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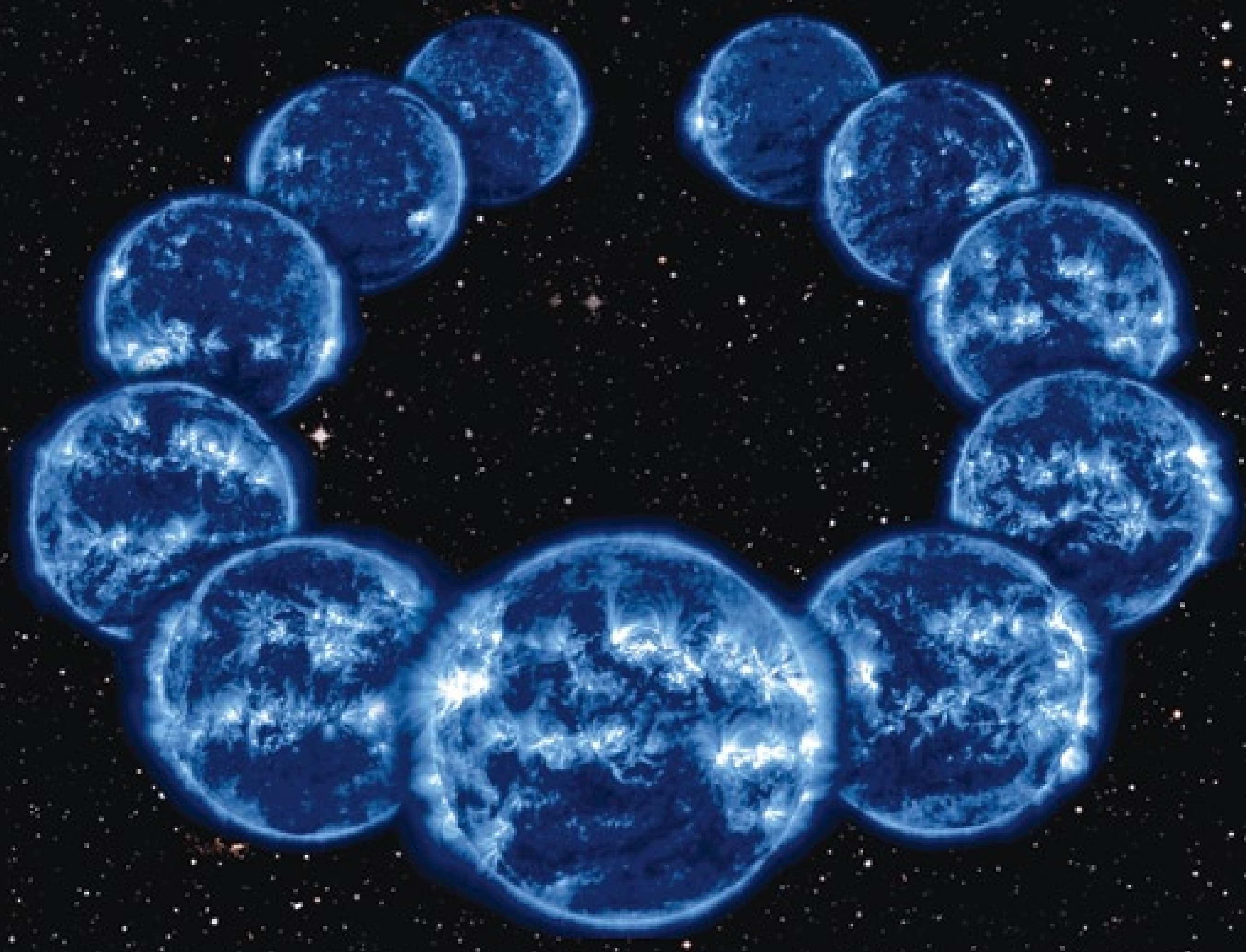

Solar Magnetism

Discovery and Investigation

Editorial

Nature has provided us with senses that are precisely tuned to our natural habitat. Our eyes carefully match the light spectrum of the Sun, but are sightless beyond. Our ears capture the sounds of our environment but are deaf for instance to the whistle of bats.

We can see the light of the Sun and enjoy its warmth, but it does not disclose its secrets to our senses. Technical means are required to overcome the limitations of our senses and to understand the daytime star. One of these secrets is the Sun's magnetic field that is responsible for such phenomena like the enigmatic spots on its surface that have been observed since the earliest times.

Baffled by the thought that a hot gaseous Sun should have a magnetic field, such ideas came up only very late. It was George Ellery Hale who suggested solar magnetism in 1908. The modern era of its exploration arrived around 1950, when new instruments provided detailed maps of the Sun's magnetic field. This led to the notion of a Sun which is not simply a leisurely shining disk, but rather a living entity with a huge range of fierce dynamic behaviours on all scales.

One of the major consequences of solar magnetism is the solar wind, a continuous high-speed stream of matter jettisoned by the Sun into its space environment. The concept of solar wind, as it is still understood today, was first proposed by Eugene Parker in 1958.

The year 2008 marks therefore not only the centenary of Hale's publication on solar magnetism but also the fiftieth anniversary of Parker's seminal paper on solar wind. This was reason enough for the International Space Science Institute to dedicate a workshop to solar magnetism in early 2008. The gathering was honoured by the presence of Eugene Parker who held a public lecture at the University of Bern on 23 January 2008.

The present issue of Spatium is devoted to solar magnetism and we are proud to present our readers herewith a written version of Professor Eugene Parker's fascinating lecture.

Hansjörg Schlaepfer
Brissago, August 2008

Impressum

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Front Cover
Every eleven years, our Sun goes through a solar cycle. A complete solar cycle has been imaged by the sun-orbiting SOHO spacecraft in extreme ultraviolet light for each year of the last solar cycle, with images picked to illustrate the relative activity of the Sun.
(Credit: SOHO – EIT Consortium, ESA, NASA)

Solar Magnetism: Discovery and Investigation[1]

Eugene Parker, University of Chicago, USA

Introduction

"Were it not for magnetic fields, the Sun would be as uninteresting as most astronomers seem to think it is."

This statement is credited to R.W. Leighton[2] who, many years ago, pinpointed the Sun's important role in astrophysics when it comes to understanding a star's enigmatic behaviour. Thanks to its vantage location, our daytime star allows scientists to gather detailed data for which all other stars are much too far away. And these data reveal a degree of complexity so that even today many observations are still waiting for scientific interpretation. What makes the Sun really interesting is its magnetism that makes it an ever-changing and active star; without its magnetic fields, as Leighton pointed out, it would be an inactive ball of fire in the sky.

No wonder then that the Sun has been the object of fascinated observers for many centuries. Special attention has been paid to the sunspots that are dark stains waning and waxing randomly on the solar disk. It has been noted for a long time that these spots exhibit a periodicity of about eleven years with times of a larger number of sunspots alternating with times of fewer spots. Beyond this regularity, it came as a great surprise that from about 1650 to 1715 the Sun produced virtually no sunspots[3]. Obviously, the Sun seems to possess periodicities of even longer cycles, in any case much longer than a human's life span. Referred to as the Maunder Minimum, the period of unusually low solar activity in the 17th century coincided with an era of chilly temperatures on Earth. The Little Ice Age, as this period is called, was a time of lowered temperatures especially in the northern hemisphere: the summers were cool, the winters were long and cold, rivers froze, and sea ice was widespread. Its effects have been widely recorded by humans be it in artwork **(Fig. 1)**, documented in contemporary papers, but also by nature itself: they are preserved in tree rings and arctic ice. Although the causes of the Little Ice Age are still debated amongst scientists, it seems likely that solar activity in general plays a key role in determining Earth's climate: if the Sun changes its energy output, it affects the Earth's climate. And in a way yet to be understood, sunspots are related to the kind of output that matters for the Earth.

