Frontiers in Dynamo Theory: From the Earth to the Stars

September-December 2022

Background

A hundred years ago Sir Joseph Larmor suggested the current paradigm for the origin of the magnetic fields of the Sun and the Earth -- a self-sustained dynamo driven by motions in an electrically conducting fluid or plasma. The fundamental magnetohydrodynamic equations that govern the mutual interaction of magnetic fields and moving fluids are well established. However, to work out the mechanism of magnetic field generation and to develop models that explain the observed properties of magnetic fields turned out to be an extremely challenging task in applied mathematics. The coupled partial differential equations are highly nonlinear and, from a physical viewpoint, the problem involves an enormous range of spatial and temporal scales.

Dynamo theory was the subject of the first programme at the newly formed Isaac Newton Institute in 1992. At that point, a fundamental understanding of the principles of magnetic field generation had been firmly established. However, realistic models explaining the spatial structure and temporal variation of planetary or stellar magnetic fields were largely missing. Since then the field has progressed in large strides. In particular for the geodynamo numerical simulations became capable of reproducing many of the observed properties of the magnetic field. The geomagnetic field has now been mapped with much improved spatio-temporal resolution, by dedicated satellites for the recent field, and by rock-magnetic methods for the past 100,000 years. In the past 30 years, space probes discovered magnetic fields or mapped previously known fields much better at Mercury, Mars, Jupiter, Saturn and Ganymede. With sophisticated spectroscopic methods magnetic fields have been discovered and mapped at stars other than the Sun. Models for the solar dynamo are now much better constrained by the results of helioseismology that revealed the general flow pattern in the solar interior.

This wealth of new observations provides challenges to improve the dynamo models for a particular object. Furthermore, in the past modellers working with similar methods on different objects, planets or stars, have not interacted as much as they might have with each other, with scientists that interpret observations, or with mathematicians that address fundamental questions in dynamo theory. A prime objective of the programme was therefore to foster the interaction of applied mathematicians, astrophysicists, geophysicists and planetary scientists, who attack the dynamo problem from different angles. Several open questions cut across the boundaries: Do numerical models capture the essential balances of forces governing the flow in the dynamo? What causes the stochastic reversals of the Earth's magnetic field and which models can explain simultaneously the eleven-year cycle of the solar magnetic field and the pattern of flow in the solar interior as revealed by helioseismology? How can the newly discovered waves in the Sun and in the Earth's core be used to better constrain dynamo models?

Programme structure and outline

The anchor points of the programme have been three workshops, described below in detail. In each of the weeks between workshops we had one formal seminar on a topic of broader interest, followed by an informal gathering with drinks which promoted lively discussions in small groups. In addition, we typically had two discussion seminars each week on more specialized topics, with a presentation that ideally took not more than 20 minutes, followed by an intense round-table discussion. Further highlights have been two "topical discussion rounds", one half-day discussion on geomagnetic reversals, and a full-day discussion session on the magnetic fields of Jupiter and Saturn and its interaction with the strong zonal jets found at these planets. Both events have been characterised by a lively exchange between numerical modellers, theorists and observers.

Workshop 1 on 12-16 September 2022 marked the very start of the DYT2 programme and set the stage for the discussions during the first part of the programme. Entitled "Dynamos in planets and stars - similarities and differences", it was specifically aiming at bringing together theoreticians, modellers, and observers with interests in planetary and stellar magnetic fields. Twenty-one speakers from the UK, USA, France, Spain, Germany and India discussed the latest developments and challenges in the study of the magnetic fields of planets and stars.

Our first aim was to ensure that participants, despite their various backgrounds, spoke a common language and could interact efficiently. With that aim in mind, five keynote lectures were scheduled, one at the beginning of each session. These one-hour long presentations were aiming to help discussions across communities and were given by renowned experts in their fields who have the ability to reach out to non-experts. Workshop 1 was kicked off by a lecture by one of the pioneers in dynamo theory, Keith Moffatt, who had been an organisers of the first dynamo programme at the Isaac Newton Institute in 1992. Other keynote speakers were Steven Tobias, Jeremy Bloxham, Johannes Wicht, and Benjamin Weiss, covering magnetism of the Sun, Jupiter, Earth, and the Moon, respectively. With 11 invited talks and 5 contributed talks, the workshop also provided an opportunity for researchers to share their latest findings and insights. Finally, discussion sessions provided a forum for researchers to exchange ideas, making the workshop a valuable opportunity for researchers to collaborate and identify research priorities.

