The Solar-Stellar Connection: Our New Sun
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Abstract. Our view of the Sun has changed dramatically over the past 10 years due mainly to a series of space satellites such as Yohkoh, SoHO and TRACE. This state of ferment will continue with the coming onto line last year of two other satellites, Hinode and STEREO, and next year SDO. Here we give a brief overview of the progress made in answering fundamental questions about the nature of the Sun which may have profound implications for other stars.

In the interior, helioseismology has revealed the internal rotation structure and suggested that the main solar dynamo responsible for active regions is located at the tachocline, although the details are highly uncertain and there may be a second dynamo responsible for generating small-scale ephemeral regions. In the photosphere, flux is mainly concentrated at the edges of supergranule cells, but recent high-resolution observations have suggested that extra flux is also located at granulation boundaries and Hinode has discovered much horizontal flux.

The solar corona is likely to be heated in myriads of tiny current sheets by reconnection, according to the Coronal Tectonics Model. Observations suggest that all the coronal field lines reconnect every 1.5 hours. Theory has shown that reconnection in 3D has many features that are completely different from the standard 2D picture. The solar wind is highly dynamic and complex and its acceleration mechanism may possibly be high-frequency ion-cyclotron waves. Many new features of solar flares and coronal mass ejections have been discovered, but it is not known whether the cause of the eruption is an instability or a lack of equilibrium.

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1. INTRODUCTION

I too would like to welcome you warmly to St Andrews. I was happy to play a part in bringing Keith, Andrew and Moira to St Andrews about 15 years ago and am thrilled to see how astronomy is now flourishing here. My interest in the solar-stellar connection was first stimulated at the workshop in Bonas in 1980 (see Figure 1 in which you will notice on the front row a youthful Roger Bonnet and an elegant Andrea Dupree).

The revolution in solar physics over the past 10 years has produced many advances in understanding which have profound implications for other stars. Most of the fundamental questions about the Sun have not yet been answered fully, but major progress has been made. Here I aim to give a brief overview of the new Sun revealed by these advances (mentioning especially contributions from the solar group here), but I shall leave you to make your own connections to other stars since hopefully these will be self-evident.

The solar MHD theory group in St Andrews consists of 8 tenured staff, half a dozen postdocs and 15 PhD students – particularly noteworthy are the new young permanent members (Clare Parnell, Duncan Mackay and Ineke De Moortel), of whom I expect you to hear a great deal over the years to come.

We are located in the Maths Department and, indeed, traditionally there has been a
close link between mathematics and astronomy. The first professor of mathematics here was James Gregory (1638-1675), who invented the gregorian telescope and was one of the founders (with Newton and Leibniz) of calculus. He was the first to write down Taylor expansions, to prove that differentiation and integration are the inverse of one another and to use change of variable in integration. You can look around the library during your stay which was originally Gregory’s laboratory, on whose floor you can see the meridian line that he laid down (Figure 2).

The recent advances in understanding have come from a combination of theoretical
modelling, ground-based and space observations. Yohkoh (1992-2002) showed to us the dynamic nature of the corona in soft and hard x-rays, while SoHO (1995-...) has revealed both the interior and atmosphere in great detail, and TRACE (1998-...) showed up the fine-scale structure of the atmosphere. Last year two other missions came on line: Hinode is using its optical and x-ray telescopes and EUV imaging spectrometer (on which MSSL in the UK is PI) to determine high-resolution connections between photosphere and corona; and STEREO consists of a pair of spacecraft that are giving stereoscopic images of the corona and coronal mass ejections.

2. SOLAR INTERIOR

The overall structure of the Sun is that the interior consists of a core out to 0.25 R⊙ and a turbulent convective zone stretching from 0.7 R⊙ to the surface. The atmosphere includes the photosphere at a temperature of about 6000 K, an overlying warmer and rarer chromosphere, and a very much hotter corona. So let me describe some advances in each of these regions.

First of all, several million global modes of oscillation of the Sun have now been discovered with amplitudes of typically a few mm s⁻¹ and the techniques of helioseismology have been used to deduce the structure of the solar interior for the first time. The internal temperature agrees with the standard solar model to less than 1%, although there are uncertainties near the base of the convection zone, as well as near the poles and in the deep interior.

