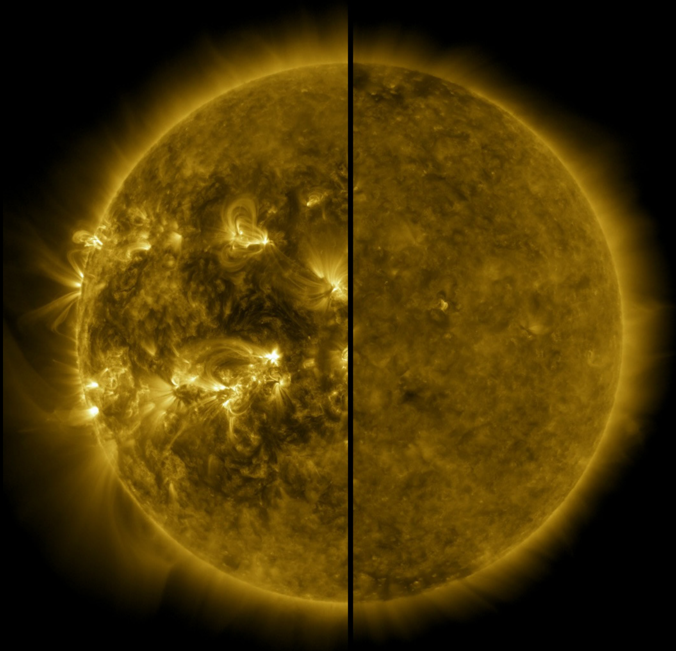
The Sun as a Star



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Front cover image: A split image showing an active Sun during solar maximum (on the left, taken in 2014) and a quiet Sun during solar minimum (on the right, taken in 2019).

Credit: NASA/SDO

Credits for all other images are in the captions

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Introduction

by the *MNRAS* Editorial Office

For the best part of 200 years, *Monthly Notices of the Royal Astronomical Society (MNRAS)* has published papers reflecting our growing understanding of the Sun. These include the Sun's effect on the planets that orbit it, through the solar wind and coronal mass ejections; its interior, through the growing field of helioseismology; how the Sun — and the Solar System — formed; and what its eventual fate will be.

In celebration of this, we have invited four experts to highlight significant papers about the Sun published in *MNRAS* in their respective fields.

First, we explore the formation of the Sun and the Solar System with Paul C Clark, including the question of how the formation of a single star — rather than a multiple system — may occur.

We then journey with Mike Lockwood through twelve papers — from the Carrington event of 1859 onwards — concerning observations of the surface of the Sun and the Sun's effect on the Earth (and other planets). These papers include work on sunspots by heliographic latitude, the famous "Butterfly Diagram" published by Annie and Edward Maunder, as well as more recent work on the magnetic fields in the inner heliosphere.

From there, we explore the growing science of helioseismology with Bill Chaplin, highlighting in particular the work of the Birmingham Solar-Oscillations Network (BiSON). Helioseismology allows us to "see" beneath the Sun's surface and, through the related field of asteroseismology, aids in our understanding of other stars.

Finally, we explore the distant future of our solar system with Dimitri Veras, considering both the period before and the period after the Sun leaves the main sequence.

We hope that you enjoy this work, and the contributions by our experts. The story that they tell is fascinating.

The formation of the Sun and Solar System

by Paul C Clark

Although we think of the Sun as relatively common type of star — perhaps because we use it as the yardstick in our astrophysical unit system — it is actually unusual as a star in several ways. First, most stars are actually lower in mass than the Sun by about a factor of 5; our star is still common in terms of its mass, just not as common as stars of lower mass. Second, our Sun's mass sits between what seems like two regimes of the stellar mass spectrum, commonly known as the initial mass function (IMF), between the lower mass stars and brown dwarfs and the rarer high mass stars. Additionally, the Sun is an only child: unlike most stars, and especially those with a similar mass, our star exists as a single star, rather than forming part of a binary, triple, or higher-order stellar system. Indeed it even goes further: the Sun is also part of the field star population. If the Sun was born in a cluster — as we believe is common **(Lada & Lada 2003)** — then it has been ejected from that stellar group at some point in its past.

That all said, perhaps in some way the Sun does encode special information about the star formation process: the mass of most stellar systems is only within a factor of ≈ 2 lower than Sun's mass. This suggests that roughly a solar mass is the "unit" of star formation, and perhaps the Sun was just unlucky in its stellar companionship.

And of course, the Sun has a planetary system, for which we are obviously grateful, as it provides us (at least for now) with our home. But even the layout of our own solar system may not be that common. With no super Earths (rocky planets 10x more massive than the Earth), no planets closer than Mercury and a generally low eccentricity of the planetary orbits **(Martin & Livio 2015; Gonzalez 2025)**, again we are forced to accept that our solar system is just a random variation from countless possibilities.

My choice of seven *MNRAS* papers that chart our understanding of how the Sun and solar system formed is based on several conditions, which partly reflect my own personal biases. First, I've focused exclusively on theoretical/numerical modelling studies, partly as I feel that we still have a long way to go in understanding the processes that form the basis of what we see in the Universe, but this also reflects the history of *MNRAS* as a home for theoretical astrophysics study. I also tried to select papers that show that a particular process is not only possible, but in some ways unavoidable, and where the paper's message is unambiguous — as a result, many excellent papers, which may finally prove more important, have likely been left out. And finally, I've selected papers that I've had a personal connection with, which have either influenced my own research, or represent studies for which I have been lucky enough to be involved — I have aimed to limit the latter!

Paper 1: Larson (1969) Numerical Calculations of the Dynamics of a Collapsing Proto-Star

At its heart, star formation is a simple process: at some scale, gravity overcomes supporting forces in the gas **(Jeans 1902)**, and the region collapses, provided the gas is able to somehow radiate away the work done by gravity **(Hoyle 1953)**. However, exactly what this looks like was unclear. In a paper that founded the field of computational modelling of star formation, **Larson (1969)** was the first to examine the details of this process, following the collapse of a uniform sphere of gas due to its own self-gravity. The notable result of the study was that the collapse is not homologous, but rather (due to pressure continuity) the radial density profile of the collapsing gas instead evolves to a flat central core which contains roughly 1 Jeans mass, with an accompanying outer radial density profile that falls off with $\rho(r) \propto 1/r^2$. There's a high degree of virtuosity on display here too: Larson's model accounts for the radiative cooling by dust grains that is necessary to power the collapse — physics that remained absent from most three dimensional simulations of star formation for another 30 years — while at the same time pioneering a new technique of Lagrangian shell fluid dynamics. The legacy of this paper is profound; Larson's radial profiles of the density and velocity are still what we see in simulations today, and are consistent with the dynamics of observed collapsing cores. The famous $\rho(r) \propto 1/r^2$ density profile was also important for the star formation theory emerging in the latter half of the 20th century, driving the move away from the simplistic picture of Hoyle's "hierarchical fragmentation", as such a density profile generates tidal forces that have been shown to help suppress fragmentation of the gas during the collapse **(Boss 1987; Pringle 1989)**. The implication here is that the window of fragmentation is short — either before (in the cloud), or after collapse (e.g. in the disc), but not during. That this paper was written at the dawn of computation modelling, and that the simulations were done on punch cards, should not be overlooked.

Paper 2: Larson (2005) Thermal physics, cloud geometry and the stellar initial mass function

As I mention in the introduction above, the mass of stellar systems is roughly 1 $M_\odot$. In his 2005 paper, Larson examines the heating and cooling processes in molecular clouds in an attempt to determine why the preferred unit of collapsing, star-forming gas is around a solar mass. At the roughly observed temperature of around 10K, a solar mass of gas will overcome pressure support (i.e. be the Jeans mass; **Jeans (1902)**) at around a number density of $n \approx 10^5$ cm^{-3}, similar to the densities of the observed "prestellar cores" in molecular clouds (as beautifully discussed in **Bergin & Tafalla (2007)**). A temperature of 10 K is roughly what one would expect from the balance between the heating generated via the photoelectric emission from the interstellar radiation field and the work done by gravitational collapse, and the cooling by either line emission or from dust grains. But Larson pointed out that the transition from line to dust cooling occurs at around $n \approx 10^5$ cm^{-3}, and perhaps more importantly, this causes a change in the effective polytropic equation of state of the gas at this density, which can result in collapse stalling slightly between the cooling handover. This "loitering" around $n \approx 10^5$ cm^{-3} gives gravity a short window of opportunity in which to fragment the gas, and thus the chance to set a scale in the mass of collapsing objects. This concept was further explored in an excellent companion paper by **Jappsen et al (2005)**.

Paper 3: Bonnell, Clark & Bate (2008) Gravitational fragmentation and the formation of brown dwarfs in stellar clusters

The lead author here is one of the main architects of the "competitive accretion" model of star formation as a way of explaining the stellar IMF (see **Bonnell & Bate (2005)** for a helpful starting point on the subject). There are many papers on this topic, but I've selected this paper on the formation of brown dwarfs for several reasons. The first is that the paper is badly named: it's actually about the formation of low-mass stars in general, and our Sun is such a low(ish) mass star. The focus on brown dwarfs stems from debate on their formation that was happening at the time, and this paper demonstrates their natural existence under the competitive accretion framework. But the paper makes a fundamental, and unavoidable point about how gas can fragment in a proto-cluster, highlighting that the Jeans mass alone is insufficient in setting the mass of collapsing objects — one also has to consider the tidal forces from the surrounding cluster, into which the gas is falling. This was also the first paper to really highlight the filamentary nature of the gas as it falls into regions where massive stars are forming — now called 'hub-filament systems' **(Myers 2009)** — and also points out that the stars that form in such filaments are likely to be ejected from the cluster, drawing parallels to our Sun, which is also lacking a host cluster.

Paper 4: Bate (2012) Stellar, brown dwarf and multiple star properties from a radiation hydrodynamical simulation of star cluster formation

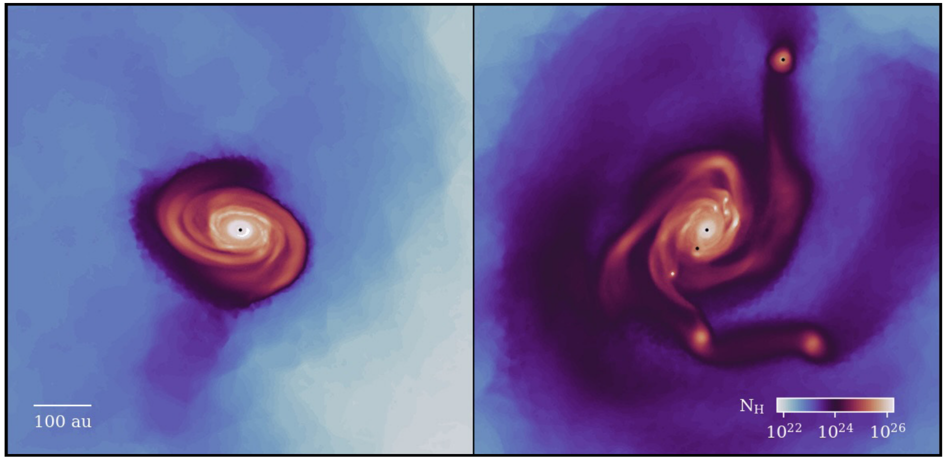
Computational modelling has come a log way since the early days of Larson, and Matthew Bate has been one of the chief architects of numerical modelling of star formation, driven by his invention of the 'sink particle' technique (another landmark *MNRAS* paper: **Bate, Bonnell & Price (1995)**, without which such modelling would be impossible). In this 2012 paper, he looks at the formation of a cluster from a dense gas cloud (likely the most common starting point for star formation, although rare within the current solar neighbourhood), capturing the formation and evolution of the young stellar systems within. The simulation is notable for being one of the first to include the radiative transfer from the dust that regulates the gravitational collapse within the cloud. The paper shows that complex accretion dynamics (i.e. "competitive accretion") lead to not only an IMF consistent with that observed for stars, but the ensuing chaotic dance that results from the mutual gravitational attraction of the protostars, also produces the same multiplicity statistics that we see for field stars. Importantly, it shows that while stars around a solar mass tend to have companions, as expected, they also exist as solitary stars, such as our Sun. From this study, we can start to see that although the Sun is not typical of a star of its mass, its existence appears to be an expected outcome of the messy star formation process.

Paper 5: Nelson et al. (2000) The migration and growth of protoplanets in protostellar discs

Although there is still some debate about whether planets can form directly from gravitational instability of the disc, or whether they form around a rocky seed core (c.f. **Stamatellos & Whitworth (2008), Forgan & Rice (2013)**), there is always the issue that any large, gaseous planet that forms in a disc is going to interact with that disc, and while the gas density in the disc remains high, this will influence the orbit of the planet. Additionally, most theories of how planets form require the objects to form quite far from the host star, where conditions are more favourable to either grain growth or gravitational instability: although this is the picture we see in our own solar system, gas giants are frequently found close to the host star. This paper by Nelson et al. was the first systematic study of how ≈ Jupiter mass planets dynamically interact with their natal protoplanetary discs. It demonstrated that migration from the outer disc to around a few AU can occur on only 10,000 orbital periods, demonstrating that gas giants can form far out in the disc, and migrate inwards, to the final position of the "hot Jupiters" that we observe. The paper also highlighted how gaps form around the planets — a phenomenon that was highlighted in the spectacular images from the Atacama Large Millimeter Array of the Sun-like star HL Tau **(ALMA Partnership et al. 2015)** and CL Tau **(Clarke et al. 2018)**. This study set the standard for an industry of protoplanetary disc modelling, developing techniques that would be used to examine many aspects of the planet formation process, and in particular examining the way planets feed from accretion streamers in the disc.

Paper 6: Clarke, Gendrin & Sotomayor (2001) The dispersal of circumstellar discs: the role of the ultraviolet switch

Given the helpful role of gas dynamics in bringing solid components (i.e the 'dust`) of protoplanetary discs together, the time over which a disc can assemble its planets is bounded by two events: the disc forming, and the disc being destroyed. The formation of the disc is likely very early, right at the end of the free-fall collapse of the prestellar core, some 10^5 yr after the gas in the cloud becomes gravitationally unstable. This early disc assembly has been long seen in simulations, but we can now see evidence in the amazing new wave of high-resolution disc observations (e.g. **Tobin et al. (2020)**) taken via ground-based interferometry in the submillimetre. The end point of disc evolution is observed to occur at an age of around 5-10 Myr. When the disc is finally disrupted, it seems from the observations that this is a rapid process, with the transition from disc to disc-less occurring in as little as 10^5 yr. This paper by **Clarke, Gendrin & Sotomayor (2001)**, shows that the UV radiation from the central star is able to make this rapid transition, providing the first model to explain the complicated observational data on protostars that was available at the time. No formal fluid dynamics "simulations" were necessary here, just some unavoidable facts about accretion disc physics and radiation, based around the self-similar models from another landmark *MNRAS* paper by **Lynden-Bell & Pringle (1974)**. **Clarke, Gendrin & Sotomayor (2001)}** set the scene for the more detailed model from **Owen, Clarke & Ercolano (2012)** that accounts for the X-ray component of protostars, and remains central to understanding of the dispersal of planet-forming discs.