Fig. 1: Enjoying ice. Painted by the Dutch artist Barend Avercamp (1612–1679), this canvas shows how life was during the cold winter months in the Netherlands during the Little Ice Age, when the Sun produced extremely low numbers of sunspots. It is thought that this phenomenon is closely related to a period of chilly winters all over Europe.

1 The present text follows a lecture by Prof. Eugene Parker held at the University of Bern on 23 January 2008. The notes were taken by Dr. Hansjörg Schlaepfer and reviewed by Prof. André Balogh, ISSI.
2 Robert B. Leighton, 1919, Detroit – 1997, US-American physicist.
3 See Spatium 8: Sun and Climate.

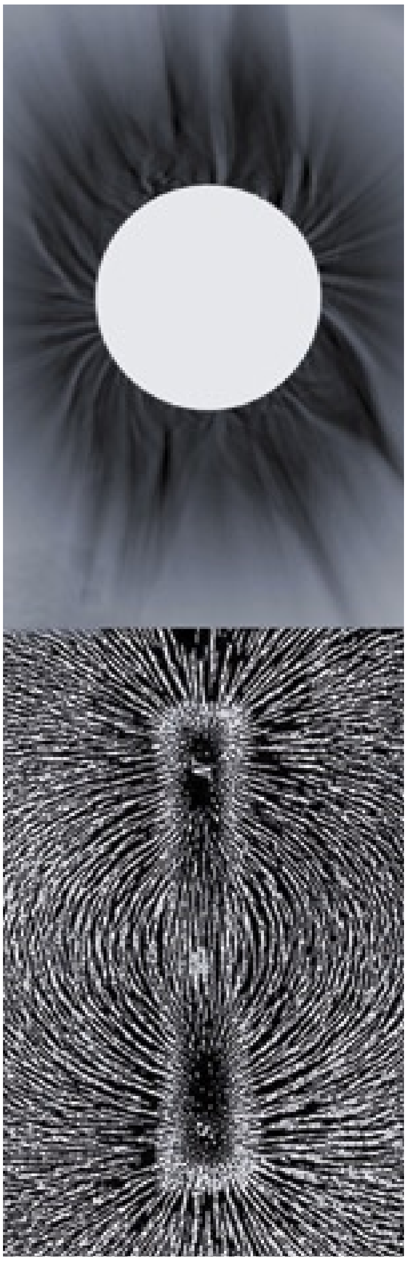

Fig. 2: The solar corona during eclipse shows some resemblance to the iron filings aligning along the magnetic field of a bar magnet.

In addition to sunspots, the solar corona was also observed for centuries at the times of total solar eclipses. Physics, however, was not yet ready to explain the common source of both phenomena: solar magnetism. The idea of solar magnetism began in the second half of the 19th century, most probably initiated by the resemblance of the solar corona to the pattern of iron filings around a bar magnet, **Fig. 2.**

In the following chapters we shall first describe some physical properties of the Sun and then report on the milestones in the history of the discovery and investigation of solar magnetism.

The Sun, an Ordinary Star

The Sun is one of over 100 billion stars in the Milky Way Galaxy. It is about 25,000 light-years from the centre of the galaxy, and it revolves around the galactic centre once about every 250 million years. The Sun is a huge, glowing ball containing 99.8 % of the solar system's mass. During the process of its formation, some 4.6 billion years ago, pressure and temperature in its core reached the critical values needed to ignite nuclear fusion processes that generate enormous amounts of energy and cause the Sun to shine[4] **(see box Nuclear Fusion).** The Sun has enough fuel to stay active for another say 5 billion years. It is this nuclear fusion process that provides ultimately the energy required for life to develop on Earth. As a consequence of its high temperature, much of the Sun is made up of plasma, that is a gas of ionized atoms, mainly hydrogen. Carrying electric charges, such ionized atoms are susceptible to magnetic fields, and, as we shall see later, may themselves generate magnetic fields.

The Sun consists of a core that extends about one-fourth of the way to the surface, **Fig. 3.** Here, most of the nuclear fusion takes place at an estimated temperature of some

[4] See Spatium 2: Das neue Bild der Sonne.

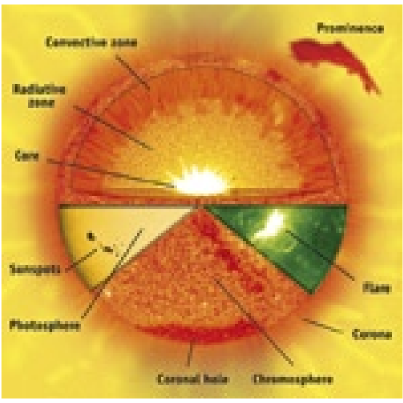

Fig. 3: Cut-away view of the Sun showing its different shells and external phenomena. (Credit: ESA/NASA)

15 million K. The core is surrounded by a shell, called the radiative zone, where the energy from the core travels through by radiation. Photons emerging from the core pass through layers of gas and are scattered by the dense particles of gas so often that an individual photon may take as much as a million years finally to reach the Sun's surface. It's a fascinating thought that the sunlight we see today may stem from the times of the dawn of mankind.

The outer limit of the radiative zone is about 70% of the way to the solar surface. Outside the radiative zone follows the convection zone that reaches to the Sun's surface. This zone consists of the "boiling" convection cells that are heated by the photons from the radiative zone below and bring up mass and magnetic fields to the surface of the Sun.

Just like the Earth, the Sun is surrounded by an atmosphere, although the Sun's atmosphere is different in most respects from that of the Earth. Its lowest layer is the photosphere (really the visible surface of the Sun) which is relatively cool, at 5,700 K, so that the gas is only partially ionized. The next zone up is the chromosphere, where temperature can reach some 10,000 K. The chromosphere is covered by the transition region, where the temperature rises very abruptly up to 500,000 K and more. This region is highly structured into loops and streams of ionized gas. As we will see later, these structures connect vertically down to the solar surface, and magnetic fields that emerge from inside the Sun shape them. The outermost layer of the Sun, the corona, is even hotter, generally in excess of one million K. It extends far into space and forms a large cavity called the heliosphere[5]. The Sun and all the planets are inside the heliosphere. Far beyond the orbit of Pluto the heliosphere joins the interstellar medium, the dust and gas that occupy the space between the stars. The flow of coronal gas into space is known as the solar wind. It makes the Sun lose close to 2 million tons of mass every second. At the distance of the Earth, the density of the solar wind amounts to about 10 to 100 particles per cubic centimetre.

