4.. Such behavior is observed (see figure 3), and the magnetic fields have been labeled "internetwork fields". Internetwork fields are difficult to detect, evolve on granular lifetimes, sometimes emerge horizontally (Lites et al. 1996), and are advected to strong down-flow regions. Like the "stable" flux tubes, these emerging fields elements most likely interact with each other and with pre-existing network fields, probably leading to interesting magnetic phenomena in the overlying atmosphere. They may be a manifestation of the small-scale dynamo discussed in section 2.4..

It is important to note that we have never seen more than the gross structure of solar surface magnetic fields. Resolving the small scale structure within the flux tubes is important because not only will it yield further clues as to the formation of flux tubes at the surface, but observations in emerging active regions could yield clues as to the state of the field within the solar interior, and hence help to constrain some of the major uncertainties relating to dynamo activity and flux emergence (see section 2.3.). Furthermore, the micro-structure of surface fields is important because their internal dynamics and interactions with the convection and with each other are expected to supply the energy to drive the overlying layers (e.g. Steiner et al. 1998, Parker 1988).

3.3. Atmospheric Heating

I now focus more closely on the surface properties of the Sun paying special attention to the clues we can find from observations concerning the long-standing problems of chromospheric and coronal heating mechanisms. Instead of subjectively reviewing an enormous volume of literature, I will take an easier option and first try to highlight the theoretical challenges facing us in the simplest physical terms, before delving into the progress made to date, and assessing some of the interesting challenges presented by the latest observational material.

The Challenges We know that mechanical energy generated by the turbulent atmosphere and convection zone can be channeled into the upper solar atmosphere via both acoustic waves and electrodynamic processes. We also know that a dominant component of chromospheric heating is magnetically related, and that essentially all coronal heating must result from electrodynamic (and not acoustic) processes (see, for example, reviews in the volume edited by Ulmschneider et al. 1991). Magnetic heating is fundamentally a difficult problem, as can be seen from the following considerations (see also Bray et al. 1991,Zirker 1993):

- The injection of electromagnetic energy from beneath is determined by the Poynting flux $P = \frac{c}{4\pi}\ \mathbf{E} \times \mathbf{B} = -\frac{1}{4\pi}\ (\mathbf{U} \times \mathbf{B}) \times \mathbf{B}$.
- Dissipation of this energy must occur
  - in the MHD limit (at frequencies $\ll$ the characteristic ion cyclotron frequency) either through Ohmic ($\mathbf{j}.\mathbf{E} = \mathrm{curl}^2\ \mathbf{B}/\sigma \sim B^2/(\ell^2\sigma)$) or viscous heating, both of which must occur on tiny physical scales ℓ.
  - via wave-particle interactions at much higher frequencies
- The photosphere-corona domain spans $13-14$ pressure scale heights. Consequently
  - The energy density of chromospheric and coronal plasma is many orders of magnitude smaller than in the photospheric or deeper layers where much of the Poynting flux can be generated. Thus unobservably small changes in the Poynting flux at photospheric heights can in principle lead to dramatic changes in the overlying plasmas.
  - The regimes switch from high to low plasma$-\beta$ with accompanying changes of physical conditions (forced states $\rightarrow\ \approx$ force-free states [non-linear force balance]; MHD wave modes change character in relation to the changes in the phase speeds of sound and Alfvén waves).

- Even if one can measure photospheric magnetic fields with high precision, the chromosphere and corona themselves can store magnetic free energy injected slowly from deeper layers, and release it under quite different physical conditions with accordingly different properties (e.g. at higher temporal and spatial frequencies than are present in photospheric layers).