At the solar surface, the equator rotates more rapidly than the poles, and before the results of helioseismology it was expected that the internal rotation would be constant on cylinders and that the magnetic field would be generated throughout the convection
zone by a dynamo that was driven by an increase with depth of the rotation. However, helioseismology has given a big surprise (Figure 3), namely, that the rotation is constant on radial lines (i.e., on cones) in the convection zone. Also, there is a strong shear layer at the base of the convection zone, known as the tachocline, and the interior rotates fairly uniformly at a rate that is intermediate between the surface equatorial and polar regions.

The site of the main dynamo responsible for sunspots and active regions is now thought to be the tachocline, but the details are very uncertain [1]. In particular, there is debate over the nature of the instability at work and over the validity of mean-field theory. In addition, the details of the coupling of the tachocline to the solar interior and convection zone are unknown and the closure in the convection zone of the observed surface meridional flow (towards the poles) has not yet been observed.

3. PHOTOSPHERE

The photosphere is covered with turbulent convection cells, including granulation with a size of 1Mm and longer-lived supergranulation with a scale of 15 Mm. Simulations by Bob Stein [2] have shown that there is a smooth spectrum of scales rather than two discrete scales, and the dominant scale increases continuously with depth.

Photospheric magnetograms such as Figure 4, in which white and black represent positive and negative magnetic field, respectively, reveal active region bands. However, they also show the presence of tiny regions of intense magnetic field covering the whole Sun and varying only weakly with the solar cycle. They are mainly vertical and are concentrated preferentially at supergranule boundaries; they arise from tiny ephemeral regions and are likely to be produced by a separate dynamo from active regions that is located either just below the solar surface or throughout the convection zone.
New white-light observations at 0.1 arcsec from the Swedish solar telescope (Figure 5) have shown that granules are surrounded by bright structures (points, lines and wiggles or flowers) that are probably associated with magnetic fields [3]. Furthermore, Clare Parnell and coworkers have analysed Hinode observations of line-of-sight magnetic fields at 0.1 arcsec and found 30% more flux than with SoHO MDI, much of it in the interiors of supergranules and with a distribution that is a power law [4]. Another discovery from Hinode by [5] is the surprising presence of large amounts of horizontal flux in the photosphere. It has a mean value of 50 G (compared with 10 G for vertical flux) and is located inside and on the edges of granules (compared with a location in the intergranular lanes for vertical fields).

Going up in the atmosphere, [6] have undertaken radiative MHD simulations of the chromosphere and corona in response to weak granular motions in the photosphere. They find that the overlying atmosphere is not in static plane layers, but instead is highly dynamic as it heaves up and down in response to the granulation (Figure 6).

### 4. THREE-DIMENSIONAL RECONNECTION

Impressive MHD simulations have also been undertaken in 3D of magnetic flux emergence by Alan Hood and Vasilis Archontis at St Andrews and their collaborators [7, 8]. They are able to explain the formation of the ubiquitous x-ray and chromospheric jets that are present in Hinode observations and show how dynamic heating by reconnection can occur in the corona.

3D reconnection possesses many new features that are not present in 2D [9]. In 2D, reconnection can only take place at X-type null points where the magnetic field vanishes, and during reconnection the magnetic field lines slip through the plasma in...
the diffusion region and change their connections only at the X-point. By comparison, in 3D, reconnection can take place either at null points or at non-null regions called quasi-separatrix layers [10, 11, 12, 13]. Also, in 3D the field lines continually change their connections in the diffusion region, and flux tubes are seen to split, flip and do not necessarily rejoin perfectly [14].

In 3D, it has also proved important to determine the magnetic topology of the field. In 2D, imagine the coronal field due to four sunspots of alternating polarity in a line (Figure 7a): there will be an X-point from which emanates 4 field lines, called separatric curves, which separate the region into topologically separate regions, in the sense that in one particular region all the field lines will start at a given sunspot and end at the
same one. Now, in 3D, there are instead *separatrix surfaces*, which separate the coronal volume into topologically distinct parts: these separatrix surfaces consist of field lines and intersect in a special field line, called a *separator* [15, 16], that goes from one null point to another.

2D reconnection transfers flux through the X-point across the separatrix curves, whereas 3D reconnection transfers flux through the separator (or quasi-separator) across the separatrix (or quasi-separatrix) surfaces. Clare Parnell, Rhona Maclean and Andrew Haynes in St Andrews are developing codes that will be invaluable in calculating the webs of separatrix and quasi-separatrix surfaces – the so-called *skeleton* – for magnetic configurations from numerical experiments or in potential or force-free extrapolations.