The Sun is far from quietly shining. Rather, tremendous amounts of energy flow from its interior towards the surface and some of the energy causes violent events on scales that are many times the size of the Earth. Solar flares are hot violent explosions in the Sun's lower atmosphere where temperatures of up to 10 million K or more can be reached and electrons, protons and heavier ions are accelerated to near the speed of light. Other violent events are coronal mass ejections. These are ejections of large amounts of solar matter, up to 10^{12} kg, which equals a cube of rock of 1 km side length that is jettisoned out to space at speeds up to 2,700 km s^{-1}. These and further spectacular features of the Sun will be addressed later in more detail.

Nuclear Fusion is the process by which atoms join together to form other atoms with heavier nuclei. It is accompanied by the release or absorption of significant amounts of energy. The fusion of two light nuclei (lighter than iron or nickel) generally releases energy while the fusion of nuclei heavier than iron or nickel absorbs energy[6]. In the Sun, most of the energy is generated by the fusion of four hydrogen atomic nuclei, or protons, into a helium nucleus that consists of two protons and two neutrons. The difference in mass between four protons and the helium nucleus is converted into energy according to Einstein's $E = mc^2$ formula. The Sun converts mass into energy at the rate of 4.28 million tons per second thereby generating its unimaginable amount of energy.

[5] See Spatium 17: The Heliosphere: Empire of the Sun.
[6] See Spatium 13: Woher kommen Kohlenstoff, Eisen und Uran?

Discovery of Solar Magnetism

The Beginnings

The first recognition of magnetic fields in the Sun was in the second half of the 19th century, more or less contemporary with the growing realization that the activity at the Sun drives the terrestrial aurora through the emission of solar corpuscular radiation.

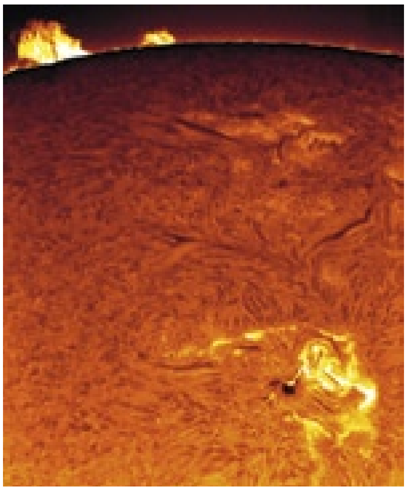

Fig. 4: The Sun's surface seen at H-alpha. Images taken at the H-alpha wavelength provide an insight into the processes on the Sun's surface, specifically the distribution of hydrogen. This table shows a very active sunspot region, larger than the Earth. Relatively cool regions appear dark while hot regions appear bright. On the left top, solar prominences are visible hovering above the Sun's surface. (Credit: Greg Piepol, sungazer.net)

In 1866, Sir Joseph Norman Lockyer[7] remarked that the coronal streamers, visible during an eclipse of the Sun, outlined a pattern resembling the magnetic field around a bar magnet. Lockyer, however, never published his thoughts and the concept of a general magnetic field for the Sun was proposed by others some years later. In 1912, solar magnetic fields of smaller scale were suggested by the strong filamentary appearance and dynamical behaviour of prominences.

In 1908, George Ellery Hale[8] published a seminal article in the Astrophysical Journal entitled "On the probable existence of magnetic field in sun-spots". This marks the first scientific recognition of magnetic fields in the Sun. His observations were made by his then newly developed spectroheliograph. This is basically a telescope which, however, allows the elimination of all but a very narrow part of the solar spectrum. Specifically, Hale used the H-alpha line (**see box H-alpha** and **Fig. 4**) from which he discovered that the filaments around sunspots sometimes show a strong spiral or vortex form.

Spurred by his groundbreaking discovery, Hale continued to observe the Sun and came to the conclusion that the Sun has an overall magnetic field of some 50 Gauss at the poles. (Note: the Earth's magnetic field has the strength of some 0.6 Gauss).

Subsequent observations, however, did not support this conclusion, suggesting that Hale was grappling with noise rather than a true signal. And there the observations rested until technological advances during the period of WW II provided a great leap forward in detector sensitivity.

Observing the Sunspots

Hale's idea that the sunspot is associated with – and is perhaps a consequence of – a rotary flow of gas motivated the British astronomer John Evershed[9] to look at sunspots near the limb to measure the Doppler shift arising from rotation about a vertical axis. He quickly discovered a radial outflow from the sunspot at the photospheric level, reaching a maximum of about 2 km/sec. Further, he found a radial inflow at higher levels, **see Fig. 5.**

Later, it was suggested that these flows near a sunspot are associated in some unspecified way with a vortex in the deep photosphere, believed at that time to be the origin of the sunspot magnetic field. The idea of a magnetic field associated with a vortex was fondly held, even if not demonstrable by theory. This prompted numerous scientists to propose theories, however, none of these has survived until today.

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7 Sir Joseph Norman Lockyer, 1836, Rugby, Warwickshire, UK – 1920, Salcombe Regis, UK, British scientist and astronomer.
8 George Ellery Hale, 1868, Chicago – 1938, Pasadena, USA, US-American astronomer.
9 John Evershed, 1864, Gomshall, Surrey, UK – 1956, Ewhurst, Surrey, UK, British astronomer.

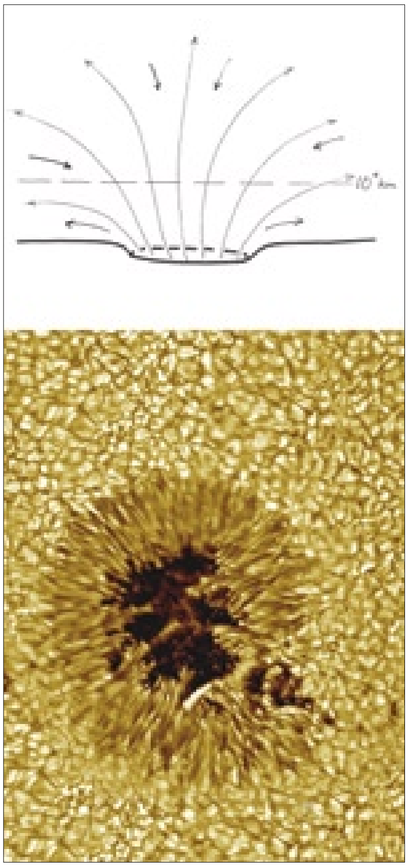


Fig. 5: Schematic diagram illustrating the outflow and the inflow of plasma above a sunspot (upper panel, illustration by Eugene Parker). The lower table shows a close-up picture of a sunspot that is slightly cooler and less luminous than the rest of the Sun. The Sun's complex magnetic fields create this cool region by inhibiting hot material from entering the spot. Sunspots can be larger than the Earth and typically last for only a few days. This high-resolution picture also shows clearly that the Sun's face is a bubbling sea of separate cells of hot gas. These cells are known as granules. A solar granule is about 1,000 kilometres across and lasts only about 10 minutes. (Credit: Vacuum Tower Telescope, NSO, NOAO).

