# VIIth Geomagnetism and Paleomagnetism Retreat

The Confluence Centre,

*Skipton,*

*Monday 24th to Friday 28th September 2001*

This informal conference organised by Andy Jackson (Leeds, UK) brought together researchers and students from the UK, France and Germany to discuss a wide range topics related to the Earth's magnetic field. A series of tutorials summarising (and re-assessing) the foundations of the subject was run along with talks on the research interests of the participants. The picturesque village of Kinsley provided an ideal location, with talks being held in the conference room of the Confluence centre while the nearby Tennants Inn provided nourishing evening meals. Unseasonal (but typically English) torrential rain on the final day provided an unexpected knee deep wade to dinner that will be hard to forget.

## Monday 24th September

### 6pm: Jack Jacobs- Origin and structure of the Earth.

J.A Jacobs (Aberystwyth, UK) started proceedings by reviewing our knowledge of the properties of the Earth's interior and describing current theories on its formation. He discussed the seismological evidence for the existence of the inner and outer core and the enigmatic nature of the D" layer at the core-mantle boundary. D. Gubbins (Leeds, UK) and A. Jackson (Leeds, UK) agreed that it would be useful to redo the D" layer calculations, re-addressing the question of its radial symmetry. The chemical constitution of the core was discussed- it is thought to be mainly iron, but must also contain some lower density elements (probably either sulpur, silicon or oxygen). The thermodynamic reasons for the formation of the inner core were described but it was pointed out that we have no reliable date for its birth. Next came an overview of the main geomagnetic field- today it is predominently dipolar but exhibits temporal variations on a wide range of scales. Local observations show variations in both inclination and declination- we suspect changes on decadal and longer timescales are caused by core motions, but they remain poorly understood. The generation of a planetary magnetic field can only be explained by dynamo theory. A short historical discussion on the development of dynamo theory followed- the contributions of Walter Elsasser and Teddy Bullard in the post-war period were noted. Next in this wide ranging tour were the famous geomagnetic reversals- paleomagnetic observations, intensity changes during reversals and the relationship between reversals and excursions were all mentioned. Finally the Earth was placed in a planetary context. Our present knowledge of the interiors of the planets is sketchy, but satellite probes have collected some data regarding their magnetic fields. The remanent magnetisation seen on Mars (more about this in K. Whaler's talk) poses interesting questions on the links between dynamo power sources and planetary evolution, while the strong magnetic fields of Jupiter, Uranus and Neptune give dynamo theorists additional physical systems in which to test their ideas. The liquid oceans thought to exist below the surface of Europa could provide an exotic new testbed for dynamo theory. Jack's talk was a lively introduction to a wide range of topics, emphasising the incompleteness of our current understanding of planetary evolution.

# Tuesday 25th September

## 9am: Kathy Whaler- Techniques of geomagnetism

K. Whaler (Edinburgh, UK) began the day by with a tutorial describing the basic techniques of geomagnetic field modelling. Our knowledge of the Earth's magnetic field is based on measurements of two types- scalar measurements (intensity only) and vector measurements. They can be made at permanent observatories, moving stations (eg. ships) or satellites which give global coverage. The specifications of the satellites Magsat, Oersted and Champ were discussed and compared. The use of star cameras to provide vector orientations and associated attitude errors were explained. J-P. Valet (IPGP, France) described the physics of the flux gate magnetometer. Kathy explained that the limiting factors in main field modelling were not the accuracy of intruments, but noise contamination by external and crustal fields. We are primarily interested in the internal magnetic field, so must subtract the contributions due to the external and crustal fields which are unwanted. Noise distributions are typically treated as being Gaussian, though as A. Jackson (Leeds, UK) pointed out, this is unlikely to be the case. The potential theory underlying field modelling was outlined, including the use of spherical harmonic expansions and the B-splines basis. If we assume that the mantle is an insulator (a reasonable first approximation) we can downward continue the model solution found at the Earth's surface as far as the core-mantle boundary which marks the top of the source region. It is important to note that higher spherical harmonics are amplified more strongly by downward continuation than lower order harmonics, so the maps at the core-mantle boundary show more small scale features than those at the Earth's surface. Inverse theory is used to find the optimium field model which both fits the data and is smooth. The trade off between low field complexity and fitting the data, specified by a damping parameter was discussed. Undoubtedly there is small scale structure which the present generation of field models cannot resolve. S. Gibbons (Oslo, Norway) explained that this leaves the question of the small scale fluctuations seen in certain dynamo models unresolved. Finally, modelling of the secular variation (rate of change of the main field) was described. Secular variation involves no crustal field mapping, so in principle could be determined extremely accurately and could be useful in comparisons to dynamo models. D. Gubbins (Leeds, UK) pointed out that at the moment it is meaningless to compare the output of fully dynamic dynamo models to observations, because they are not operating in an Earth-like regime.

## 10.30am: Steve Gibbons- Convection in the core

S. Gibbons (Oslo, Norway / Leeds, UK) gave a tutorial on the theory of core convection, paying particular attention to the tractable non-magnetic problem. He began by defining convection as the transport of heat by the movement of liquid. The Earth's outer core is (to a first approximation) a rapidly rotating shell of liquid with low viscosity and convective overturn time of order 1000 years. To model core convection, we impose a radial temperature difference between the inner and outer shell boundaries. The force balance in the non-magnetic case will be between the Coriolis force, the pressure gradient force, the buoyancy force, and the viscous force. The Taylor-Proudman theorem tells us that flow in the core tends to be invariant along the rotation axis. The presence of the inner core means we can divide the outer core into 3 distinct dynamical regions: outside the inner core tangent cylinder (parallel to the rotation axis), and above and below the inner core, inside this tangent cylinder. Outside the tangent cylinder we expect convection to occur in characteristic Busse convective rolls. By taking the curl of the momentum equation, we find that if radial buoyancy forces are present, finite viscosity is required for vorticity balance. Numerical models (and analytic asymptotic limits) suggest that as viscosity is reduced, the characteristic length scales for core motions (including convective columns) will decrease. However, the presence of the magnetic Lorentz force could balance the buoyancy force, so small length scales are not inevitable for the Earth. The influence of the mantle was discussed. It convects on a much longer timescale, so we might expect that lateral temperature variations exist at the core-mantle boundary. In principle these temperature differences can be determined by seismology: slow S waves imply high mantle temperatures, fast S waves imply low mantle temperatures (see Masters et al 1996). Steve discussed how this seismic model of the lateral temperature variations at the CMB can be incorporated in a non-magnetic core model: this represented an advance over the usual assumption of isothermal boundaries. Temperature variations were found to drive fluid flows near the top of the core. Rapid rotation of the core meant that these were not simple flows transporting heat from hot regions to cooler regions, but complex eddies and gyres like those seen in the atmosphere and oceans. The penetration of these flows into the core was found to depend crucially on the stratification of the core (unknown at present). This numerical model was able to reproduce some features seen in flow models derived by inverse theory from magnetic observations, but did not produce the well known Atlantic-Pacific hemispherical dichotomy. This failure is probably a consequence of incomplete seismic data, the non-magnetic nature of the model and perhaps failures in the flow inversion techniques. A possible problem with the current generation of geodynamo models was discussed. Models with fixed, isothermal heat flux at their boundaries preferentially generate m = 1 flows at Ekman number 0.001. For non-linear calculations, these large scale flows interact with m = 6,7 flows to produce hemispherical assymmetries, even for uniformly imposed heat flux. This mechanism could explain the hemispherical assymetries seen in current dynamo models but doesn't occur for the much lower Ekman numbers actually found in the core. Finally new work on understanding the Pacific anomoly was reported. With homogeneous heat flow, we find drifting convective rolls on a global scale (moving eastward for most parameter choices) for low Rayleigh number and vacillation for higher Rayleigh numbers. When we introduce a heat flux with departures from $Y_2^2$ symmetry (hemispherical assymmetry at high lattitudes) then covective rolls are disturbed below the Pacific: they move towards the Pacific region, dissolve and reappear on the far side. The symmetry of the lateral heat flux at the boundaries of the outer core seems to be important in understanding regions high and low secular variation. Work on this problem is ongoing.