These are some of the most obvious problems facing researchers searching for the heating mechanisms – the "Holy Grail" of coronal physics – other problems have been made abundantly clear by others (e.g., Zirker 1993). It is clear that a *direct* observational attack on the heating problem requires very high precision observations in at least two steps: First, very precise measurements of surface velocities and the vector magnetic field are needed to evaluate the Poynting flux at some level; second, the dissipation in the higher atmospheric layers must be determined. Magnetic field measurements are most accurate in the photosphere and become increasingly difficult with increasing height in the atmosphere. This direct approach is extremely difficult or impossible at present, but nevertheless the first step appears to be feasible with the advent of the next generation of instruments observing with adaptive optical seeing corrections. While some gross thermodynamic signatures of the dissipation – the second step – can easily be seen in the intensities of spatially unresolved spectral features, to see features at the expected dissipation scales (fractions of a km?) and the evolution of the *magnetic* field in response to the dissipation requires magnetic field observations in the chromosphere and higher layers with sensitivities and angular scales orders of magnitude below present observational capabilities.

Approaches The enormous challenges listed above have meant that, in practical terms, other approaches to the heating problem must be pursued, that can be grouped into four classes. First, some workers have bravely attempted the direct approach using available data (e.g., Fisher et al. 1998 and references therein). It is acknowledged from the outset that for the above reasons the observations fall far short of constraining heating mechanisms in themselves, but nevertheless some conclusions can be drawn if one is willing to accept that the small-scale phenomena can be handled in a statistically meaningful fashion. The second (and most common) approach consists of studying simplified physical models where assumptions concerning the nature of the driving motions and dissipation are made, the conversion of magnetic into thermal energy is studied in some detail, and comparisons are drawn with available observations of both the drivers and the corona itself. Examples are the Joule-heated coronal heating studies of Spicer (1991), the (MHD) Alfvén-wave resonance absorption models reviewed by Davila (1991), and the (non-MHD, high frequency) ion cyclotron wave absorption models for the fast solar wind problem by Cranmer (2000). In passing, I note that Mandrini et al. (2000) have provided in their table 5 some scaling laws for the Poynting flux and its dissipation in terms of the magnitudes of photospheric velocities, magnetic fields and other relevant parameters amongst 22 different physical models. The third approach is semi-empirical in nature, where an *ab-initio* energy equation is not solved, but instead a judicial mixture of observations and models are used to derive simple constraints on terms in the energy equation – such as the distribution of electron temperature with height – and the dissipation of energy is determined as a function of height in the atmosphere, distance along a loop, or even temperature (e.g. Avrett 1981, Jordan & Brown 1981, Jordan 1991). A fourth class of models is a step farther from a physical approach, which instead focuses on a statistical description of energy release in terms of many small-scale "flaring events" whose distribution is constrained by observations of brightenings in the corona (e.g., Charbonneau et al. 2001).

Historically, attacks on the coronal and chromospheric heating problems have differed substantially, because, even if the dissipation mechanism is similar, energy transport is quite different owing to the dominant rôle of (field-aligned) heat conduction by the electrons in coronal plasma. Conduction, when it is important, couples the temperature structure at all points along magnetic field lines. This helps to explain why loop structures appear to be the building blocks of the active solar corona (Rosner et al. 1978, henceforth "RTV"), but it does beg some interesting additional questions (see section 3.3.). At coronal temperatures, characteristic times for conductive heat transport are far shorter than those for radiative losses: temperature fluctuations in the corona are quickly suppressed by conduction along field lines which thus masks any local signatures of the heating mechanism that might emerge in the radiative output. Instead such energy fluctuations are more likely to emerge as radiative emission from plasma emitting at transition region temperatures and/or as kinetic and/or potential energy of mass flows. Furthermore the coronal pressure scale-height is a substantial fraction of a solar radius and images resolving partially the structure of the coronal plasma's geometry were available already in the 1960s. In contrast, the chromosphere is geometrically much smaller, conduction is essentially unimportant so that energy balance is achieved locally in which heating competes with radiative losses and other sources and sinks such as internal ionization energy changes and enthalpy flux divergence.

Progress: Corona Essentially all coronal work has been concerned with the analysis of the thermal properties derived from spectral features, mostly emission lines or their collective intensity seen through broad-band instruments.

