Magnetic Reconnection Theory

2 August to 27 August 2004

Report from the Organisers:
ER Priest (St Andrews), TG Forbes (Durham, USA) and J Birn (Los Alamos)

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Left to right: TG Forbes, ER Priest and J Birn

Scientific Background

Magnetic reconnection is a fundamental process in a plasma of high magnetic Reynolds number, whereby magnetic field lines (which are normally attached firmly to the plasma as it moves) become detached, break and rejoin. During this process, the topology of the magnetic field can sometimes change and magnetic energy is converted into other forms, such as heat, plasma kinetic energy and fast particle energy. Since the process involves topology, advection, diffusion, boundary layers (resolved by, for instance, magnetic diffusion) and sometimes shock waves, the mathematical problems associated with describing it are formidable.

There is a wide variety of physical phenomena where magnetic reconnection is important, including: solar flares and coronal heating on the Sun; geomagnetic substorms and flux transfer events in the Earth's magnetosphere; disruptions in laboratory tokamaks; and many dynamic processes in distant astrophysical objects. Indeed, wherever the magnetic Reynolds number is large and the magnetic field dominates the plasma pressure, it is bound to be a common process.

As well as these different applications, there have been two main strands of theory, one based on magnetohydrodynamics (MHD) and the other based on collisionless plasma theory. Until recently, the MHD and collisionless theories and the solar and geomagnetic applications have been studied by four separate communities. The aim of the programme was therefore to bring together the world's main theorists in these four distinct areas and to explore common ground.

Overview

The four-week programme involved 47 participants, many of whom stayed for the whole time. Virtually all of those we asked did accept the invitation, and so we were highly fortunate to have most of the major world figures in the field present.

The programme was an enormous success in many respects. This was the first time that many of the key researchers had been able to have in-depth discussions with those from the other areas, so there was an initial phase of learning. A sense of vitality, ferment and excitement pervaded the programme as many new ideas were born and thrown around, which will continue to bear fruit for years to come. It is clear that this was a landmark occasion marking the start of many new developments in the field.

Structure of the Programme

In view of the short length of the programme and the need to come up to speed rapidly, we spent the first day with each person introducing themselves and throwing in ideas on which they would like to focus. The second day was spent listening to a series of overviews of the key outstanding problems and questions in reconnection theory, given by ER Priest (MHD and coronal heating), JF Drake (collisionless theory), TG Forbes (solar flares and coronal mass ejections) and J Birn (the

magnetosphere). This was followed for the remaining three mornings of the first week by a series of tutorial lectures on the basic concepts of reconnection (G Hornig) and on collisionless reconnection (MH Hesse and P Pritchett).

At the start of the second week we held two highly stimulating, well attended meetings: a Spitalfields Day on basic theory and a Hewlett-Packard Day on applications (see below). Thereafter we held just two in-depth seminars each morning, so as to enable the participants plenty of time to interact as they wished. The emphasis was very much on the sharing of ideas and genuine cross-fertilisation on the basic theory of 3D MHD and collisionless reconnection.

Magnetic Reconnection Theory

Spitalfields Day, 9 August 2004

Organisers: TG Forbes and ER Priest

This highly successful and stimulating one-day meeting was attended by 65 people. Its purpose was to discuss the mathematical aspects of reconnection theory that have been developed for various applications in laboratory and space plasmas. Each application tends to have different scientific objectives and this has led to different mathematical developments of the theory which are little known outside the specific area of application. Presentations and discussion periods during the day allowed participants to obtain a global overview of reconnection theory and to learn of recent mathematical developments over a wide range of applications.

The day began with two reviews, one by G Hornig on the topology of 3D reconnection and another by JD Gibbon on singularities in 3D Euler and MHD, followed by three contributed talks: D Pontin on kinematic 3D reconnection at nulls, J McLaughlin on MHD wave propagation near a 2D null, and G Abel on fractal reconnection at the Earth's magnetopause. After coffee P Pritchett gave a review of collisionless reconnection theory, MH Hesse reviewed diffusion-region theory and J Huba gave a contributed talk on Hall reconnection.