## 12am Andy Jackson- Historical secular variation and core field structure

A. Jackson (Leeds, UK) presented a tutorial on historical records of the Earth's magnetic field describing the compilation of a database of observations, associated error analysis and the construction of time dependent field models. Records of the Earth's magnetic field have been made for hundreds of years: mariners using compasses to navigate routinely measured the difference between magnetic north and astronomical north (the declination). From 1590 onwards there is enough data available to enable us to construct global field models. The mariners observations were suprisingly accurate (average standard deviation around 1/2 degree): the main problem was their inaccurate measurement of longitude- this was done by simple 'dead reckoning' calculations pre-1780. A novel computer 'voyage editor' has been employed to deal with this problem. The other major problem in obtaining accurate measurements of the internal geomagnetic field was noise contamination by crustal sources. Andy emphasised the needed for realistic error assessments, if the techniques of inverse theory are to be applied— the error budget for the data was described. Present data coverage is good with satellites such as Champ, Oersted and Magsat providing almost global vector coverage. As we go further back in time the coverage becomes sketchier and before 1832 only directional measurements were available. These factors must be included in the inversion via the covariance error weighting matrix. The construction of time dependent magnetic field models was explained. Andy finished by showing various videos of the time dependent evolution of the field models from 1590 to 1990. He highlighted several intriguing features which are not yet fully understood, but which will be the study of future investigations. Watching the field evolve at the surface, one could clearly pick out westward drift by the following the agonic line (separating regions of eastward and westward declination), but if we wish to understand the origin of secular variation, it is necessary to look at the magnetic field at the top of the source region (the core). Later in the week, Andy was to show Steve Gibbon‘s animation of the downward continuation procedure: this delightful film captured the physical process of preferential amplification of higher harmonics as we move down through the insulating mantle- something difficult to visualise from the equations. The field model at the CMB contained more small scale features than that at Earth's surface. Interesting features included a ”core spot” of reverse flux which starts in the Indian Ocean moves westward and intensifies, a prominent flux lobe over Canada which appears to split into 2 and then remerge as time goes on (this could be due to an interaction with a magnetic wave). The model also suggests there is a time dependent oscillation in the magnetic equator over Indonesia. The presentation finished with animations of frozen flux, tangentially geostrophic fluid flow models for the post-1830 period. Their construction was described by Kathy Whaler in the next talk. Strong westward flow could be seen in the Atlantic Hemisphere, while flow in the Pacific region was less pronounced. The film then focused in on specific regions: oscillations are obsereved under South America and Eurasia while under Florida there was a feature almost like a solid body rotation. The realism of these flow models is still under debated, but Andy pointed out that they can be used to explain decadal changes in the length of day- an important non-geomagnetic constraint. D. Gubbins (Leeds, UK) pointed out that we could in principle extend the historical record using archeomagnetic data if the measurements were accurate to 2$\mu$T or better. J-P. Valet (IGPG, France) suggested this was within the reach of present magnetometer technology, but the problem would be to obtain enough measurements within each time period, so a global picture of geomagnetic field could be obtained on a timescale of centuries.

## 12am: Kathy Whaler- Core flows and core-mantle coupling

Kathy Whaler (Edinburgh, UK) presented a short tutorial on the construction of models of fluid flow at the top of the Earth's outer core. This involves inverting the induction equation, so given models of the magnetic field and the secular variation, the fluid velocity can in principle be determined. In practise several simplifying assumptions are made to render the calculation tractable. The first assumption is that the frozen flux hypothesis of Roberts and Scott (that magnetic field lines move with the fluid) is valid. There is some debate over this assumption (See D. Gubbins talk on ‘What is wrong with the frozen flux hypothesis?’) but most workers agree that it provides a useful first approximation. Even with this assumption we still require another condition if we are to obtain the fluid velocity perpendicular to the field lines. Several techniques are currently employed, the most popular being the steady motions assumption, the toroidal assumption and the tangentially geostrophic assumption. Kathy explained each of these in turn. (i)Steady motions assumption: On historical timescales, the changes in the magnetic field are mainly steady, so it is a reasonable first approximation to assume the fluid motions are steady. This assumption is however clearly incorrect, for example around the time of geomagnetic jerks. (ii)Torodial assumption:

In a stably stratified layer near the top of the outer core there would be no upwelling/downwelling and fluid motions would be purely toroidal. There is no direct evidence for the existence of such a layer, infact there is strong evidence that upwelling/downwelling must occur near the top of the core. An important objection to this approach is the fact it doesn't consider rotation. (iii)Tangentially geostrophic assumption: we assume that the Lorentz force and viscosity are unimportant then taking the radial part of the curl of the momentum equation the force balance is between the Coriolis force, the pressure gradient and the buoyancy force. This assumption can be tested using integral constraints and is found to be no worse than the frozen flux assumption. Using these assumptions and expanding the velocity field as the sum of poloidal and torodial parts, we can carry out an inversion to find a smooth solution with large length scales. The 3 assumptions give slightly different flow models- their major features were compared and contrasted- a common feature in all the models is an equatorward jet from the South Pole feeding westward drift under the Atlantic. D. Gubbins (Leeds, UK) asked where geographically these frozen flux models fitted the observations badly. Kathy replied that such analysis has never been carried out, but it would be useful and interesting to look at. A major reason for believing frozen flux flow inversions comes from their correlation with decadal fluctuations in the length of day- a brief summary of this work was given. We suppose that decadal length of day variations are due to the exchange of angular momentum between the core and the mantle. There are then two possible approaches: the kinematic approach where we show that a certain fluid flow in the outer core can account for decadal changes in the mantle rotation rate, or dynamical approach whereby a forward model of the precise core-mantle coupling mechanism (either topographic, electromagmetic or gravitational) can produce the observed changes in the mantle rotation rate. There has been considerable success using the kinematic method, but progress has been slow on the dynamic front- no consensus exists on the preferred coupling mechanism.