The direct approach has been tried by, for example, Fisher et al. (1998), who examined magnetic properties from vector field measurements in the photosphere and their relationship with *YOHKOH* X-ray luminosities in active regions. Because of the limitations outlined above, this kind of analysis can only be done in a statistical rather than detailed fashion. Thus, Fisher et al. could measure only very crude properties of the magnetic field in active regions (compared with the physical scales of flux tubes and magneto-convective phenomena mentioned above), so they had to assume statistical properties of the Poynting flux based on low resolution data, and that the estimated Poynting flux was entirely dissipated in the corona. While they attempted to assess the relative merits of three classes of models of coronal heating (dissipation of Alfvén waves, dissipation via Parker's 1988 "nanoflares" which release free energy stored over long timescales, and the minimum current coronal model of Longcope 1996), no convincing conclusions could be drawn. This is because of the incompleteness of the data needed to constrain both the Poynting flux at the photosphere and in the dissipation thereof in higher layers. In other words, to address this problem properly requires at least the detailed measurement (or simulation) of, and not statistical treatment of, photospheric properties. At least some aspects of this approach might work in the forsee-able future.

Most semi-empirical approaches have been based on one-dimensional models. These rely on the dominance of field-aligned heat conduction at coronal temperatures to make such models (including most "loop models") a useful first step towards constraining heating mechanisms by making comparisons with spatially resolve or unresolved observations. Jordan (1992) has shown how the effects of conduction in hydrostatic (or constant pressure) solutions to the 1D energy equation with *ad hoc* magnetic heating terms lead to generalizations of the well-known "loop scaling laws" originally made explicit by RTV. The RTV laws are seen to be a subset of more general cases in which the relative effects of radiative losses and the particular functional dependence of the *ad-hoc* heating rate on height or temperature are allowed to vary.

The RTV laws are a good starting point from which to examine recent work which attempts to analyze the spatially resolved structure along coronal loops as seen with the latest generation of coronal imagers: *YOHKOH*, *TRACE* and the EIT instrument on *SOHO*. 1D analyses of the intensities along "individual loops" (e.g., Lenz et al. 1999, Aschwanden et al. 2000 and references therein) have revealed that while the hotter loops seen in active regions with *YOHKOH* are compatible with the original RTV formulation, the cooler loops seen with EIT and *TRACE* are qualitatively different: the cooler loops are much more isothermal along their lengths and extend much higher than expected. As little as 30% of the loops seem compatible with static 1D (i.e. loop) models, the majority being significantly denser than models predict. The precise meaning of these results is still under debate, but it at least appears that heating must not occur uniformly along the cooler loops but instead it must occur closer to the foot-points, and suggests that something is missing from the hydrostatic force balance. A similar analysis performed by Priest and colleagues using *YOHKOH* data which sees the hotter loops yields ambiguous results, in spite of early optimism (MacKay et al. 2000). In short, only very crude constraints on mechanisms seem to be possible using such techniques. Attempts to constrain the class of heating models compatible with the data (e.g. even wave vs. steady current pictures) are premature not only because of the inherent uncertainties in the data but also because the models are physically too incomplete.

