★ The magnetic fields and behaviour of the sun have long fascinated astrophysicists. Sunspot observations, theoretical models and computer simulations can provide important insights into solar behaviour, says **Professor Axel Brandenburg**, who expands on developing an accurate model of the solar dynamo

Cycles of the Sun

The cosmos has been a source of study for some of history's most celebrated scientists, including Galileo, Copernicus and Newton, whose observations and analysis of celestial objects underpin much of today's astrophysics research. The availability of accurate observational data has allowed scientists to develop evidence-based theories on the physical behaviour of the Earth, the Sun and the planets, work which is very much still in progress. While this is a vast, technically demanding field which offers enormous scope for scientific exploration, researchers do have some concrete findings on which to build. "We know that magnetic fields operate in many objects of interest to astrophysicists, including the Sun, the Earth and accretion discs. Over recent years there has been a lot of focus on the magnetic field of the sun. This is not an irregular magnetic field; rather there is some systematic order, in that it shows a regular 11-year cycle," explains Professor Axel Brandenburg. Based at the Nordic Institute for Theoretical Physics (NORDITA) in Stockholm, Professor Brandenburg's research group is involved in a number of projects in cutting-edge areas of astrophysics, including galactic magnetism, black hole electro-dynamics and the solar dynamo. Existing data on this final area, the physical process that generates the Sun's magnetic field, presents a complex picture, and demands correspondingly advanced scientific expertise. "The remarkable thing about the Sun is that its magnetic field shows order on a much larger length scale than you would expect in comparison to the size of the turbulent motions. This is despite the fact that its fluid motions are quite chaotic – in fact turbulent, with quite low length scales," continues Professor Brandenburg.

"We are trying to develop a model of the solar dynamo building on the correct physical foundations. What has been described so far are simulations where we already understand the physical processes involved. The goal now is to use those to build an accurate model of the solar dynamo."

Solar observation

This work is based on both physical observations of the Sun and theoretical research, an approach which takes full account of not only the complexity of the field, but also the need for computational simulations to be built on solid foundations. The Sun's 11-year cycle, which manifests itself through the number of sunspots which can be observed on its surface, is of particular importance in this regard. "In 1609 the Italian astronomer Galileo became the first scientist to use a telescope to systematically observe sunspots on the Sun. However, it was Heinrich Schwaber who found, after only 18 years of observations and data gathering, that sunspots come about cyclically over approximately 11 years," says Brandenburg. The meticulous recordings of sunspot observations, which date right back to Galileo's time, provide an invaluable resource for Brandenburg and his colleagues. "At the Greenwich laboratory they have been recording detailed positions of each sunspot since the late nineteenth century, while we also have other sources from around the world," he says. "The Sun rotates, so in analysing sunspots we have identified an equator and map them by their latitude. We know that sunspots behave cyclically, and that they emerge at higher latitudes at the beginning of a cycle – around 30° on either side of the Sun. Then, as the cycle becomes stronger the sunspots emerge predominantly at lower latitudes. It's not that each sunspot moves, but new spots tend to emerge at lower latitudes – that's what we call a dynamo wave. We believe the underlying mechanism for this is a large-scale magnetic field that propagates gradually during this 11-year cycle, from mid-latitudes to lower-latitudes, and that sunspots emerge as a local manifestation of the larger-scale magnetic field beneath the surface. The Sun's magnetic field is highly turbulent, so if you were to follow each field line it would be a chaotic bundle."

Theoretical development is crucial to the search for an improved understanding of these kinds of processes, and indeed this is an area that has attracted much research attention, along with efforts to improve computer simulations of astrophysics problems. The turbulent time-scales in the Sun are measured in minutes near the surface and significantly longer at the bottom of the convection zone, an aspect of solar behaviour that the alpha-omega dynamo theory seeks to explain. "The alpha-omega dynamo theory tries to explain the behaviour of a turbulent system – like the Sun – and to calculate the behaviours of the mean magnetic field and the mean velocity field by taking into account correlations between small-scale fluctuations in velocity. Turbulent diffusion is a very simple example of such an effect, it can be illustrated by the simple process of mixing cream into coffee, although in magnetic or velocity fields the effects are of course felt on a much larger scale. From this there can be generating effects: including not just dissipative effects, but also generative effects. One of them is called the Alpha effect, which is responsible for generating the sun's large-scale magnetic field, including the 11-year cycle," says Professor Brandenburg. The project uses computer-based numerical simulations of flow-dynamics equations, together with the Maxwell equations and Magneto-Hydro Dynamics, to pursue this work. However, the use of these advanced techniques has led to the identification of some problems with existing theories and models. "There are real problems with our understanding of the Alpha effect, largely related to a quantity called magnetic helicity. This is a conserved quantity, and in particular in closed systems – where there is no flow through the boundaries, or the magnetic field doesn't penetrate the boundaries – this magnetic helicity cannot escape," explains Professor Brandenburg. "In the case of dynamo theory this has now been identified as being the crucial point which explains the behaviour of some simulations."

Significant progress

Findings such as these demonstrate the ongoing nature of astrophysics research, and with new data on solar behaviour continuing to emerge, models must be refined and theories re-examined on a regular basis. Nevertheless, the relatively well-established equations currently being used in direct computer simulations have proven accurate thus far, providing real encouragement to Professor Brandenburg and his colleagues. "I believe we are making significant progress. Already we understand a number of new things that suggest previous models of the solar dynamo cannot be right. In the Sun the boundaries are not closed – they are open – so magnetic helicity does evolve. The specific way that magnetic helicity evolves will tell us how big this alpha is at every position, place and time within the Sun," he says.

While computers are not yet able to run simulations at a Reynolds number – a measure of inertial forces in comparison to viscous forces – comparable to that of the Sun, Professor Brandenburg nevertheless has some ambitious plans for the future. "I aim to produce a model sun which has a Reynolds number as high as can be achieved by a computer and to understand the wealth of large-scale behaviour which is solar-like, but not actually directly comparable to the Sun," he says. "The goal is to understand the physics behind the solar cycle. As such we are trying to model the Sun through direct simulations at smaller Reynolds numbers, and to understand it with a tool – like the mean field approach – in terms of the alpha effect and turbulent diversity. This is so that first of all we can develop a physical understanding in terms of the underlying, simple equations, but also to then use those equations to predict future development, like the way the solar cycle will behave over the next few years." ★

At a glance

Full Project Title
Astrophysical Dynamos

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Project Objectives
This work couples large-scale numerical simulations with numerically guided analytical approaches. An ultimate goal is to have a physically consistent model of the solar dynamo.

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Axel Brandenburg received his PhD at the University of Helsinki in 1990. After two postdocs at Nordita and at the National Centre for Atmospheric Research in Boulder/ Colorado he went in 1996 as Professor of Applied Mathematics to the University of Newcastle upon Tyne. In 2000 he became Professor of Astrophysics at Nordita.