## 6pm- Graeme Sarson: Fundamentals of dynamo theory

G. Sarson (Newcastle, UK) provided an introduction to dynamo theory- thought to be the mechanism of magnetic field generation in stars, galaxies and most importantly to us, in planetary cores. Dynamo theory starts with pre-Maxwell equations in the MHD regime and Ohms law for a moving conductor which combine to give the induction equation. When conductivity is constant this equation says that the change in magnetic field is given by induction due to fluid motion and the diffusion of the magnetic field. The ratio of these components is known as the magnetic Reynolds number. The magnetic energy equation was constructed by taking the dot product of the induction equation with the magnetic field and integrating throughout space. This gives an equation where the magnetic energy is equal to the work done by the velocity field against the Lorentz force, minus the Ohmic dissipation, minus the net energy lost via transport processes. For magnetic fields to be maintained by MHD processes, we thus require a velocity field strong enough to counteract Ohmic dissipiation. Two limits to the induction equation were described (i) negligible magnetic Reynolds number, for which we obtain a simple diffusion law and the existing magnetic field must decay (ii) infinite magnetic Reynolds number, when diffusion is negligible and the magnetic field can be thought of as ”frozen into the fluid” and acting as a tracer. The kinematic dynamo problem was analysed in detail— this involves solving the induction equation when the velocity field is specified as constant, leaving a linear eigenvalue problem in the magnetic field. In the form relevant to the geodynamo, it should be solved within a conducting sphere surrounded by an insulator. The velocity and magnetic fields are expanded into toroidal and poloidal parts. From observations of the geomagnetic field and our knowledge of the dominance of rotation, it is worth considering an axisymmetric field geometry in some detail and to work in a cylindrical co-ordinate system. We can decompose the velocity and magnetic fields into axisymmetric and non axisymmetric parts. This enables us to rewrite the induction equation as two coupled, scalar partial differential equations. By examining their energy evolution equations we find that if the velocity field is truly axisymmetric, then the dynamo action will ultimately decay. The $\omega$ effect (named after a term in one of the scalar induction equations which involves $\omega$) which is capable of creating magnetic energy was introduced. Physically this mechanism can occur when there is differential rotation of the velocity field which can take polodial magnetic field, twist it into a helical shape and then a little diffusion detaches the links to the external poloidal field leaving a purely toroidal field. For a complete field amplification process we also require a mechanism which generates poloidal field from toroidal field. This is known as the $\alpha$ effect. It requires that the non-axisymmetric velocity field is finite and enters the induction equation as a term $\alpha\mathbf{B}$ which is why we call it the $\alpha$ effect. Physically it involves fluid flow creating a loop in a magnetic field line, twisting the loop in the plane perpendicular to the field line and diffusion snipping off the loop, leaving a poloidal field. Complex flows capable of producing the $\alpha$ effect are characterised by ”helicity”, a feature of convection in a rapidly rotating shell (for example in the model of Busse 1975). Nearly axisymmetric dynamos can be classified according to the generation terms present: $\alpha^2$, $\alpha\omega$, $\alpha^2\omega$ dynamos have all been studied numerically in some detail- $\alpha^2$ dynamos prove stationary, while $\alpha\omega$ dynamos have been found to be oscillatory, with flux migrating in periodic waves, though the addition of meridional circulation means that they too can be stabilised. A velocity field with nearly axisymmetric flow and meridional circulation is the simpliest model of the geodynamo, which is thought to be of $\alpha\omega$ type, though not simply periodic. To fully understand the dynamo process, we must ultimately perform 3D calculations, which reduce to the simple axisymmetric models as special limits. The most widely studied 3D kinematic dynamo is that of Kumar and Roberts (1975)- it provides a parameterisation of toroidal flow, meridional circulation and convective rolls. We now have a reasonable understanding of how a given velocity field can generate a magnetic field, but this is only part of the dynamo problem: we must also explain the maintainence of the velocity field. The full dynamic equations include the momentum equation, the temperature equation as well as the induction equation complete with fully non-linear coupling and appropriate boundary conditions. This full MHD dynamo problem remains poorly understood- in the next section of his talk Graeme briefly addressed the topic of dynamic mechanisms. He described one example showing plots of axial vorticity, magnetic field and the temperature field , both near the equator and near the surface to illustrate such mechanisms. Another perspective on the convective dynamo problem is to recognise it as a non-linear dynamical problem and investigate the sequence of bifurcations which occur as the Rayleigh number (Ra) is increased. In low order or axisymmetric systems the magnetic and velocity fields gradually become more complex as Ra increases. Fluctuations in the system (in Ra) are therefore not important. When we move to consider full MHD dynamos the contrasting influences of rapid rotation and the magnetic field means there is no such simple sequence of bifurctaions. Graeme described the recent work of Zhang and Gubbins (2000) on convection in rapidly rotating systems at low Ekman number with varying strengths and configurations of imposed magnetic fields. These studies show that small changes in the imposed magnetic field (particularly the ratio of toriodal field to poloidal field) can have large effects on the critical Rayleigh number and hence the ability of the system to generate a magnetic field. Parallel studies on 3D kinematic dynamos show that small changes in the imposed velocity field can also alter the regime of the dynamo. Taken together these studies suggest that a convective dynamo in a rapidly rotating system, at small Ekman number will be extremely sensitive and susceptible to a ”dynamo catastrophe” whereby field generation collapses. We can picture this scenario in terms of a bifurcation diagram with a sub-critical bifurcation (where small changes in the magnetic field can lead to a large change in behaviour) linking the strong field dynamo and the weak field dynamo, both being unstable. Graeme concluded that we still have much work to do in understanding the feedback between the kinematic dynamo problem and the magnetoconvection problem- there are many different components to the full 3D coupled MHD dynamo problem. The overheads from this thorough tutorial are available to download from http://www.mas.ncl.ac.uk/∼ngrs/skipton.ps.gz.

## Wedneday 26th September

### 9am: Jean-Pierre Valet- Paleomagnetic observations

The session of palaeomagnetic talks was introduced by J-P. Valet (IPGP, France) with a comprehensive overview of all aspects of palaeomagnetic observations, emphasising the advances made in this subject over the past 20 years. Factors influencing relative paleointensity (PI) determination in sediments were described, including the blocking function, grain size, magnetic mineralogy, magnetic mineral concentration and most importantly, magnetic field intensity. The basic mathematics of these relationships were presented, emphasising climatic control over several of the variables (natural remanent magnetisation and susceptibility). Archeointensity data for the past 3000 years was described- the efforts made by Eastern European workers in this area was noted. Magnetic field behaviour during excursions and reversals was discussed. The controversy over preferred longitudinal reversal paths was vigorously debated, with D. Gubbins (Leeds, UK) pointing out that it is vital to consider the geographical position of the sampling site, when assessing the relevance of the VGP reversal path. Attention also focused on the asymmetric saw-tooth pattern of intensity across a reversal, seen in sedimentary records of relative intensity, with lower values before, and higher values after reversal, perhaps suggesting some unknown regeneration mechanism of the geomagnetic field. The records of relative paleointensities from paleomagnetic sources (SINT 800) and Beryllium nuclides produced by cosmic rays (also expected to be a measure of magnetic field intensity) were compared: the records close correlation gives strong confidence in the reliability of the paleointensity records.

