Magnetohydrodynamics of Stellar Interiors

6 September to 17 December 2004

Report from the Organisers:
DW Hughes (Leeds), R Rosner (Chicago) and NO Weiss (Cambridge)

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NO Weiss, R Rosner and DW Hughes

Scientific Background

At the heart of all observed stellar magnetic activity – whether as dark spots, bright flares or X-ray emission from a hot corona – lies the dynamical behaviour of the magnetic field in a star's interior. This programme focussed on the complex nonlinear interactions between convection, rotation and magnetic fields in the interiors of stars with deep outer convection zones, like the Sun, and aimed to confront theory with observations. This was timely because research into the magnetohydrodynamics (MHD) of stellar interiors is currently at an extremely exciting stage, with ever-improving observations posing a number of new theoretical challenges. High-resolution observations of the solar surface and solar atmosphere, from the ground and from space, have yielded amazingly detailed images. Helioseismology has provided important information on the solar interior: in particular, the unexpectedly strong rotational shear (the tachocline) at the interface between the convection zone and the underlying radiative zone came as a surprise to theoreticians. Moreover, Doppler imaging is revealing starspots on the surfaces of more distant stars.

Understanding these observations, and the fundamental physical questions to which they give rise, requires a combination of computational and analytical approaches. The rapid development of high-performance computers is now making it possible to explore aspects of MHD turbulence that are of direct astrophysical interest. These results are not only of importance in themselves. They also provide crucial input into the formulation of new and general theories, for these problems are intrinsically nonlinear and there has been a strong overlap with research on nonlinear dynamics.

The programme addressed all the fundamental issues concerning the magnetic fields of stellar interiors, bringing together not only theoreticians and observers, but also experts on numerical techniques and experimentalists studying the MHD of liquid metals. The central question was the nature of the dynamo responsible for maintaining a magnetic field against its natural tendency to decay. Considerable attention was devoted to this problem, particularly with regard to how the dynamo mechanism may vary between different types of stars. For many purposes, astrophysicists still have to rely on mean field dynamo theory – which may capture the essential physics but relies on approximations that are not valid in a star. It remains important, therefore, to understand the behaviour of magnetic fields in highly turbulent fluids and to settle such questions as how the α-effect saturates and what is the corresponding effect on the turbulent diffusivity. These issues are crucial in trying to understand the generation of both large-scale and small-scale magnetic fields in stellar convection zones.

Structure of the Programme

The programme began with a two-week conference that introduced the main themes that occupied us for the next three-and-a-half months, which were themselves punctuated by three one-week meetings on specialised topics. Most of the talks given at these meetings are accessible on the Newton Institute's website. Eleven of the participants (including all the organisers, together with A Brandenburg, PH Diamond, A Ferriz Mas, DJ Galloway, AD Gilbert, R Hollerbach, JH Thomas and SM Tobias) were present at the Institute throughout the whole programme; in addition there were 29 long-stay visitors and another 41 short-stay visitors, as well as 11 locals. At any time there were at least 20 resident participants at the Newton Institute, and numbers swelled to over 40 during the various conferences. Of the non-local long-stay participants, 15 came from the UK, 8 from other EU countries, 10 from the USA and 7 from elsewhere.

Outside the meetings, we had a regular diet of two seminars a week from participants in the programme, and these talks often led to vigorous and argumentative discussion that continued over coffee. Our Rothschild Visiting Professor was R Rosner, who gave a lecture on *Burning Stars in One's Office* to a fairly wide audience. The most important interactions, however, were informal, whether in individual offices or over coffee in the central space, which proved an extremely stimulating forum for discussion and arguments.

