Introduction: Astrophysical processes on the Sun

Author(s): Clare E. Parnell

Source: *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, 13 July 2012, Vol. 370, No. 1970, Astrophysical processes on the Sun (13 July 2012), pp. 3043-3048

Published by: Royal Society

Stable URL: https://www.jstor.org/stable/23250385

REFERENCES
Linked references are available on JSTOR for this article:
https://www.jstor.org/stable/23250385?seq=1&cid=pdf-
reference#references_tab_contents
You may need to log in to JSTOR to access the linked references.

INTRODUCTION

Astrophysical processes on the Sun

BY CLARE E. PARNELL*

School of Mathematics and Statistics, University of St Andrews, North Haugh, St Andrews KY16 9SS, UK

Over the past two decades, there have been a series of major solar space missions, namely Yohkoh, SOHO, TRACE, and in the past 5 years, STEREO, Hinode and SDO, studying various aspects of the Sun and providing images and spectroscopic data with amazing temporal, spatial and spectral resolution. Over the same period, the type and nature of numerical models in solar physics have been completely revolutionized as a result of widespread accessibility to parallel computers. These unprecedented advances on both observational and theoretical fronts have led to significant improvements in our understanding of many aspects of the Sun's behaviour and furthered our knowledge of plasma physics processes that govern solar and other astrophysical phenomena. In this Theme Issue, the current perspectives on the main astrophysical processes that shape our Sun are reviewed. In this Introduction, they are discussed briefly to help set the scene.

Keywords: Sun; astrophysics; magnetic fields; dynamo; corona; flares

1. Dynamos and magneto-convection

The nuclear core at the centre of the Sun is surrounded by a fairly rigidly rotating radiative zone, above which lies a convection zone. However, this is not true of all stars. Low mass ($\lesssim 0.35$ solar masses $M_\odot$) main sequence stars of spectral class M3 and greater, such as red dwarfs, are convective throughout their interiors [1,2], as are pre-main-sequence stars on the Hayashi track. Main sequence stars with masses in the range $0.35 \lesssim M_\odot \lesssim 2$ (i.e. spectral class M3 to A2 with effective temperatures between 3200 and 9000 K) have a radiative zone surrounded by a convection zone [2], although the proportional sizes of these two zones vary. For instance, main sequence stars—such as the Sun, with spectral class F2 to A2 (effective temperatures from 7000 to 9000 K)—have shallow convective envelopes. On the other hand, in warmer, more massive, main sequence stars, energy transport is dominated by radiation throughout the interior of the star. These changes in behaviour in the interior of the star have a marked effect on the typical magnetic field strength and magnetic activity of the star. Indeed, by comparing the Stokes V and I parameters with a number of stars, Reiners & Basri [1] find

*clare@mcs.st-and.ac.uk

that fully convective stars appear to have less dominant large-scale fields and more small-scale, mixed polarity fields than solar-like stars, thus indicating that dynamo action within such stars may be different.

As the recent, and unexpectedly low, solar minimum from 2007 to 2010 has reminded us, understanding the true nature of the solar dynamo is not easy, not only because of the opaqueness of the solar interior but also because the global evolution of the Sun's magnetic field is highly dynamic and unpredictable. For the Sun, the interface between the radiative zone and the convection zone—known as the tachocline—plays an important role and is the likely location for the generation of the large-scale sunspot-forming magnetic fields. However, dynamo action is not restricted to the tachocline, as new global and local numerical experiments of the convection zone—coupled with observations—are showing us. Instead, turbulent convection operates in a highly complex system where rotational shear, global circulation and boundary conditions on local and global scales are all important. Miesch [3], describes the complexities behind the generation mechanisms of the Sun's magnetic field and explains the circulatory patterns within the solar interior.