## 11.30am: Mimi Hill- Paleomagnetic techniques I

M. Hill (Liverpool UK) continued the theme with the first part of an introduction to palaeomagnetic techniques, entitled 'How do we find the vectorplot?' This began by explaining the basic types of magnetism (diamagnetism, paramagnetism, ferromagnetism, ferrimagnetism). The different classifications of remanent magnetisation were described in detail and linked to the theory behind rock magnetic experiments (including Curie curves and hysteresis loops). Mimi went on to describe how the vector of the palaeomagnetic field is plotted and interpreted, using an Orthogonal Vector Plot. The discussion was illustrated by case studies of recent Hawaiian and tertiary Australian lavas. The use of laboratory instrumentation and rock-sampling techniques were discussed. The talk concluded by outlining cautions to be remembered when carrying out palaeomagnetic investigations such as the important isolation of the primary magnetic component and a full understanding of the process of acquisition.

## 12.15am: Nick Teanby- Paleomagnetic techniques II

The second part of the introduction to palaeomagnetic techniques was given by N. Teanby (Leeds, UK) and concentrated on the analysis and processesing of palaeointensities (PI's). To begin, the acquisition process of thermal remanence magnetisation (TRM) was discussed as an introduction to the absolute PI Thellier-Thellier technique. The basic assumptions of this technique (law of additivity, minimal thermal-chemical alteration) and the experimental procedures were described. The Arai plot was introduced as the conventional method of graphically representing the results. The acceptance criteria for absolute PI determinations were mentioned, describing the use of partial TRMs as a check for thermo-chemical alteration, and the statistical methods of Coe (1969). The complex acquisition processes of relative PI in sediments were described, reiterating the influencing factors such as bioturbation, compaction and magnetic mineral concentration. The absolute and relative PI methods were compared, highlighting the advantages and disadvantages of each. A series of PI data from Hawaiian SOH lava cores, basaltic glasses and the NAPIS-75 (North Atlantic Palaeointensity Stack) were shown as examples of both methods. Finally Nick talked about the use of cosmogenic isotopes Be-10 and C-14 to validate the PI measurements.

## 4pm: Anne Wintle- Dating techniques

A. Wintle (Aberystwyth, UK) talked about dating techniques for paleomagnetic samples. An overview of the different methods was given, with particular emphasis on the Potassium-Argon technique. The principles of luminescence dating (based on the release of electrons trapped in crysal defects), Carbon-14 dating of organic material and Oxygen-18 records from plankton were discussed before moving on to Potassium-40 techniques. Potassium-40 undergoes radioactive decay by electron capture to Argon-40. This noble gas escapes from magma by diffusion but some becomes trapped in cooling lavas. By measuring the amount of Argon-40 and Potassium-40 in the sample, we can date the lava sample, if we assume a simple exponential radioactive decay law. We find that for rocks younger than 1 billion years, the age of the sample is approximately equal to the ratio of the concentrations of Argon-40 and Potassium-40 divided by the half-life of Potassium-40. The methods of measuring the abundance of Potassium-40 by atomic absorption spectroscopy, of releasing the trapped Argon-40 by heating the sample in steps, then measuring its abundance using a mass spectrometer were described. This technique involves a number of assumptions, the most problematic being that the system is closed after crystallisation and no reheating or recrystallisation has occurred. Problems with Potassium-Argon dating including the need to measure both K and Ar separately and the requirement for high measurement accuracy were mentioned. Finally Anne used the example of a paper by Laj et al (2000) on paleomagnetic intensities in Hawaii to illustrate the direct dating of a reversal chronology. In this case the K-Ar methods gave a dating precision to within 1.5 percent compared to the standard chronology for reversals obtained at a variety of sites around the world. Finally Anne stressed that the main problem in dating lavas is discontinuous eruption rates which mean different periods are sampled with different resolutions.

## 4.30pm Kathy Whaler: Martian magnetic anomolies

In the first of the research talks, K. Whaler (Edinburgh, UK) dicussed ongoing work in modelling Martian magnetic anomoly data collected by the Mars Global Surveyor satellite. At present Mars has no working dynamo; but the presence of strong remanent magnetisation (around 1500nT at 120km) suggests that there must have been a strong working dynamo, earlier in the evolution of the planet. Inverse modelling techniques (see Whaler and Langel 1996) were used to find the best fitting magnetisation which minimised the integral of the square of magnetisation, over the whole volume of magnetised crust. The numerical and computational details of the inverse method were discussed, in particular how to deal with a numerically sparse problem. Preliminary results of the crustal field models were presented. A clear dichotomy in the anomolies was visible between the northern and southern hemispheres, though results near the poles are known to be less robust. The most interesting anomolies lie in the Southern hemisphere, with some intriguing evidence of changing patterns in inclination and declination. Overall, the magnetisations were found to be an order of magnitude higher than those seen on Earth. In particular the vertical component is large, though the $/X$ and $/Y$ components are also significant. Comparison of this inverse technique with the forward models of other workers showed preliminary agreement in relative sizes and patterns of magnetisation, but there remain significant differences in the absolutes sizes of the magnetisations predicted by the two approaches. Much work continues to be done in this area as new data is released. D. Gubbins (Leeds, UK) questioned whether terrestrial basalt could sustain the high levels of magnetisation being proposed, J-P. Valet (IGPG) felt that such remanent magnetisation was possible, if the original field was large enough.