Examples of discs from the simulations presented in **Cusack et al. (2026)***, depicting the total column density (in units of cm^{-2}) in the region around two low-mass protostars. Typically gravitational instability (GI) in the disc leads to violent fragmentation the formation of companion protostars and proto-brown dwarfs, as we see in the right-hand panel. However in some cases, such as around the protostar on the left, the GI in the disc remains high, but the disc refuses to fragment — it is likely that the protoplanetary disc that formed our solar system was such a case.*

Paper 7: Cusack et al. (2026) The impact of radiation environment on the evolution and fragmentation of protostellar discs

The fact that rocky planets such as the Earth exist, tells us dust coagulates to form larger objects; the coplanarity of planets suggest that this happens in a disc. While dust grain growth in idealised (typically steady-state) protoplanetary discs is well studied, how they form in the chaotic mess of a dynamic proto-cluster environment, is only just emerging. The first paper to attempt this was **Bate (2018)** in which he catalogues the discs that surround the protostars in his 2012 paper. While this paper provides the best statistics on the disc properties that one would expect in a cluster environment — and is where we point the reader interested in the properties of the ensemble — we highlight here instead the disc paper by **Cusack et al (2026)** for our story of the Sun, as it highlights some important features. The first is that it shows that, on occasion, a prestellar core collapses to form a single, approximately solar mass star, with an accompanying protostellar/ protoplanetary disc that remains stable to fragmentation: in other words, a system very much like our Sun, in its companion-less state. More interestingly, however, is that although the disc remains stable to fragmentation, it does show prolonged signs of gravitational instability (GI), in the guise of spiral density waves. A recent paper by **Bate (2022)** has demonstrated that the spiral density waves associated with GI can significantly kick-start the planet formation process, by accelerating grain growth in the disc, resulting in grains above 100 μm in size in a few 1000 years. One might expect a disc that exhibits GI to then go on to fragment to create

a companion star or brown dwarf, likely disrupting the planet-formation process; **Cusack et al. (2026)** shows that while this often the case — and indeed all the discs studied exhibit GI, and most *do* fragment — discs can also sit on the cusp of GI fragmentation for long times without fragmenting, allowing for grain growth without the disruptive process of companion formation. Studies such as this paper by Cusack are likely to be the focus of future numerical modelling, sitting right at the interface between the star and planet formation processes.

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Meteor observation, 1850. Historical artwork of three people (lower left) observing a meteor passing across the sky, as seen from the Fulham Road, London, UK. This meteor was observed on 11 February 1850. At this time, this area of London was open countryside.

Credit: Royal Astronomical Society/Science Photo Library

Twelve Key Space Physics Papers Published in *Monthly Notices*

by Mike Lockwood

Monthly Notices of the Royal Astronomical Society has published some key papers in the development of space physics. This paper reviews the author's selection of a dozen papers and explains the context and significance of each. The papers numbered 1 to 9 are ordered by date and are early, foundational and seminal contributions in that they were key in building our modern understanding. Paper 10 is the first of a number of recent examples of *MNRAS* papers that present a re-analysis of historic events making use of our modern understanding. Papers 11 and 12 are two examples of recent contributions that are moving the field in exciting new directions, particularly in regard to exoplanets.

Introduction

Monthly Notices of the Royal Astronomical Society (*MNRAS*) is one of the longest running scientific journals in the world: it is eleventh in the longevity list of all science journals that are still published today, having been first published in February 1827. At that time, space science did not exist as a discipline at all. *MNRAS* played a fundamental role in establishing the science of solar system exploration. Subsequently the journal has taken a distinctive role in the development of the field: what is remarkable is the number of *MNRAS* papers that one finds when tracing major paradigm shifts in the field back to the pivotal or foundational papers that started the development of the key advance.

The NASA ADS database shows that since 1960 (a rough date for the start of the space age) 15,897 papers in *MNRAS* have dealt with subjects inside the heliopause (i.e., solar, magnetospheric, ionospheric, planetary, or heliospheric research) which is close to 20% of the total of ≈ 82,000 papers published in the journal in that interval. Hence the emphasis of the journal is on extra-solar-system astronomy, astrophysics and cosmology. However, the 20% forms a vital contribution because the science and phenomena predicted and discovered within our solar system are frequently applied to gain an understanding of more distant objects — famous examples being stellar winds, magnetic reconnection, flares, collisionless shocks, magnetospheres, Alfvén, whistler and ion cyclotron waves, plasma and beam instabilities, plasma turbulence cascades, pick-up ions, magnetically trapped particles and atmospheric erosion. *MNRAS* is a good place to publish space science for authors who see opportunities for application of their work outside the heliosphere. Hence the solar system can be viewed as a natural laboratory and the recent surge in interest in exoplanets is a clear example of how this crossover contributes to exploration beyond the heliopause.

This paper discusses twelve publications that appeared in *MNRAS* that have been picked by the author as important contributions to space science. In each case, the state of knowledge (or accepted wisdom) at the time is described to put the paper in context. How the subsequent evolution of the discipline was influenced by the paper is then discussed. Papers 1-9 are presented sequentially and are examples of early and seminal contributions to our understanding of space plasmas. These come from the interval 1859-1963. After that date, the numbers of papers on space science in *MNRAS* fell because a number of specialist journals were founded and, as a result of NASA leading the exploration of space, American journals were often the favoured forum for publication. However in recent years, more space science papers are appearing in *MNRAS* again. One reason for this is that there has been an important trend to re-analyse past events and observations in the light of discoveries that have been made, and *MNRAS* is a logical place to publish such work. Paper 10 is an early and influential example of this trend. This paper highlights the long history of publishing innovative papers that moved space science in new directions: Papers 11 and 12 are recent examples of this.

In this review, articles that were published in *MNRAS* are denoted using an obelus symbol (†). So, for example, **Chapman (1929, †)** means the article was published in MNRAS and **(Chapman 1929; Chapman & Ferraro 1929; Chakrabarty & Chapman 1946, †)** means that all the articles cited in the parentheses were published in MNRAS.

Paper 1: Carrington (1859, †) Description of a Singular Appearance Seen in the Sun on September 1, 1859

This paper marks the start of the discipline of space science. It is actually, in itself, a purely solar paper but it began a long process of discovery that still has implications for many areas of science as diverse as fusion reactors, stellar "super-flares", exoplanets and pulsar magnetospheres. It also has implications for many of humankind's operational systems and for the health of humans in space (an area of research known as "space weather").

The paper describes observations made by gentleman scientist Richard C. Carrington on 1 September 1859. We now know it was the first documented solar flare ever observed and so this paper marks the start of flare physics. It was a rare bright white-light flare in a large sunspot group. Carrington noted its highly transient nature in that it lasted about 5 minutes. He also recorded detailed drawings and timings. Independent confirmation of the event was provided, also in *MNRAS*, by amateur astronomer Richard Hodgson **(Hodgson 1859, †)**. In the early 1870s, Father Angelo Secchi published systematic drawings and records of sunspots and solar prominences; he also observed the second known white-light flare on 13 November 1872. A third was seen on 10 September 1886 by a 17-year old amateur called Juan Valderrama y Aguilar **(Valderrama y Aguilar 1886; Vaquero et al. 2017)**. The occurrence of white-light flares was reviewed by **Neidig & Cliver (1983)**. In 1868, Hα spectroscopy of the Sun began and was conducted by scientists such as Pierre Janssen, Norman Lockyer, Angelo Secchi and Pietro Tacchini. The first observations of a flare in Hα were made by George Ellery Hale on 27 October 1905 **(Hale 1908; Benz 2017)**.

By 1930 photographic and spectroheliograph observations of flares were available in various spectral lines, allowing systematic cataloguing of solar flares beyond sporadic visual observations, as reviewed by **Bai & Sturrock (1989)**. The 1940s saw the discovery of solar radio bursts associated with flares **(Hey et al. 1948, †)**, and in the 1960s space-based observations revealed X-ray and UV components **(Benz 2017)**. Thus the high-energy nature of flares was slowly revealed, with typical energies of 10^{22} to 10^{25} J and the largest observed solar flares exceeding $\approx 10^{26}$ J **(Kowalski 2024)**. **Greatrix (1963, †)** found a statistical relationship between flare intensities and sunspot group complexity and flare classification schemes were developed **Bai & Sturrock (1989)**. Flares give rise to hazardous energetic particles in space called SEPs (Solar Energetic Particles) of which a class called "impulsive SEPs" arise directly from the flare. A second class called "gradual SEPs" are accelerated by shock fronts ahead of CMEs (Coronal Mass Ejections) as they propagate away from the Sun through the heliosphere **(Reames 1999)**. There is an association between CMEs and flares **(Yashiro et al. 2005)** but it is not exact as some ("stealth") CMEs are not accompanied by a flare **(Robbrecht et al. 2009)** and not all flares generate a CME **(Andrews 2003)**. Building on the formulation of diffusive particle acceleration at collisionless shocks by **Krymskii (1977)**, **Bell (1978a,b, †)** developed the first self-consistent theory of diffusive shock acceleration, explicitly coupling particle transport, pitch-angle scattering, and shock hydrodynamics. Bell's work demonstrated that repeated scattering across a shock naturally produces a power-law energy spectrum and

established diffusive shock acceleration as a robust and efficient mechanism for galactic cosmic-ray and SEP production.

Figure 1 compares Carrington's drawing of the first known white light flare with images of flares seen with modern instrumentation. The latter were during a major series of events on 10-11 May 2024 which generated a terrestrial disturbance which, in some features (e.g., latitudinal extent of aurora), was almost as large as the corresponding perturbation in the Carrington event **(Lockwood et al. 2025b †)**.

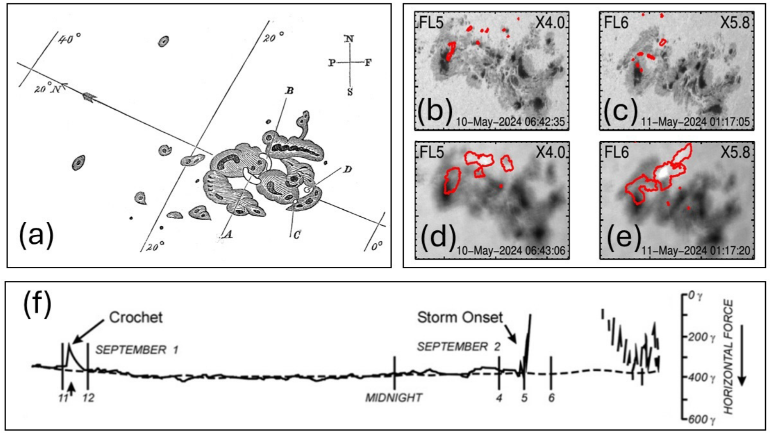

Figure 1: Solar Flare observations. (a). Carrington's drawing of the sunspot group he observed on 1 September 1859: the white light flare brightenings are the paired kidney-shaped regions labelled A and B and the paired circular regions C and D **Carrington (1859, †)**. *Parts (b)-(e) show sunspot group number 13664 on 10 and 11 May 2024 from Figure 2 of* **Li et al. (2024)**. *(b) and (c) are from the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory spacecraft (SDO) and (d) an (e) from the White-light Solar Telescope (WST) on board the Advanced Space-based Solar Observatory. The red contours mark a constant threshold of detected 6173 Å emission, which is a good proxy for the white light emission observed by Carrington. (b) and (d) are at the start of a strong flare (classified as X4.0) on 10 May 2024 and (c) and (e) for a X5.8 flare on 11 May 2024. Part (f) shows the variation of the horizontal component of Earth's magnetic field, as observed by the Kew Observatory on 1–2 September 1859: it reveals the magnetic crochet at 11:15 UT on 1 September and the great geomagnetic storm that followed 17.6 hours later causing the trace to go off-scale.*

However, even greater implications of the Carrington event did not start to emerge until some time after the publication **(Chapman & Bartels 1940; Cliver 1994)**. The paper found itself at the centre of a major debate that was not fully resolved until a century later with the advent of the space age and in-situ detection of the solar wind.

The debate revolved around the influence of the Sun on terrestrial auroras and geomagnetic activity. In 1843, Heinrich Schwabe had identified the (approximately) 11-year cycle in sunspots **(Schwabe 1844)** and, in a series of papers in the early 1850s, Edward Sabine **(Sabine 1852)** had found the same cycle in geomagnetic activity. Within months of Sabine's discovery, it was confirmed by both Rudolf Wolf and Jean-Alfred Gautier. However, the mechanism for any connection was not known and it was noted, for example by John Broun **(Broun 1877)** and by Edward Maunder (**Maunder 1904a, †),** that on short timescales the relationship failed. The connection was dismissed by the highly-influential William Thompson (later Lord Kelvin). He first printed his objection in a comment on a paper by **Chambers (1863)** which was that superposition of the Sun's field with Earth's field would have a negligible effect, given the large distance between the Earth and the Sun. He had also voiced this opinion at Royal Society Anniversary Meeting of 30 November 1892 (reported in Nature, Volume 47, pages 106–111) famously saying ``the supposed connection between magnetic storms and sun-spots is unreal, and that the seeming agreement between the periods has been a mere coincidence."

The repercussions of Carrington's observations fell right in the middle of this debate. Due to the enhanced EUV and X-ray fluxes emitted in the flare, the ionospheric E region densities and currents above several magnetometers were enhanced. This included, in particular, the Kew observatory where these changes to ionospheric currents caused a clear "crochet" signal to be recorded at exactly the same time as the observed white light flare **(Hudson et al. 2025 †)**. Just 18 hours after that the largest geomagnetic storm known began that sent the Kew magnetic deflections off scale, as shown in **Figure 1f**. This caused a great many violent space weather effects, particularly in telegraph systems across Europe and North America, and aurora to be seen at latitudes close to the equator **(Lockwood et al. 2025b, †)**. Carrington was reticent about connecting these events with the transient brightening he had seen but the then director of Kew observatory, Balfour Stewart, was in very little doubt, saying "it is not impossible to suppose that in this case our luminary was taken 'in the act'." **(Stewart 1861)**.

We now know that Stewart was right. Observations of many such events, albeit smaller ones, tells us that there would have been an Earth-directed CME associated with this flare, and probably others associated with the same sunspot group, that caused the massive geomagnetic storm. We also now know that the flaw in Kelvin's argument was that he did not know about the solar wind which flows continuously (but with major enhancements in CME events) and which, because of the magnetohydrodynamic "frozen in flux" theorem that applies to large magnetic Reynolds number plasmas, drags with it magnetic field of solar origin. This understanding took the best part of a century to acquire and some of the other articles reviewed in this paper tell parts of that story.