Stein [4] focuses on the role of magneto-convection and explains the coupled behaviour of a fluid (plasma) undergoing convection and the magnetic field that permeates the fluid. Within the many stars that have no radiative zone, the dynamo action driven by magneto-convection is the likely magnetic field generation mechanism, and it is shown that this can produce both large- and small-scale fields. Obviously, where the magnetic fields are weak, the fluid motions dominate, dragging the field with them, but if sufficiently strong fields are generated then the fluid motions may be restricted by magnetic forces. Understanding this intricate coupling between the magnetic field and the plasma is key to determining the consequences of convective behaviour in stars.

2. Sunspots and surface magnetic fields

The largest magnetic features on the Sun's surface are sunspots. Large sunspots and sunspot groups may be seen with the naked eye (although this is definitely not a good idea), with the earliest recorded observation dating back to the fourth century BC by Chinese astronomer Gan De [5, p. 549], who correctly recognized them as a solar phenomenon. Many centuries later, the West eventually acknowledged the existence of sunspots, post Galileo, and there have been continuous sunspot observations for more than 160 years, starting in 1849 at the Zurich Observatory.

The Sun is not unique in having spots. Numerous observations have been made of starspots on a range of other stars [6,7]. The sizes, locations and lifetimes of starspots can be significantly different from those of sunspots. Indeed, young Sun-like stars appear to have massive starspots (or clusters of starspots) that may cover up to 50 per cent of their surfaces [8]. Both starspots and sunspots are created by the emergence of magnetic flux from the interior of the star through its surface.

The process of flux emergence is considered by Archontis [9]. Here, the non-trivial mechanism by which an omega-shaped magnetic loop fully emerges through the photosphere (the Sun's surface) to produce a pair of opposite

polarity sunspots is considered. Furthermore, the effects of this emergence on the integrity of the flux tube and the consequences of the subsequent interaction of the newly emerged flux with the surrounding pre-existing magnetic field are discussed.

Sunspots are cooler than their surroundings and so, in the Sun's photosphere, they appear as dark patches when observed in white light. This is due to an absence or depletion in the observed light; thus, measuring their magnetic field strength on distant stars is not easy. On the Sun, however, new telescopes have revealed their amazingly intricate and detailed structure. Equally surprising is that now many of these details can be reproduced, such as the multi-angled penumbral field, light bridges and complex flow patterns found in observed sunspots. Rempel [10] shows the latest results from sunspot modelling and discusses the key physics behind the complex structure of sunspots.

3. Solar atmosphere

Flux emergence on the Sun occurs on a wide range of scales producing magnetic features with fluxes ranging over five to six orders of magnitude, from 10^{20}–10^{21} Mx down to 10^{15}–10^{16} Mx and probably even weaker. Rutten [11] gives an overview of the quiet-Sun photosphere and chromosphere (the atmospheric layer above the photosphere). The quiet-Sun photosphere is characterized by a carpet of small-scale magnetic features with fluxes around 10^{18} Mx and less. The entire surface of some stars appears to be covered with similar carpets of mixed polarity flux, with no evidence of starspots [1]. In such stars, the photosphere and the overlying chromosphere may well be home to a range of highly dynamic phenomena that result from the continuous moving, shredding, coalescing and cancelling of the magnetic fields that thread the surface, as is observed on the Sun. Such behaviour is driven by the overshoots of convection cells from below the surface and results in ceaseless chromospheric upflows and downflows with a range of different speeds, frequencies and lifetimes. These flows, which may be important for energy transport in the solar atmosphere, are now beginning to be understood with the use of advanced numerical codes which, by necessity, must consider more complex physics than magnetohydrodynamic (MHD).

On larger scales, the behaviour of global magnetic fields of stars [12,13] and the Sun [14,15] has been modelled using a combination of surface flux transport and potential flux source surface models. These potential models have been used to explain the structures and emission observed in solar and stellar coronae and to determine the amount of open flux from the Sun. Potential magnetic fields are field configurations with the lowest magnetic energy and thus such fields cannot be responsible for highly energetic events such as solar flares and coronal mass ejections (CMEs). Mackay [16] describes the new generation of solar global field models in which stresses may be built up over months, producing nonlinear force-free magnetic fields. Not surprisingly, these models are much more successful in determining the location and chirality (twistedness) of filaments (prominences) and also in identifying which filaments may erupt forming CMEs. They are also better at predicting the amount of open flux from the Sun, demonstrating the importance of going beyond potential models.

