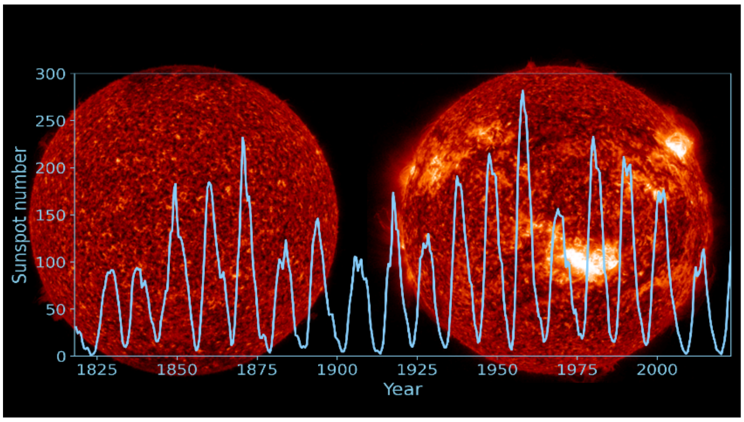

Dynamos, Dynamics, and the Solar Cycle at Cycle 25 Maximum

Royal Astronomical Society

10th January 2025

10.30-11:00 Laurent Gizon (Max Planck Institute for Solar System Research)

Acoustic and Inertial Modes as Probes of the Solar Dynamo

Acoustic-mode helioseismology provides a powerful tool to study the dynamics of the solar interior, offering crucial constraints on solar dynamo models. Understanding the solar cycle requires insights into the Sun's differential rotation, meridional circulation, and their temporal variations. Global mode helioseismology reveals the north-south symmetric component of rotation, while local techniques such as time-distance helioseismology and helioseismic holography enable the study of meridional flows and north-south asymmetries in rotation.

A recent breakthrough from our team has been the discovery of solar inertial modes—quasi-toroidal global oscillations with periods on the order of the solar rotation period, restored by the Coriolis force. These modes are detectable in the horizontal flow maps constructed using acoustic-mode local helioseismology. We have identified dozens of these modes and developed eigenmode calculations that demonstrate their sensitivity to latitudinal differential rotation and poorly constrained convection zone properties, such as superadiabaticity and turbulent viscosity.

Among these, the m=1 high-latitude solar inertial mode stands out, with a velocity amplitude (~15 m/s) approximately ten times larger than that of most other modes. Numerical simulations reveal that this mode is linearly unstable due to baroclinic instability and saturates through a back-reaction mechanism, which redistributes heat equatorward and smooths out the Sun's latitudinal differential rotation. Using data from Mount Wilson, GONG, and SDO spanning five solar cycles, we have tracked the evolution of the mode's amplitude, uncovering a connection with the solar cycle that remains to be fully understood. Solar inertial modes emerge as both diagnostic tools for the solar interior and active players in the Sun's global dynamics, providing new constraints on the solar dynamo and opening pathways for future exploration.

11-11.30 Rekha Jain (Sheffield)

Mixed Inertial modes within the internal layers of the Sun

I will give a description of how, thermal Rossby waves propagate within gravitationally stratified atmospheres such as a star's convective zone. Under the conditions of rotationally constrained dynamics, a local dispersion relation for atmospheric waves in a fully compressible stratified fluid is derived. I will illustrate the conditions for which radial trapping occurs and demonstrate that stable thermal Rossby waves could exist in the lower portion of the Sun's convection zone, despite that region being unstably stratified. I will also talk about the radial and latitudinal wave cavity for inertial waves that propagate at an angle to the zonal direction and discuss the implications for observations.

11:30-11.45 Rachel Howe (Birmingham)

Looking for far-side activity in short-timescale helioseismology with BiSON and GONG

Even with time series as short as seven days, we can detect the effect of solar activity on helioseismic mode frequencies. Using data from the Birmingham Solar Oscillations Network Group (BiSON) and the Global Oscillations Network Group (GONG), we study these changes and show that they are sensitive to activity on the far side of the Sun as well as the Earth-facing side.