Carrington's paper not only marked the birth of a new discipline of science. The Carrington event remains the largest space weather event known. It has become a key reference in evaluating space weather risk and hazard **(e.g. Hudson 2021)**. Being an event with a probable recurrence period of 100-200 years it is not a worst case scenario, but it has become the standard reference to which the likelihood and severity of other events is compared **(Cannon et al. 2013: Hapgood et al. 2021)**. The Carrington storm is the largest space weather event known, but it was not the first. That was on 19 March 1847 when aurorae were seen over much of England and Geomagnetically Induced Currents (GICs) were detected in the telegraph system of the Midland Railway **(Barlow 1849)**. (Note that an earlier event near Exeter that was retrospectively reported in Nature can be discounted as the railway and associated telegraph system had not yet been constructed at the date invoked).

A footnote about Carrington is that although we knew a great deal about his life, as detailed in the excellent book *The Sun Kings* by Stuart Clark **(Clark 2009)**, there was no known surviving photograph of him. It was thought that one had existed **(Cliver et al. 2021)**, but that it had been lost. However, recently it was discovered by RAS archivist Kate Bond, who also found compelling evidence that it is indeed the lost photograph of Carrington **(Bond 2026)**.

Paper 2: Maunder (1904b, †) On the Distribution of Sun-Spots in Heliographic Latitude, 1874-1902

This is another hugely influential paper that appeared in *MNRAS*. It was the work of the wife-and-husband team Annie and Edward Maunder. There is no doubt that Annie was a key part of this work, and indeed quite possibly the dominant one. At the time the paper was published, women in Britain faced institutional barriers to scientific authorship and professional status. They were not fully admitted to scientific academies: sadly Annie, despite her obvious talent and brilliance, was refused Fellowship of the Royal Astronomical Society until 1916, more than twenty years after she first applied to join. It was not uncommon at the time to fail to credit women as authors even when they did substantive research, particularly if they were collaborating with their husbands. In defence of Edward, he was a great supporter of bringing about change so that women did get the recognition that they deserved and his marriage to Annie seems to have been very harmonious as well as scientifically productive.

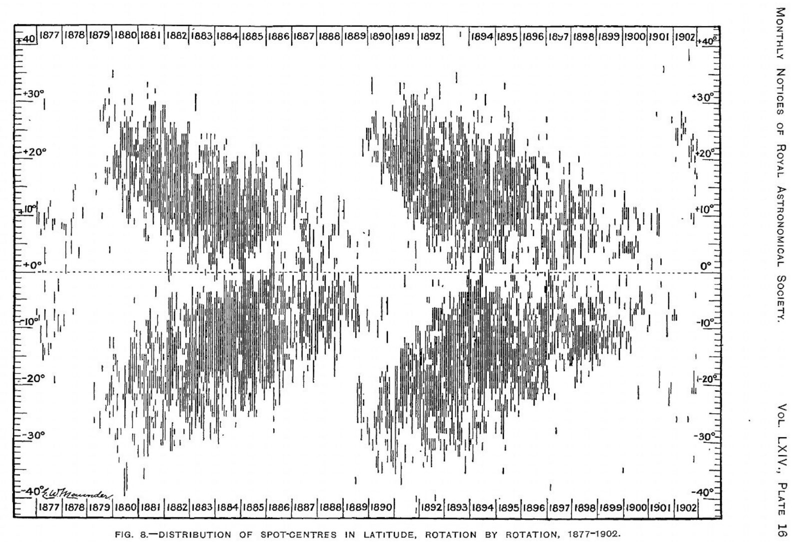

Figure 2: The original "butterfly diagram" generated by Annie and Edward Maunder, as published in MNRAS *in the paper by* **Maunder (1904b, †)**. *The original is on display in the High Altitude Observatory, Boulder, Colorado. This is because on 21 May 1940 Annie Maunder mailed it from London to Walter Orr Roberts of the HAO to protect it from the blitz of London in World War 2, whilst she herself stayed in London to try to protect other historic science artefacts.*

The Maunder "butterfly diagram", which depicts the heliographic latitude of sunspot emergence as a function of time, remains a fundamental observational constraint on models of the solar magnetic cycle. It was known that sunspot activity migrated equatorward during the course of each ≈11-year cycle from the work of Richard Carrington **(Carrington 1863)** and Gustav Spörer **(Spörer 1880)**. The butterfly diagram (see **Figure 2**), was constructed from Royal Greenwich Observatory sunspot records and provided graphical representation and confirmation of this equatorward drift and revealed important details. Any successful dynamo model must reproduce this systematic latitudinal progression of a band of magnetic flux emergence (e.g. **Charbonneau 2010**).

The pattern of equatorward drift of activity belts has been used extensively to constrain the spatial distribution of differential rotation and the nature of the dynamo wave or flux-transport processes operating in the solar interior, in particular through comparisons of observed wings with model predictions (e.g., **Parker 1955; Yoshimura 1975; Schüssler & Schmitt 2004; Cloutier et al. 2025**). It is also a valuable way of defining the phase of the cycle of a particular event in a physical way **(Owens et al. 2011)**; and this was used by **Owens & Lockwood (2012)** to show that the loss of open solar flux (magnetic flux that extends out from the solar corona into the heliosphere) depends on solar cycle phase. This gives model reconstructions of open solar flux which best match that derived from geomagnetic data and which have been used to interpret long time series of cosmogenic isotope abundance from cores into ice sheets and ancient trees **(Owens et al. 2016)** and hence to constrain centennial reconstructions of total solar irradiance that are based on these radioisotope data **(Lockwood & Ball 2020)**. The solar cycle phase also has applications in predicting short-term space climate change **(Barnard et al. 2011; Lockwood et al. 2012)**, insofar as the sunspot cycle is predictable **(Petrovay 2010; Cameron et al. 2013)**.

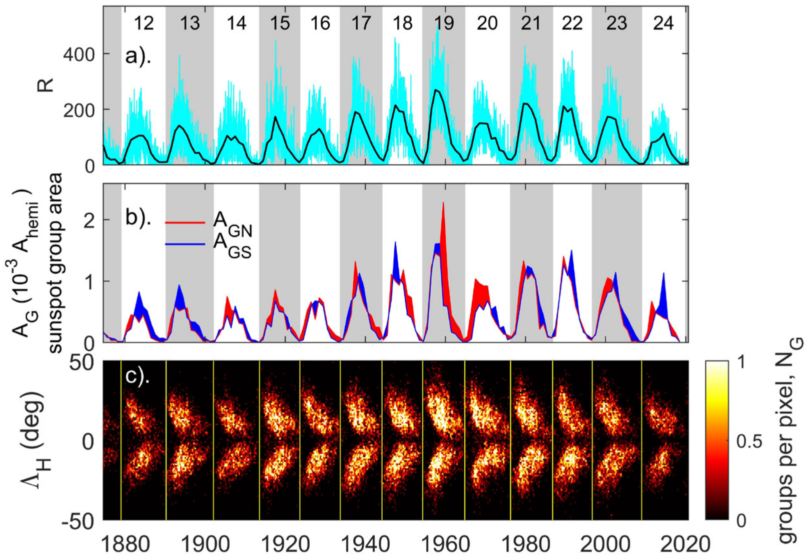

Figure 3: Part (c) shows the butterfly diagram extended up to the start of the current solar cycle. Part (a) shows the annual and monthly mean sunspot numbers, R (in black and cyan, respectively) and part (b) annual means of the hemispheric areas of sunspot groups in the northern (red) and southern (blue) hemispheres (A_{GN} and A_{GS}, respectively) with areas in red showing an excess of A_{GN} over A_{GS} and those in blue an excess of A_{GS} over A_{GN} . The sunspot minima in are marked in (c) by vertical yellow lines, and white and gray bands in (a) and (b) mark the even- and odd-numbered solar cycles, numbered along the top of part (a).

Beyond its role in dynamo model discrimination, the butterfly diagram has proven useful in quantifying hemispheric cycle asymmetries and relative phase shifts between northern and southern activity belts, which carry implications for hemispheric coupling and stochastic forcing in the dynamo (e.g. **Li et al. 2010; Norton et al. 2014**). The diagram also captures the temporal overlap of successive cycles and the dependence of emergence latitude on cycle

strength, features that are exploited in defining cycle phase and in studies of extended solar cycles and deep-seated regeneration mechanisms (**e.g. Wilson et al. 1988; McIntosh et al. 2014; Zhang et al. 2022**). Moreover, observed properties of the latitude–time distribution — such as the width of activity wings and the rate of equatorward progression — serve as indirect constraints on meridional circulation profiles and surface flux transport, linking surface observations with subsurface flow dynamics in both mean-field and Babcock–Leighton dynamo frameworks (e.g. **Hathaway 2010; Dikpati & Charbonneau 1999**). An interesting feature to note in **Figure 2** is that in the declining phase of the solar cycle some spots form very close to, or even on, the heliographic equator. These spots may hold a particular significance because reconnection may occur between emerged field line flux loops in opposite hemispheres and small eddy flows or diffusion can cause the footpoints of field line loops that emerged under the influence of rotation in one solar hemisphere to end up evolving in the differential flow of the other hemisphere. Both these possibilities are almost random in occurrence and both have a disproportionately large effect on the subsequent evolution of the solar field as discussed by **Cameron et al. (2013)** and **Lockwood et al. (2017)** — they may well be the limiting factor in the predictability of sunspot cycle amplitudes (**Petrovay 2010**). Collectively, these applications underscore the understanding that any comprehensive theory of the solar cycle must account not only for the temporal modulation of sunspot number but also for the detailed spatio–temporal structure encapsulated by the Maunder butterfly diagram.

Because of the value of constraining solar dynamo models to understanding of centennial-scale variability of the Sun, there is a great deal of interest in using snippets of data from observers who recorded the heliographic latitudes of sunspots or sunspot groups before the start of the regular data from the Royal Observatory Greenwich. These can be used to extend the butterfly diagram to earlier times **(Arlt et al. 2013; Carrasco et al. 2019, 2021; Hayakawa et al. 2024a, †), (Arlt 2009; Vaquero et al. 2015; Leussu et al. 2017; Hayakawa et al. 2020)**. This is of particular importance for understanding the solar activity decline into the Maunder minimum **(Lockwood et al. 2011)** and its recovery at the end of the Maunder minimum **(Hayakawa et al. 2021a)**. Note that we call the grand solar minimum between about 1645 and 1715 the "Maunder minimum" but it was actually first discovered by **Spörer (1887)**. Edward Maunder alerted astronomers to the work of Spörer in *MNRAS* **(Maunder 1890, †)**. Astonishingly, this pronounced and significant minimum in sunspot activity was hardly discussed again until the seminal paper by **Eddy (1976)**, who named it after Maunder rather than Spörer. This was possibly because Maunder was clear that it was a period of significantly lower sunspot activity, particularly in his article of 1894 **(Maunder 1894)**, whereas Spörer put more emphasis on the disruption of the regular decadal-scale cycles.

Paper 3: Chapman (1918, †) The energy of magnetic Storms

When Sydney Chapman wrote this paper in 1918, geomagnetic storms were well documented observationally but very poorly understood physically. Since the mid-19th century, they had been recognized as global phenomena correlated with sunspots and aurorae, yet explanations remained largely phenomenological with little quantification of the magnitude of the event. Crucially, the magnetosphere did not yet exist as a concept and both magnetohydrodynamic theory of plasmas and *in-situ* space measurements were decades away. All Chapman had at the time was data from a global network of magnetic observatories, and Maxwellian electrodynamics. There was, however, a growing belief that geomagnetic storms were externally driven by the Sun. This paper was the first to attempt to quantify the energy that an external source would require to drive a storm. Chapman's paper is the first to analyse storms as energetic events governed by the dissipation of electromagnetic energy.

Most observers agree that the first space scientist was the Norwegian Kristian Birkeland, who in 1896, proposed that aurorae and magnetic storms were caused by electrically charged particles emanating from the Sun, which interact with the Earth's magnetic field (**Birkeland 1908)**. Birkeland obviously inspired and informed Chapman, but Chapman did not agree with everything that Birkeland proposed. The famous example is field-aligned currents: Chapman had a good argument in that they were not needed to explain geomagnetic perturbations, which was true in the sense that they could have been caused by horizontal ionospheric currents alone; however, that did not mean that they did not exist and field aligned "Birkeland" currents were detected directly *in-situ* in 1966 by **Zmuda et al. (1966)** using the spacecraft *1963-38C*. Chapman framed storms in terms of magnetic energy and induced currents, but avoided Birkeland's particle precipitation: a modern view understands that both are a key part of storms.

Rather than treating disturbances as local currents or induction effects, Chapman emphasized their global coherence, implying large-scale current systems and magnetic reconfiguration. Chapman's discussion anticipates a storm-time current system encircling the Earth, storing magnetic energy and producing the main phase depression in the field that is observed in the main phase of a storm. This is extraordinary, because like Birkeland's field aligned currents the ring current, which fits this description, was not discovered until the space age: the idea growing from particle drift theory of trapped particles **(Singer 1958)** which were linked to Chapman's geomagnetic depression by **Dessler & Parker (1959**) and **Sckopke (1966)**. Chapman's concept was directly exploited by **Sugiura (1964)** when he devised the *Dst* index which is widely used to this day.

Chapman showed that the inferred energies were too large to be explained by atmospheric or crustal processes, strengthening the argument for a solar origin long before the solar wind was identified. This energetic reasoning was a conceptual leap that reframed geomagnetic storms as a problem in space electrodynamics. By making energy the key quantity of interest, Chapman set the stage for later papers that focus on the energy input from the Sun, energy storage in near-Earth space, and energy dissipation via currents, aurorae, and Joule heating **(Gonzalez et al. 1994)**.

This paper implied a structured region surrounding Earth capable of storing magnetic energy, a clear precursor of the magnetosphere concept, which he proposed in 1931 with Vincenzo Ferraro and which will be discussed again later in this paper **(Chapman & Ferraro 1931a,b)**.

Paper 4: Greaves & Newton (1928, †) Magnetic Storms and Solar activity 1874 to 1927

Maunder (1904a, †) was one of many observers who noted that large sunspot groups tended to coincide with magnetic disturbances on Earth, but the statistical foundation of this relationship remained limited. William Greaves and Harold Newton were the first to provide this, working at the Royal Observatory Greenwich (ROG). Neither author is well-known today, but Greaves was a famous and prize-winning astronomer who went on to be RAS president and Newton was a long-term solar observer at ROG with deep practical experience in sunspot record-keeping.

Greaves and Newton carried out one of the first systematic statistical analyses of the connection between solar activity (measured by sunspots) and geomagnetic storms over an unprecedented 54-year interval. They examined a catalogue of magnetic storm events and sunspot group data to test if Lord Kelvin has been right to dismiss the connection as "mere coincidence". Their key finding was that a majority of significant magnetic storms began within a few days of large sunspot groups transiting the central solar meridian, significantly

more than would be expected by chance. This removed any lingering doubt that the Sun was the cause of great storms and so gave impetus to the drive to understand the physics of the connection.