Conferences and Workshops

Magnetohydrodynamics of Stellar Interiors

Training Course, 6–17 September 2004

Organisers: DW Hughes, R Rosner and NO Weiss

This Marie Curie Training Course was very successful: it was attended by 87 participants from 15 countries, including 19 graduate students, 18 postdoctoral researchers and 50 experienced researchers. The course covered the interactions between convection, rotation and magnetic fields in the Sun and other stars with deep outer convection zones. Observers described both the new observations (from space and from the ground) that are revealing fine details of surface features, and the helio- and astero-seismological techniques that probe the internal structure and rotation of the Sun and stars. Their lectures alternated with those from theoreticians, whose models are becoming increasingly more realistic and sophisticated as the availability of ever more powerful computers makes it feasible to follow nonlinear processes in much greater detail. The course ran for two weeks and was constructed around a series of invited lectures, each lasting one hour, followed by 10 minutes for discussion. In all there were 27 lectures, covering observations as well as theory, plus 28 contributed talks, each lasting 20 minutes with 5 minutes for discussion, and 6 poster presentations. Taken together, these talks provided not only an account of the underlying phenomena and the basis of their theoretical explanation, but also an up-to-date survey of current difficulties and controversies in this field. Having so many of the world's experts present for discussions made this meeting a remarkable experience for the younger participants. The course was structured so as to leave ample time and scope for free discussion, not only in the lecture hall itself but also during morning and afternoon coffee breaks, while the early afternoons were kept free for the same purpose.

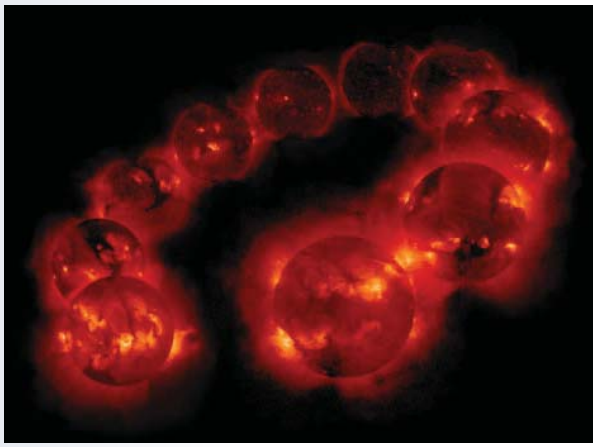
Bob Rosner, Henk Spruit and Jack Thomas at the first conference dinner

Large-scale Computation in Astrophysics

Conference, 11–15 October 2004

Organisers: R Rosner, F Cattaneo, SAEG Falle, NE Hurlburt, E Müller and JM Stone

Astrophysical plasmas are typically in an extremely turbulent state, characterised by high values of the



Cyclic variation of solar magnetic activity revealed by Yohkoh X-ray images

key parameters, the Reynolds number and the magnetic Reynolds number. The aim of the conference was to cover the differing computational approaches to the problem of MHD turbulence, together with the many theoretical ideas that underly them, and to discuss in depth both strong and weak features of these various approaches. This meeting was particularly timely since the last few years have seen a dramatic leap in the nature of the problems that can be studied computationally. The advent of affordable parallel computing facilities, allied to techniques such as adaptive mesh refinement, now allow, essentially for the first time, realistic computational exploration of turbulent fluids.

Since there is a great concentration of expertise and experience in the United States, a major aim of the conference was to disseminate this knowledge among European research groups. It was therefore funded as a Marie Curie conference by the EU. There were 12 invited lectures, together with 15 contributed talks. In all there were 65 participants, 42 from EU countries, 19 from the USA and 4 from elsewhere; 14 of them were students, 16 were junior researchers and 35 had established posts. Thus the aim of spreading know-how was achieved. The talks covered the construction and verification of codes as well as applications of high-performance computing. Everyone emerged with an enhanced appreciation of the power of modern computing facilities and also of the need to focus on developing codes that are not only accurate but also properly validated.

Tachocline Dynamics

Workshop, 8–12 November 2004

Organisers: P Garaud, DO Gough, NO Weiss and J-P Zahn

The tachocline is the layer at the base of the Sun's outer convection zone where there is a steep radial gradient in angular velocity, Ω. Through most of the convection zone Ω varies with latitude but not significantly with radius, while the inner radiative zone rotates almost uniformly. The existence of the tachocline was revealed by helioseismology about 15 years ago, and it came as a complete surprise to theoreticians. Even now, there is no generally accepted theory of its origin and structure, or of its role in the solar dynamo. This was the first meeting ever to be entirely devoted to the subject and it brought all the key players together to discuss it. The workshop was informal, involving 48 invited participants who were taking part in the programme, and it was clearly a great success. Our aim was to maximise opportunities for argument and discussion. The number of invited lectures was therefore restricted, so as to leave plenty of time for structured discussions, led and organised by appropriate experts. This format worked extremely well. In all, there were 14 formal talks and eight hours of scheduled discussion, which continued informally outside the lecture room. The workshop certainly clarified the main issues, although no consensus was expected or achieved.