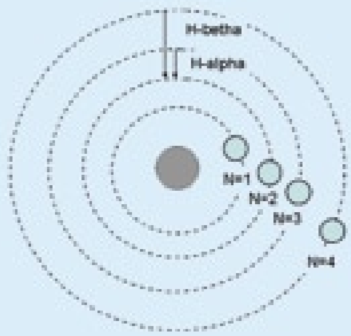
Struggling for Theoretical Understanding

Quite apart from the theoretical problem of the origin of the magnetic fields of the Sun, there was the stark fact of their existence, with wide-ranging implications. Hale's idea of a 50 Gauss polar magnetic field stimulated the construction of diverse theories over the next several decades. For instance, such a strong polar field represents a substantial investment in energy. A rough estimate delivers an energy content of the Sun's magnetic field at that strength of an equivalent of about 50 sec of the solar energy output. Not impossible, but impressive nonetheless!

Now, the magnetic field stipulated by Hale extrapolates out to the orbit of Earth to be 2.5×10^{-6} Gauss. Alfvén[10] seized upon this dipole field to argue that cosmic rays are a local solar phenomenon, created by the Sun and trapped within the enormous dipole magnetic field of the Sun. Alfvén's concept was in opposition to the view espoused by Fermi[11], that the cosmic rays originate in interstellar space and circulate freely along the interstellar magnetic field lines.

Alfvén's concept of localized cosmic rays played a crucial role in his idea that half of the stars in the Galaxy are composed of antimatter, distributed randomly among the stars of ordinary matter. For it was apparent from exposures of photographic emulsions above the terrestrial atmosphere that cosmic ray particles are made up of protons, with smaller numbers of heavier nuclei, and with no more antiprotons than would be expected from collisions of cosmic ray particles

H-alpha is the name of a specific emission line of hydrogen at 656.281 nm in the red part of the visible spectrum.



In the Bohr model of the atom, electrons exist exclusively in quantized energy levels surrounding the atom's nucleus. These energy levels are described by the principal quantum numbers n = 1, 2, 3, etc. Electrons may only exist in these states, and may only transit between these states. The set of transitions from $n \geq 3$ to $n = 2$ are called the Balmer series, specifically

- the transition from energy level 3 to energy level 2 is called Balmer-alpha or H-alpha
- from n = 4 to n = 2 is called H-beta, etc.

As this light is generated by ionized hydrogen, it allows tracing hydrogen in astronomical objects.

10 Hannes Olof Gösta Alfvén, 1908, Norrköping, Sweden – 1995, Djursholm, Sweden, Swedish plasma physicist and Nobel Prize laureate 1970.

11 Enrico Fermi, 1901, Rome – 1954, Chicago, Italian physicist, Nobel Prize laureate 1938.

with the nuclei of the ambient interstellar gas. On the other hand, Fermi's galactic concept of cosmic rays applied to Alfvén's matter-antimatter stars would predict that half of the cosmic rays are antiprotons, contrary to observed facts. Solar local confinement of cosmic rays was essential for the matter-antimatter universe concept.

The theoretical problem of solar confinement of cosmic rays was that a solar dipole magnetic field of 50 Gauss could not possibly confine, even temporarily, a proton above some 4 GeV, whereas the cosmic ray energy spectrum is observed to extend unbroken to much higher energies[12]. So cosmic rays are galactic in their distribution and provide proof that there are few, if any, antimatter stars in the Galaxy. We see that Hale's idea of a 50 Gauss solar field set in motion an interesting train of thought.

There were other important consequences of Hale's 50 Gauss solar magnetic field. It was recognized that the Sun sometimes emits bursts of "solar corpuscular radiation", presumed to consist of equal numbers of electrons and protons, at speeds of the order of 1,000 km/sec. This plasma impacts the Earth's magnetic field a day or two after emission from a big flare on the Sun, producing a geomagnetic storm that is a temporary disturbance of the Earth's magnetosphere, see **Fig. 6.** Magnetic storms usually last 24 to 48 hours, but some may last for many days. In 1989, such an electromagnetic storm disrupted power throughout most of Quebec, and it caused auroras as far south as Texas.

So one may ask, if Hale had been correct with his estimates of 50 Gauss polar magnetic fields of the Sun, how is it that a burst of solar corpuscular radiation ejected by a solar eruption passes freely out through space at that speed? The difficulty is obvious today, but a hundred years ago the solar corona was a mysterious entity. It was not until the pioneering work of Grotrian, Edlen, and Lyot in the 1940s that the corona was convincingly understood to be a million degree plasma with a density of about 10^8 ions/cm^3. Even then the solar corpuscular radiation was considered as being emitted from active regions in the form of intense beams. It was not until much later that the expansion of the corona was demonstrated and understood, producing the supersonic solar wind.

The solar wind was recognized by Eugene Parker in 1958 as the conventional solar corpuscular radiation phenomenon, **Fig. 7.** It is amusing to note, then, that Hale's 50 Gauss dipole magnetic field at the Sun would overpower the tenuous corona, holding it in a tight embrace with a magnetic pressure some 300 times the pressure of the coronal plasma.

The Hard Vacuum Concept

Now, prior to about 1950, space was generally regarded as a hard vacuum, devoid of free electrons and ions except for the occasional fast particles from solar eruptions passing by Earth and conveniently dis-

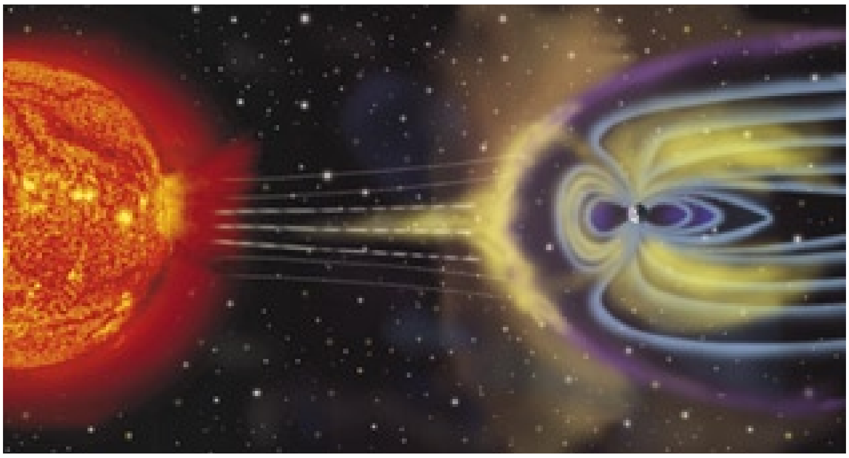


Fig. 6: Artist's view of a solar burst interacting with the Earth's magnetic field. (Credit: NASA/GSFC)

[12] See Spatium 11: Cosmic Rays.

DYNAMICS OF THE INTERPLANETARY GAS AND MAGNETIC FIELDS*

E. N. PARKER

Enrico Fermi Institute for Nuclear Studies, University of Chicago

Received January 2, 1958

ABSTRACT

We consider the dynamical consequences of Biermann's suggestion that gas is often streaming outward in all directions from the sun with velocities of the order of 500–1500 km/sec. These velocities of 500 km/sec and more and the interplanetary densities of 500 ions/cm^3 (10^{14} gm/sec mass loss from the sun) follow from the hydrodynamic equations for a 3×10^6 ° K solar corona. It is suggested that the outward-streaming gas draws out the lines of force of the solar magnetic fields so that near the sun the field is very nearly in a radial direction. Plasma instabilities are expected to result in the thick shell of disordered field (10^{-5} gauss) inclosing the inner solar system, whose presence has already been inferred from cosmic-ray observations.