A persistent feature of solar emission line spectra that certainly reflects (directly or indirectly) heating mechanisms, and that has yet to be fully explained, is that the form of the derived emission measure distribution remains qualitatively the same across a wide variety of different features (quiet Sun, active Sun). Emission measure analysis has been used to set constraints on the form of the heating function as a function of temperature and, with an assumed structure, height (e.g. Jordan 1980), irrespective of whether structures in the corona are spatially resolved or not. If we make the simplest assumption, namely that the emission from which the emission measure distribution is derived is a relatively homogeneous structure varying in temperature only along the magnetic field lines, then the invariance of the shape of the emission measure distribution above 10^5 K implies that the classical (Spitzer 1962) conductive flux is roughly constant, i.e. its divergence dominates all terms in the energy equation. With the same assumptions the shape below 10^5 K implies substantial local heating far beyond what can be deposited by classical conduction from the corona. But near 10^5 K the same analysis implies substantial mechanical *cooling.* The implied cooling and heating occur immediately adjacent to one another, suggesting perhaps that the basic assumptions need to be re-examined. Some authors (e.g. Feldman 1983, Rabin & Moore 1984, Antiochos & Noci 1986) have argued that the transition region emission we see is not determined at all by electron conduction, and instead the shape is largely determined by statistical averaging of many different and energetically disconnected magnetic structures (perhaps even loops) whose temperatures never approach coronal values. Such structures must occur, given the time and space varying complexity of the magnetic field injected from below, the only question is, which type of structure dominates- those that are conductively heated or thermally isolated? I return to this question below (section 3.3.), but emphasize that the issue of cross-field conduction (Athay 1990) should be resolved once and for all before conductive heating alone can be firmly ruled out (see section 3.3.).

Interestingly, perhaps the most important advance to come from the *SOHO* and *TRACE* era has come from a relatively low angular resolution, spectroscopic instrument: UVCS on SOHO, in one of the dimmest parts of the corona- the solar wind. The UVCS team has found evidence for anisotropic ion distributions functions in the solar wind using clever spectroscopic "tricks" (Kohl et al. 1998). If substantiated, this implicates Alfvén waves with frequencies above the ion cyclotron resonance frequencies (kHz and above) in the solar wind as a heating mechanism. It begs the question: what is the source of the high frequency Alfvénic disturbances? Cranmer et al. (1999) and Cranmer (2000) have shown that because the ion cyclotron wave dissipation is rapid, the extended heating seems to demand a constantly replenished population of waves over several solar radii, rather than an initial injection of wave energy at the coronal base. Mechanisms for doing this are being proposed (e.g., Markovskii 2001).

I finish this section with a discussion of work on small scale flares as a clue to coronal heating. The basic idea is almost entirely observational, but it is based on the physical picture that energy is driven slowly into the corona via slow footpoint motions, and then released impulsively via reconnection of some components of the vector field in loops (for example, the toroidal component), following ideas of Parker (1972, 1988). The ideas of self organized criticality (SOC) have been brought to bear on the problem, by describing the evolution of the system in terms of a lattice model driven to a critical state (Charbonneau et al. 2001). If magnetic free energy is released in small packets ("micro- or nano-flares") with a distribution such that the number of packets with energy between E and $E + dE$ is proportional to $E^{-\alpha}dE$, then if $\alpha > 2$ the sum of all such events is dominated by the low energy component of this distribution. Various observational attempts have been made to determine the shape of this distribution, as recently reviewed by Charbonneau et al. (2001). Unfortunately, the problem has some nagging issues concerning how one extracts E from time-series data of EUV or X-ray intensities. Furthermore, the SOC paradigm forming the basis of explaining the distribution for *bona fide* flares at high energies, has difficulty in producing $\alpha > 2$ as required to explain "quiet" coronal heating in terms of the same physical processes, while at the same time explaining flare properties. The interpretation of the data is once again, an unresolved issue.

Progress: Chromosphere Interestingly, the traditionally more challenging chromosphere has succumbed first to the direct approach of determining the heating mechanisms, albeit in regions of the internetwork that are far from strong network magnetic fields. While non-magnetic in nature, this example is nonetheless very instructive and some lessons learned from it should serve as a warning to workers interested in heating mechanisms.

