# *The* QUARTERLY JOURNAL *of the*

Published for the Royal Astronomical Society

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**Blackwell Science**

Annual Subscription: £87.00, Europe; $155.00, USA and Canada; £96.00, Rest of World
ISSN 0035-8738

*Q. Jl R. astr. Soc.* (1987) **28**, 339–343

# Reconnection MIST Meeting

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(Received 1987 January 16)

A meeting on 'Reconnection in Solar System Plasmas' was held in the Society of Antiquaries' Lecture Theatre, Burlington House, London W1 on 1986 May 9. The meeting was the 36th in the series of Magnetosphere, Ionosphere and Solar-Terrestrial (MIST) meetings sponsored by the Royal Astronomical Society and the Institute of Physics.

The morning session, chaired by Professor E.R.Priest (St Andrews) was mainly devoted to the magnetosphere and interplanetary space. It opened with a discourse by J.W.Dungey (lately of Imperial College). Dungey, whose 1953 paper is generally considered to be one of the historic pioneering papers on the subject, spoke on 'Plasma physics of a neutral sheet'. He chose three topics to illustrate the peculiarities of a neutral sheet.

First, he discussed Speiser orbits, which are explained with zero electric field. A particle of small pitch-angle approaches a neutral sheet, is swung round and departs along a different field line. A frame change leads to a mechanism which fits observed beams. Second, a Cowley electric-field normal to the sheet is needed for charge neutrality. It drives currents along field lines to the ionosphere, which are more correctly described as Alfvén waves, generating aurorae and kilometric radiation. Third, wave modes in a neutral sheet are quite different from those in a uniform magnetic field and are unfamiliar, but the fast mode exists and is ducted. Studies of waves have been motivated by the need for an estimate of anomalous resistivity and have culminated in a quasilinear formulation; for the geomagnetic tail, this shows that strong turbulence is needed.

The tail problem is quantitative and is demonstrated by rough numbers: 1 electron $cm^{-3}$ at 1000 km $s^{-1}$ gives a sheet thickness of only 100 km. An electric field of 1 mV $m^{-1}$ accelerates electrons to 1000 km $s^{-1}$ in a few milliseconds. If the important region is even thinner and very small (so perhaps never visited by spacecraft) a noise-free mechanism is possible. A version of Speiser orbits with $B_z$ proportional to $x$ provides a 'residence time' proportional to $(\partial B_z/\partial x)^{-\frac{1}{2}}$ and it is easy to imagine that reconnection would increase $\partial B_z/\partial x$, which would imply explosive behaviour.

V.M.Vasyliunas of the Max-Planck-Institut für Aeronomie, Katlenburg–Lindau, German Federal Republic, spoke on the 'Global geometry of magnetospheric reconnection'. The geometry of the reconnection process is usually described in terms of magnetic field lines; an essential element is the magnetic $X$ line ('neutral' line), formed by the intersection of two branches of the magnetic separatrix surface. An equally valid description can be given in terms of lines of plasma mass flux density $\rho \mathbf{V}$ (in fact, observational evidence for reconnection in the earth's magnetosphere comes more from observations of **V** than of **B**). The magnetic *X*-line is also a flow *X*-line ('neutral' or stagnation line), which should correspond to the intersection of two flow 'separatrix' surfaces separating different flow topologies. To identify the flow topologies, it is necessary to consider the global geometry, and a useful tool is a representation of **B** and ρ**V** on electric equipotential surfaces.

It is found that flow lines extending from the solar wind into the closed field line region of the magnetosphere (a) do not exist in the case of ideal north–south symmetry, even for an open magnetosphere and (b) otherwise connect the region of 'lobe plasma' in the magnetotail to the dayside. The results raise questions about the distinction between plasma flow lines and particle trajectories, about the role of plasma exit as well as plasma entry regions, and about the identification of direct inflow into the deeper parts of the magnetosphere.

There followed three papers from the Imperial College group. S.W.H.Cowley and I.G.Richardson, under the title 'Reconnection in the geomagnetic tail–theory and observation', summarized the results of theoretical work on tail reconnection undertaken at Imperial College over the past 15 years, and its relevance to observations. Particular emphasis was given to the deep tail observations recently made by the *ISEE*-3 spacecraft and how they can be used to measure the tail reconnection rate. In the next paper, M.A.Saunders and R.P.Rijnbeck recalled that magnetic field observations at the Earth's dayside magnetopause have clearly indicated that reconnection often occurs there as a localized, impulsive process, termed flux transfer events. They summarized the achievement of five years' study of this phenomenon at Imperial College using data from the *ISEE*-1 and *ISEE*-2 and *AMPTE UKS* spacecraft, and highlighted the difference in occurrence statistics evident in these data sets. In the following paper, 'Ionospheric signatures of impulsive dayside reconnection', D.J.Southwood and S.W.H.Cowley discussed theoretical expectations concerning the ionospheric signature of impulsive reconnection occurring at the dayside magnetopause boundary, and related them to recent observations made by the EISCAT, STARE and SABRE radars.