The compendium *The Greenwich Sunspot and Geomagnetic-Storm Data, 1874–1954* **(Jones 1955)** specifically cites the Greaves and Norton paper as setting the methodology used in its compilation. This complete record of the ROG data has been an important resource for a great many studies of long-term variations **(e.g. Clette et al. 2023)** and for re-analysis of historic space weather events **(e.g. Lockwood et al. 2025a)**. However, over the 80-year interval, instrument changes were implemented and observing and recording practices drifted: hence considerable work has subsequently been needed to recalibrate the data and make it a fully homogeneous set **(e.g. Willis et al. 2013)**. The Greaves and Newton study moved the field from qualitative observation to quantitative analysis of the link between solar activity and geomagnetic storms. **Newton (1943, †)** later generated a very useful catalogue of major storms associated with major flare events which is very useful in comparative studies of historic events because the time lag to the onset of the subsequent storm can give us a rough estimate of the average speed of propagation of the CME that caused the storm **(Lockwood et al. 2025a)**.

Paper 5: Milne (1926, †) On the possibility of the emission of high-speed atoms from the Sun and stars

This is a widely overlooked paper by Edward Arthur Milne that was absolutely vital to the development of space science. Part of the reason for it being overlooked may well be the use of the term "atoms" in the title. This comes from a change in the language used in science: in 1926 the term atoms was used for both neutral and ionised particles. So reading the paper today we must translate "atoms" in this title as "atoms and ions".

In 1908 Birkeland had proposed that the terrestrial aurora was generated by energetic electrons propagating from the Sun. **Schuster (1911)** argued that such streams of electrons from the Sun cannot be maintained over interplanetary distances because of electrostatic repulsion and the build-up of charge. Between 1917 and 1924, Chapman repeatedly raised this objection. **Lindemann (1919)** had suggested a solution would be that when electrons left the Sun they were accompanied by positive ions in an electrically neutral gas. The paper by Milne gave a physical explanation of Lindemann's suggestion.

Ionised gases had been discussed before (by William Crookes, Eugen Goldstein, J.J. Thomson, John Sealy Townsend and Peter Debye) but the term "plasma" was not introduced until after this paper in 1928 by Irving Langmuir **(Langmuir 1928)**. Meghnad Saha had provided a theory of ionisation and demonstrated theoretically that significant ionisation would occur under chromospheric conditions **(Saha 1920, 1921)**. Martin Johnson **(Johnson 1924, 1926, †)** and Ramani Kanto Sur **(Kanto Sur 1926)** proposed that radiation pressure could drive ions outward, though Johnson treated ions largely as test particles and Kanto Sur focused on Ca^+ in erupting solar prominences. Milne subsequently combined these radiation-pressure arguments with Saha's ionisation theory to argue that ionised stellar atmospheres could not in general remain strictly hydrostatic, and that ionised material could be preferentially driven outward by radiation as a global atmospheric effect. Milne established the concept, but a full quantitative solar wind model only came with the work of Eugene Parker in 1958 **(Parker 1958)** who employed hydrodynamic/thermal escape equations, supersonic flow, mass flux. Milne's insight was cited as the inspiration of the paper by Sydney Chapman and Vincenzo Ferraro **(Chapman & Ferraro 1929, †)** just three years later, and that led to the introduction of the concept of the magnetosphere, as discussed in the next section.

In summary, Milne's contribution is greatly under-appreciated but pivotal. Birkeland correctly understood that auroral optical emissions are produced by precipitating energetic electrons exciting atmospheric gases, but he incorrectly envisaged those energetic electrons as originating directly from the Sun and propagating across interplanetary space on their own. Milne's key contribution was the concept that electrons did leave the Sun but along with positive ions in electrically neutral plasma (the solar wind), resolving the electrostatic difficulties of Birkeland's model. While it is often still said today that auroral electrons come from the Sun, modern understanding is that this is more often untrue than true: the solar wind supplies energy to accelerate auroral electrons inside Earth's magnetosphere; however, the electrons themselves, particularly during geomagnetic storms, mainly originate from Earth's own ionosphere rather than the solar wind, as discussed by **Lockwood et al. (2025b, †)**.

Paper 6: Chapman & Ferraro (1929, †) The electrical state of solar streams of corpuscules

Sydney Chapman and Vincenzo Ferraro (hereafter C&F) soon recognised the great implications of the paper by **Milne (1926, †)** that was discussed in the last section. This paper is the result of that and it is the basis of the work that led C&F to predict what we now call a magnetosphere. This work was published in a series of six papers over the subsequent four years: unfortunately all six were entitled "A new theory of Magnetic Storms": that has caused some confusion in the on-line versions of website of the journal *Terrestrial Magnetism and Atmospheric Electricity*, which was renamed *Journal of Geophysical Research* in 1949 **(Chapman & Ferraro 1930, 1931a,b, 1932a,b, 1933)**.

C&F and **Chapman (1929, †)** (a companion paper in the same issue of *MNRAS*) considered what a cloud of ions and electrons emitted by the Sun, what we would now term a CME, would look like when it reached the Earth. They concluded it would be electrically neutral, although they did consider the suggestion by **Milne (1926, †)** that the leading/trailing edge would be positively/negatively charged due to a different effect of radiation pressure on ions and electrons.

Because of Birkeland's suggestion that energetic electrons from the Sun gave rise to the aurora, C&F were concerned about how the solar cloud particles could enter Earth's magnetic field. Their 1929 *MNRAS* paper showed that a current sheet would form what we now call the magnetopause that would exclude the cloud and confine Earth's field. A year after the publication of their *MNRAS* paper C&F wrote a letter to *Nature* **(Chapman & Fereraro 1930)**. As with the paper by **Dungey (1961)**, the component of that *Nature* letter that had great impact was a schematic, in this case showing the parabolic-shaped cavity in the solar wind flow. Because this is easily identified as what we call the magnetosphere, the *Nature* letter is often cited as the origin of the concept of the magnetosphere, but the physical analysis that gave rise to that schematic is in the *MNRAS* paper. C&F correctly associated the initial positive phase of a geomagnetic storm with the compressive effect of the arriving CME. They also invoked a "ring current" (the term still in use today) that gave the main, negative phase of the storm, but did not venture an explanation of how this arose.

Figure 4a is a modern rendition of the first ever schematic of the magnetosphere in **Chapman & Ferraro (1930),** which is based on the analysis in their *MNRAS* paper **(Chapman & Ferraro (1929, †))**. It is in the equatorial plane and the points O (the centre of the Earth), A (the nose of the magnetosphere) and the points in B and B' (in the dawn flank of the magnetopause) and C and C' (in the dusk flank of the magnetopause) are as in C&F's original schematic. The cross tail current and $\underline{\mathbf{J}}_{CT}$ and the bow shock have been added: although not included in the schematic the texts of their 1929 and 1930 papers shows that C&F were aware of both. **Figure 4b** is a modern view in the noon-midnight plane from **Lockwood**

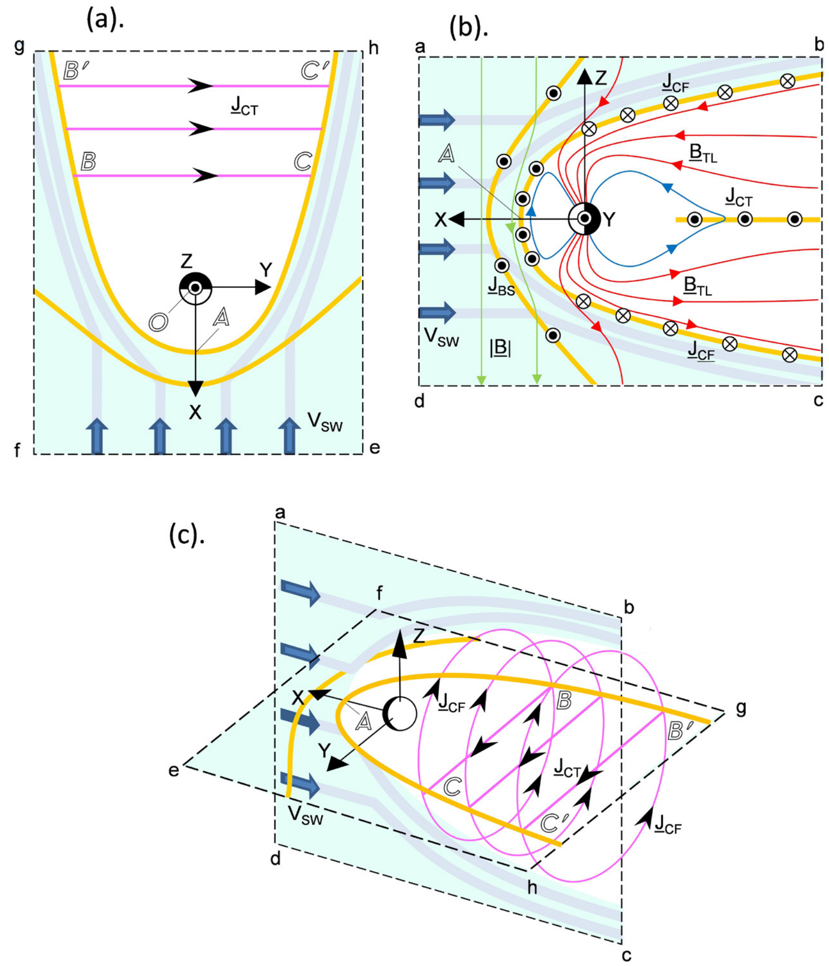

Figure 4. Earth's magnetosphere. Part (a) is a modern rendition of the schematic in **Chapman & Ferraro (1930)** *which is the first to show the magnetosphere and was based on their* MNRAS *paper. As discussed in the text, the bow shock and the cross tail current* $\underline{\mathbf{J}}_{CT}$ *have been added. The diagram is in the equatorial* XY *plane and the labels are as in CF's original, O, being the centre of the Earth and A being the nose of the magnetosphere. (b) a modern view of the magnetosphere in the noon-midnight XZ plane, abcd. In addition to* $\underline{\mathbf{J}}_{CT}$ *the Chapman-Ferraro currents in the magnetopause,* $\underline{\mathbf{J}}_{CF}$, *the bow shock current* $\underline{\mathbf{J}}_{BS}$ *are shown. Open, closed and interplanetary field lines are shown in red, blue and green, respectively. The IMF is* $|\underline{\mathbf{B}}|$, *the tail lobe field* $\underline{\mathbf{B}}_{TL}$ *and the solar wind speed* V_{SW}. *Part (c) combines (a) and (b) into a 3-dimensional schematic in which the magnetosphere is viewed from the middle latitudes in the northern hemisphere in the pre-midnight sector.*

(2013). Note this panel includes field lines and the dayside Chapman-Ferraro currents that circle the magnetospheric cusp that C&F introduced in their 1931 and 1933 papers and also the currents in the bow shock. **Part (c)** combines parts (a) and (b) into a three dimensional schematic that shows how the cross tail current closes in the Chapman-Ferraro currents,

$\mathbf{J}_{CF}$, as described in the text of C&F's 1930 paper. In the 1930 *Nature* letter, C&F discuss the possibility that the cross tail current sheet is the origin of the negative equatorial depression of the field seen in the main phase of storms. However. in other papers they are clear in conceiving this is caused by a current that encircles the Earth: we now know that the ring current does indeed circle the Earth and is closer to the Earth than the cross-tail current and on dipolar field lines.

The considerations of C&F gave a remarkably accurate description of modern thinking about a geomagnetic storm. One thing that has changed is that C&F considered only CMEs to be launched by the Sun, with no steady solar wind between events, and so they regarded the formation of the magnetosphere as transient events rather than an ever-present feature. There was a reason for this: C&F knew nothing of Dungey's reconnection (discussed below) and so applying frozen-in and a steady solar wind would mean that field would pile up as it was draped over the nose opf the magnetosphere and so would exert ever-increasing pressure on the magnetosphere. Hence without Dungey's reconnection, C&F could not conceive that a steady state magnetosphere could exist. The first realisation that there was a continuous outflow between CME events came from studies of comet tails. That solar outflows might be forming comet tails was discussed by **Eddington (1910, †)** but it was **Biermann (1951)** who used them to show the solar wind was continuous and this was confirmed by the first in-situ measurements in interplanetary space **(Neugebauer & Snyder 1962)**.

Papers of stellar and pulsar magnetospheres in *MNRAS* are extremely numerous but those on Earth's magnetosphere are rare. However, **Carolan et al. (2019, †)** recently published a very interesting *MNRAS* paper that examined how the solar wind (see also **Ó Fionnagáin & Vidotto 2018, †**), and hence Earth's magnetosphere, evolved as the Sun aged during the early to mid main sequence. Their models span solar ages from ≈10^8 yr to near-present conditions, parameterized by a decline in solar rotation rate from ≈50Ω⊙ to ≈0.8Ω⊙, where 1Ω⊙ denotes the present-day solar rotation rate. As the rotation rate decreases, the authors consider how the large-scale magnetic field strength declines, how the field becomes less complex and less intense and the open solar magnetic flux decreases. They do not consider other potential changes in the Sun which might have influenced the solar wind. In addition. this paper assumes Earth's magnetic field has stayed the same. This may be be a reasonable approximation, for example **Tarduno et al. (2007)** find Earth's field strength 3.2 x 10^9 years ago within 50 percent of the present-day value, and they point out that this indicates that a viable magnetosphere sheltered the early Earth's atmosphere from solar wind erosion. Nevertheless the study by **Carolan et al. (2019, †)** points to an exciting new field exploring "paleomagnetic magnetospheres" which will be very important in exoplanet research of the type discussed in Paper 11 of this paper **(Nichols & Milan 2016, †)**.

Paper 7: Cowling (1933, †) The magnetic field of sunspots

This paper by Thomas Cowling is notable for two reasons. Firstly, it demonstrated that the strong magnetic fields observed in sunspots cannot be maintained by simple, axisymmetric electric currents (that is, currents that are symmetric around the Sun's rotation axis). At the time, this was surprising because it challenged the prevailing assumption that steady, symmetric currents were sufficient to explain sunspot magnetism. This paper revealed a fundamental limitation on the mechanisms that sustain solar magnetic fields, laying the groundwork for later developments in solar dynamo theory and our broader understanding of stellar magnetism.

The second reason why this paper is important is that it contains the first statement of the magnetic induction equation. It is not in the vector form that we know it today, but rather deals with the three components separately. It was derived in the way that we would regard as a text-book standard today, using Faraday's law, Ohm's law with finite conductivity and considering bulk fluid motion. This is a major advance because from it **Alfvén (1942)** developed the frozen-in flux theorem for the ideal limit. (This is sometimes called the infinite conductivity limit but, in reality, it applies to large, but not infinite, conductivities if the magnetic Reynolds number is large, which is often the case in space plasma because spatial dimensions are large). The induction equation also shows that magnetic field can also diffuse through the plasma if the magnetic Reynolds number is low. This was later used by Peter Sweet **(1950, †)** when discussing magnetic field in turbulent plasmas and also by Sweet **(1958)** and Eugene Parker **(1957)** in developing what is known as the Parker-Sweet reconnection theory.