Work by Carlsson & Stein throughout the 1990s, utilizing time-series observations of photospheric lines and the Ca II H-line observations of Lites et al. (1993), marks an important advance in chromospheric physics, albeit in explicitly "non-magnetic" regions of the atmosphere. Their work provides the first self-consistent treatment of radiation hydrodynamics and a remarkable (unanticipated?) compatibility with detailed time-series observations, suggesting that at least some of the basic physical processes have been captured. The basic physics is 1D nLTE radiation hydrodynamics, in which the mechanical energy flux is represented by an observationally-constrained piston at the photosphere which drives vertical acoustic oscillations into the chromosphere. These oscillations steepen into shocks several scale heights up in the mid chromosphere, where they dissipate acoustic energy and account for the appearance of the Ca II H-line in remarkable detail. These models reveal the quintessentially *dynamic* nature of the "non-magnetic" chromosphere, calling into question (Skartlien 1994, Carlsson & Stein 1995) the time-honored semi-empirical methodology (e.g., Vernazza et al. 1973) which had previously be used to try to constrain heating mechanisms. The conclusion is simple: when large fluctuations in thermodynamic variables exist (in the model these variables are highly time dependent), then solving for the average temperature structure from spatially and temporally averaged data, prior to examining the energy equation in an average model, can lead to gross errors! The limitations of the radiation hydrodynamic model are currently being explored through observation and theory (e.g. Judge et al. 2001, McIntosh & Judge 2001, Rosenthal et al. 2001). We expect that magnetic fields both from the internetwork photosphere (figure 3) and the chromospheric "canopy" (consisting of almost horizontal network fields overlying the internetwork chromosphere) will be important. Nevertheless this work highlights the need for care in applying semi-empirical instead of more direct methods in the outer atmosphere of the Sun. Extensions of some of these ideas to the transition region and corona are discussed by Wikst øl et al. (1998) and Judge & McIntosh (2000).

As might have been anticipated, the magnetic chromosphere is not so well understood. The most serious attempt to combine observed photospheric velocity and magnetic field properties (again from Lites et al. 1993) with a theoretical study of Alfén wave propagation and dissipation via Ohmic dissipation through ion-neutral collisions has been performed by Goodman (2000). This paper also provides an excellent summary of this area, and is recommended reading. It is observationally unclear if the magnetized chromosphere is subject to large fluctuations which, like the internetwork chromosphere, might render semi-empirical methods unreliable. While fluctuations in time are certainly observed to be less important in network than in internetwork regions, the dynamics of the convection zone and photosphere discussed in sections 2.4. and 3.2., together with simulations (Steiner et al. 1998) strongly suggest that we treat semi-empirical methods with care.

Further Challenges The following is a subjective list of outstanding problems that should, if solved, lead to an improved understanding. The questions listed below are prompted by the basic idea that the Sun's corona is fed with mass, momentum and energy by the turbulent atmosphere below.

1. What is the relationship between the observed plasma loops and the magnetic field? In particular,

    - How does the Sun know how to choose certain field lines on which to load plasma and heat it to a certain temperature? Consider Figure 5: given photospheric data, could one predict locations of bright coronal emission? In case the figure is not convincing enough, detailed analyses of radio data show that the answer is no. Radio measurements have repeatedly failed to find any obvious relationships between the coronal magnetic field and the regions that are bright in EUV images (White 2000). Of the various heating mechanisms proposed, only one, the minimum current coronal model proposed by Longcope (1996), seems to have specific predictions of where bright coronal emission should be found in relation to the large scale magnetic structure (see the appendix of Fisher et al. 1998).
    - Are some of the loops actually ribbons of current flow (e.g., Fort & Martres 1974, Klimchuk et al. 1992) that delineate topological "separators" which demark strong coronal current systems (Longcope 1996)?
    - Why do active region loops often expand very little with height, in a manner in gross disagreement with fields that are nearly potential (e.g., Klimchuk 2000, Watko+Klimchuk 2000?

2. What makes the corona apparently so *well organized* on large scales? This statement may come as something of a shock, given that we are all too familiar with the fine structure seen down to resolution scales with instruments such as *YOHKOH* and *TRACE*. But consider figure 7, which shows that the Sun is quite well organized into large and physically separate volumes of material predominantly at different temperatures (the figure is not just different shades of gray). As noted by Litwin & Rosner (1993), this presents conceptual difficulties because the temperatures within these structures are quite similar over lengths that are much bigger than those which heat conduction can efficiently transport heat across field lines.