4. Fundamental plasma processes

Magnetic fields embedded in a plasma are affected by two fundamental plasma physics processes: magnetic reconnection and MHD waves. The process of magnetic reconnection is one in which magnetic currents can be dissipated and magnetic fields may be permitted to globally restructure, thus reducing the magnetic energy of the system. This magnetic energy is converted to thermal energy, bulk acceleration of the plasma, as well as particle acceleration. Pontin [17] focuses on magnetic reconnection in three dimensions, revealing the wide range of types of reconnection, as well as the numerous magnetic field configurations in which they can occur. Reconnection was first proposed as a mechanism for powering solar flares, and so, naturally, it is likely to be a key mechanism for stellar flares. It is also likely to be important in heating solar and stellar coronae, and to be the key to many other astrophysical processes. Examples include the acceleration of jets from active galactic nuclei and gamma ray bursts [18–20] and the heating of the warm-ionized medium of galaxies [21].

Traditionally, the study of MHD waves has focused predominantly on those waves found in plane parallel media, such as fast and slow magnetic acoustic waves and Alfvén waves. However, attention is increasingly turning to understanding the wave types and their behaviour in nonlinear three-dimensional media. In particular, the latest suite of space- and ground-based telescopes now regularly observes a wide range of wave modes, including Alfvénic waves and kink modes, which, as discussed by De Moortel and Nakariakov [22] may well play important roles in a wide range of different solar phenomena. Although extremely difficult to observe, waves will inevitably be present in almost all astrophysical objects, and so their existence and importance should not be forgotten when seeking explanations to observed astrophysical phenomena.

5. Atmospheric heating and flares

The high average temperatures seen in the outer atmosphere (corona) of the Sun are some 150–200 times hotter than the surface of the Sun, but the average coronal temperature of other, more rapidly, rotating stars can be a factor of 40 or more higher still. Pevtsov *et al.* [23] have shown that the average temperature of a star's corona is proportional to the strength of its magnetic field. This is clear from the Sun too, where the average coronal temperature is observed to be proportional to photospheric flux [24]. The nature of the magnetic activity on stars changes as the star loses angular momentum. Young, rapidly rotating stars show much larger and more frequent flares than the Sun, and they have a significantly stronger hard X-ray spectral irradiance. As the star ages and slows, magnetic activity decreases and the dominant coronal emission comes more from quiescent heating rather than flares [25–27].

Parnell and De Moortel [28] present a contemporary review of coronal heating. It is now very clear that the heating of the corona cannot be considered in isolation, but is intrinsically linked to the heating of the chromosphere. These two regions form a strongly coupled system with heat transferred back and forth between them. The most likely heating mechanisms are described along with the supporting observations.

Although solar flares require large-scale and intense regions of magnetic fields, they are distinct from coronal heating. During a solar minimum, many months and sometimes several years may pass without a solar flare, but the corona is maintained at a temperature of around a million degrees throughout each minimum. Furthermore, the frequency of flares is insufficient and their distribution too patchy to account for the heating of the entire corona. However, solar flares do result in enormous amounts of energy released very rapidly. In fact, they are some of the most spectacular events occurring on the Sun, but even larger stellar flares have been observed. A number of superflares, bright enough to be mistaken as gamma ray bursts and with increases in soft X-ray luminosity of more than a factor of 100 compared with the normal value, have been observed, e.g. on young rapidly rotating flare stars [29,30] and magnetars [31,32].

Flares are typically associated with a major global restructuring of the magnetic field and they result in local heating of the corona and chromosphere, but also the acceleration of huge numbers of particles producing hard X-ray and gamma ray radiation. Finally, Vilmer [33] describes solar flares with a particular emphasis on particle acceleration, including both the latest observational and theoretical highlights.