Fig. 7: Facsimile of Eugene Parker's Article in Astrophysical Journal, volume 128, p. 664 (1958).

appearing into the "infinite" void outside the solar system. The solar particles somehow "cleaned up" after themselves, leaving no stray remnants to provide electrical conductivity in interplanetary space. An extreme consequence of this concept was put forth by Lord Kelvin at the end of the 19th century. By that time, science was aware of the fluctuations of the geomagnetic field that recur with the 27 day period of rotation of the equatorial regions of the Sun, and of the stronger fluctuations that often follow a day or two after a large flare on the Sun. A Sun – Earth transit time of a day or two implies a speed of the order of 1,000 km/sec, obviously particles of some kind. However, Kelvin had the idea that a magnetic variation here at Earth could only represent a variation of the general dipolar magnetic field of the Sun. Kelvin confidently announced that no possible magnetic field activity at the Sun could provide the observed fluctuations of the geomagnetic field, and, hence, solar activity could have nothing to do with the geomagnetic fluctuations. Spoken with the authority of Kelvin, there was no further pursuit of the geomagnetic fluctuations until Sydney Chapman[13] entered the field in 1918. He pursued the effects of the solar particle emission and the impact of those particles against the magnetic field of Earth. Together with V. C. A Ferraro[14] he showed how the impact creates the initial compressive phase of a geomagnetic storm.

Finally note that simultaneously with the "hard vacuum" concept of space there was the thriving contrary notion that the faint sky brightness known as the zodiacal light represented scattering of sunlight from free electrons. The observed intensity of the zodiacal light indicated about 500 electrons/cm^3 at the orbit of Earth. Not a vacuum hard enough to allow electrostatic fields in interplanetary space. Yet the idea of interplanetary electrostatic potential differences of 10^9 Volts or more was introduced in the middle of the 20th century to explain the recently discovered variations in the cosmic ray intensity. What produced the electrostatic fields was never specified. Such are the scientific dilemmas sometimes forced upon scientists when interpreting their observations. Today it is appreciated that the zodiacal light represents the scattering of sunlight by dust grains, of cometary and meteoritic origin, orbiting the Sun.

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13 Sidney Chapman, 1888, Eccles, England – 1970, Boulder, Co., USA, British physicist and mathematician.
14 Vincenzo Consolato Antonio Ferraro, 1907–1974, Italian/British applied mathematician.

The Modern Era of Solar Magnetism Investigation

The modern study of solar magnetic fields is best defined as beginning with the invention of the magnetograph **(see box The Magnetograph)** in the middle of the 20th century. That was the step that sparked the research of solar magnetism and expanded into a new world of exploration as observations turned up the immense complexity of the active magnetic fields on the Sun, ranging from the dynamical small-scale fibril structure of the photospheric "magnetic carpet", to the active fine structure of the "quiescent" prominences, to the universal magnetic flaring phenomenon, to the coronal X-ray emitting regions, to the coronal mass ejections, etc.

If one thing is clear, it is that magnetic fields are the driving factor in solar activity. Without magnetic fields the Sun would be a serene, gently convecting, self-gravitating gaseous sphere: the classical concept of a star. But the magnetic fields change all that, driving many mysterious dynamical activities that are still only partly understood. The essential point is that observations lead the way into the mysterious world of solar and stellar magnetic activity, with theory working to understand the dynamical phenomena discovered by the observations. The effort is aimed at developing an understanding of the physics of solar activity, and stellar activity in general. The overall subject of solar magnetism – synonymous with solar activity – has become so extensive that we can do little more than summarize some of the major phenomena below.

The Magnetograph is a scientific instrument that allows remote sensing of magnetic fields. It exploits the Zeeman effect as outlined below:

In the box H-alpha on page 7 we noted that the electrons orbiting an atomic nucleus can occupy only a specific set of quantized levels. Furthermore, electrons can transit between these quantized levels. Such a transition gives rise to a loss or gain of energy. As stated in that box, the H-alpha line specifically corresponds to the transition of the electron of a hydrogen atom from level 3 to level 2 whereby a photon of wavelength 656.281 nm is emitted. This spectral line is produced by the hydrogen atom exclusively: it constitutes therefore a fingerprint of the hydrogen atom. As the laws of physics are universal, a hydrogen atom emits this very line irrespective of whether it is in an Earth-bound laboratory or billions of light-years away. This and other spectral lines may be measured in the lab and used to trace the respective atoms throughout the universe.

Now, light waves are capable of carrying much more information. It was in 1886 that Pieter Zeeman[15] observed the spectrum of the light emitted by a sodium flame. More specifically, he placed the sodium flame between the poles of a strong magnet. Of course, he expected to find the typical emission lines of sodium, which he did of course, but, remarkably, these lines were splitted into several individual lines, a fact he correctly attributed to the effect of the magnet. From more laboratory experiments he found that the amount of splitting is dependent on the magnitude of the magnetic field strength at the location of the light emitting atoms. Light waves, therefore, can be used to trace the magnetic (and also the electric) fields at the location where they were generated.

The splitting of a spectral line into several components in the presence of a magnetic field is called the Zeeman effect. It is this physical process that allows a magnetograph to display distant magnetic field strengths and it is the magnetograph which set the stage for the next quantum leap in the study of the Sun.

[15] Pieter Zeeman, 1865, Zonnemaire, the Netherlands – 1943, Amsterdam, Dutch physicist, Nobel Prize laureate 1902.

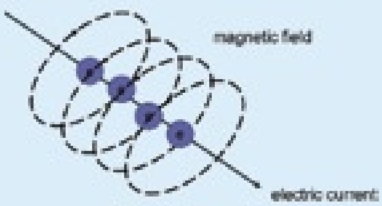
The Major Phenomena

The Origins of Solar Magnetism

Applying Ampère's law **(see box Ampère's Law)**, one concludes that at the root of the Sun's global magnetic field there must be strong electric currents. This is confirmed by the following reasoning: as the Sun is a huge ball of gaseous plasma it allows the gases at different latitudes rotating at different rotation speeds: while at the equator one full revolution is completed within about 25 days, near the poles the period is about 35 days. Between the different shells of the Sun rotating at different rates, a shear is created, which in turn creates an electric current deep within the Sun. It is this current that produces the Sun's global magnetic dipole field. Such a system is called magnetohydrodynamic dynamo. Yet, the detailed mechanism of the solar dynamo is not known and is the subject of current research. Theoretically, depending on the structure of the flow, the dynamo may be self-exciting and stable, self-exciting and chaotic, or decaying. The Sun's dynamo is self-exciting and chaotic: the direction of the field reverses about every eleven years, causing the sunspot cycle and magnetic field lines rise to the surface of the Sun and manifest themselves as sunspots on the surface.

Ampère's Law

Some 200 years ago, André-Marie Ampère[16] discovered the basic laws of magnetism. He found that an electric current creates a magnetic field around it as outlined below. The strength of the magnetic field is proportional to the electric current, while the direction of the magnetic field is orthogonal to the direction of the electric current.



For comparison, the Earth also possesses a magnetic field. It is generated by the flow of conducting fluid in the core across a pre-existing magnetic field, which generates electric currents that in turn reinforce the magnetic field. In contrast to the Sun, however, the reversal of the Earth's magnetic polarity is chaotic with periods between tens of thousands and many millions of years. Just like in the case of the Sun, there is no conclusive theory as to why the Earth reverses its magnetic field.