Magnetic Fields in Plasmas, Stars and Galaxies

Spitalfields Day, 6 December 2004

This event (supported by the London Mathematical Society) attracted over 40 participants. There were five lectures from members of the programme covering magnetic fields in ionised plasmas, on scales ranging from laboratory experiments, through stars like the Sun, to galaxies.

Stellar Dynamos

Satellite Meeting, 13–17 December 2004

Organisers: DW Hughes, SM Tobias, PJ Bushby and SC Cowley

This conference, funded by the London Mathematical Society and the Royal Astronomical Society, was held at the University of Leeds during the final

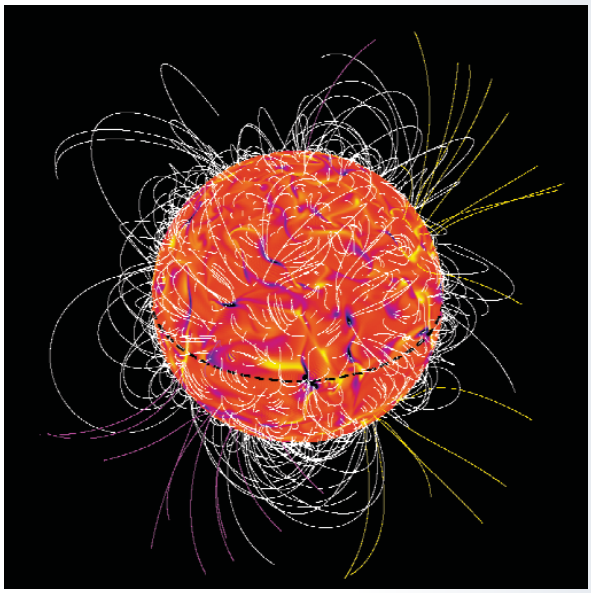
week of the programme and attracted 53 participants, many of whom had been at the Newton Institute earlier. The meeting concentrated on the generation of magnetic fields in astrophysical bodies, particularly stars. There were seven principal speakers, each of whom gave a one-hour lecture. The latest observations of stellar magnetic fields and of stellar differential rotation were presented in extremely accessible reviews, while other speakers dealt with the mathematical and theoretical aspects of astrophysical dynamo theory. In addition there were 26 contributed talks, covering a range of mathematical, computational and theoretical issues.

The University of Leeds hosted this conference extremely successfully, and it provided a stimulating finale to the programme.

Outcome and Achievements

Part of the programme was carefully structured, with meetings and seminars, while the rest was left free for more intensive informal collaboration and discussion. The structured part satisfied different needs. It allowed research students and postdocs to meet the leading figures in this field and to broaden their scientific understanding, especially through the more pedagogical reviews. Experienced researchers also appreciated being brought up to the forefront of research in a wide range of problems related to their individual interests. By giving proper attention to theory, numerical simulations and analyses of observations, these workshops encouraged better formulations of the fundamental problems that need focussed mathematical treatment, and also offered guidance to future observational programmes.

Participants welcomed the opportunity of working alongside key colleagues in a supportive research environment and away from the pressures and distractions of their regular teaching duties. Informal discussions proved extremely fruitful both in generating ideas and in getting new work done. Naturally, the subject that attracted most attention was dynamo theory, encompassing dynamo models for the Sun, rapidly rotating and fully convective stars, and supernova progenitors, as well as fundamental difficulties of describing the



Extrapolation of the radial field generated by dynamo action in a computational model (Brun, Miesch & Toomre)

α-effect and transport properties in MHD turbulence (whether forced or convectively driven, and especially at low magnetic Prandtl numbers). Among the other topics discussed were kinetic and magnetic helicity, interactions of magnetic buoyancy with convective pumping and shear, chaotic mixing, magneto-rotational instabilities and of course the origin and structure of the tachocline.

A volume arising out of the workshop on *Tachocline Dynamics* will be published by Cambridge University Press, and three other publication proposals are being considered. Several major reviews were completed, and a total of 24 papers are so far projected to arise out of this programme.

Participants visited or gave seminars at Bristol, Exeter, Imperial College, Manchester, Newcastle, the Open University, Oxford, Portsmouth, St Andrews, Southampton, Sussex, UCL and Warwick, as well as in Cambridge.