## 5.15pm: Jack Jacobs- Problems with reversals of the Earth's magnetic field

J.A. Jacobs (Aberystwyth, UK) reviewed our ongoing struggle to understand various aspects of reversals of the Earth's magnetic field. He began by discussing new ideas about the influence of the Earth's inner core on reversals and the results of recent supercomputer models. The presence of the inner core will split the outer core into 3 distinct dynamical regions (see S. Gibbons earlier talk), its growth could help power compositional convection (see D. Gubbins talk on energetics of the core) and perhaps most importantly if the inner core is finitely conducting, magnetic field diffusing into it could help to stabilise the outer core against reversals. In this case, an excursion would occur when the magnetic field in the outer core reversed, but didn't stay reversed long enough for the field in the inner core to be reversed. An important new method of testing such ideas has become accessible in the last few years with the development of the first fully self consistent numerical dynamo models. Models incorporating a finitely conducting inner core have now been constructed by Glatzmaier and Roberts and seem to show that the inner core does indeed have a strong influence on the reversal process. Such models are important as they include fully non-linear coupling and don't treat the Lorentz force as a perturbation, but the validity of their parameterisation of viscous and inertial effects remains controversial. Kuang and Bloxham (1997) have produced another numerical dynamo model which incorporates different boundary conditions and obtain different azimuthal flows. More recently Glatzmaier et al (1999) considered inhomogeneous thermal boundary conditions and concluded that the pattern of heat flux from the core to the mantle can affect the frequency of magnetic reversals. Next Jack addressed the thorny issue of whether reversals could be examples of deterministic chaos (a consquence of non-linear coupling and feedback within a system) such as seen in the Lorentz system and in various disk dynamo models. In such systems, reversals are aperiodic and long term prediction is impossible. The present geomagnetic time series is not long enough for us to conclusively classify the geodynamo as a chaotic system. It also seems likely that external forcing (changing boundary conditions) could have an important role to play in our understanding of the reversal sequence, particularly in regard to explaining superchrons. The issue of periodicities within the geomagnetic reversal record was described in some detail. There have been many attempts to link magnetic reversals with other geophyscial phenomena including changes in the Earth's orbital parameters, though none have stood up to close scrutiny. The problems in interpreting the geomagnetic record were discussed, in particular the lack of precise dating of reversals and the incomplete nature of the reversal record. Finally some unresolved issues worth future consideration were discussed. These included the coupling between core and mantle convection; the role of D$''$ layer; the behaviour of secular variation during excurions and reversals; the effect of memory in physical systems- can the duration of a chron be influenced by the magnetic field intensity before a reversal; and the question of magnetic field intensity during superchrons.

## 6pm: Melina Macouin- Field intensity recorded from precambrian dykes

M. Macouin (IPGP) discussed new paleointensity estimates from precambrian dykes in Canada. These measurements improve our sketchy knowledge of the Earth's magnetic field early in the history of the planet and could help constrain theoretical models, particularly regarding the influence of inner core growth on magnetic field generation. The Fort France, Matachewan and Marathon dykes (dated at 2.4-1.1 billion years by zircon fission track and U/Pb methods) were subjected to rock magnetic experiments and Thellier-Thellier analysis (Coe variant). Two magnetic components were commonly found, with a stable NRM held by single- and pseudo-single-domain grains (reversible Curie curves). High blocking temperatures (600 degrees centigrade) indicated that significant viscous decay might have occurred. Small heating steps of 2 degrees centigrade were taken between 500 and 600 degrees centigrade. This was achieved by modifying a conventional oven using an accuracy of $\pm$ 1.5 degrees centigrade. Results indicated low field values, with a 60 percent success rate. Some samples were subjected to AF (alternating field) demagnetisation and remagnetisation (Shaw method) and gave a PI estimate of about 8$\mu$T. These results show that it is possible to obtain paleointensity results for very old data. If we make the geocentric dipole assumption and calculate the magnetic moment, we find a magnetic moment 4 times weaker than previous estimates for this period. D. Gubbins (Leeds, UK) pointed out that the inner core had probably formed by this time, so it is unlikely the absence of an inner core could explain such low intensities, but if the axial dipole assumption was not valid, this could explain the lower intensities observed. Melina commented that it is difficult to test this proposal since a large amount of data from the time period would be required.

## 6.30pm: Agnes Elmaleh- Evidence of anomolous paleofields in the Pacific

A. Elmaleh (IPGP) discussed palaeomagnetic results from four groups of sedimentary records from Hawaii, Central Pacific, SW Pacific and Indonesia, with an emphasis on the SW Pacific area. Evidence from previous studies for low paleofields in the pacific during the last 500 million years was discussed- the anomoly is a robust feature of several studies, but the spatial structure varies between them. This study aimed to obtain a more accurate picture of the spatial structure of the anomaly by analysing 14 cores in Hawaii, Indonesia and Fiji. Sedimentary cores were dated with Oxygen-18 chronology and correlated using magnetic susceptibility. Samples were AF cleaned (under 100mT) and many showed single magnetic components. Results showed a persisent magnetic anomaly on a millennial time scale- maps showing spatial details of this anomoly were presented. Alternative explanations for the origin of the anomoly (non-vertical drilling, viscous components, and crustal contamination) were ruled out- it must be of geomagnetic origin. This studys paleointensity results correlated well with the SINT 800 compliation, the global database of Carlut and Courtillot (1998) and other sedimentary databases. The most important result was the correlation between the low paleointensity anomoly and a large negative inclination anomaly (-15 degrees), perhaps suggesting that non dipole components are more important when the magnetic field intensity is low. The paleomagnetic anomoly in the Pacific was then compared to the Pacific anomoly seen in geomagnetic models from historical observations (see Bloxham, Gubbins and Jackson 1989). The long term nature of this feature suggests it might be a consequence of core-mantle interaction. D. Gubbins (Leeds, UK) asked whether there was any prospect of obtaining declination measurements for these cores, Agnes replied that unfortunately these cores were unoriented, so no declination measurements were possible.

## 7pm: Art Jonkers- Long range dependence in the cenozoic reversal record

Art Jonkers (Liverpool, UK) presented a talk on his efforts to interpret the geodynamo as a critical system (where small fluctuations can have long range effects) characteristed by a power law distribution of frequency of reversal verses time between reversals. Art began with a philosophical overview of scientific progress in the 20th century, emphasising the emergence of the new subjects of non-equilibrium physics, chaos theory and in the last few years complex system studies. This revolution has lead to an emphasis on understanding the long term (non-linear) dynamics governing a system's evolution in phase space (including the ideas of attractors), rather than the traditional method of finding a closed solution which we can write down and use to predict all future behaviour of the system. The historical evolution of a non-linear system (memory) has a major influence on what the system will do next. One example of the application of these techniques is in the theory of self organisation- we picture a large number of isolated elements interacting so that when the system is in a critical state a large scale change in behaviour can be triggered by a small change in one of the elements (fluctuation). These ideas were pioneered by Per Bak in simple models where grains were continuously added to the top of a sand pile. By plotting the frequency of the collapses against the size of the collapses a power law was obtained. Art argued that the geodynamo might be in such a critical state, in which case we might expect the frequency of reversals and the time between reversals to follow a power law. A plot of log (frequency) against log (interval between reversals) for the past 484 geomagnetic reversals (Cenozoic period) was presented. He found evidence (though by no means conclusive) for a power law dependence. Stated simply this says that there are many more short intervals between reversals than there are large intervals between reversals- a statistical fact with no obvious explanation in conventional geodynamo theory. It appears to suggest some form of long term ”memory” in the system. Art suggested this could be quantified using a Hurst parameter- the value calculated suggested some long term correlation was present in the reversal data. A. Jackson (Leeds, UK) asked whether there was any physical basis for thinking that the geodynamo was in a critical state. Art felt he wasn’t qualified to judge, but perhaps the wider geophysics community would be equiped to answer the question. D. Gubbins (Leeds UK) questioned the omission of superchrons from Art’s study. Art said he felt that some external mechanism must be operating during the superchrons, so they did not represent the usual reversal process.