Returning to the Sun, the net effect of these processes is a dynamo that creates bands of east – west fields that migrate from middle latitudes to the equator over a period of some years, duplicating the 11-year magnetic cycle that one is

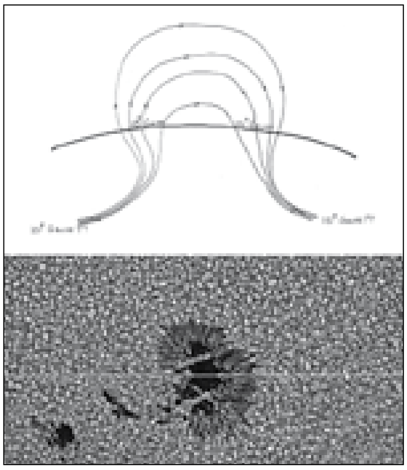


Fig. 8: The secrets of a sunspot: The lower panel shows a sunspot on the Sun's surface. Hot and cold regions are shown light and dark, respectively. The upper panel shows a theoretical interpretation of the magnetic fields producing the sunspot. (Credits: Eugene Parker, upper panel; Vacuum Tower Telescope, NSO, NOAO, lower panel)

Fig. 9: This image shows the looping structures of the magnetic field above the Sun's surface. It was acquired in the ultraviolet light from Fe IX/X (hot gas of iron atoms) by NASA's TRACE spacecraft. (Credit: NASA)

[16] André-Marie Ampère, 1775, Lyon, France – 1836, Marseille, French physicist, main discoverer of magnetism.

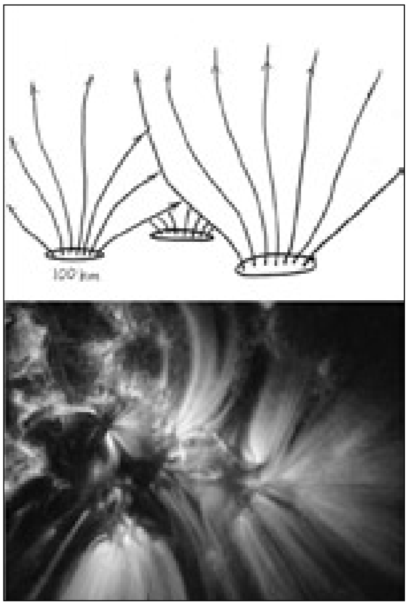


Fig. 10: Microfibrils: The Sun's surface displays a fine structure called microfibrils. The upper table shows a theoretical interpretation of the formation of such fibrils by Eugene Parker. Microfibrils consist of hot gas at about one million K, which emits extreme ultraviolet light as shown in the lower table. It occurs in large patches some 100 km in extent, and appears between 500 and 1,000 km above the Sun's visible surface. These microfibrils are typically persisting for tens of hours. (Credit: NASA)

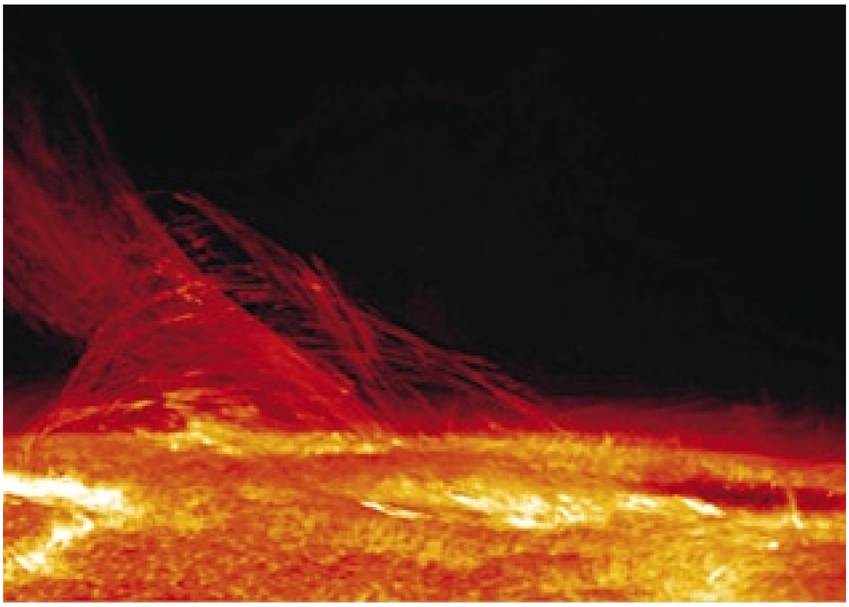


Fig. 11: The plasma of the Sun captured by the Hinode spacecraft's Solar Optical Telescope. Hinode (Japanese for sunrise) is a project to study the Sun, led by the Japanese Aerospace Exploration Agency (JAXA) in collaboration with international partners. It aims at exploring the magnetic fields of the Sun, and improving our understanding of the mechanisms that power the solar atmosphere and drive solar eruptions. This image reveals the filamentary nature of the plasma connecting regions of different magnetic polarity. (Credit: JAXA, NASA)

seeing at the surface. Unfortunately, we cannot see the magnetic fields below the surface to establish in what convective flows and at what depths the dynamo is operating. So there are a dozen or more configurations that can be constructed with enough free parameters to fit the surface observations. The theoretical dynamo is further challenged by such phenomena as the Maunder Minimum, when there were no sunspots on the Sun and the magnetic activity of the Sun appeared to be switched off.

The theory of the magnetohydrodynamic dynamo effect has become an extensive topic in theoretical physics establishing that almost any sufficiently vigorous flow of conducting fluid lacking simple symmetry has the ability to increase the magnetic flux, i.e. amplify or regenerate magnetic fields. Unfortunately the hydrodynamics of the fluid motion is a more formidable problem, and has not yet been solved for the convective zone and the non-uniform rotation of the Sun.

Sunspots

Sunspots are part of the bipolar magnetic regions that form with the upward bulging of an east – west magnetic field lying somewhere near the bottom of the convective zone, at a depth of about $^2/_7$ of the solar radius, see **Fig. 8 and 9.** The form of the upward bulge suggests the appellation Ω-loop. Sunspots form in the regions where the Ω-loop extends through the visible surface of the Sun. It is, however, not understood why the laws of physics compel the formation of sunspots in these surface magnetic regions.

Now it should be noted that the buoyant rise of the Ω-loops through the surface of the Sun as outlined in **Fig. 8** poses a serious theoretical challenge that has not yet been resolved.