This paper by Cowling is absolutely fundamental to the development of viable dynamo theories. It showed that no steady, axisymmetric magnetic field can be maintained by an axisymmetric flow. The key person in finding a way around this major problem was Eugene Parker **(1955)**. He recognised there was no flaw in Cowling's logic and it was a fundamental limitation — but also that breaking the symmetry gave a potential solution. This gave rise to what we now know as his ``α-Ω" dynamo. Cowling's paper allowed the Ω–effect and Parker noted that differential rotation can stretch poloidal field into toroidal field, but these two effects on their own could only generate axisymmetric toroidal fields. Parker introduced the α-effect: small-scale, non-axisymmetric, helical turbulence generated by rotating, stratified convection twists toroidal field lines into poloidal loops which breaks axial symmetry. Mean fields can be maintained only through correlations of fluctuations and the laminar flow used in previous models was not sufficient.

In the α-Ω dynamo model, differential rotation winds up a magnetic field into strong toroidal bands, while helical convection regenerates a poloidal field and moves it. Because both effects vary with latitude and depth, the dynamo doesn't remain still, rather it behaves like a travelling wave that naturally drifts equatorward, so the latitudes where a toroidal field is strongest (and where sunspots emerge) moves toward the equator as the cycle progresses, giving butterfly diagram described above.

Paper 8: Dungey (1953b, †) The motion of magnetic fields

In 1961 Jim Dungey published the most well-known and most highly-cited paper in space physics in the journal Physical Review Letters **(Dungey 1961)** . That paper is just two pages long and is based on two cartoons, but it completely revolutionised space physics, areas of astrophysics and laboratory plasma physics because it introduced the concept of magnetic reconnection. A search of Web of Science for the topic "magnetic reconnection" (conducted in June 2016) yielded over 23,000 journal articles, which had amassed almost a third of a million citations **(Lockwood 2016)**. A great many scientists dismissed Dungey's PRL paper as "cartoon physics", not understanding those cartoons were a visualisation of a great deal of physical and mathematical work done by Dungey, a key part of which is in this, his 1953 *MNRAS* paper. In fact, *MNRAS* is more deeply involved in the development of Dungey's 1961 citation classic, and that will be discussed below.

When I first worked in space physics in 1978, the debate about reconnection still raged, which was very strange because, with judicious application, it explained all the major features of the magnetosphere and by then the mechanism was accepted and exploited in solar physics, fusion research, and astrophysics. A frequent objection was the use of the concept of moving magnetic field lines. If one takes the Coulomb force law and the Lorentz-Fitzgerald transformations of distance, time and force from special relativity one can derive the Lorentz equation for the force on a moving charged particle. That gives mathematical expression for a group of terms we can identify as the electric field and a second group that we can identify as the magnetic field. If we then transform those groups of terms from one frame to another we find that the electric field is frame-dependent but the magnetic field, at non-relativistic speeds at least, is frame-independent. As a young student, working through this, I realised that what it really meant was that, given field lines are a construct to allow you to understand the behaviour of charged particles, one was free to consider them as moving if it helped but there could difficulties if you applied it across some boundaries across which the field was continuous (i.e., no magnetic monopoles) but the motion of particles was not. Hence one cannot always apply the motion of field lines across all boundaries. It was for this reason Dungey's 1953 *MNRAS* paper was so illuminating.

The concept of magnetic field lines being "frozen into" a conducting fluid originates from Alfvén's seminal work on magnetohydrodynamic waves **(Alfvén 1942)**. This result became a cornerstone of ideal MHD and was later formalised by **Alfvén & Fälthammar (1963)**. However, the use of frozen-in field lines was subsequently questioned, most explicitly by Alfvén himself **(Alfvén 1986)**, who quite correctly noted that it did not always apply. He was particularly concerned by the fact that it predicted moving field lines as he felt field lines were just visual aids, not physical realities. However, instead of rejecting frozen-in completely as Alfvén later did, Dungey clearly articulated the physical conditions under which one could consider field lines in a magnetoplasma as moving and when it broke down. In particular he showed that magnetic flux through a loop (which Alfvén did regard as a physical quantity) could change if the magnetic topology of the field lines threading the loop changed. A change of magnetic topology is precisely what magnetic reconnection is: in other words in his 1953 *MNRAS* paper, Dungey was describing the effects of reconnection without giving it a name. This was a crucial step beyond Alfvén's frozen-in theorem and became the standard paradigm that is used today which invokes frozen-in applying in most of space because of the high magnetic Reynolds number but diffusion of fields through the plasma can occur in small regions of large magnetic shear (current sheets). The diffusion allows the field lines to reconfigure (changing their topology from running along the current sheet to threading it) which is what Dungey later termed "reconnection". The originality of this paper from Dungey is exceptionally subtle but exceptionally profound: the paper reframed how physicists think about magnetic topology and evolution rather than introducing a single new equation or model. This paper directly paved the way for Dungey's later, far more famous, work in 1961 on reconnection in Earth's magnetosphere that explicitly showed the topology changes at work. This was transformational for space and solar physics and underpins modern explanations of solar flares, coronal mass ejections, magnetospheric substorms and energy transfer from the solar wind to planetary magnetospheres.

Dungey's work led to a full and highly predictive understanding of Earth's magnetosphere with a key distinction being the roles of "open" and "closed" field lines. Open field lines thread the boundary between the magnetosphere and the (shocked) solar wind, the magnetopause, and connect the Earth's magnetic field with interplanetary space, whereas closed field lines that stay confined within the magnetopause, as shown in parts (a) and (b) of **Figure 5** from **Lockwood (2023)**. The Dungey cycle is the motion of field lines that are opened by reconnection at the dayside magnetopause, transferred into the tail by the solar wind flow where they are closed by reconnection in the cross-tail current sheet. Once re-closed they convect back to the dayside magnetopause, passing to either the dawn or dusk flank of the Earth. Hence the motion of field lines is a critical concept that Dungey justified in this paper. This "convection" motion also been found in the magnetised gas giant planets **(e.g. Cowley & Bunce 2001, 2003; Badman & Cowley 2007)** and recently inferred in exoplanets.

What is widely thought to be the first detection of an exoplanet magnetosphere was published in Nature Astronomy by **Ben-Jaffel et al. (2021)**. These authors constructed an exoplanet magnetosphere by modelling the interaction between the planet's magnetosphere and the stellar wind, assuming a dipolar planetary magnetic field. The exoplanet studied is

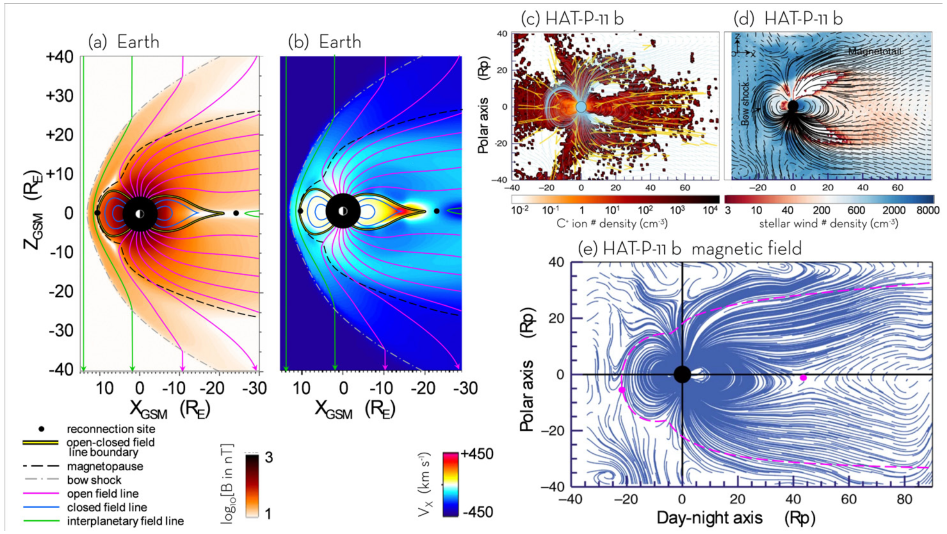

Figure 5. The application of Dungey's open magnetosphere model. Parts (a) and (b) are global numerical model predictions of the Earth's magnetosphere made using the simulations by the SWMF MHD model **(Toth et al. 2012)** *with a geocentric dipole model of the intrinsic geomagnetic field and zero tilt of Earth's dipole axis. The solar wind during the run time used here (90 min) was steady at 400 km s^{-1} in the –X direction with an IMF pointing due southward in the GSM fame (i.e. in the –Z direction) and of magnitude 5 nT. The solar wind number density input was 3 x 10^6 m^{-3} and the mean ion mass 1.1 amu. Part (a) shows the magnetic field, B (on a logarithmic scale) and (b) shows the sunward plasma velocity, V_X. Mauve, blue and green are open, closed and interplanetary field lines, respectively. Note that mauve field lines that reach X = –30 R_E (where 1 R_E = 6370 km is a mean Earth radius) are open because they thread the magnetopause at X < –30 R_E (from* **Lockwood 2023**). *Parts (c), (d) and (e) are from the analysis of the exoplanet HAT-P-11 b by* **Ben-Jaffel et al. (2021)**. *Part (c) shows the planetary C^+ (CII) ion abundances deduced from absorption spectra during transits of the parent star HAT-P-11: these ions are seen in the magnetosphere of the exoplanet and escaping from it along open field lines. Part (d) shows the model-inferred magnetic field line segments superposed on a colour-coded plot of the derived stellar wind proton number density and part (e) shows the magnetic field derived using pressure balance with the stellar wind and open field lines from where C^+ ions are escaping through the inferred magnetopause location.*

HAT-P-11 b, a Neptune-like exoplanet (so larger and more massive than Earth but smaller than Jupiter or Saturn) which is just 0.052–0.053 AU from the parent star HAT-P-11, (i.e., roughly 5% of the Earth-Sun distance) and has an orbital period of ≈4.9 days. HAT-P-11 is an orange dwarf star at a distance of about 123 light-years from Earth. They use UV transit observations of absorption by ionized species made by the Hubble Space telescope; specifically the C II lines used are the 133.45 nm and 133.57 nm multiplet which identify ions of planetary origin and they infer the surrounding plasma environment that interacts with the planetary magnetic field using neutral hydrogen (H I) Lyman-α at 121.6 nm, which is sensitive to both escaping planetary hydrogen and the background stellar/stellar wind environment. These authors then apply pressure balance between stellar wind ram/magnetic pressure and planetary magnetic pressure to estimate the magnetopause stand-off distance. By matching the observed absorption morphology with this physically motivated magnetospheric geometry, they infer the presence of a strong planetary magnetic field that confines the ionized outflow and shapes the extended exosphere. Specifically, Ben-Jaffel et al. assume a dipolar planetary magnetic field and define magnetospheric boundaries, not only through pressure balance with the stellar wind, but also distinguishing between closed field lines and open field lines along which the planetary C^+ ions escape into the interstellar wind, thereby constructing a steady-state geometry of a magnetosphere with a Dungey cycle. It should be added that some of the inferences by **Ben-Jaffel et al. (2021)** have been questioned by **Belenkaya (2023)**, however the usefulness of applying Dungey's open magnetospheric model to exoplanets is well demonstrated.

An interesting quirk of history is that Dungey did submit a second paper discussing reconnection more specifically to *MNRAS* in 1953. Dungey's memoirs recollect that it was rejected because he had not explicitly allowed for the effect of plasma pressure **(Dungey 1997)**. This was a valid concern because the rising pressure in the current sheet, due to inflowing and heated plasma, could have choked off the reconnection by opposing the inflow. I do not know if Dungey knew why this was not a problem at the time, of if he worked it out later. The answer to this objection is that the reconnection site is highly localised in the current sheet so instead of accumulating in the current sheet, it is jetted out in opposite directions along the current sheet. However, it later transpired that this problem was not yet fully solved: in the Parker-Sweet formalism the outflows are confined to the centre of the current sheet which meant that the outflow along the current sheet was still insufficient. As a result, although reconnection still took place in the Parker-Sweet theory, it was too slow to explain the voltages (reconnection rates) it had been proposed to explain. The solution was suggested by aerodynamicist Harry Petschek who proposed shock fronts standing in the inflow region (in fact, we now think of these being Alfén waves rather than shocks) which open the width of the outflow region allowing more rapid escape down the current sheet **(Petschek 1964)**. However, the story still did not end there: Eric Priest **(1972, †)** noted that this solution did not work because the diffusion region would grow in size and the fast reconnection predicted by Petschek would soon decay into the slow Parker-Sweet form. This was confirmed by others to be the case (e.g. **Biskamp 1986**). A solution was found by **Ugai & Tsuda (1979)** who showed that quasi-steady Petschek configurations emerge when resistivity is non-uniform. Another solution was noted by Eric Priest, working with Hubert Baty and Terry Forbes, who showed how non-uniform viscosity or time-dependence could also allow fast Petschek reconnection **(Baty et al. 2009)**. The paper rejected by *MNRAS,* on the advice of Sydney Chapman, was submitted to and published by *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **(Dungey 1953a)**. However, the schematic which made the PRL paper so successful was omitted, even though it had been included in Dungey's Cambridge PhD thesis **(Dungey 1951)**. This was because Dungey had noted schematics attracted the "cartoon science" criticism, which seems bizarre to scientists today. Looking back on this history, it becomes clear that *MNRAS*, ironically, lost a hugely well-cited paper to PRL through a review that was actually very insightful and raised a genuine problem that was not properly solved until at least 25 years later!

Paper 9: Hewish (1958, †) The solar corona in interplanetary space

The paper by Hewish established radio scattering as a diagnostic of coronal plasma. It showed that the angular diameter of the Crab nebula is considerably increased when viewed through the solar corona. A second paper in *MNRAS* by **Hewish & Wyndham (1963, †)** showed that the corona flattened toward the solar equatorial plane. That flattening is consistent with what we now interpret as the large-scale density manifestation of the streamer belt in the outer corona. They also argued that fine filaments have transverse scales ≤ 5000 km at 60 $R_\odot$ (where 1 $R_\odot$ is a mean solar radius) indicating small-scale structure in the outer corona. These papers led to the understanding of the interplanetary scintillation (IPS) phenomenon by **Hewish et al. (1964)**. These authors observed second-scale temporal variations in compact radio sources as well as angular scattering and interpreted the scintillation in terms of density irregularities carried outward by the solar wind. Their analysis of radial variation in scattering was shown to be consistent with an outflowing solar wind, with slight equatorial convergence of streamlines.

The work of **Hewish (1958, †)** and **Hewish & Wyndham (1963, †)** stand as a classic observational contribution that pioneered the use of radio scattering techniques to probe the outer corona and interplanetary medium remotely. It also provided early empirical support for the expanding solar corona and variability in density structure, helping cement the solar wind paradigm developed theoretically by **Parker (1958)**.