3. What is the nature of the coupling between the corona and the lower atmosphere?

    - Berger et al. (1999) examined the relationship between the EUV, soft X-ray emission and lower atmosphere in solar active regions, at high spatial and temporal resolution. They concluded that, by at least partially resolving the structure and dynamics of the conductively heated upper transition region (Figure 6), the upper transition region plasma is highly structured and in contact with cooler chromospheric material, suggesting that the interaction of hot material with chromospheric jets may provide sufficient interface area and/or turbulent mixing to significantly enhance thermal exchange across magnetic field lines.

- Athay (2000) has suggested that, under conditions where neutral and charged particles are heated at different rates, then the upper chromosphere can become unstable to thermal perturbations. The subsequent behavior is expected to become essentially dynamic, with the upper chromosphere and corona undergoing a continual evolution which may also lead to spicules, and render coronal physics inextricably dependent on chromospheric physics.
- Is the observed transition region really formed in a thermal interface between chromosphere and corona, or is it dominated by emission from magnetically and thermally isolated structures? It is important to realize that current studies remain inconclusive simply because the cross-field heat conduction problem has not been solved, yet exploratory parameter studies of isotherms (which are not solutions to the energy equation) by Athay (1990) and Ji et al. (1996) suggest that it may provide a solution to this long standing problem, and might even solve the puzzle posed by the relatively invariant shape of the emission measure distribution.
- Which physical process – presumably chromospheric – underlies the well-known FIP effect (Geiss 1982, the chromospheric context is reviewed by Judge & Peter 1998)?

The stark contrast between the observed large-scale organization of the corona represented by figures such as fig. 7 and the fine, time-varying spatial scales of their foot-points represented by fig. 6 suggests to me that there are two, probably related, key challenges: what controls the thermal structure *across* the field lines (Litwin & Rosner 1993), and what is the nature of the coupling of the corona to the underlying layers (Athay 2000)?

4. The Stars As A Guide To The Sun

This discussion would be incomplete without a brief mention of how stellar data can help address some of the difficult problems. Much of this is repeating long-held opinions through the cool star community, but it is worth re-emphasizing and putting into the solar context. Several important avenues for research should be pursued. First, any information concerning the surface magnetic structure of any star other than the Sun is going to help us to understand dynamo models. The established techniques of Doppler imaging and especially the emerging technique of Zeeman Doppler imaging hold great promise for us to derive (albeit crude) diagrams of the emergence and structure of stellar surface fields analogous to those shown in Figure 1. These will be invaluable for our fundamental understanding of the solar dynamo, in that such data can address some of the difficult unresolved issues concerning the storage, amplification and emergence of magnetic fields throughout stellar interiors. Second, the stellar cyclic activity studies made with the Mt. Wilson survey data are beginning to yield real challenges for our understanding of large-scale, cyclic dynamos, including that of the Sun (e.g., Charbonneau & Saar 2001). These should continue to be aggressively pursued. Third, the M dwarfs near the fully convective state (spectral type M3.5) should be studied to see evidence for magnetic activity cycles, even though they are very faint. This might help us understand the central rôle of the toroidal flux rope that is currently believe to be a centerpiece of solar dynamo models.

Acknowledgments. I am very grateful to Karel Schrijver, Alan Title, Gøran Scharmer & colleagues, for providing me with excellent animation material immediately prior to the meeting. I remain indebted to Paul Charbonneau for his enthusiastic willingness to share his expertise, especially concerning dynamo problems.

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A Web Resources

Much of the phenomena discussed here are intrinsically very small scale and highly dynamic in nature. The following URL's point to animations that highlight the small scale dynamics of the solar atmosphere.