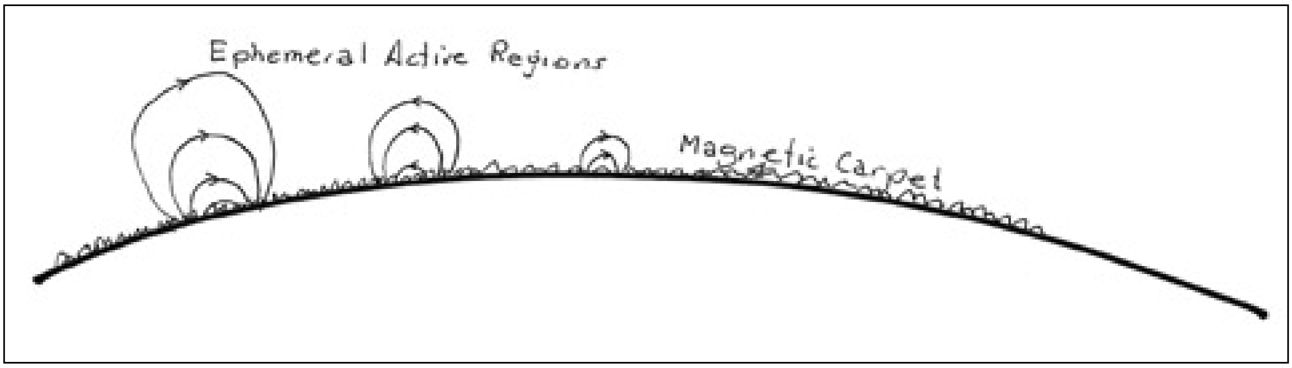


Fig. 12: The fine structure of the Sun: The smaller bipolar magnetic regions on the Sun's surface are called ephemeral active regions while the even smaller structures are termed magnetic carpet. (Credit: Eugene Parker)

Fibril Texture

It came as a substantial surprise about 25 years ago to discover that the photospheric magnetic fields exhibit a microfibril structure rather than the expected continuum indicated by the limited resolution of the magnetographs. Some clever scientific detective work showed that the individual fibrils have magnetic fields of 1–2 kilogauss with diameters of only 100 km, well below the resolution of the magnetographs. The observed mean fields of 5–10 Gauss in quiet regions and 100 Gauss in active regions represent the spacing of the fibrils. Why the magnetic field is in this enhanced magnetic energy state (compared to being spread out smoothly) is not clear. The individual fibrils are observed as bright spots against the normal photosphere **(Fig. 10).** The waxing and waning of fibril numbers as the active regions vary over the 11-year magnetic cycle is responsible for most of the solar luminosity variations of one part in 10^3 in step with the magnetic activity.

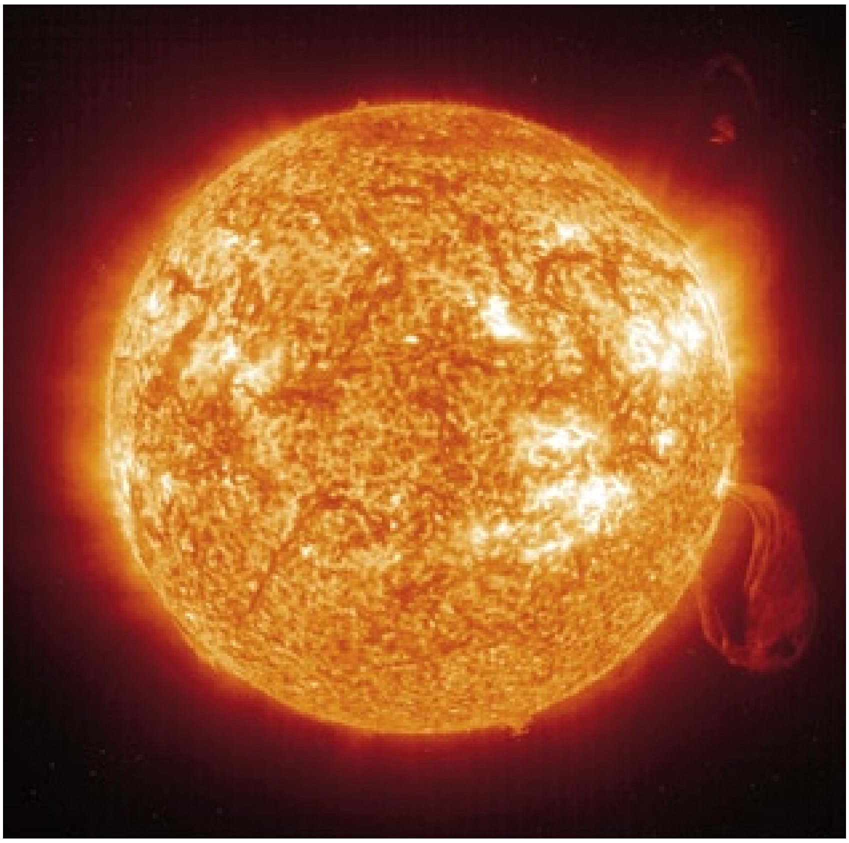


Fig. 13: The ESA/NASA SOHO spacecraft captured this image of a magnificent prominence above the Sun's limb. Seen at the lower right, streams of relatively cool dense plasma are lofted along looping magnetic field lines extending outward about 30 times the diameter of Earth. Far above the limb at the upper right, a disconnected ghostly arc surrounds a dark cavity with bright central emission. These features are telltale signs of a coronal mass ejection. (Credit: SOHO-EIT Consortium, ESA, NASA)

The bipolar magnetic regions created by the emergence of Ω-loops have maximum longitudinal (east - west) dimensions of the order of 300,000 km, i.e. a significant fraction of the solar radius, and they appear with increasing frequency on smaller scales down to a few times 10 km. Below about 20,000 km they are called "ephemeral active regions", see **Fig. 12.** These are distributed over all latitudes and with the east - west alignment fading away toward the smaller end of the scale. Ephemeral active regions do not develop sunspots, and the smaller ones vary but little with the 11-year magnetic activity cycle. It has been suggested that their magnetic fields have an origin different from the main east - west magnetic field deep in the convective zone.