'Pitch angle distributions of electrons in dayside flux transfer events (FTEs)' were described by C.P.Chaloner, D.A.Bryant and D.S.Hall of Rutherford Appleton Laboratory, using data from the 3-D electron spectrometer on *AMPTE-UKS*, which measured the full (12 eV to 18 keV) spectrum and pitch-angle distribution of electrons with a time resolution of better than 10 s. They presented such distribution functions measured in magnetospheric and magnetosheath-FTEs, and discussed the implications for the structure of the magnetopause and the microstructure of flux transfer events.

'Particle acceleration from reconnection processes in solar and cometary phenomena' was the subject of J.Pérez-Peraza of UNAM, Mexico City, with co-authors M.Alvarez-Madrigal and A.Sânchez, respectively of UNAM and of the Instituto Nacional de Astrofísica, Optica y Electrónica, Puebla (Mexico). Particle acceleration is often a typical signature of reconnection processes in astrophysical sites, as the impulsive acceleration in solar flares and geomagnetic substorms, or the long-lived acceleration in latent coronal neutral sheets activated by the passage of flare shocks across them. Impulsive particle acceleration in comet tails may hypothetically be associated with disconnection events of the tails when comets cross sector boundaries, while long-lived acceleration may be expected from the latent current sheet in the tail when it is processed by interplanetary or flare shock waves. The authors investigated the energy spectrum of the accelerated ions and the characteristics of the photon fluxes produced by electron capture of the energetic ions during their interaction with cometary plasmas and neutral matter (profiles, frequency drifts during acceleration and energy spectra). The confrontation of these predictions with data may be a useful tool to probe the nature of reconnection processes.

The morning session closed with a contribution by S.K.Runcorn (Newcastle) on 'A theory of geomagnetic 'jerks''. Runcorn attributed the sudden changes in second derivatives $d^2(X, Y, Z)/dt^2$ of the geomagnetic $X, Y, Z$ components, that were widely observed in 1969/70, and possibly also in 1912 and around 1840, to sudden changes in field line geometry at the core–mantle boundary. A lively discussion ensued concerning the accuracy and plausibility of this theory, it being argued that the short-term changes can instead be explained in terms of exchange of angular momentum between the atmosphere and the solid Earth.

The afternoon session, chaired by Professor J.C.Brown (Glasgow), was mainly devoted to solar and laboratory phenomena. E.R.Priest (St Andrews) spoke on 'Reconnection in solar flares', and outlined several possible roles of reconnection. One is to create small flares due to the interaction of separate magnetic flux systems when new flux emerges from below the photosphere or when small satellite sunspots move horizontally. In large flares, one role is to initiate the impulsive phase when reconnection starts below a slowly rising flux tube (a prominence) and another is to create rising hot-flare loops in the main phase in a quasi-steady fashion for thousands of Alfvén times. The classical theory of fast, steady reconnection involves several distinct mechanisms, proposed by Sweet and Parker, Petschek, Sonnerup, and Sonnerup and Priest. A unified theory of such reconnection, recently proposed by Priest and Forbes, includes all these as special cases, together with new families of reconnection. In particular, the new hybrid and flux pile-up regimes, which may have reconnection rates much faster than Petschek's mechanism, are being used to reinterpret the previous numerical experiments.

J.A.Robertson (St Andrews), speaking on 'Numerical experiments in reconnection', presented two-dimensional numerical solutions in a square domain for steady-state driven reconnection of an incompressible fluid having uniform viscosity and uniform magnetic diffusivity. These solutions complement analytical solutions of Priest and Forbes and, like theirs, demonstrate that not only the Mach number $M = V/V_A$ and magnetic Reynolds number $R_m$, but also (and crucially) the boundary conditions are important in determining the flow and field structure. Contrary to the analytical models, the outflow velocity is very sub-Alfvénic and the angle between the Petschek shocks large, since there is significant ohmic dissipation. Contrary to numerical models of Biskamp, who finds that the current-sheet width $\delta \sim R^{0}_{m} M^{1}$ for large $R_m$, the author finds that $\delta \sim R_m^{-\frac{1}{2}} M^{-\frac{1}{2}}$ for smaller $R_m$.

In her paper on 'Heating the solar corona by reconnection', P.K.Browning

(UMIST) discussed the magnetic mechanisms involved in heating the solar corona to over $10^6$ K. One approach to the problem is to consider slow photospheric velocities, which shuffle the footpoints of the coronal magnetic fields and generate direct currents in the corona. Magnetic reconnection provides a means of dissipating these currents, on sufficiently fast time-scales for coronal heating. The problem is to determine the energy released as heat by reconnection, in relation to the photospheric driving motions A solution has been developed to this problem, making use of a generalization of Taylor's relaxation theory. As the field is stressed by the footpoint motions, it reconnects and relaxes towards a minimum energy state, subject to the constraint that the magnetic helicity is fixed. The relaxed state is a linear force-free field. If the footpoint motions are slow compared with a reconnection time-scale, the field evolves through a series of relaxed states. The time dependence is determined by the changes in magnetic helicity produced by the boundary motions. The energy dissipation may then be evaluated by applying an ideal displacement to a relaxed field, which subsequently relaxes again to a new linear force-free state, releasing some energy as heat. In this way, the evolution and heating in a variety of coronal structures, such as an arcade of loops and a network of twisted flux tubes, may be calculated. The results give realistic values for the coronal heating rate.