After lunch there were two more reviews, the first by F Pegoraro on Kelvin–Helmholtz instability and the second by B Shivamoggi on critical exponents and universality in fully developed turbulence.

Some of the key participants

After tea C Watt gave a contributed talk on the basic theory of ion acoustic instability and P Petkaki gave a second on its nonlinear development. The last talk was a magnificent one delivered by A Bhattacharjee on impulsive reconnection dynamics. The day concluded with much lively discussion over wine and beer.

Magnetic Reconnection at Work in the Sun and Magnetosphere

Hewlett-Packard Day, 10 August 2004

Organisers: J Birn, TG Forbes and ER Priest

This exciting one-day meeting followed on immediately from the Spitalfields Day by discussing the way in which magnetic reconnection is thought to operate in the Sun and the magnetosphere.

Two review talks on the Sun started the day, the first by L Culhane on observational evidence for reconnection in the solar corona and the second by C Parnell on reconnection and coronal heating. Three young people then each gave a contributed talk: S Higgins on impulsive heating of coronal loops, I Coleman on testing reconnection theories at the Earth's magnetopause, and M Kuznetsova on anti-parallel and component merging. After coffee B Kliem reviewed some open problems for reconnection in solar flares and H Hudson described the perturbations of active regions by flares, while R Maclean discussed the topology of magnetic breakout.

Lunch provided ample opportunity for lively discussion of these provoking talks and was followed by two reviews, the first by D Alexander on the nature of reconnection in coronal mass ejections and the second by K Trattner on merging and reconnection at the Earth's magnetopause.

Relaxing – but not always going in the intended direction!

Then after tea J Dorelli gave a fascinating review of reconnection at the dayside terrestrial magnetopause and W Baumjohann described Cluster results on bifurcated and thin current sheets. The day ended with two contributed talks from S Eriksson on shock analysis of flows in the magnetotail and T Moretto on Cluster observations of the high-latitude magnetopause.

Altogether, it was a rich experience of excellent presentations with plenty of time for lively discussion and exchange of ideas.

Outcomes

The main outcomes were: a series of new ideas that will be worked on in the months to come (see below); the development of a set of new collaborations; and the writing of a major monograph on reconnection by the main participants.

Limitations of space mean that we can only mention briefly a few of the new directions, but there were many more.

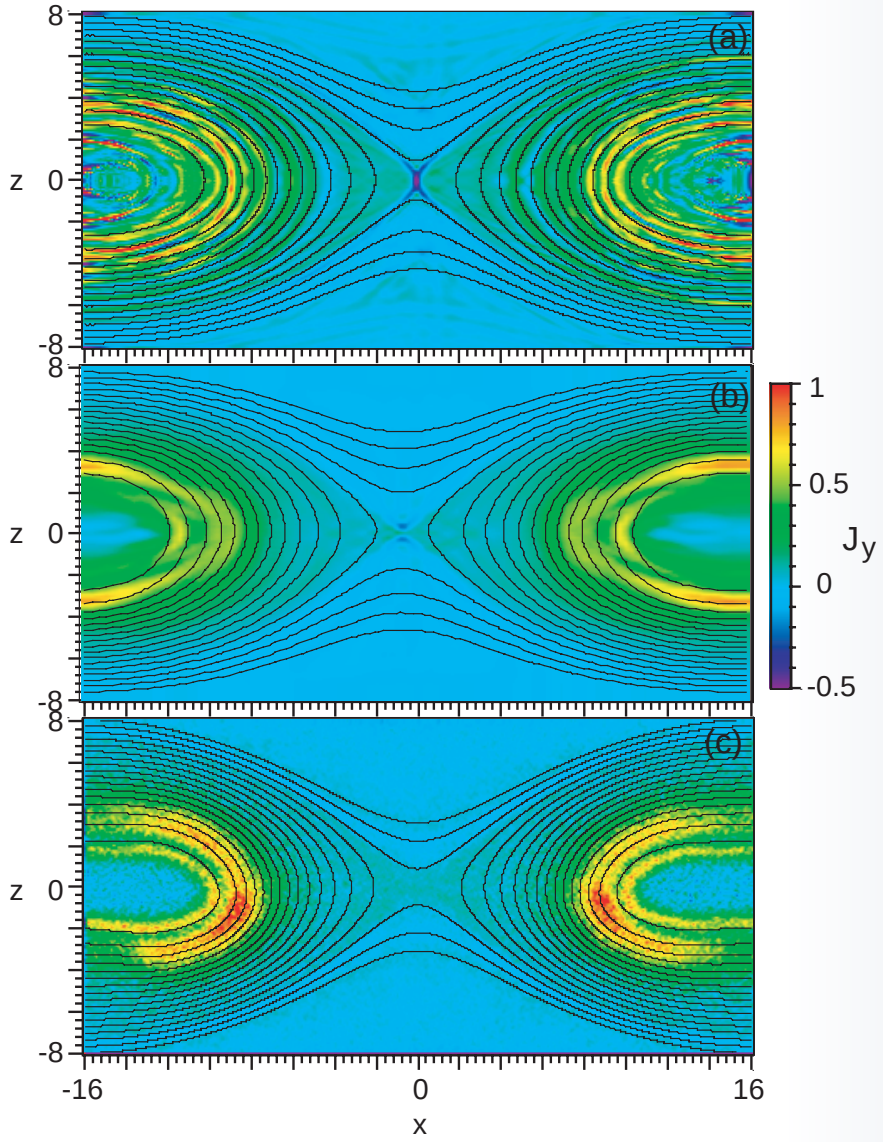
One important topic that engaged several of the participants was the nature of 3D reconnection. The outline of a theory had previously been developed by ER Priest and V Titov for reconnection at a 3D null by spine reconnection or fan reconnection or separator reconnection. However, this model was purely kinematic in the non-standard sense of satisfying the induction equation and deducing the steady state velocity and electric field in 3D for a given magnetic field. During the programme two new developments were initiated: the first a technique for also satisfying the equation of motion, and the second a full numerical resistive MHD experiment to test the validity of the model.