## Thursday 27th September

### 9am: Nick Teanby- Stetching correlation technique

The second presentation from N. Teanby (Leeds, UK) introduced a new method of correlating relative and absolute palaeointensity records, involving the stretching of one record to match the other. In records of both sediments and lava, poor dating makes it difficult to compare two different records of the same periods. Traditionally such comparisons have been done by eye and by using linear interpolation, but this is subjective and can introduce inaccuracies. Nick described a new method to stretch one record and fit it to another by minimising an objective function. This method promises to be both less subjective and more exact. The timescale of one reference record was plotted against the depth record of another. A cubic B-splines basis was used to represent the record to be fitted and the coefficients chosen by minimising a misfit function. The danger of time reversals in the newly stretched records was a problem, so a weighting function is used to avoid these false solutions. Several criteria need to be met before stretching can begin- we require two records being of the same signal, the stratigraphic ordering and approximate initial alignment. Case studies from Pacific sedimentary cores and the SOH1 and SOH4 Hawaiian cores were presented. Nick concluded that the stretching optimisation method could be used to improve the timescales of both sediments and lava records if the the reference and the record to be fitted measure the same signal, are strtigraphically ordered, reasonably well aligned and continuous. D. Gubbins (Leeds, UK) pointed out that the misfit function was nonlinear, so the problem had to be solved by iteration.

## 9.30am: Mimi Hill- Comparison of microwave and thermal paleointensity techniques

M. Hill (Liverpool, UK) gave her second talk on the comparison of the conventional Thellier-Thellier method and the new microwave technique of absolute paleointensity determination. A basic introduction to microwave theory was given- essentially high frequency microwaves stimulate the magnetic elements in the sample, but avoid heating the sample matrix. This causes reduced sample alteration and means much smaller cores can be used. Instrumentation and experimental procedure were described- photos of the Liverpool apparatus were shown. Comparisons of thermal and microwave demagnetisation were discussed, showing smearing between magnetic components in the microwave method in some lava samples (two components were laboratory-induced). Other test results showed the microwave analysis of a laboratory-induced TRM and the Thellier-Thellier analysis of a microwave-induced TMRM (thermoremanent microwave magnetisation), both using a 50mT field. The experiments agreed, both giving 50mT within small error limits, though less thermo-chemical alteration was seen in the microwave method (data from the Thellier-Thellier method failed at 450 dgrees centegrade). A set of ‘real-life’ results were presented from Australian Tertiary basalts. Low quality results were obtained from the Thellier-Thellier method (0 percent success rate), but a 63 percent success rate was achieved with the same samples, using the microwave method. Mimi concluded that the microwave paleointensity method is applicable to both ancient and modern rock, and can provide paleointensity measurements with less sample degradation than traditional methods. J-P. Valet asked whether there was a linear relationship between the temperature needed to demagnetise the sample and the power input by the microwaves. Mimi replied that it wasn’t that straightforward- there was no simple conversion between the two measures since the heating methods were based on different physical processes.

## 10am Steve Gibbons- What can kinematic dynamos tell us about reversals?

Steve Gibbons (Oslo, Norway / Leeds, UK) gave a talk on his recent work on 3D kinematic dynamos, dynamo waves and their influence on reversals. He began by reviewing the progress made in understanding reversals through different dynamo models. The famous Glatzmaier and Roberts (1995) reversal model was described- unfortunately this was in an inappropriate parameter regime, employed unphysical hyperviscosity and may have simply been a transient phenomena, so doesn't teach us much. Earlier reversal schemes included those of Parker (1969) based on fluctuations of convection cells and Levy (1972) based on a 2D $\alpha\omega$ model where a high lattitude $\alpha$ effect could reverse the toroidal magnetic field near the equator. These reversal schemes used extremely simplistic forms for inductive effects- Roberts (1972) showed that if $\alpha$, $\omega$ effects were continuous then oscillatory dynamo waves would be generated - steady fields are only found when the $\alpha$, $\omega$ effects are sufficiently separated. Lately Hollerbach and Jones have used mean field models to test the influence of a conducting inner core on reversal mechanisms. A more realistic approach involves considering 3D kinematic dynamos such as that of Kumar and Roberts (1975) described in G. Sarson's talk. This method prescibes a flow which includes differential rotation, meridional circulation and convective overturn. Steve gave an account of recent work searching the parameter space of the Kumar-Roberts dynamo, to find how the relative strengths of differential rotation and meridional circulation affect the nature of the dynamo solution (none, steady, oscillatory etc). 36 percent were found to act as dynamos and 64 percent failed to generate a self sustaining magnetic field- small linear regions of oscillating dynamo action separated these two regimes. The oscillatory regions are found when radial and azimuthal field concentrations occur at the same spatial position in the spherical shell. Steve argued that the oscillation could be a reaction to having radial and azimuthal fields close together. The kinematic models show that steady solutions require optimal separation of the radial and azimuthal fields. A systematic parameter study of kinematic dynamos showed that it is the meridional flow which is primarily responsible for changing the relative postions of the radial and azimuthal field concentrations. We might then expect that dynamically, a thermal plume from the inner core boundary (which would change the meridional circulation) could initiate a reversal (as observed by Sarson and Jones 1999). In conclusion, Steve suggested that any process which forced the radial and azimuthal magnetic fields into the same region could trigger a geomagnetic reversal. More detailed studies of such correlations in fully dynamic models must be carried out to fully test this hypothesis.

## 10.30am: Ingo Wardinski- Decadel and subdecadel secular variation

I. Wardinski (Potsdam, Germany) discussed his PhD project which aims to use all available data (observatory, ships, Magsat, Oersted, Champ) to derive simulataneous models for the magnetic field and the secular variation for the period 1980-2000. These models will be used to investigate time dependent behaviour of crustal fields, construct core flow models and to examine the nature of geomagnetic jerks. The definition of a geomagnetic jerk (a discontinuity in the second time derivative of the magnetic field) was discussed and some examples of the 1979 jerk were shown. It is thought that another jerk occurred in 1991- right in the middle of the period being studied. Ingo next discussed work completed so far in the analysis of observatory data. There are two main sources of time variations- on short time scales we see variations due to external fields (for example due to the ring current in the ionosphere) while the changes on longer time scales are due to changes in the Earth's internally generated magnetic field. The method of Stewart and Whaler (1992) to remove the effect of external fields was described. It used a cubic expansion to deterministically fit the external fields. The model can incorporate variations in the solar cycle, though if possible it is preferable to use quiet time data. The model and residuals were displayed graphically. Ingo showed how including the solar cycle in this simple model significantly reduced the residuals. D. Gubbins (Leeds, UK) pointed out that it may be possible to use 'sunspot numbers' when modelling external fields in this way. A. Jackson (Leeds, UK) asked why the model only contained terms up to cubic order- Ingo explained this was all that was necessary to model external magnetic fields.