Interplanetary scintillation became a routine remote sensing method for measuring solar wind speed and density turbulence long before extensive spacecraft data became available. The addition of tomographic techniques allowed the propagation of Corotating Interaction Regions (CIRS) and CMEs (which generate recurrent and quasi-random geomagnetic storms, respectively) to be imaged using tomographic techniques (e.g. **Jackson et al. 2011**) which has applications in space weather forecasting (e.g. **Xiong et al. 2023**).

Paper 10: Hayakawa et al. (2019, †) The extreme space weather event in September 1909

Another class of paper that has become a feature of *MNRAS* in recent years involves the re-analysis of major historic space weather events **(Hayakawa et al. 2019; Hattori et al. 2019; Hayakawa et al. 2021b, 2022, 2023, 2024a,b, †) (Hudson 2021)** and recently a quantitative comparison of the various aspects of known events **(Lockwood et al. 2025b, †)**. The example of this kind of paper selected here is **Hayakawa et al. (2019, †)**, which was the first of this series of holistic event examinations and caused a major re-appraisal of the severity of the event.

Before this paper and the others in the *MNRAS* series, the literature on extreme historical space-weather events was dominated by the Carrington Event of 1859 (discussed in Paper 1) and a small number of papers on other events based largely on data from Europe and North America. The low-latitude aurora in the storm of 25 September 1909 had been noted by **Chapman (1957)**, studied further by **Silverman (1995)** and included in comparative studies of major events (e.g., **Willis et al. 1997**). However, discussion of it was fragmented and scattered in various papers and it had not been analysed in the comprehensive manner adopted by this paper. It was known to be a "large" event but was not well characterised globally and, crucially, was not widely recognised as a near Carrington-class event. The study of auroral latitudes by **Lockwood et al. (2025b, †)** placed the event as 13th when ranked by auroral extent, but the *Dst* index inferred in this paper places it at a considerably higher rank when considering the geomagnetic disturbance.

The paper employed solar, auroral and geomagnetic observations and combined them to give a holistic view that allows the event to be compared to modern events for which the observations are much more precise and detailed. A major (and often underappreciated) contribution of this (and the other) papers is methodological: the authors showed that non-instrumental historical records can be dated precisely, geographically constrained, quantitatively linked to physical parameters (e.g., the low-latitude auroral boundary). This requires careful, thorough and deep research into the historical documents which can bridge the gap between humanities-style archives and quantitative historical space science.

Paper 11: Nichols & Milan (2016, †) Stellar wind-magnetosphere interaction at exoplanets: computations of auroral radio powers

As shown by **Figure 5**, **Ben-Jaffel et al. (2021)** have used the Hubble Space Telescope to observe that the exoplanet HAT-P-11 b has a cloud of charged carbon ions forming an extended tail and surrounding region that is best be explained by the presence of a magnetic field and magnetosphere — similar to Earth's magnetic bubble interacting with the solar wind. This is widely regarded as the first detection of a signature of a magnetic field of an exoplanet. However, direct observation and quantification of an exoplanetary magnetic field will almost certainly involve its auroral radio emission. Magnetised planets naturally produce such radio emission via the electron cyclotron maser instability (ECMI) — the mechanism responsible for Jupiter's intense radio bursts. The key point is that the emission frequency is set directly by the magnetic field strength which could therefore be measured if the radiowaves could be detected.

The paper by Nichols and Milan marks the start of what will be an ongoing field for several decades to come — namely the detection and quantification of exoplanet magnetic fields using auroral radiowave bursts. It was the first to compute auroral radio power that would by emitted by an exoplanet using a physically-consistent model of the Dungey cycle driven by the stellar wind, in contrast to previous work that relied largely on empirical scaling relations such as the Radiometric Bode's Law (RBL) for estimates of radio emission flux **(Desch & Kaiser 1984)**. Hence it was the first to apply the science on Earth's magnetosphere that developed in the papers discussed above.

Studies show that Jupiter has two circulation patterns, a Dungey cycle driven by the solar wind via dayside and nightside magnetic reconnection (i.e., analogous to the Dungey cycle in Earth's magnetosphere) and a Vasyliunas cycle which is an internal, rotation-driven plasma circulation. **Badman & Cowley (2007)** show that although the Vasyliunas cycle usually dominates at Jupiter because of its rapid rotation, the Dungey cycle can be appreciable. The field-aligned current systems associated with these circulations have been mapped by **Cowley & Bunce (2001)** and **Cowley & Bunce (2003)**. These currents are often carried by flows of energetic electrons which interact with the planetary magnetic field to produce coherent radio emission (called the Electron Cyclotron Maser Instability, ECMI) which is at the local electron cyclotron frequency which depends primarily on the local magnetic field strength. The currents associated with the Vasyliunas cycle are internal and are not a significant source of radio emission, which comes almost entirely from the currents associated with the Dungey cycle.

The paper used an ionospheric convection model to estimate field-aligned currents and resulting radio emission associated with Dungey cycles. Importantly, the paper explicitly included "saturation" of the convection potential, a phenomenon observed and numerically modelled for Earth's magnetosphere. One theory to explain this is that the "region 1" field aligned currents that transfer energy and momentum of the magnetosphere down into the ionosphere, produces a magnetic field that opposes the Earth's dipole field at the dayside magnetopause, reducing the magnetic reconnection rate there **(Siscoe et al. 2002, 2004)**. It is further modulated by the effect of solar wind pressure on the dayside magnetopause. Another theory is by **Kiveson & Ridley (2008)** who argued that the saturation results from Alfvénic "wing" perturbations on the open field lines that causes drag on the field lines. A third interpretation is that the non-linearity of the convection response actually arises using an over-simplistic solar wind-magnetosphere coupling function **(Lockwood & McWilliams 2021)**. However, the modelling of the extrasolar planets' radio emission will also employ a coupling function, so this paper is absolutely correct to include the saturation effect. However, the point raised by **Lockwood & McWilliams (2021)** means that care is needed to ensure the saturation factor adopted is consistent with the coupling function used. The modelling in the paper generated power-law approximations for radio power and flux density as functions of orbital distance and planetary magnetic field strength. This represents a meaningful advance over earlier works that simply scaled Solar System observations to exoplanets without accounting for underlying magnetospheric physics.

The paper has several significant implications. It showed that radio powers from "hot Jupiters" are typically much lower than predicted using RBL, largely because magnetospheric convection saturates at high stellar wind electric field. This will decrease their detectability. Despite lower power, certain configurations of exoplanets, especially those with moderate magnetic fields at larger orbital distances, could produce radio emissions detectable by future telescopes such as the Square Kilometre Array (SKA). The study suggests that planets with weaker fields at moderate orbital distances sometimes produce higher relative radio powers than predicted by simple scaling laws, broadening the range of targets for radio detection. The work is important as it moved beyond empirical scaling laws toward mechanistic, physics based predictions of radio emission. The paper also provided quantitative predictions tied to telescope sensitivities, enabling more rigorous planning for radio exoplanet searches.

Since its publication, this study has influenced follow on modelling efforts that use global 3D magnetohydrodynamic (MHD) simulations of star–planet interactions to refine emission estimates. It has often been cited in studies of exoplanet magnetospheres and radio emission, and serves as a baseline for comparing analytic and numerical predictions that can inform observational strategies for upcoming and existing low frequency radio facilities (e.g., LOFAR, SKA, NenuFAR), because it provides realistic flux ranges and scaling relations grounded in physics.

Papers by **Turner et al. (2021), Turner et al. (2024)** and collaborators present LOFAR low-frequency beam-formed observations of multiple exoplanet systems and report tentative radio bursts emanating from the constellation τ Boötis potentially linked to the planet's magnetic field.

Theoretical studies have looked at the link between detected radio signals and habitability **(Peña-Moñino et al. 2024)**. The radiowave emission frequency from ECMI is 10-100 MHz for the strong fields of hot Jupiters but 0.8–2.8 MHz for Earth-like rocky planets. This is below Earth's ionospheric cut-off and so could not be observed from the ground. Hence space-based observations would be needed and there are active proposals for "lunar farside low-frequency arrays" (Dark Ages Radio Explorer (DARE), Farside Array for Radio Science Investigations of the Dark ages and Exoplanets (FARSIDE)) specifically to observe <10 MHz signals, which would include emissions from Earth-analogue exoplanets or even early-Earth analogues that would tell us about the history of our Solar System. Nevertheless the Square Kilometre Array (SKA) will bring this area to the fore. SKA-Low is optimized exactly where strongly-magnetized close-in planets should emit (i.e., hot Jupiters, warm Neptunes).

Paper 12: Macneil et al. (2020, †) The evolution of inverted magnetic fields through the inner heliosphere

This paper examined how "inverted" heliospheric magnetic fields (field lines that have been bent backward towards the Sun), evolve with radial distance through the inner heliosphere. The study began as preparation for the Parker Solar Probe (PSP) mission and re-analysed Helios spacecraft measurements taken between ≈0.3 AU and 1 AU during the interval 1974-1981, applying new understanding gained since the data were first analysed. The paper assesses how the occurrence and magnetic properties of these inversions change as the solar wind carries them outward. Inversions were identified from the atypical sunward propagation of the “strahl” — a beam of field-aligned suprathermal electrons which forms in the hot solar corona and thus predominantly propagates away from the Sun **(Kahler & Lin 1994).** Thus strahl on classical, un-inverted field orientations are parallel to the magnetic field in the antisunward sectors of heliospheric field, and antiparallel in sunward sectors: in inverted flux the opposites apply.

The reason why strahl on inverted flux was of interest was that it gives an accurate way to correct open flux estimates from spacecraft **(Frost et al. 2022)**, needed because inverted flux causes “excess flux” in estimates of the global integrated open solar flux (OSF), based on local measurements of the radial field component, B_r. These local measurements at the spacecraft can be used to give global average values by averaging over solar rotation intervals to allow for longitudinal structure. Corresponding averaging over latitude is not needed because tangential pressure balance close to the Sun makes the tangential magnetic pressure $B_r^2/2\mu_o$ become constant with heliographic latitude as the solar wind leaves the corona and thus the modulus of the radial field component $|B_r|$ is constant with latitude, as was observed by the Ulysses spacecraft. Hence at a heliocentric distance r the global (unsigned) flux threading the heliocentric sphere of radius r, F_r, can be estimated from $F_r = 4\pi r^2\langle|B_r|\rangle_\tau$ where τ is the average coronal rotation period. However, this integrated global estimate F_r for each solar rotation contains inverted flux as well as the true OSF (flux that threads both the coronal source surface at the top of the corona and the spherical surface at heliocentric distance r). Therefore to measure OSF, a correction to F_r of the excess caused by field inversions is required **(Lockwood et al. 2009b)**. A survey using many spacecraft in the heliosphere by **Owens et al. (2008)** found the excess flux increased with heliocentric distance r, which raised questions about the radial production profile of inverted flux in the heliosphere and for how the inverted flux evolves as it propagates away from the Sun. Why this was the case was addressed by Allan Macneil and his coworkers using the Helios data.

The study contrasted two broad formation scenarios of inverted flux, namely near-Sun origin or heliospheric origin. In the former, field inversions are generated close to the Sun (e.g., by interchange reconnection or coronal jets) and then decay with heliocentric distance, becoming progressively straighter as they propagate. For this scenario, the excess flux would decrease with r. For the latter scenario, inversions are continually generated or amplified during transit through the heliosphere (for example by velocity shear, draping over structures, turbulence, or other processes) leading to changes that depend on distance and local dynamics. This second scenario would cause the excess flux to increase with r, as was observed by **Owens et al. (2008)** and **Lockwood et al. (2009a)**.

Macneil et al. (2020, †) found that the occurrence rate of inverted magnetic fields increases with distance between 0.3 and 1 AU, rather than decreasing. This trend suggests that the dominant processes creating or enhancing inverted fields are likely in-transit rather than solely near-Sun in origin. This is consistent with the dependence of excess flux on r observed by **Owens et al. (2008)**, confirming inverted field lines are the cause of the excess flux. Importantly, the authors linked this radial evolution to changes in the magnetic field characteristics associated with inverted structures, arguing that the observed trend is more consistent with heliospheric driving processes (e.g., shears, turbulence, velocity gradients) than with simple decay of features created at the Sun. The evolution aspects highlighted in the paper are important. Because the occurrence rate of inverted field increases with distance: Contrary to a simple decay model, inverted fields become more common between 0.3 and 1 AU, implying active processes in the solar wind itself. The paper examined how magnetic properties associated with inversions change with radial distance, suggesting that different mechanisms (e.g., turbulence vs. shear) leave distinct evolutionary signatures — though disentangling them remains complex.

The detail of observation of inverted flux, in particular as seen in higher resolution data and closer to the Sun by PSP (0.045-0.5 AU and so with some overlap with the Helios data) showed that inverted flux was a ubiquitous feature of the heliosphere in ”switchbacks” **(Badman et al. 2026, Raouafi et al. 2023, Jagarlamudi et al. 2023)**. Some of these have been shown to arise low in the solar atmosphere (e.g. **Hou et al. 2024**) whereas others arise in the heliosphere (e.g. **Akhavan-Tafti & Soni 2024**). Studies also show they evolve in nature as they propagate **(Soni et al. 2024)**. PSP observations closer to the Sun than the Helios data show that switchback occurrence, angular deflection, and morphology all vary with distance and that large angular field deflections in the field become more common with increased heliocentric distance, while very small ones decrease in occurrence. Given that the Helios study was for large deflections, this is consistent with the results of Macneil et al. Very close to the Sun, switchbacks tend to be sharper and more tightly structured, and many appear as rotational discontinuities. In these cases, links to near-Sun magnetic topology become clearer. In studies of such structures, the ability to map field lines from the in-situ observation site to the remotely-sensed features in the corona, chromosphere or photosphere is highly challenging, but progress is being made using multiple data sources **(Yardley et al. 2024)**.

The Helios re-analysis by Macneil et al., by looking to confirm the explanation of why the excess in the globally-integrated open solar flux increased with heliocentric distance, has informed PSP observation strategies and interpretation and is helping to define other future observational strategies (for example, highlighting the need for joint observations by PSP and Solar Orbiter). It placed a focus on evolution of the structures and showed that combining data from a broad range of distances can yield key insights into the mechanisms responsible for switchbacks, disentangling near-Sun sources from in-situ processes. It has become clear that evolution of inverted flux is a key constraint on models and understanding how switchbacks change, not just where they originate, is of great importance. Hence it is now recognized as essential that models treat switchback generation, propagation and erosion. These studies have broader relevance to heliophysics and the interaction of stars with the interstellar medium. Switchbacks are now seen as ubiquitous and dynamically evolving features, not rare anomalies. The study described by this paper highlights that inverted magnetic field structures evolve significantly as they propagate through the inner heliosphere, implying that switchbacks should be regarded as a dynamic population rather than static features rooted solely at the Sun. This evolving population is very likely to influence the properties of heliospheric turbulence, magnetic connectivity, and plasma heating. Their large amplitudes, intermittency, and contribution to magnetic field-line curvature suggest they may indirectly affect particle transport, scattering, and density microstructure through their role in shaping the turbulent solar wind. As such, understanding the radial evolution, formation, and erosion of switchbacks is increasingly important not only for interpreting Parker Solar Probe and Solar Orbiter observations, but also for constraining models of solar wind acceleration, inner-heliospheric turbulence and heating, and energetic particle transport. The study of inverted flux to explain the excess flux effect on the integrated open solar flux has opened up into a whole new area of understanding the heliospheric structure and dynamics.