Workshop 2 was a five-day satellite meeting entitled "Fluid flow and magnetic field generation in fluids and plasmas" held at the University of Leeds on 17-21 October. There were 65 participants with 37 talks and 10 posters covering a wide range of problems. The focus was on how theory and laboratory experiments can both inform our understanding of the way in which magnetic fields are generated in stars and planets. The University of Leeds made a substantial financial contribution to running the workshop, as it gave an opportunity for the large group of PhD students and postdocs at Leeds to learn about the latest developments in dynamo theory.

There were six keynote talks. Frank Stefani outlined the progress being made with a precession-driven dynamo experiment in Germany. Hantao Ji reported on successful new laboratory experiments at Princeton on the magneto-rotational instability, an important mechanism in astrophysical disks. Julien Aubert discussed force balances in geodynamo models, addressing the key question of how the dynamics found in numerical models relates to what is going on inside the Earth. Mike Calkins told us about recent advances in plane layer dynamo models, and the role of asymptotic theories in helping to understand convection driven dynamos. The question of the possible subcriticality of the geodynamo was raised by David Hughes, which sparked a subsequent discussion session on this issue back at the INI in Cambridge. Celine Guervilly gave a review of recent progress in rapidly rotating double diffusive convection. Michael Lebars told us about recent experiments in the Marseilles laboratory which can be used to stimulate and inform new types of dynamo models, a theme developed by Susanne Horn, in her discussion of recent progress in magnetoconvection experiments. There were notable contributions from some the younger researchers on the use of new data driven techniques for developing novel approaches to dynamo theory. Although the main theme of the meeting focussed on magnetic fields in stars and planets, we also had talks on magnetic fields in more exotic objects such as neutron stars.

The feedback from the meeting was very positive, and led to further discussions which have sparked off new research projects.

Workshop 3 was a 5-day meeting on "Modelling, observing, and understanding flows and magnetic fields in the Earth's core and in the Sun," held on 28 November - 2 December. It attracted over 80 participants from more than a dozen countries, the vast majority of whom attended in-person. The workshop focused on the Earth and the Sun as "Rosetta Stones" for dynamos more generally, with participants carefully considering the detailed observational constraints available for these two objects and comparing these to theory and simulation.

The meeting was largely organised around several "themes" – waves, the role of stratification, reversals, and simulation -- that were felt to be of interest to both the terrestrial and Solar dynamo communities. Talks by participants from both communities were interleaved with one another to encourage cross-talk, and to highlight the commonalities between the two.

In total there were 31 scientific talks: four keynotes, 11 invited talks, and 16 contributed ones. The four keynotes, on the first day of the meeting, set the stage for the rest of the meeting by providing introductions to Solar magnetic observations (Hannah Schunker), Solar dynamo theory (Steve Tobias), geomagnetic observations (Cathy Constable), and geodynamo theory (Bruce Buffett). Each subsequent day was devoted primarily to one theme, which was typically introduced by invited talks from at least one geo-focused speaker and one solar-focused one.

A highlight of the meeting was the realisation among many participants of the important role that various classes of waves – mediated by rotation and magnetism – may play in both the Earth and the Sun, and the very exciting prospects these hold for probing the interiors of both objects. For example, Laurent Gizon spoke about observations of solar oscillations in the inertial frequency regime. Comparison of these and other wave modes with numerical simulations, as discussed by Yuto Bekki, is beginning to provide fascinating new constraints on properties of the deep Solar convection zone. More constraints from wave observations are certain to come. In the geomagnetic context, Nicholas Gillet discussed the recent detection of hydromagnetic waves in the Earth's core; Dominique Jault provided an analysis of the underlying theory of such waves; and Julien Aubert spoke about numerical modelling that seeks to capture their dynamics.

An **Open for Business Event** on *Liquid Metal Batteries* was associated with the DYT2 programme and held on 15-16 November. Large-scale energy storage is one of the key issues of future energy systems based on renewables, and liquid metal batteries can potentially address this need in an economic way. This two-day event brought together mathematicians and scientists working on dynamo theory with engineers from industry and academia to discuss the potential role of liquid metal batteries in renewable energy storage. The discussion focussed on recent progress in scientific research and industrial development. It also provided a platform for fostering knowledge exchange.

There were 73 attendees, including academics from the US, UK, France, Italy, India, Norway, Switzerland, and Germany, as well as industrial researchers, representing companies and research institutes such as Schlumberger, Skip Technology, Helmholtz-Zentrum Dresden-Rossendorf, Forschungsverbund Berlin, Geothermal Engineering Ltd, Deutsche Gesellschaft für Internationale Zusammenarbeit, the Weierstrass Institute and SINTEF Industry.