Animations of magneto-convection and small-scale dynamo models:

`http://astro.uchicago.edu/Computing/` University of Chicago numerical simulations homepage. *3D Magneto-convection and fast dynamo simulations in Boussinesq fluids.*

`http://www.journals.uchicago.edu/ApJ/journal/issues/ApJ/v495n1/35939/video.html` Ap. J. animation. *2D simulations of magneto-convection including radiation transfer by Steiner et al. (1998).*

Photosphere and chromosphere:

`http://dot.astro.uu.nl/` Dutch Optical Telescope homepage. *High resolution filter-gram images and movies of G-band and chromospheric (mostly Ca II H, some H-α) data, 1-3 hour movies, typically* 60×30 *arcsecond*^{2} *field of view.*

`http://www.astro.su.se/English/groups/solar/solar.html` Swedish Vacuum Solar Telescope (SVST) homepage, and the New Swedish Solar Telescope. *Links to images and movies of photosphere and chromosphere from the SVST, including some new adaptive optics corrected data.*

`http://www.sunspot.noao.edu/AOWEB/index.html` NSO adaptive optics website. *A description of the adaptive optics project at the Dunn Solar Telescope (DST) at Sacramento Peak Observatory, demonstrating the power and importance of this technique for present and future observations.*

`http://www.lmsal.com/LaPalma/` Lockheed-Martin Solar and Astrophysics Lab ground based website, based on SVST observations. *More SVST images and movies, including connections to* TRACE *of 2-3 hour duration and 2-4 arc-minute fields of view, and close-ups of the dynamics of moss and the chromosphere/corona interface (section 3.3.).*

Transition region and corona:

`http://vestige.lmsal.com/TRACE/` TRACE web site *Many animations of coronal and transition region dynamics from the* TRACE *spacecraft.*

The future. Among many other planned projects, perhaps the most relevant to the issues addressed in this review is:

`http://www.sunspot.noao.edu/ATST/index.html` ATST web site *The 4m-class Advanced Technology Solar Telescope (ATST) currently represents the 10+ year future of ground-based solar observatories devoted to studying the kind of scientific issues discussed in section 3..*