Discussion and Conclusions

Monthly Notices of the Royal Astronomical Society has carried some papers that played a crucial role in acquiring our modern understanding of the behaviour of space in our heliosphere. That work has given rise to usable forecasting of space weather hazards and has found many applications in astronomy and astrophysics beyond the heliopause. This review has picked just 12 such papers that are the author’s personal choice but other space scientists would make different choices. Because of the cross-fertilisation of ideas between solar system space science and astronomical studies of more distant objects, *MNRAS* remains an exciting journal for publishing space science papers: this is particularly true because studies of gas giant exoplanets are set to grow in importance in the near future and this is expected to be followed by more studies of rocky, and potentially Earth-like, extrasolar planets, areas in which *MNRAS* is now playing a role by publishing some of the foundational papers, analagous to the journal's role in the development of space science as a discipline.

Recent *MNRAS* studies illustrate how progress in exoplanet science increasingly relies on coupling detection, interior structure, atmospheric evolution, and plasma–magnetospheric physics and draws heavily on studies of Earth and gas giants in our own solar system. Foundational advances in detection and characterisation (e.g., **Pearson et al. 2018; Schwarz et al. 2016; Saha 2025, †**) enable precise constraints on planetary properties that are prerequisites for assessing magnetic environments. Interior and composition studies (e.g., **Bloot et al. 2023; Deb et al. 2025, †**) provide critical links between internal structure, convective energy flux, and the operation of planetary dynamos, thereby connecting observable atmospheric properties to magnetic field generation. A central theme emerging from this body of work is the importance of the role of planetary magnetic fields potentially mitigating atmospheric erosion by the stellar wind and so allowing long-term habitability. Global plasma simulations demonstrate that intrinsic magnetic fields can both enhance and suppress ion escape depending on stellar wind conditions, bridging solar-system knowledge to exoplanets in extreme environments (**Egan et al. 2019b,a †**). Complementary magnetospheric and wind–planet interaction models for hot Jupiters and Neptunes (**Alexander et al. 2016; Kilmetis et al. 2024, †**) extend these ideas to giant exoplanets, linking interior-driven dynamos to observable signatures such as ultraviolet absorption and potential radio emission.

Together with climate and atmospheric evolution studies (**Quarles et al. 2021; Liu et al. 2023; Loeb & Maoz 2013, †**), these papers establish magnetic fields as a key mediator between planetary interiors, stellar environments, and observable atmospheric properties. This integrated framework positions magnetic field physics as a cornerstone of next-generation exoplanet characterization, habitability assessment and even bio-signatures (**Deb et al. 2025; Limbach et al. 2022, †**). Hence, work that began with Carrington's chance observation of a flare 167 years ago and just eight light-minutes away (**Carrington 1859, †**) is now of great help in understanding exoplanets throughout the Milky Way, between about four and tens of thousands of light-years away.

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Data Availability

Most of the information in this paper is drawn from the scientific literature. **Figure 3** contains data on Sunspot Number data that can be freely downloaded WDC-SILSO, Royal Observatory of Belgium, Brussels, URL: **https://sidc.be/SILSO/home (DOI: 10.24414/qnza-ac80)**. The sunspot group data also used in the **Figure 3** are available from URL: **https://solarscience.msfc.nasa.gov/greenwch.shtml**

Use of Artificial Intelligence

AI was employed by the author (mainly Connected Papers, but also ChatGPT, Gemini and CoPilot) to aid the literature search on the subjects reviewed in this paper. For every publication found that way, the citation was checked and the paper read or re-read by the author to check its contents: Connected papers was always reliable but about 20% failed these checks for the Chatbots. The text of the paper was generated by the author.

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Helioseismology: probing the Sun's interior

by Bill Chaplin

Helioseismology, the study of the Sun by observation of its internally trapped p-mode oscillations, provides a unique window on the solar interior. The following selection captures how papers that have been published in *MNRAS* have charted the development of this field over the past 50 years. The selection spans a range of topics to show how helioseismology has matured over time. It is not possible in this brief accompanying narrative to name-check every important contributor; and so just a few pioneers from the early period are named.

The Sun's "5-minute" oscillations were discovered in the early 1960s, and theoretical work in the late 1960s and early 1970s established the oscillations as the visible manifestation of trapped, standing sound waves in the solar interior. However, the modes that had then been detected engaged only a thin layer, just beneath the visible surface, in pulsation. The oscillations were therefore regarded as being a "local" phenomenon.

MNRAS picked up the story of helioseismology from the mid-1970s, just as concerted attempts to detect truly global, "whole-Sun" oscillations were being made by several international teams. One team in Birmingham, led by George Isaak, had for several years been developing a solar spectrometer to make exquisitely precise Doppler velocity observations of the "Sun as a star" **[1]**, employing the novel technique of atomic resonance scattering. The goal had not initially been the detection of solar oscillations. Instead, the spectrometer was built to test techniques to detect exoplanets orbiting bright, nearby stars, by what we now call the Doppler-wobble method. An obvious concern was whether levels of intrinsic stellar noise might be so high as to significantly hinder making any detections, and so the team set about measuring intrinsic noise levels on the Sun. This yielded some exciting results: by the mid-1970s, the intriguing detection of 5-minute signals in data collected in Birmingham meant the focus had pivoted to solar oscillations. Further campaigns — culminating with observations in 1976, 1977 and 1978 at Observatorio del Teide at Izaña, Tenerife — led to the discovery of global 5-minute modes of oscillation of the entire Sun. This heralded the beginning of the field of global helioseismology.

Along with other theorists, Douglas Gough and (his then PhD student) Jørgen Christensen-Dalsgaard had been working in Cambridge throughout the 1970s to put the scientific potential of the solar oscillations on a firm footing. Following the discovery by Isaak and colleagues — independently confirmed by Eric Fossat and colleagues from Nice using an instrument based at the South Pole — Gough and Christensen-Dalsgaard were able to show **[2]** that the detected oscillations were consistent with being overtones of low-angular degree modes formed by sound waves penetrating the solar core. As such, these modes would provide an unprecedented probe of the structure and rotation of the solar interior.

The BiSON telescope at the Narrabri Observatory, Australia. [Picture courtesy of S. J. Hale.]

Over the decade that followed, the Birmingham team would expand its observations, establishing a permanent global network of robotic telescopes called the Birmingham Solar-Oscillations Network (BiSON). The network continues to provide Sun-as-a-star helioseismology data to the international community. BiSON's unique database now extends over 45 years — some 35 years in its full network configuration — with core data products being published in *MNRAS* **[e.g., see 3, 4]**.

By the early 1980s the term helioseismology, coined by Gough, was gaining wide recognition as the accepted name for the emerging field, and methods were being developed to fully exploit the data.

Inversion techniques have produced some of the most important results from helioseismology. They use observed oscillation frequencies or frequency splittings to infer the hydrostatic or rotational structure of the solar interior. By utilising data spanning a wide range of angular degrees — from the low-degree modes that penetrate the core, to higher-degree modes that are confined closer to the solar surface – it is possible to construct high-fidelity profiles in radius and latitude, in essence producing a high-quality 3D map of the solar interior.

Early inversions for sound speed made use of the so-called Duvall Law, named after another of the field's pioneers, Tom Duvall. It captures the interference condition of the trapped, standing sound waves. The technique exploited the fact that the ratio ω/k of a mode of angular frequency ω and wavenumber k carries information on the internal depth to which the mode penetrates, allowing the frequencies of many modes probing to different depths to be directly inverted to obtain the speed of sound against radius.

A major advance came in the late 1980s **[5]**, when it was recognised that improvements to the accuracy and precision of the inversions could be made by linearising the Duvall Law around the equations describing a standard solar model. One could then invert the frequency differences to obtain the difference in structure between the Sun and the model. This established the accepted approach by which inversions for solar sound speed and density would be performed in the years that followed.

The results have demonstrated very good agreement between the Sun and standard solar models; and have, for example, ruled out non-standard models as a potential solution to the solar neutrino problem. However, it should be emphasised that while small in absolute terms, some of the observed differences are very significant, and for example have shed light on diffusion and settling processes, and the heavy element abundance, in the solar interior.

The transition from adiabatic to radiative stratification at the base of the Sun's convective envelope leaves a characteristic signal in the sound speed and its gradient, and subtle phase shifts in the sound waves that traverse this region. These signatures allow the depth of the envelope to be measured through helioseismology — something that would not be possible without the oscillations — and the extent of overshooting of material into the radiatively stratified layer to be constrained **[6, 7]**, providing important tests of stellar evolution theory and stellar interiors' physics.

Helioseismic inversions for rotation uncovered a picture in which the differential rotation observed at the solar surface — where the equatorial regions rotate more rapidly than the poles — persists through the convective envelope; but then switches to a solid-body-like profile in the radiative interior, having a rotation rate similar to the mid-latitude rate in the envelope. These surprising results **[8]** have presented significant challenges to theories of angular momentum transport in stellar interiors.

The helioseismic data used to infer the rotation profile can also be used to compute the Sun's total angular momentum and gravitational quadrupole moment. The latter quantity has a central role to play in a well-known test of Einstein's general theory of relativity: the advance in the perihelion of Mercury. The advance has a contribution from relativistic effects; but any distortion of the Sun's gravitational potential will subtly alter the forces the Sun exerts on Mercury, contributing to the advance and thereby potentially placing the predicted contribution from relativity in tension with the observations. The helioseismic data imply a negligible quadrupole moment **[as shown in 9]**, and as such the observed advance was found to be consistent with Einstein's theory.

The transition from differential to solid-body rotation is mediated across a thin layer called the tachocline ("speed slope"). This region of strong shear is now believed to play a key role in the solar dynamo and the resulting solar activity cycle, through the so-called Ω effect that converts poloidal (north-south oriented) into toroidal (east-west oriented) magnetic field.

The helioseismic discovery of the tachocline was wholly unexpected. Its narrow radial extent is likely due to confinement by weak magnetic fields in the radiative interior. By the mid-1990s the helioseismic data were good enough to allow the careful measurement of the properties of the tachocline, including hints it might not be spherical in shape **[8]**. We now know the tachocline bulges outwards (to larger radii) at mid latitudes. Its existence, and its varying shape, have important implications for our understanding of the generation and variation of magnetic activity in Sun-like stars.

The Sun's oscillations may also be used to seismically track the solar cycle, and to probe sub-surface changes in structure and rotation (flows) associated with the cycle. It is an interesting time for such studies. The past few cycles have shown marked cycle-to-cycle differences in well-known proxies of activity, e.g., in the sunspot number and the global 10.7-cm radio flux. The current Cycle 25 and the preceding Cycle 24 were significantly weaker than the previous several "modern maximum" cycles, which spanned an extended period when levels of solar activity were high. Levels of activity in the past two cycle minima have not been as deep (i.e., weak) in more than100 years.

As the helioseismic database has been progressively extended to cover more cycles so *MNRAS* has recorded some of the results, in particular those derived from BiSON data, which are illuminating a fifth consecutive solar cycle. A recent example **[10]** reported how changes in seismic behaviour uncovered in Cycle 23 — which were commensurate with sub-surface, cycle-related perturbations being more confined near the surface than in Cycle 22 — had persisted into Cycle 24. More recent BiSON results indicate that this near-surface confinement has become even more pronounced in the current Cycle 25, suggesting possible subtle changes to the solar dynamo over an epoch that spans multiple cycles.

The Sun is a Rosetta stone for stellar astrophysics, a touchstone and anchor for studies of the internal physics, structure, dynamics and evolution of stars. Helioseismic data have thrown up many surprises over the years and studies using the technique will continue to be of wide-ranging importance.

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Solar eclipse observers. Women, men and children observing the 1870 solar eclipse in a London street during the Victorian era. This eclipse took place on 22 December 1870, and totality was visible in an arc stretching from southern Portugal and Spain, across southern Europe, to the Ukraine. In London, only a partial solar eclipse was seen. This artwork, by the English illustrator Fred Barnard (1846-1896), was titled 'The Eclipse of the Sun — a Street Scene'. It appeared in the 31 December 1870 issue of The Illustrated London News.

Credit: Royal Astronomical Society/Science Photo Library

The Distant Future of the Solar System

by Dimitri Veras

Introduction

Predating modern astrophysics, the topic of the fate of the solar system has been researched since Issac Newton (1642-1727) posed a law of universal gravitation at the end of the 17th century. Ever since, the closely related question, "Is the solar system gravitationally stable?" has been the subject of rigorous investigation. Joseph–Louis Lagrange (1736-1813) and Pierre–Simon Laplace (1749-1827), luminaries who were born in the decades after Newton's death, pioneered subsequent studies of solar system stability by codifying the theory of secular and resonant mutual perturbations amongst the planets.

In the 300 years since their seminal works, progress on answering the solar system stability question slowed until the occurrence of two major events: (#1) the invention of the modern computer, and (#2) the realisation that the Sun cannot be treated indefinitely as a static gravitational point-mass. For #1, the ability to quickly numerically integrate the equations of motion — in whatever form they may have taken — reignited interest and triggered a series of stability papers from the 1960s that showcased increasingly longer and more accurate simulations as computer processor speed and capacity increased. Contrastingly, for #2, the realisation of how stars evolve and the Sun's likely post-main-sequence fate did not prompt similar interest until much later — the 2010s — when observations revealed that a large number of white dwarf exoplanetary systems actually foreshadow the fate of the solar system.

As such, this article is split into two distinct halves, representing the two branching directions that researchers have pursued regarding the question of the distant future of the solar system. The first branch does not consider the post-main-sequence evolution of the Sun, and instead focusses on timescales, all within about 6 billion years from now, during which the Sun's properties are relatively static. The other branch focusses almost exclusively on the solar system's post-main-sequence evolution, with typically broad assumptions made about the stability of the solar system's contents until the Sun leaves the main sequence.

Through both of these branches, the *Monthly Notices of the Royal Astronomical Society* has played a key role in disseminating research progress. In this article, I highlight seven of these *MNRAS* papers. All of them were published after the year 2000, which is ironically recent given the long history of both the research question and the journal, but appropriate given where and when an important cluster of activity occurred.