The discussion was lively and the event was well received by the attendees, who said they found the meeting stimulating. In participant feedback forms the balance between industrial and academic content was scored as excellent, and the organisation as excellent or good. The participants estimated that they met, on average, four relevant contacts or potential collaborators. Following the event, one of the keynote speakers and the inventor of the liquid metal battery, Donald Sadoway, gave a podcast interview with the Plus Magazine team whom he met during the event.

Scientific outcome

Regarding the state of the field and open problems, a broad consensus has been achieved on a number of important points.

- The most advanced models of the geodynamo have become realistic in the sense that they approach the balance of forces that is thought to be relevant in the Earth's core, although an interesting discussion arose on whether force balances are a good means to characterise the dynamical regime of a dynamo. Numerical simulations of the solar dynamo are much more challenging for various reasons, such as a much higher degree of turbulence and a weaker ordering influence of rotational forces. They still have problems to match key observables simultaneously, such as the eleven-year cycle and the pattern of differential rotation. Various solutions to this problem have been proposed and need to be followed up.
- While some geodynamo models show dipole reversals resembling those of the Earth's field, in most cases they seem to do so for the wrong reason, namely through the influence of inertial forces on the flow. These are thought to be very subordinate in the Earth's core. There is a need to develop physically consistent reversing dynamo models.
- Recently discovered hydrodynamic and magnetohydrodynamic waves, both in the Earth's core and in the convection zone of the Sun, offer novel opportunities to constrain the structure of the convecting regions and magnetic field in the interior. The most advanced geodynamo models have just reached a stage that allows for the excitation and identification of such waves, but the potential of this needs still to be exploited.
- Understanding the very different magnetic fields of the two large gas planets, Jupiter and Saturn, remains a big challenge. Saturn's field is completely axisymmetric with observational uncertainty, whereas Jupiter's field is characterized by a very prominent non-axisymmetric magnetic flux concentration, the so-called great blue spot which was discovered a few years ago by the Juno mission. Furthermore, the strong zonal jets seen at the surface of the planets extend several thousand kilometres deep into the interior but are cut off below. Concepts for the axisymmetrisation of the dynamo field and for the role of magnetic forces in cutting off the jet flow at depth exist, but need to be tested and consolidated.

The programme has been a great success in joining different scientific communities and in fostering new collaborations, which in several cases bridge disciplinary boundaries. 26 participants, a little more than 50% of those who stayed for at least two weeks, responded to a post-programme questionnaire send out by the INI and 27 responded to a request for feedback from the organisers. Out of those 96% rated the scientific quality of the programme as excellent. Ten of them reported that they started new collaborations while attending the DYT2 programme, some of them with several different partners on different projects. Our Rothschild fellow Steve Tobias even reports five new collaborative projects. An additional eight of the respondents indicated that a collaboration could develop out of intense discussions that they had with other participants, or that they revived at the INI previous collaborations that had become dormant. Two collaborative grant proposals have been prepared during the DYT2 programme.

Most participants praised the setting of the Isaac Newton Institute and the programme as inspiring and conducive to informal discussion and interaction with colleagues. Here we mention a few quotes from the feedback that we received.

"Wonderful opportunity to interact with fluid dynamicists and dynamo modelers and get an updated view of the state of the art. […] I also felt that numerical modelers appreciated the opportunity to hear about the observational side of things."

"The stay at INI was very inspiring, as it provided me with new views on constraints and functional principles for (numerical) models, experiments and real dynamos …"

"[The programm] was very thought-provoking. […] I get the feeling that there is much progress to be made in the years to come."

"I learned a lot […] also about the current understanding of the dynamos in other planets and in stars. Although this is further from my direct area of work, it certainly was extremely interesting, broadened my horizon and led to some new thoughts for my work, too."

"The programme brought my attention to aspects of dynamo theory which I haven't paid much attention to before, in particular: paleomagnetic field of the Earth, small-scale dynamo actions, debates on convective velocities inside the Sun."

"I profited from participating in the program by … getting to meet all sorts of people who think about similar problems (fluids/MHD /convection) … [as I do, but with] … completely different applications from me (e.g., the geodynamo)."

"After a hectic teaching period, I had the chance to concentrate fully on getting back on track with research in an inspiring atmosphere that gave me a lot of new ideas and many collaborations were either started or intensified. The institute infrastructure is also excellent […]."

In summary, the DYT2 programme was fully successful in its aims to advance the field of dynamo theory, bridging gaps between different scientific communities, and to inspire new collaborations. We wish to thank the Isaac Newton Institute, its sponsors and funding agencies, for the unique and outstanding opportunity for scientific interaction and cooperation. We also thank the INI staff for their extremely supportive attitude and for creating a very comfortable setting for scientific exchange.

The organisers
Matthew Browning   Ulrich Christensen   Peter Davidson   Emmanuel Dormy   Christopher Jones