Together, the articles in this Theme Issue of *Philosophical Transactions of the Royal Society A* provide a fascinating and up-to-date overview of many of the key astrophysical processes that occur not only on the Sun but also on many, if not most, other stars.

References

1 Reiners, A. & Basri, G. 2009 On the magnetic topology of partially and fully convective stars. *Astron. Astrophys.* **496**, 787–790. (doi:10.1051/0004-6361:200811450)

2 Schrijver, C. J. 2009 On a transition from solar-like coronae to rotation-dominated Jovian-like magnetospheres in ultracool main-sequence stars. *Astrophys. J. Lett.* **699**, L148–L152. (doi:10.1088/0004-637X/699/2/L148)

3 Miesch, M. S. 2012 The solar dynamo. *Phil. Trans. R. Soc. A* **370**, 3049–3069. (doi:10.1098/rsta.2011.0507)

4 Stein, R. F. 2012 Magneto-convection. *Phil. Trans. R. Soc. A* **370**, 3070–3087. (doi:10.1098/rsta.2011.0533)

5 Moore, P. 2011 *Patrick Moore's data book of astronomy.* Bristol, UK: Canopus Publishing Limited.

6 Berdyugina, S. V. 2005 Starspots: a key to the stellar dynamo. *Living Rev. Solar Phys.* **2**, 8.

7 Thomas, J. H. & Weiss, N. O. 2008 *Sunspots and starspots.* Cambridge, UK: Cambridge University Press.

8 Schrijver, C. J. 2002 Solar spots as prototypes for stellar spots. *Astron. Nachr.* **323**, 157–164. (doi:10.1002/1521-3994(200208)323:3/4<157::AID-ASNA157>3.0.CO;2-Q)

9 Archontis, V. 2012 Magnetic flux emergence and associated dynamic phenomena in the Sun. *Phil. Trans. R. Soc. A* **370**, 3088–3113. (doi:10.1098/rsta.2012.0001)

10 Rempel, M. 2012 Numerical models of sunspot formation and fine structure. *Phil. Trans. R. Soc. A* **370**, 3114–3128. (doi:10.1098/rsta.2011.0556)

11 Rutten, R. J. 2012 The quiet-Sun photosphere and chromosphere. *Phil. Trans. R. Soc. A* **370**, 3129–3150. (doi:10.1098/rsta.2011.0537)

12 Hussain, G. A. J., van Ballegooijen, A. A., Jardine, M. & Collier Cameron, A. 2002 The coronal topology of the rapidly rotating K0 dwarf AB doradus. I. Using surface magnetic field maps to model the structure of the stellar corona. *Astrophys. J.* **575**, 1078–1086. (doi:10.1086/341429)

13 Mackay, D. H., Jardine, M., Collier Cameron, A., Donati, J.-F. & Hussain, G. A. J. 2004 Polar caps on active stars: magnetic flux emergence and transport. *Mon. Not. R. Astron. Soc.* **354**, 737–752. (doi:10.1111/j.1365-2966.2004.08233.x)

14 Wang, Y.-M., Lean, J. & Sheeley, N. R. 2000 The long-term variation of the Sun's open magnetic flux. *Geophys. Res. Lett.* **27**, 505–508. (doi:10.1029/1999GL010744)

15 Schrijver, C. J. & De Rosa, M. L. 2003 Photospheric and heliospheric magnetic fields. *Solar Phys.* **212**, 165–200. (doi:10.1023/A:1022908504100)

16 Mackay, D. H. 2012 The Sun's global magnetic field. *Phil. Trans. R. Soc. A* **370**, 3151–3168. (doi:10.1098/rsta.2011.0536)

17 Pontin, D. I. 2012 Theory of magnetic reconnection in solar and astrophysical plasmas. *Phil. Trans. R. Soc. A* **370**, 3169–3192. (doi:10.1098/rsta.2011.0501)

18 Romanova, M. M. & Lovelace, R. V. E. 1992 Magnetic field, reconnection, and particle acceleration in extragalactic jets. *Astron. Astrophys.* **262**, 26–36.