Before the Sun leaves the main sequence

The four highlighted MNRAS papers in this section each emphasise a different aspect of the growing body of research that analyse the stability of the solar system before the Sun leaves the main sequence: **Ito & Tanikawa (2002)** performed a direct *N*-body integration of all eight planets plus Pluto; **Hayes (2008)** assessed the stochasticity of the solar system and how that relates to numerical integrations; **Brown & Rein (2022)** analysed the effect of external influences; and **Hernandez, Zeebe & Hadden (2022)** analysed the danger case of Mercury, the only planet that might destabilise the inner solar system.

Paper 1: Takashi Ito and Kiyotaka Tanikawa (2002) Long-term integrations and stability of planetary orbits in our Solar system

By the time **Ito & Tanakawa (2002)** was published, a growing number of papers had performed long-term *N*-body integrations of the solar system. Few, however, succeeded in integrating for over 1 billion years into the future. **Ito & Tanakawa (2002)** did so, and they integrated a 10-body system, including the eight planets and Pluto. An important choice in *N*-body papers like these is how to treat Earth's Moon (they merged it with the Earth) as well as the other moons, and Ceres (they ignored those). The choice of integrator is also crucial for both accuracy and speed; they used the second-order Wisdom–Holman symplectic map. Their results did not showcase strong hints of instability, conforming to the expected outcome at the time.

Paper 2: Wayne B. Hayes (2008) Surfing on the edge: chaos versus near-integrability in the system of Jovian planets

Hayes (2008) provided an important contribution by explicitly comparing observational uncertainties in the ephemerides of the planets with characteristics of their future orbital evolution. The author performed multiple nearly-equivalent sets of integrations where the only difference was that the initial locations of the planets were offset by mere millimetres. The result was that some integrations showed that the solar system is chaotic, and others did not. Consequently, even just classifying the dynamical state of the solar system represents a challenge.

Paper 3: Garett Brown and Hanno Rein (2022) On the long-term stability of the Solar system in the presence of weak perturbations from stellar flybys

The solar system has not existed in isolation for the last 4.5 billion years, and it will not exist in isolation for many Hubble times in the future. Although a close, instability-inducing stellar flyby is extremely unlikely, a near-constant stream of perturbative effects on the solar system does occur due to the march of stars passing along the outskirts. **Brown & Rein (2022)** quantified the effect of these external influences (see **Fig. 1**). They found that the Sun's immediate Galactic environment (the "Local Neighbourhood") is probably dense enough to affect the solar system's evolution meaningfully over billions of years, and that the requisite level of disturbing a planet's orbital parameters to trigger a meaningful change is about 0.1 per cent.

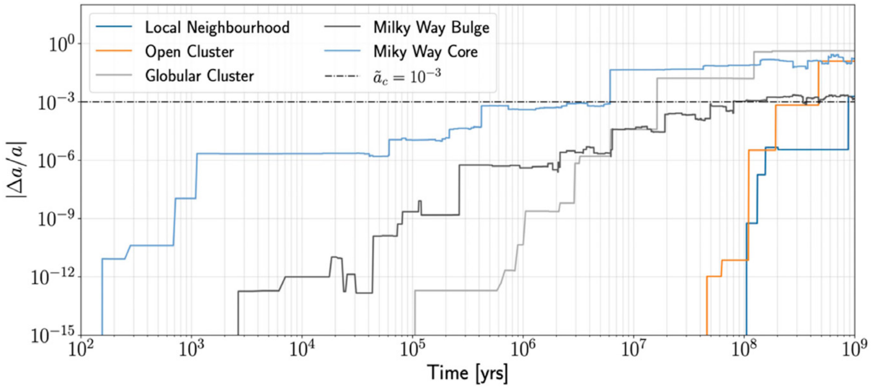

Fig. 1: How successive stellar flybys change the semi-major axis of Neptune over time. From **Brown & Rein (2022)**.

Paper 4: David M. Hernandez, Richard E. Zeebe and Sam Hadden (2022) Stepsize errors in the N-body problem: discerning Mercury's true possible long-term orbits

By 2022, the long-term stability of Jupiter, Saturn, Uranus and Neptune had been well-established; despite these planets potentially harbouring chaotic orbits, they will remain in the same order and not scatter off of one another. However, the evolution of the inner solar system was, and continues to be, much more uncertain. In particular, Mercury, with an orbital eccentricity (0.206) which is at least double that of any other planet, had been shown to trigger violent instability (as through collisions with other planets or the Sun) before the end of the Sun's main sequence in a non-negligible fraction of long-term integrations. **Hernandez, Zeebe & Hadden (2022)** critically evaluated how different numerical schemes resolve Mercury's pericentre passage — a deterministic lynchpin — and how that treatment affects Mercury's subsequent eccentricity evolution. Consequently, they showcase the dangers of using fixed-timestep integrators for long-term solar system numerical simulations.

After the Sun leaves the main sequence

The three highlighted MNRAS papers in this section each emphasise a different aspect of the solar system's post-main-sequence evolution: **Schröder & Smith (2008)** simulated the fate of the Earth, considering the tricky question of whether it will be engulfed into the Sun; **Veras & Wyatt (2012)** determined the future escape boundary of the solar system as a function of different Solar evolutionary pathways; and **Veras (2016)** determined how the fate of the solar system would change if Planet Nine exists.

Paper 5: Klaus-Peter Schröder and Robert Connon Smith (2008), Distant future of the Sun and Earth revisited

When the Sun increases in size as it passes through the giant branches of stellar evolution, it will engulf Mercury and Venus, but allow Mars and the giant planets to survive. Earth, however, coincidentally resides in-between these two extreme outcomes. Complicating the picture is that the Sun will lose about half of its mass — pushing the Earth's orbit outwards — and that the future time evolution of the Sun's mass loss is unknown. **Schröder and Smith (2008)** tackled the still-unresolved issue of whether the Earth will successfully outrun the Sun. Using the latest informed assumptions about the Sun's future mass evolution, they found that the Earth will not survive, leaving the Solar white dwarf with just five planets.

Paper 6: Dimitri Veras and Mark C. Wyatt (2012) The Solar system's post-main-sequence escape boundary

For objects far from the Sun, post-main-sequence mass loss may have a more severe consequence than just orbital expansion: the mass loss may trigger escape from the system. **Veras & Wyatt (2012)** quantified this critical distance beyond which orbiting objects were potentially subject to escape. They determined it to be between 1,000 and 10,000 astronomical units, depending on the functional form of the Sun's future mass loss. Hence, the entire Oort cloud, as well as the most distant scattered disc objects, are in danger of escape, and may not survive the Sun's transition into a white dwarf.

Paper 7: Dimitri Veras (2016) The fates of Solar system analogues with one additional distant planet

The potential existence of an additional planet larger than Mercury — but beyond the Kuiper Belt — has received significant attention in the last decade. This so-called "Planet Nine" could change the potential long-term stability of the outer solar system. In this paper, the author showed how Planet Nine could trigger instability after the Sun becomes a white dwarf. The mass loss from the Sun during the giant branch phases would extend Planet Nine's orbit to a far enough separation such that billions of years after the Sun became a white dwarf, Galactic tides could increase Planet Nine's orbital eccentricity. This increase could be severe enough to create a pinball effect on the other planets, whose orbits also will have been expanded (see **Fig. 2**).

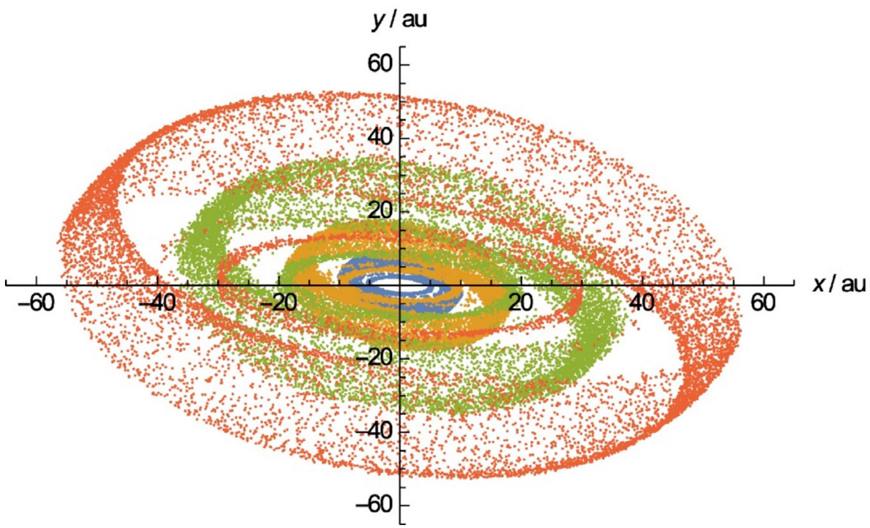

Fig. 2: How the orbits of Jupiter (blue), Saturn (orange), Uranus (green) and Neptune (red) expand due to stellar mass loss from the Sun. From **Veras (2016)**.

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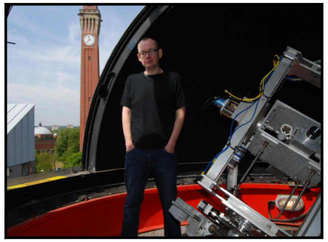
About the Authors

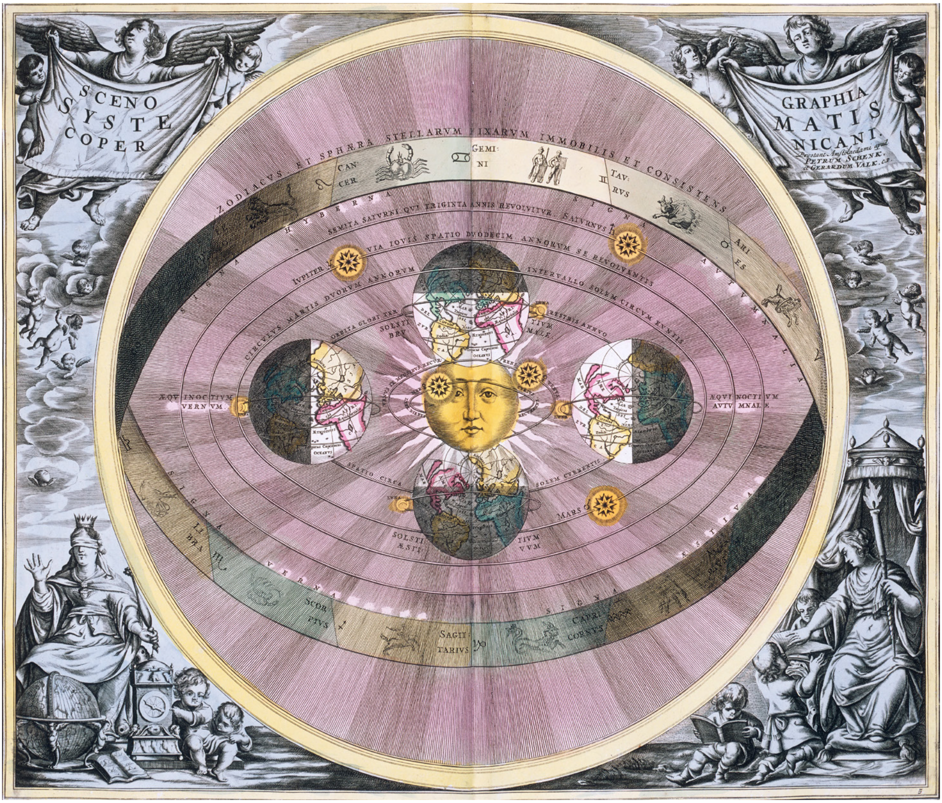
Paul C Clark is a numericist and theoretical astrophysicist who explores the physics and chemistry of the interstellar medium. Much of his work has focused on the formation of stars — including the formation of the very stars in the Universe, as well as the present-day star formation we see in the solar neighbourhood. A particular focus of his work has been to explore the ways in which the mass of stars is set during the star formation process. He is a Professor of Theoretical Astrophysics and current head of the Astronomy Group at Cardiff University.

Mike Lockwood holds a chair in space environment physics at the University of Reading, and served as RAS President from 2024 to 2026. He specialises in the cutting-edge study of space weather, the Northern Lights and solar radiation. After completing his PhD in ionospheric physics at Exeter University, his research career began with studies of how Earth's upper atmosphere is influenced by the Sun and, in particular, through the processes associated with the aurora. Much of this was done using the state-of-the-art radars in northern Scandinavia, called EISCAT, and a wide variety of European Space Agency and NASA spacecraft. He has also investigated the impact of radiation on humans in space, the extent to which solar variability has influenced Earth's climate, and the effects of space weather on the world's communication and operation systems.

Bill Chaplin is a Professor of Astrophysics at the University of Birmingham. His research is focused on using observations of the natural oscillations of the Sun (helioseismology) and other Sun-like stars (asteroseismology) to further our understanding of stellar evolution theory, the solar cycle and stellar variability more generally. He is the PI of the Birmingham Solar-Oscillations Network (BiSON) and holds leadership roles in a number of international research consortia associated to missions like *Kepler*, TESS and PLATO. He won the 2020 Institute of Physics Fred Hoyle Medal and Prize for revolutionary progress in the understanding of the interiors of stars. He is also the author and co-author of two books, one on helioseismology and one on asteroseismology. He is actively engaged in promoting solar and stellar research, including a programme of engagement in the arts-science domain involving artists with a variety of different practices. He was Head of the School of Physics & Astronomy at Birmingham from 2021-2025.



Dimitri Veras researches the contents of planetary systems, including our own solar system, in a wide variety of contexts, across both time and space. He has published academic articles about forming, destroying and evolving planets, asteroids, moons and comets while they interact with their parent star or stars. He is the lead author on over 65 refereed journal publications, he is a co-author on over 80 refereed journal publications, and he has led the authorship of 3 invited review articles about the fates of planetary systems. In 2025, he was awarded the George Darwin Lectureship by the Royal Astronomical Society. Veras was also the exoplanet and solar system Section Editor for Elsevier's Encyclopedia of Astrophysics, 1st Edition, and he is currently an Associate Editor of the journal Celestial Mechanics and Dynamical Astronomy. He has created and maintains The Astronomy Map of the World, a clickable worldwide repository containing the locations and websites of every institute where astronomy is researched professionally or taught in classrooms at the university level: (**https://warwick.ac.uk/fac/sci/physics/research/astro/people/veras/map**).



Copernican worldview. This is plate 5 from the 1708 edition of the star atlas 'Harmonica Macrocosmica' by the Dutch-German mathematician and cosmographer Andreas Cellarius (1596-1665). It shows the Sun-centred (heliocentric) worldview of Polish astronomer Nicolaus Copernicus (1473-1543, lower right). Circling the Sun are Mercury, Venus, Earth (with the Moon and Earth phases), Mars, Jupiter, Saturn, and the zodiac. First published in 1660, 'Harmonica Macrocosmica' had 30 colour plates with Latin text. This edition was published in Amsterdam by Petrus Schenk and Gerard Valk.

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