11:45-12:00 Dmitrii Kolotkov (Warwick)

Cycle dependence of helioseismic oscillations near the acoustic cut-off frequency

Acoustic waves with frequencies below the acoustic cut-off frequency reflect at the photosphere and form standing p-mode oscillations in sub-photospheric acoustic cavities. Above the cut-off, the waves can propagate through the acoustic barrier and form so-called pseudo-modes. Recently, the characteristic frequencies of propagating pseudo-modes were observed to vary in anti-phase with the 11-year solar cycle, which remains an open question for theoretical modelling and interpretation. We use the Klein-Gordon equation with a piecewise acoustic potential to study the frequency stability of the trapped p-modes and propagating pseudo-modes, affected by the photospheric cut-off and position of the sub-surface wave source. For trapped p-modes, the oscillation frequencies are shown to decrease (by up to 200 μHz) by the acoustic cut-off effect and be insensitive to the source position. Using the link of the acoustic cut-off frequency with the plasma parameter β, we show how the 11-year variability of the Sun's photospheric magnetic field can result in the p-mode frequency shifts consistent with observations. The frequencies of propagating pseudo-modes, in contrast, are found to depend on both the acoustic cut-off effect and the sub-surface wave source position. We demonstrate that the observed anti-phase behaviour of the pseudo-mode frequency shifts with the 11-year cycle can be qualitatively reproduced in terms of the considered model, while its use for detailed comparison with observations requires generalisation for 2D effects, more realistic profiles of the acoustic potential, and broad-band stochastic drivers.

12:00 -12:15 Chloe Griffin (University of Southampton)

Solar oscillations during Snowball Earth

Solar irradiance variations play important roles in regulating the Earth's climate, where sunspot cyclicity can modulate interannual to decadal climatic changes that are recorded in sediments as far back as 2.5 billion years ago. However, the geological record of solar forcing is limited by conditions suitable for the preservation of the solar climate signal in the rock record. The Cryogenian period (~720-635 Ma) is a critical time interval in Earth's history marked by two "Snowball Earth" glaciations - the Sturtian (~717-658 Ma) and Marinoan (~654-635 Ma) -- when ice reached equatorial latitudes and persisted for millions of years. Sediments from before and after the Sturtian glaciation document frequencies comparable with solar forcing, however due to limited high resolution environmental archives, the persistence of solar cycles during Snowball Earth remain undocumented. This limits our understanding of the stability and magnitude of solar-climate variability during extreme event. We studied thinly laminated (<1 mm) sediments from a Sturtian glacial succession in West Scotland, which record high-frequency cyclicity, to investigate whether solar cycles occur during global glaciation. Spectral analysis of laminae thickness reveals statistically significant periodicities equivalent to interannual climate phenomena alongside decadal and centennial solar cycles, indicating the presence of solar-induced freeze thaw glacial cycles during the Sturtian glaciation. This section provides a rare archive of the evolution and stability of solar activity and provides a link between solar and cryosphere dynamics during the Sturtian glaciation.

12:15-12:30 Tomás Muñoz-Salazar (Universidad Austral de Chile)

600 years of late-spring frosts events registered in tree-rings from Patagonia and its relation to periods of minimum solar activity

This study presents a 600-year reconstruction of late-spring frosts events from northern Patagonia in South America, using wood anatomical markers of frost damage called "frost ring", in annual growth rings from Araucaria araucana trees. Frost rings are caused by extremely low temperature events below the 5th percentile of spring temperatures. Our results reveal a significant association between the frequency of frost rings and periods of minimum solar activity inferred by the reconstructed solar modulation (MeV) and the number of Sunspots, particularly during the Maunder and Dalton minimum. Utilizing wavelet coherence and singular spectrum analysis we identified a strong relation between the Gleissberg cycle and our record of late-spring frost events. These results provide a multi-century perspective of linkages between solar activity and the occurrence of extreme events of low temperatures on Earth.

13:30-13.45 Prof. Valentina Zharkova (Northumbria)

Comparison of solar activity indices derived from Eigen vectors of solar background magnetic field and sunspot numbers

We explore the links between the averaged sunspot numbers (SSN) and a modulus summary curve (MSC) of two largest eigenvectors of the solar background magnetic field (SBMF) derived from principal component analysis. MSC has rather close correspondence with the whole set of SSN revealing close cycle timings, duration, and maxima times for the cycles 12–24, 6, 7, and −4, −3, while for a few cycles in the mid-18th and mid-19th centuries there are discrepancies in the maximum amplitudes, durations, and times of the maxima. Possible reasons of these discrepancies related to uncertainties in the SSN observations in the 18th–19th centuries, in MSC definition and the different solar activity entities they represent: toroidal (SSN) and poloidal (MSC) magnetic fields, are discussed. Wavelet and Fourier spectral analysis of SSN and MSC series reveal within 95 per cent confidence levels the same prominent period of 10.7 yr, whereas SSN series show a period of 101 yr and MSC of 342 yr close to or above 95 per cent red-noise level. The correlation coefficients between SSN and MSC series vary from 0.25 for the whole SSN data set (from 1700), to 0.56 for the data sets from 1860, to 0.67 for the data sets from 1900 when all SSN restorations agree. These SSN and MSC data sets are confirmed to be closely but not identically related representing the solar activity in different entities of solar dynamo.