19 Drenkhahn, G. & Spruit, H. C. 2002 Efficient acceleration and radiation in Poynting flux powered GRB outflows. *Astron. Astrophys.* **391**, 1141–1153. (doi:10.1051/0004-6361:20020839)

20 Giannios, D. 2010 UHECRs from magnetic reconnection in relativistic jets. *Mon. Not. R. Astron. Soc.* **408**, L46–L50. (doi:10.1111/j.1745-3933.2010.00925.x)

21 Reynolds, R. J., Haffner, L. M. & Tufte, S. L. 1999 Evidence for an additional heat source in the warm ionized medium of galaxies. *Astrophys. J. Lett.* **525**, L21–L24. (doi:10.1086/312326)

22 De Moortel, I. & Nakariakov, V. M. 2012 Magnetohydrodynamic waves and coronal seismology: an overview of recent results. *Phil. Trans. R. Soc. A* **370**, 3193–3216. (doi:10.1098/rsta.2011.0640)

23 Pevtsov, A. A., Fisher, G. H., Acton, L. W., Longcope, D. W., Johns-Krull, C. M., Kankelborg, C. C. & Metcalf, T. R. 2003 The relationship between X-ray radiance and magnetic flux. *Astrophys. J.* **598**, 1387–1391. (doi:10.1086/378944)

24 Fisher, G. H., Longcope, D. W., Metcalf, T. R. & Pevtsov, A. A. 1998 Coronal heating in active regions as a function of global magnetic variables. *Astrophys. J.* **508**, 885–898. (doi:10.1086/306435)

25 Güdel, M., Audard, M., Kashyap, V. L., Drake, J. J. & Guinan, E. F. 2003 Are coronae of magnetically active stars heated by flares? II. Extreme ultraviolet and X-ray flare statistics and the differential emission measure distribution. *Astrophys. J.* **582**, 423–442. (doi:10.1086/344614)

26 Guinan, E. F., Ribas, I. & Harper, G. M. 2003 Far-ultraviolet emissions of the Sun in time: probing solar magnetic activity and effects on evolution of paleoplanetary atmospheres. *Astrophys. J.* **594**, 561–572. (doi:10.1086/376859)

27 Ribas, I., Guinan, E. F., Güdel, M. & Audard, M. 2005 Evolution of the solar activity over time and effects on planetary atmospheres. I. High-energy irradiances (1–1700 Å). *Astrophys. J.* **622**, 680–694. (doi:10.1086/427977)

28 Parnell, C. E. & De Moortel, I. 2012 A contemporary view of coronal heating. *Phil. Trans. R. Soc. A* **370**, 3217–3240. (doi:10.1098/rsta.2012.0113)

29 Favata, F., Flaccomio, E., Reale, F., Micela, G., Sciortino, S., Shang, H., Stassun, K. G. & Feigelson, E. D. 2005 Bright X-ray flares in orion young stars from COUP: evidence for star-disk magnetic fields? *Astrophys. J. Suppl.* **160**, 469–502. (doi:10.1086/432542)

30 Osten, R. A. *et al.* 2010 The mouse that roared: a superflare from the dMe flare star EV lac detected by swift and konus-wind. *Astrophys. J.* **721**, 785–801. (doi:10.1088/0004-637X/721/1/785)

31 Hurley, K. *et al.* 2005 An exceptionally bright flare from SGR 1806-20 and the origins of short-duration γ-ray bursts. *Nature* **434**, 1098–1103. (doi:10.1038/nature03519)

32 Giannios, D. 2010 Superflares from magnetars revealing the GRB central engine. *Mon. Not. R. Astron. Soc.* **403**, L51–L53. (doi:10.1111/j.1745-3933.2010.00813.x)

33 Vilmer, N. 2012 Solar flares and energetic particles. *Phil. Trans. R. Soc. A* **370**, 3241–3268. (doi:10.1098/rsta.2012.0104)