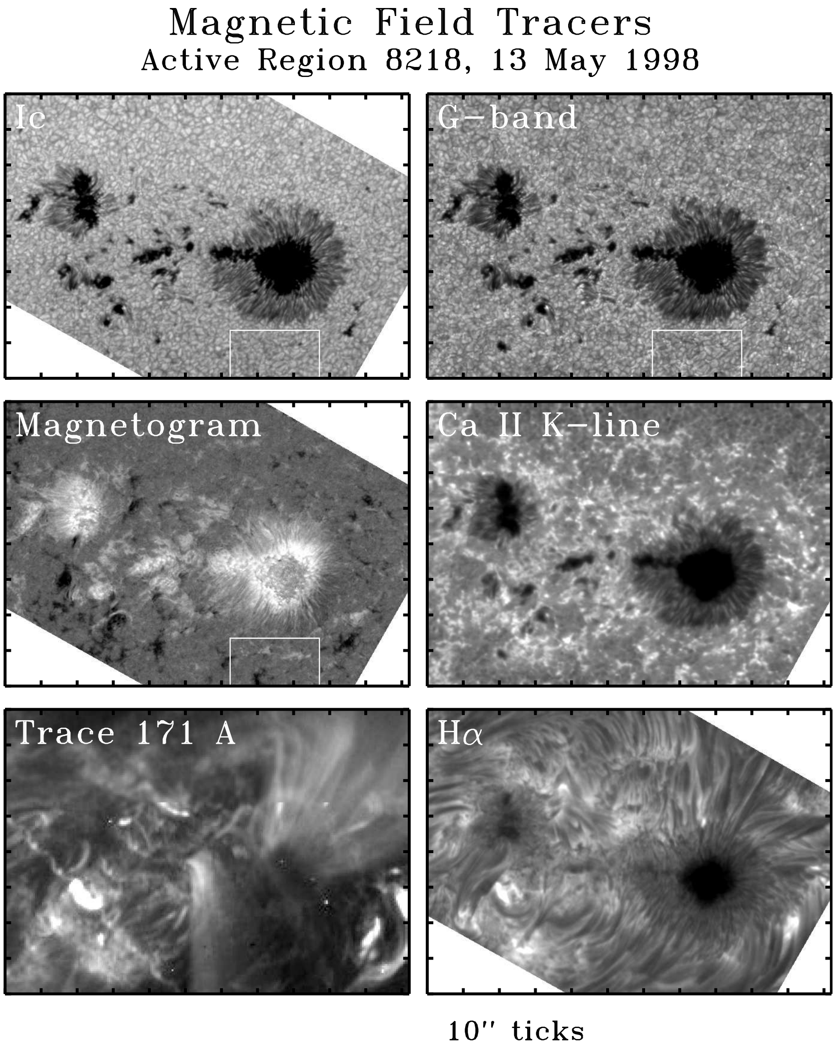

Figure 5. Monochromatic images at a variety of wavelengths indicate the location (in the photosphere) and the topology (above the photosphere) of the magnetic field without the actual measurement of the field itself. Brightenings in the G-band frequently reveal the location of intense photospheric flux tubes, while more diffuse chromospheric emission in the Ca II K-line also overlies locations of magnetic flux. Notice that the Sun has somehow picked several particular footpoints from which particularly prominent 171 Å (10^6 K) emitting loops emerge, and not others. Figure prepared by B. W. Lites.

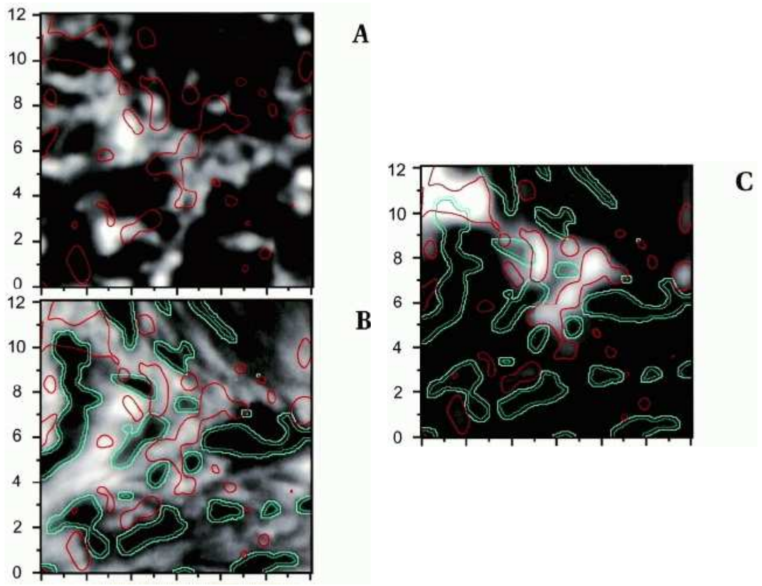

Figure 6. (A) SVST Ca II K-line image, bright areas demarcate the location of magnetic elements in the lower chromosphere, red contours outline the regions of bright moss emission defined from the TRACE 171 image shown in C. (B) Same region seen in a summed image of SVST Hα -350 and +350 mÅ filter-grams, green contours outline dark areas of increased absorption which demarcate transient "jets" of chromospheric plasma. (C) TRACE Fe IX/Fe X 171 Å image. From Berger et al. (1999).

Figure 7. An early false-color image of an active region observed with *TRACE*, taken from the *TRACE* image web site. The 171/195/284 bands are shown as blue/green/red, reflecting gas that emits Fe IX + Fe X / Fe XII / Fe XV respectively. Notice that the Sun has somehow organized itself to emit radiation from ions formed at different temperatures in physically distinct, but quite large volumes (the image is mostly colorful, not just shades of gray).