13:45-14: 15 Barbara Perri

Dynamical interactions between the solar magnetic field and the solar wind

The interplanetary medium is shaped by the constant interaction between the solar magnetic field generated inside the star by dynamo effect and the solar wind accelerated by its dynamical atmosphere. Although at minimum of activity, the solar magnetic field evolves slow enough that we can decouple these two phenomena, this kind of assumption is not true anymore at maximum of activity, which means that we need to understand and quantify the dynamical interaction between these two physical components of the solar activity.

We will start by presenting a demonstration of this phenomena based on a real event: in February 2021, an active region emerged on the far-side of the Sun, visible only thanks to Solar Orbiter quadrature with Earth. It became visible in the Earth field of view only a week later, and we will show how this fast evolution of the surface magnetic field of the Sun can affect solar wind simulations and thus our understanding of the structure of the corona as well as the environment of the Earth.

Then, we will present a way to directly couple dynamo models responsible for the generation of magnetic fields inside the sun with coronal models that can propagate in real-time the corresponding disturbances in the interplanetary medium. Although ab-initio, this coupled model can teach us about the time scales of information exchange between the solar interior and outer layers, especially in periods of maximum of activity.

14:15-14:30Anthony Yeates (Durham)

Rogue active regions and solar cycle predictability

In the Babcock-Leighton framework, cycle-to-cycle amplitude variations are now believed to arise from fluctuations in the active-region emergence process. I will outline how we can quantify the impact of any individual active region on the solar cycle, using surface flux transport modelling. This has led to the idea of "rogue active regions" and the possibility that they could put fundamental limits on solar cycle predictability.

14:30-14:45 Scott Hopper (Newcastle)

Tearing Instability in the Solar Tachocline

The tachocline is thought by many to play a critical role in the Sun's dynamo process, but the question of how its profile is confined against angular momentum redistribution via meridional circulation remains unanswered. One theory is that inward diffusion of the dynamo field can prevent the spread of shear into the radiation zone via a Lorentz torque. Due to the dynamoâ€™s 22-year oscillations however, the diffusing field would decay with depth due to a skin-effect, and its polarity reversals would travel inward also. We propose that such a field may be susceptible to â€˜tearing instabilityâ€™ â€“ a resistive instability which arises in highly-conductive fluids where one component of the field changes sign. We study whether this instability could survive under the tachoclineâ€™s strong stable stratification, and discuss its implications for this particular confinement model.

14:45-15:00 Craig Duguid (Durham)

Dynamo action in the solar tachocline

The leading theoretical paradigm for the Sun's magnetic cycle is an alpha-omega-dynamo process (Parker 1955), in which a combination of differential rotation and turbulent, helical flows produces a large-scale magnetic field that reverses every 11 years. Most alpha-omega solar dynamo models rely on differential rotation in the solar tachocline to generate a strong toroidal field. The most problematic part of such models is then the production of the large-scale poloidal field, via a process known as the alpha-effect. Whilst this is usually attributed to small-scale convective motions under the influence of rotation, the efficiency of this regenerative process has been called into question by some numerical simulations (Cattaneo and Hughes 2006, Favier and Bushby 2011).

Motivated by likely conditions within the tachocline, we investigate an alternative mechanism for the poloidal field regeneration, namely the magnetic buoyancy instability in a shear-generated, rotating magnetic layer. Guided by our previous work (Duguid et al. 2023, 2024) we have used numerical simulations to investigate this mechanisms potential to operate as a solar-like dynamo.

In this talk I will present results of our simulations that demonstrate that this mechanism can indeed produce a naturally migratory dynamo with many solar-like properties.

15:00-15:30 Paul Charbonneau (Montreal)

Subcritical dynamos and solar cycle variability

In this talk I will review the patterns of solar-cycle variability that can arise in large-scale dynamos, focusing on the interaction between stochastic forcing and amplitude-limiting nonlinearities. In this context I will also discuss the recently proposed idea of sub-critical large-scale dynamos, i.e., a large-scale dynamo which, despite operating at a dynamo number placing it in the subcritical regime, can nonetheless sustain a finite amplitude large-scale magnetic field through energy input by an independently operating small-scale dynamo.