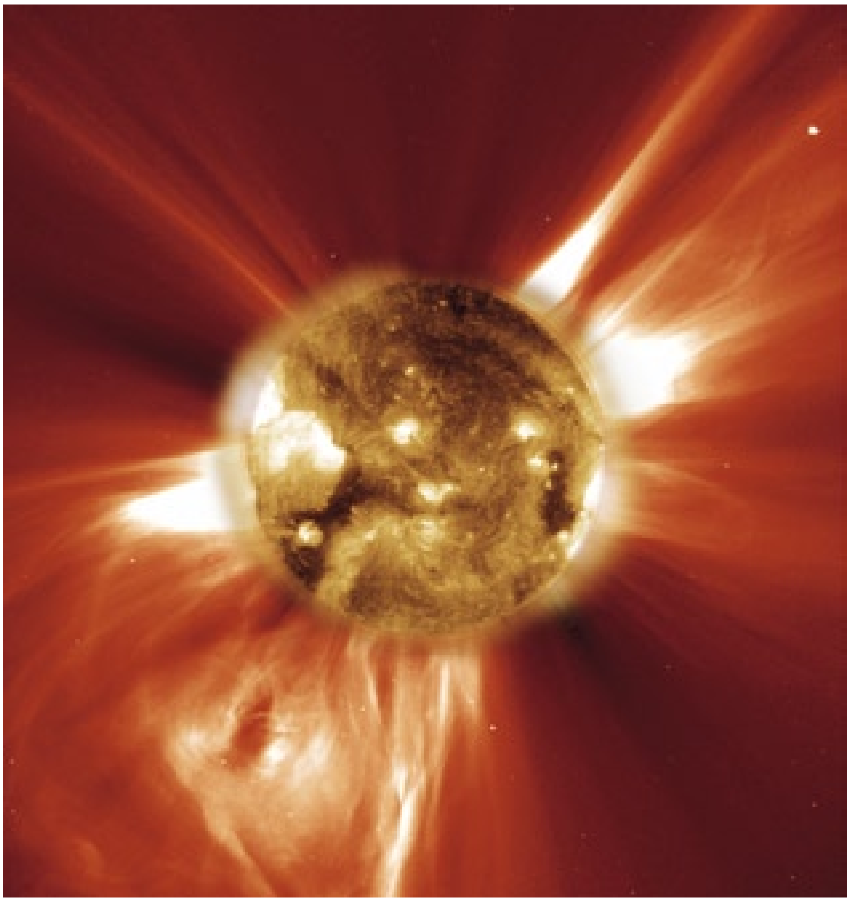


Fig. 14: Coronal Mass Ejections: This image shows many erupting filaments lifting off the active solar surface and blasting enormous bubbles of magnetic plasma into space. Direct light from the Sun is blocked in the inner part of the above image, and replaced by a simultaneous image of the Sun in ultraviolet light. The field of view extends over two million kilometres from the solar surface. Near the minimum of the solar activity cycle CME's occur about once a week, but near solar maximum rates of two or more per day are typical. (Credit: SOHO Consortium, ESA, NASA)

The Living Sun

Advanced instrumentation such as on ESA's SOHO spacecraft, or NASA's Advanced Composition Explorer (ACE) and Transition Region and Coronal Explorer (TRACE) spacecraft have provided evidence of a photosphere peppered by the small magnetic fibrils with continual dissipative activity as the squirming fibrils reconnect among their neighbours. These small-scale fields are referred to as the "magnetic carpet", with which the photosphere is very much alive.

Now the Ω-shape of the magnetic fields of the bipolar active regions traps coronal plasma, preventing it from expanding away from the Sun to join with the solar wind from the regions of weak open magnetic fields. The enclosed plasma is heated to temperatures of 1–10 million K with the density rising above the normal corona (10^8 ions/cm^3) to somewhere in the vicinity of 10^{10} ions/cm^3. At this enhanced density, the X-ray emission becomes significant, providing the quiet time X-ray luminosity of the Sun. The occasional large flare of course produces a very intense burst. The X-ray emitting temperatures in the enclosing Ω-shaped fields appear to be the result of many tiny (micro, nano, and pico) flares in the interlaced field lines of the Ω-fields. The interlacing is carried on continuously by the swirling gases at both foot points of the Ω-fields. This is evidently the reason why stars with convective zones like the Sun are all X-ray emitters.

Coronal Mass Ejections

A particularly interesting facet of solar magnetic activity is the spectacular coronal mass ejection (CME, **see Figures 14 and 15).** Such an event is created when the convection below the surface of the Sun increasingly deforms the Ω-loops. The internal deformation and twisting of the field accumulates in the bipolar Ω-loop to the point where the increasing internal energy produces instability, exploding outward while rapid magnetic reconnection cuts the loop free from the photospheric foot points to allow escape from the Sun. The coronal mass ejections escape with speeds up to 2,000 km/sec. It is the impact of coronal mass ejections that are directed towards the Earth against the geomagnetic field that produces the terrestrial magnetic storm phenomenon.

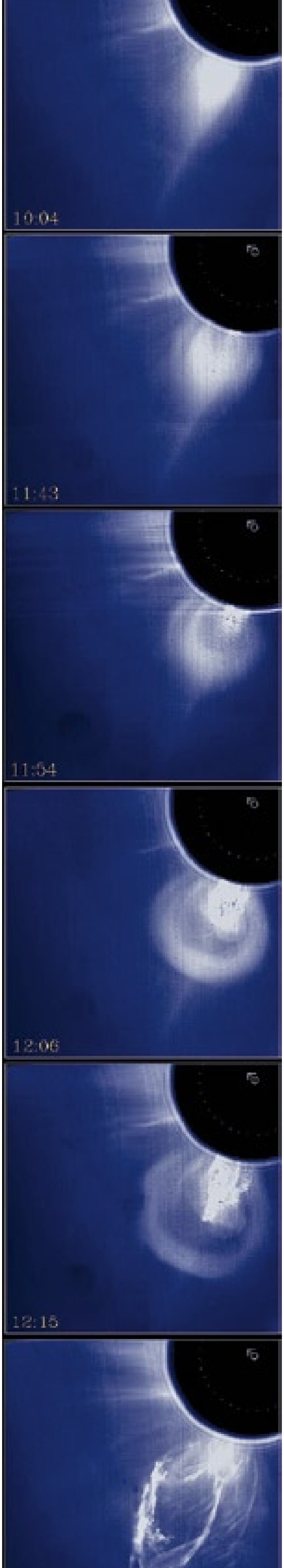


Fig. 15: The dynamics of a coronal mass ejection and prominence eruption observed in white light from the SMM (Solar Maximum Mission) spacecraft. The time of each panel increases from the top to the bottom. The dashed inner circle in each panel is the solar radius, the occulting radius is at 1.6 solar radii. (Credit NASA/GSFC)

Outlook

Never believe an observation for which you do not have a theory. This dictum by Sir Arthur Stanley Eddington[17] is the paradigm for all those active in the field of solar magnetism, where observations have always led the way at every step, with theory running along behind in an ongoing attempt to catch up.

Future generations of scientists will be challenged to recognize the clues for an advanced understanding of our daytime star. New means of observations based on refined theoretical concepts and advanced instruments with much greater spatial and temporal resolving power may lead the way to further understanding. In the meantime it is reassuring to know that the Sun will continue to shine as it mercifully did since 4.6 billion years.

[17] Sir Arthur Stanley Eddington, 1882, Kendal, UK – 1944, Cambridge, UK, British astrophysicist.

The Author

The general curiosity of young Eugene Parker about why things do what they do captured his interest as a young child. By the time he was in high school, he found physics class so interesting that it sealed his career path: astrophysics is simply applying the laws of physics to large-scale phenomena that cannot unfold inside a laboratory. Later, Eugene Parker visited Michigan State University and California Institute of Technology. Then, he spent four years at the University of Utah and since 1955 has been at the University of Chicago, where he has held various positions in the physics department, the astronomy and astrophysics department, and the Enrico Fermi Institute.

In the mid-1950s the British mathematician Sydney Chapman calculated the properties of the gas in the Sun's corona that must extend way out into space. At about the same time, the German scientist Ludwig Biermann observed that a comet's tail always points away from the Sun prompting him to postulate that this happens because the Sun emits a steady stream of particles that push the comet tail away. Parker realized that the heat flowing from the Sun in Chapman's model and the comet tail blowing away from the Sun in Biermann's theory had to be the result of the same phenomenon and that Chapman was right near the Sun and Biermann was right far from the Sun.

Initially the opposition to Parker's theory on the solar wind was strong and the paper he submitted to the Astrophysical Journal in 1958 was rejected by two reviewers. It was in the 1960s only that his theory was fully confirmed through direct satellite observations of the solar wind. This made Eugene Parker the leading authority on the solar wind and the effects of magnetic fields in the heliosphere. His work has greatly increased understanding of the solar corona, the solar wind, the magnetic fields of both Earth and Sun, and their complex electromagnetic interactions. He has seen spacecraft go out into the heliosphere and confirm the theoretical models he had developed before the space age, when observations of comet tails provided nearly all the data available.