A second important topic was to understand the nature of 2D collisionless reconnection. So far there had been several intriguing numerical experiments by participants in the programme but no analytical model had yet been proposed. A group therefore decided to study the results of the numerical experiments in detail in order to understand physically the reasons for their different features, namely, the internal electron region and the intermediate ion region where Hall effects dominate. Having developed some such explanations they are now in the process of setting up an analytical model of the whole process, which hopefully will lead to a much deeper understanding of how reconnection in a collisionless plasma occurs.

A major new collaboration was begun during the programme on comparing the results of different codes on a model problem. A concerted effort involving 12 participants undertook a state-of-the-art numerical comparison of reconnection in the collisionless regime (to be published in *Geophysical Research Letters*). A test 'challenge problem' was designed to compare MHD, two-fluid Hall–MHD and full particle codes. The problem concerned the response of an initial current sheet to an external force that causes localised thinning and reconnection. The figure opposite illustrates the final states.

Despite the differences in dissipation mechanism, the reconnection rates and final states are surprisingly similar. The comparisons also revealed new details about the influence of the magnitude of the boundary deformation, the role of electron mass and the role of gradient scales. The results have important implications for the onset of reconnection in the Earth's magnetic tail and the solar corona.

A monograph, entitled *Reconnection of Magnetic Fields: Magnetohydrodynamics and Collisionless Theory and Observations*, edited by J Birn and ER Priest, is to be published by Cambridge University Press. Written by many of the participants, it



Late stages of the magnetic field (contour lines) and current distribution (colour coded) for various simulations: (a) MHD using localised diffusivity (J Birn); (b) Hall–MHD without explicit dissipation (J Huba); (c) PIC simulation (M Hesse)

summarises the state of the art and the advances made during the programme. Its chapter headings reflect the topics studied during the programme:

- Basic Theory of MHD Reconnection
- Basic Theory of Collisionless Reconnection
- Reconnection in the Magnetosphere
- Reconnection in the Sun's Atmosphere

The Future

In order to build on the links so usefully formed at the Newton Institute, we agreed to try to meet annually in a workshop format. In particular, we are holding a week-long workshop on reconnection in August 2005 in Santa Fe and are proposing to hold a series of ISSI workshops on reconnection in Berne in 2006.