5. CORONA

How is the corona heated? Clare Parnell and her research student (Robert Close) have constructed the coronal field lines from observed magnetograms (Figure 8) and shown how at low heights the field is extremely complex, whereas at higher locations it becomes simpler. They also followed the motion of the photospheric magnetic fragments and recalculated the coronal field lines in order to estimate the time required for all the coronal field lines to reconnect and change their photospheric connections – they were amazed to find that this is only 1.5 hours [17], so there is an incredible amount of reconnection continually taking place in the corona.

This provided the basis for the Coronal Tectonics model for coronal heating [18], which is a next-generation development of Parker’s nanoflare idea. Each coronal loop that we currently observe (even the finest in TRACE) consist of many subloops, since the magnetic flux in the loop reaches down to the solar surface in many magnetic sources. The fluxes from each source are separated by separatrix surfaces and so, as the sources move around, current sheets appear on the surfaces and lead to reconnection and heating. Thus the corona is filled with myriads of current sheets heating impulsively. The coronal tectonics mechanism is much more efficient than Parker’s mechanism, since the latter
requires complex braiding motions to produce current sheets whereas separatrix current sheets will form in response to much simpler motions.

Clare Parnell and Andrew Haynes and co-workers have modelled an elementary heating event driven by the "flyby" of one photospheric source past another of opposite polarity in an overlying horizontal field [19, 20, 21]. Initially, the two sources were not joined, but in response to their motion coronal reconnection produced connections between them. Surprisingly, the process of reconnection was much more complex than expected, as can be seen in the vertical sections through the configuration (Figure 9). Initially, two separatrix surfaces can be seen, one arching above each source, and as time progresses these surfaces intersect one another in complex ways to produce reconnection at two, one, five, three and one separator in turn.

Other aspects of the corona being studied at St Andrews include: modeling the global evolution of the Sun’s surface magnetic field and deducing the overlying nonlinear force-free field in order to deduce the location and chirality of prominences (Mackay and Yeates); using techniques of coronal seismology to deduce the properties of the corona from observed oscillations (De Moortel and Roberts).

**6. SOLAR WIND**

Ulysses has revealed that at solar minimum there is fast solar wind at 700 km s\(^{-1}\) coming from coronal holes near the poles, together with slow solar wind at 300 km s\(^{-1}\) coming from coronal streamers, as well as a nonsteady component due to coronal mass ejections. At solar minunum, on the other hand, the solar wind is much more sporadic and irregular. In either case, the mechanisms for accelerating the winds have not yet been identified, although an interesting possibility is by high-frequency ion-cyclotron
waves that have cascaded from lower-frequency Alfvén waves. Indeed, recent evidence from Hinode for such Alfvén waves has been obtained by [22] in terms of movies of the chromosphere at the solar limb, in which spicules give the appearance of grass waving to and fro. Furthermore, [23] has discovered strong persistent outflows from active regions at 140 km s\(^{-1}\) which may supply a quarter of the solar wind.

7. FLARES AND CORONAL MASS EJECTIONS

The cause of the eruption that is at the core of a large solar flare or a coronal mass ejection (Figure 10) has not yet been identified — it may be either an instability such as kink instability or a nonequilibrium or catastrophe process [24]. In St Andrews we are working on various aspects of the flare process, including: the storage of preflare energy in a nonlinear force-free field (Regnier); the magnetic topology (Maclean and Parnell); the 3D reconnection process (Priest, Parnell and colleagues in Dundee); and particle acceleration mechanisms, such as a DC electric field or a collapsing trap (Neukirch).

8. CONCLUSIONS

Solar physics is currently enjoying a golden age stimulated by space observations, with the result that huge progress has been made on the fundamental questions: the main dynamo responsible for sunspots is based in the tachocline but is not a simple \(\alpha\)-\(\omega\) model; magnetic flux emerges through the photosphere over a wide range of scales and creates many small regions of horizontal flux in the quiet Sun; the corona has a highly complex topology and may well be heated by the Coronal Tectonics mechanism; the solar wind is highly variable, with an unknown acceleration mechanism; the solar flare
mechanism has many complex parts; and magnetic reconnection in 3D is completely different from 2D.

I would encourage you over the next few years to forge links with solar physicists, so that together we may make further progress on these major issues, but in the meantime please enjoy your week in St Andrews.

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REFERENCES