## 11.30am: David Gubbins- What's wrong with the frozen flux assumption?

D. Gubbins (Leeds, UK) gave a provocative short talk in which he challenged a major assumption used in the inversion of the induction equation to obtain fluid flow near the top of the core. The induction equation (see G. Sarson's talk) was analysed- we know that the radial component of magnetic field will be continuous across the CMB, but the argument is less clear for the horizontal component because of the possibility of a current sheet near the boundary. Previous attempts to address this problem (Roberts and Scott 1965, Backus 1968, Hide and Stewartson 1972, Backus 1991 and Gubbins 1996) were discussed. It was emphasised that the analysis of Hide and Stewartson was incomplete because they only considered steady motions. David argued that time dependency is likely to be an important part of this problem, suggesting that MAC waves could propogate in the boundary layer. The properties of such Alfven-Coriolis waves have never been fully elucidated. Assuming only our knowledge of the radial component is sound, progress on the inversion problem is usually made by assuming that the diffusion term in the induction equation is much smaller than the advection term. If we neglect the diffusion term completely then magnetic flux becomes fixed to the fluid- this is the so called frozen flux assumption. It is usually justified by a simple scaling argument where the length scale is taken to be of order of the core radius and the velocity scale taken to be that of westward drift. This yields a diffusive time scale much longer than the advective timescale. Several reasons why the frozen flux assumption could be inadequate were proposed: (i) The diffusion timescale could actually be much shorter, for example, taking the length scale to be the depth of a boundary layer then diffusion could be extremely important in producing secular variation. (ii) By setting the diffusive term equal to zero we are reducing the order of the problem and losing possible solutions- this is mathematically incorrect. (iii) Only a very small amount of diffusion can be important- if the frozen flux hypothesis were true then null flux curves could never merge, but an infinitesimal amount of diffusion would permit this to happen. Physcially we would expect there to be some diffusion (even if only a small amount) so we expect to observe diffusive processes if our observational data is of high enough quality. (iv)The frozen flux hypothesis doesn't allow flux expulsion, which several workers feel could be an important mechanism for secular variation, although as A. Jackson (Leeds, UK) pointed out, it is possible to create adequate field models without flux expulsion. (v) Diffusion is vital if steady dynamo action is to be maintained (See Gubbins and Kelly 1993, Love 1999)- since the frozen flux assumption neglects diffusion, it imposes a different balance (between secular variation and advection). Having shown that there are some problems and inconsistencies involved with adopting the frozen flux assumption, David went on to describe his method for including diffusion in the inversion of the induction equation. The inversion equation is solved as an intergal problem to find the radial component of the magnetic field, using an appropriate Greens function (see Gubbins 1996). It turns out that this approach yields an extra correction term (compared to the frozen flux method) which scales as the product of the magnetic diffusivity and the observation time. In the limit of zero diffusivity the frozen flux solution is recovered. This methodology has yet to be employed practically. Possible approaches to studying the full induction problem in the frequency domain were mentioned. Taking the Fourier transform we are left with a convolution of the Fourier transforms of velocity and magnetic field- perhaps we could investigate this convolution for certain frequencies of geophysical interest. David finished his talk with a challenge to A. Jackson (Leeds, UK) to defend the frozen flux assumption against the problems mentioned. A. Jackson said that it would take a lot longer than the few minutes available to satisfactorily rebuff all the points raised- the debate was postponed to a later date- there is another side to this argument which was not presented here!

## 12pm: Peter Jimack- Some work of the Leeds computation PDE Unit

P. Jimack (Leeds, UK) gave a short introduction to cutting edge computational techniques likely to be of use to Earth scientists. He concentrated on adaptive mesh refinement techniques, parallel algorithms and multigrid solver methods. Adaptive mesh refinement is a technique of selectively and efficiently achieving better resolution in numerical models. It uses a hierarchical system of embedded rectangular and triangular meshes. The meshes are continually refined and redefined adapting to the time dependent nature of the solution. The use of this technique was illustrated by a model of the evolution of a free surface where significant free surface deformations could be dealt with. In this example, the fluid density determined the resolution of the adaptive mesh- fine meshing is distributed where it is needed, elsewhere, coarser meshing is employed in order to save computation time. Such techniques are particularly important for 3D calculations. Next Peter discussed parallel algorithms. A problem is separated into different parts and the parts distributed to different processors before being recombined. Ideally we would like to dynamically distribute the load between the processors. The procedure of nesting by which different grids are combined to produce a global solution was discussed. The final section of Peter's talk dealt with multigrid solvers. These have practical applications in a variety of demanding non-linear problems such as elastahydrodynamic lubrication where the non-linear Reynolds equation must be solved to determine the pressure evolution. It involves a sequence of nested meshing where iterative methods are employed and coarser meshing can be projected onto finer meshing to save computation time. The EHL problem solving environment was described- this user friendly software allows non experts to take advatage of these advanced computational methods. D. Gubbins (Leeds, UK) pointed out that such adaptive methods would be perfect for modelling propagating features. S. Gibbons (Oslo, Norway) felt that the methods described could be extremely useful in computationally demanding dynamo problems.

## 12.30pm: Phil Livermore- Variational treatment of kinematic dynamo equations

P. Livermore (Leeds, UK) described a new approach to the problem of finding bounds on the growth rate of the magnetic energy in the dynamo problem. The growth of magnetic energy (M) and that for the magnetic flux density (B) could be different because B can be decomposed into a sum of eigenmodes with different decay rates; it is the superposition of these modes which determines M. Phil described two previous approaches to this problem: that of Backus who considered a conducting sphere embedded in an insulator with constant diffusivity, and Proctor who considered much the same problem but with a conducting mantle with varying diffusivity with radius. Both used approaches involving knowledge of the maximum strain rate. The new method involves considering a stationary case to find the maximum growth rate, and results in an additional constraining equation. The equations for the stationary problem relating to the case considered by Proctor, have been solved in the limit of an insulating mantle, giving the same result. Numerical calculations show that the inclusion of Earth-like mantle conductivity makes little difference to the upper bound on the growth of magnetic energy - this is a new confirmation of the hypothesis that mantle conductivity is unimportant in the geodynamo problem. In conclusion, the merits of this new variational approach were discussed: the new method includes the full strain rate tensor field, not just the maximum strain rate considered by Backus and Proctor, so we should be able to observe how changing the form of the velocity field affects the upper bound on the growth rate of magnetic energy. There is also some hope that the critical magnetic Reynolds number for M will approach that for B (always being a lower bound anyway). D. Gubbins (Leeds, UK) suggested it would be numerically easier and possibly physically instructive to consider the simpler case of a periodic dynamo, before attempting to use an expansion of the full velocity field.