Turning now to laboratory plasmas, D.C.Robinson (UKAEA/Euratom, Culham), speaking on 'Driven and natural recombination in hot plasmas', listed three key characteristics of toroidal magnetic confinement systems (such as tokamaks) as (1) the rapid initial-phase current penetration; (2) the disruptive instability (which can be catastrophic); and (3) sawtooth oscillations. All are believed to involve resistive instabilities which involve changes in field-line topology, the production of magnetic islands and their overlap. This leads to rapid reconnection of the magnetic lines of force which may involve a transition to magnetic turbulence and a sudden redistribution of the plasma current allowing the configuration to relax to a state of lower magnetic energy. On the present large tokamaks such as JET, the reconnections are observed to proceed anomalously rapidly, as compared to fluid predictions which agree with the observations on smaller devices.

Driven reconnection has been used in an attempt to study the above characteristics. At a low perturbation amplitude it can result in a stabilizing effect, removing sawteeth and disruptions. At larger amplitudes even faster reconnections are observed. Subsequently, T.R.Jarboe (UKAEA/Los Alamos) described an 'Experiment in helicity injection'. The Taylor minimum-energy principle is an important concept for understanding the physics of RFPs and Spheromaks. It states that a system of plasma and magnetic field will relax to a state of minimum energy with the constraint of constant magnetic helicity. Helicity is the linkage of flux with flux. A corollary to the principle is that the magnetic fields are uniquely specified once the boundary conditions and the amount of helicity present are known. Thus RFPs and Spheromaks can be formed and sustained by first setting up the proper boundary conditions so that the relaxed state is the desired topology and then raising and maintaining the amount of helicity. An oblate flux conserver (which is a proper boundary condition for a Spheromak) and two different types of helicity injectors were discussed. A quantitative comparison was made between the amount of helicity injected by a coaxial helicity source and the amount arriving in the relaxed state (the Spheromak) and good agreement was found.

Returning to solar physics, N.O.Weiss (DAMTPE, Cambridge) discussed 'Differential rotation, magnetic fields and reconnection in the solar interior'. By measuring the rotational splitting of five-minute oscillations on the Sun it is possible to determine the variation of the angular velocity, $\Omega$, with radius $r$ in the solar interior. These helioseismological results suggest that the inner radiative core ($r < 0{\cdot}2\ R_{\odot}$) is rotating at about twice the surface rate. Is such a rapidly spinning core consistent with the presence of a significant radial field? L.Mestel and N.O.Weiss have tried to establish the maximum field strength consistent with the survival of a large rotational shear. If perfect conductivity is assumed, magnetic torques can eliminate differential rotation in an Alfvénic transit time; as is well known, survival of a significant shear requires that the poloidal field strength should not exceed a few microgauss, which is plausibly small. Differential rotation produces a strong toroidal field which will be dynamically unstable. These instabilities could lead to reconnection and so reduce the magnetic torque. It was concluded that the poloidal field strength would still have to be less than $3 \times 10^{-2}$ G in order to preserve differential rotation. Estimates of the residual field in the inner part of the solar radiative zone yield values in the range $1\text{–}10^3$ G. If $\Omega$ varies rapidly near $r = 0{\cdot}2\ R_{\odot}$, then the inner and outer parts of the radiative zone must be magnetically decoupled. Future helioseismological observations will be able to establish whether $\Omega$ really doubles near the centre of the Sun.

Finally, C.Jordan (Oxford) spoke on 'What are the observational consequences of reconnection in the solar atmosphere?' In particular she addressed the question 'if reconnection has a role in heating the average solar atmosphere, how might it be observed?' Reconnection is usually discussed in the context of solar flares as a source of heating and as the cause of post-flare loops. Examples of this are provided by the work of Kopp, Pneuman, Priest and Forbes. Active region loops, such as observed in ATM UV images, are long-lived structures with no obvious interaction with external magnetic fields but their heating could result from the dissipation of the magnetic field within the loop. Regarding the quiet atmosphere, the most interesting features which could be related to small-scale impulsive heating are regions in the UV spectra, obtained with the NRL High Resolution Telescope and Spectrograph, where large Doppler shifts are observed. Regions of a few arcseconds in extent where blue-shifted lines exist, corresponding to velocities of 100 or 200 km $s^{-1}$, and where the simultaneous presence of small red-shifts in adjacent regions suggest mass-motions in a loop geometry, could perhaps represent interactions between small regions of emerging flux and existing fields, rather as envisaged by Heyvaerts, Priest and Rust. New spectra obtained on the *Spacelab 2* mission could be used to evaluate the statistics and energetics of these regions to find whether or not they represented a significant source of coronal energy.

The MIST organizer, H.Rishbeth, thanked the chairmen and speakers, and the meeting then adjourned to join the R.A.S. Ordinary Meeting in Savile Row.