## 4.30pm: David Gubbins- Energetics of the Earth’s Core

D. Gubbbins (Leeds, UK) gave the last tutorial of the retreat on the thermodynamics of the Earth’s core, paying particular attention to the mechanisms for cooling the core and driving the geodynamo. Not much energy is required- only enough power for one light bulb per cubic kilometre in the outer core. Possible sources of energy include radioactive heat, latent heat, gravitational energy, chemical energy, and rotational energy. Geophysical observations provide some crucial contraints on the energetics of the core: core covection must be sufficiently vigorous to generate the observed magnetic field, but the heat flux out of the core must be sufficiently low that the mantle is not melted. In addition, thermodynamic accounts of the Earth's history must incorporate a reasonable growth rate for the inner core. Gubbins, Masters and Jacobs (1979) sought to put our ideas on the thermal evolution of the core on a firm theoretical basis. David described how he has recently returned to re-evaluate these calculations using 1st principles (Quantum mechanical) high pressure data for the substances thought to make up the core. To understand the energetics of the core we must use the second law of thermodynamics and in particular the concept of entropy. We consider a basic state of pure iron which is well mixed, has an adiabatic temperature gradient, where the hydrostatic pressure is much larger than the dynamic pressure and the fluid flow is steady or at rest. Entropy dissipation can then occur by thermal conduction, electrical heating, molecular diffusion or viscous diffusion. Adding these together we obtain a figure around $10^9 WK^{-1}$ for the dissipation which must be overcome by any mechanism capable of powering the geodynamo. Next possible energy sources were discussed quanitatively. Uniform radioactive heating throughout the core for a reasonable heating rate yields a heat flux from the surface much larger than that observed- this mechanism must be rejected. The possibility of a gravitational energy source associated with thermal convection was analysed. It was shown that much of the gravitational energy produced by thermal convection was cancelled out by work done by pressure forces on surfaces in squashing/expanding fluid parcels. This subtle point was not picked up by many who read the original paper, but implies that thermally based gravitational energy sources are insufficient to drive the geodynamo. The final power source discussed was the release of latent heat due to the freezing out of the outer core fluid onto the solid inner core and the associated gravitational energy from compositional convection. We must now abandon the simple model of the core as pure iron. New models propose that the core is a mixture of Iron, some Silicon/Sulphur and Oxygen. About 7.7 percent Oxygen is frozen out at the inner core boundary. This lighter material will rise producing significant compositional convection- it is thought to be a major power source for the geodynamo. Calculations show that this mechanism can produce 1.44x$10^{13} WK^{-1}$: enough to drive the fluid motions giving the obeserved geomagnetic field, overcome the dissipation mechanisms and yet not generate a heat flux out of the core so large that the mantle would melt. It also gives a feasible rate of growth for the inner core. Even with the new figures we are pretty pushed to make the available numbers balance (some squeezing is required!)- this could be because there is something about the structure of the outer core we do not yet fully understand, for example the existence of a stably stratified region where no convection occurs. It is unlikely that there are new energy sources waiting to be discovered. In conclusion David emphasised that to understand the energetics of the core we must consider not just thermal processes, but also compositional changes.

## 6pm: Andy Jackson- Fourier methods on a sphere

A. Jackson (Leeds, UK) described ongoing investigations (in collaboration with Torben Risbo) into an alternative basis for representing functions on a sphere. The geophysical motivation for these studies was presented. Many atmospheric/geodynamo models are based on expansions in spherical harmonics. These are eigenfunctions of the horizontal Laplacian operator, with many attractive properties including no singularities at the poles of a spherical surface. However they tend to be computationally slow at high resolution. In particular for an NxN grid, the spherical harmonic transform costs $N^3$ operations. This poses the question: is there any better representation which could transform with fewer operations? Several such basis have been suggested, but all have so far proved numerically unstable. The new approach being investigated involves a knowledge of hyperspheres. These are higher dimensional objects in which the equator of any hypersphere is the perimeter of a unit hypersphere in a space one dimension lower, for example the equator of a sphere in 3D describes the perimeter of a circle in 2D. If we consider 4D space there are 2 separate co-ordinate systems which satisfy the Laplacian operator- the hyperspherical co-ordinates (which don't appear to be of interest) and the bispherical polar co-ordinates which label any point in space by radius r and 3 angles $\alpha$, $\beta$, $\gamma$; $\alpha$ varies between 0 and $\pi/2$ while $\beta$, $\gamma$ variy between 0 and $2\pi$. If we fix $\alpha$ at $\pi/4$ then this co-ordinate system gives full coverage on a sphere. For fixed r, the angles $\beta$, $\gamma$ tell us how to navigate on the sphere- it isn't in the conventional $\theta$, $\phi$ way! Paths along lines where one of $\beta$, $\gamma$ is kept contant were shown. The new co-ordinate system has $2\pi$ periodicity in both angles when we consider a 2D conformal map, unlike the traditional spherical basis where we find a discontinuity in $\theta$. The Fourier transform of the new mapping system allowed NxN operations to be described by order ($N^2 \log N$) operations- a significant improvement on the spherical harmonic transform. Andy concluded that although this work was at an embryonic stage (in particular an explicit fast Fourier transform has not yet been formulated) it does have lots going for it- the next step will be some practical trials involving Fourier decompositions of data on a sphere.

## 6.30pm: Alastair Rucklidge- A heteroclinic model of geodynamo reversals

A. Rucklidge (Leeds, UK) described how simple dynamo models can be made to exhibit mostly steady behaviour punctuated by abrupt, aperiodic reversals. Alastair began by explaining what was meant by the term ”heteroclinic cycle”. When we have 3 interacting modes (belonging to different symmetry classes) which are coupled by non-linear terms, we can obtain behaviour where the system continually moves on a cycle, for example between 3 saddle points in phase space, where 2 of the 3 modes are always zero. Examining time series for such trajectories we find one mode stays steady for a long period before abruptly decaying to zero while the other modes grow. The system soon recovers to its original almost stable configuration and the cycle continues. In this system there are none of the reversals that interest us geomagnetically. This situation is remedied by adding noise to break the symmetry of the system. In the simple model presented, 3 external parameters were introduced. Now intermittent reversals are seen in the time series (along with features where there is a burst from modes which were previously zero, before the original solution is recovered- Alastair suggests these could be similar to excursions). This simple model reproduces both a predominantly steady stable state and the reversals and excursion which are characteristic of the geodynamo, unlike many other simple dynamo systems which have been studied. Alastair concluded that although physical reality won't be this straightforward, the model illustrates several important points: (i) a magnetic field with at least 3 different interacting symmetry modes (one being dominant) is required to obtain a heteroclinic orbit and (ii) symmetry breaking noise/external forcing is required to produce reversals and excursions. G. Sarson (Newcastle, UK) asked whether the behaviour presented had been the result of careful parameter choice. Alastair agreed that he had picked parameters to give behaviour most similar to that of the geodynamo, but felt this didn't affect the main conclusions of the study.

By Chris Finlay (Leeds, UK) and Martin Gratton (Liverpool, UK)