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The Sun: Structure, Magnetic Activity, and Its Influence on the Solar System

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Abstract:
The Sun is a magnetically active, approximately 4.6-billion-year-old G2 V main-sequence star and the dominant source of energy and gravitational influence in the Solar System. Although it appears relatively stable on human timescales, the Sun is a highly dynamic plasma system characterized by convection, differential rotation, magnetic-field generation, solar-cycle variability, flares, coronal mass ejections, and a continuously expanding solar wind. Understanding these processes is central not only to stellar astrophysics but also to heliophysics and the study of space weather. This review synthesizes major developments in the understanding of the solar interior, energy transport, atmospheric structure, magnetic dynamo, solar activity, coronal heating, solar wind, and Sun–Earth interactions. Particular attention is given to helioseismology and magnetohydrodynamic (MHD) models as complementary approaches to investigating regions that cannot be observed directly. Contemporary dynamo theory attributes solar magnetic variability to inductive processes associated with turbulent convection and differential rotation, although the precise location and mechanism of dynamo action remain subjects of active debate. Recent work has challenged traditional models that place the dominant dynamo mechanism deep within the solar interior, with helioseismic and theoretical evidence suggesting an important role for the near-surface shear layer. Likewise, the physical mechanisms responsible for coronal heating and solar-wind acceleration remain incompletely resolved. The review concludes that advances in high-resolution solar observations, numerical MHD simulations, helioseismology, and spacecraft observations are progressively transforming the Sun from an observationally accessible star into a laboratory for plasma physics, stellar magnetism, and space-weather science.

Keywords: Sun; solar interior; helioseismology; solar dynamo; solar cycle; sunspots; corona; solar wind; magnetohydrodynamics; space weather

Introduction:

The Sun is the nearest star to Earth and the central gravitational and energetic component of the Solar System. With an age of approximately 4.6 billion years, it is a relatively ordinary main-sequence star in terms of mass and evolutionary state, but its proximity permits an observational level of detail unavailable for other stars. This makes solar physics a fundamental component of modern astrophysics: the Sun provides a natural laboratory for investigating plasma processes, magnetic-field generation, stellar atmospheres, particle acceleration, and the interaction between stars and their surrounding planetary environments. The Sun is composed primarily of hydrogen and helium plasma. Nuclear fusion in its core converts hydrogen into helium and supplies the energy that ultimately emerges as electromagnetic radiation and particles. Energy generated in the core is transported outward through radiative and convective regions before reaching the photosphere and escaping into space. Above the photosphere lie the chromosphere, transition region, and corona, where the plasma becomes increasingly dominated by magnetic processes.

Solar activity varies on multiple temporal and spatial scales. The most recognizable variation is the approximately 11-year sunspot cycle, which is associated with a roughly 22-year magnetic polarity cycle. Changes in the solar magnetic field produce sunspots, flares, prominences, coronal mass ejections (CMEs), and variations in the solar wind. These phenomena can substantially influence the near-Earth environment, producing what is collectively termed *space weather*. Despite decades of observations, fundamental questions remain unresolved. These include the precise physical origin of the solar magnetic cycle, the mechanism responsible for heating the corona to temperatures far exceeding those of the photosphere, the acceleration of the solar wind, and the mechanisms controlling the magnitude and predictability of solar activity. These unresolved problems make the Sun an active area of contemporary research.

Fundamental Properties and Composition of the Sun:

The Sun contains approximately 99.8% of the mass of the Solar System. Its radius is approximately 6.96×108 m, while its mass is approximately 1.989×1030 kg. The effective temperature of the photosphere is approximately 5,500 K, whereas the central temperature reaches approximately 15 million K. The enormous temperature and pressure in the core allow nuclear fusion to proceed efficiently. Spectroscopic and helioseismic studies indicate that hydrogen constitutes approximately 92% of the atoms in the Sun, with helium accounting for most of the remainder and heavier elements comprising a small fraction. OOUP Academic

The Sun's enormous mass produces the gravitational field that governs planetary orbits. Its electromagnetic radiation provides the dominant energy input to Earth's climate system, while its magnetic field and solar wind determine the large-scale plasma environment throughout the heliosphere.

The Sun is therefore simultaneously:

- a nuclear fusion reactor;
- a self-gravitating plasma;
- a magnetically active star;
- a source of energetic particles and electromagnetic radiation; and
- The central driver of heliospheric space weather.

Internal Structure of the Sun:

The solar interior is conventionally divided into the **core, radiative zone, and convection zone**. These regions differ primarily in their mechanisms of energy transport and plasma dynamics.

The Core

The core extends approximately through the innermost 20–25% of the solar radius. It contains the temperatures and densities necessary for nuclear fusion. The dominant process in the present Sun is the proton–proton chain, through which hydrogen nuclei are ultimately converted into helium.

A simplified representation of the net reaction is: $4\ 1H \rightarrow 4He + 2e^{+} + 2\nu e + \gamma + energy$. The small difference between the initial mass of the hydrogen nuclei and the final mass of the helium nucleus is converted into energy according to Einstein's relation: $E=mc^2$. The reaction produces both electromagnetic energy and neutrinos. Solar neutrinos are particularly important because they escape almost directly from the core, providing a unique observational probe of nuclear processes occurring deep inside the Sun.

The Radiative Zone:

Beyond the core lies the radiative zone. Here, energy is transported primarily through the absorption and re-emission of photons. A photon generated by nuclear processes does not travel directly from the core to the photosphere. Instead, it undergoes an enormous number of interactions with matter. Consequently, the effective transport of energy through this region is extremely slow compared with the speed at which an individual photon travels.

The radiative zone therefore functions as an optically thick environment in which radiative diffusion dominates energy transport.

The Convection Zone:

At approximately 70% of the solar radius, the temperature and opacity become such that radiative transport becomes inefficient. Energy is then transported predominantly through convection. Hot plasma rises toward the surface, cools, and sinks again. This convective motion produces the granulation observed on the photosphere and contributes to the complex turbulent environment that interacts with the solar magnetic field. The interaction among convection, rotation, and magnetic fields is fundamental to theories of the solar dynamo. Contemporary dynamo theory generally considers fluid motions within the solar interior responsible for inductively generating and maintaining the Sun's magnetic field.

Helioseismology and the Hidden Solar Interior:

Direct observations cannot penetrate deeply into the solar interior. Consequently, one of the most important developments in modern solar physics has been helioseismology. Helioseismology studies oscillations propagating through the Sun. These waves contain information about the internal sound speed, density, rotation, and flows. By measuring oscillation frequencies and comparing them with theoretical solar models, researchers can infer properties of otherwise inaccessible regions. Helioseismology has substantially improved knowledge of the boundaries between the radiative and convective zones and has revealed important characteristics of solar differential rotation.

This technique is conceptually analogous to terrestrial seismology: earthquakes allow geophysicists to infer Earth's internal structure, while solar oscillations allow astrophysicists to investigate the Sun's interior. The combination of helioseismic observations and numerical models has become particularly important in current debates about the solar dynamo.

The Photosphere and Solar Atmosphere:

The photosphere is the visible layer of the Sun and has a temperature of approximately 5,500 K. It is not a solid surface; rather, it represents the region from which much of the Sun's visible radiation escapes. Above the photosphere are three principal atmospheric regions:

1. the chromosphere;
2. the transition region; and
3. the corona.

The chromosphere exhibits strong magnetic and radiative activity. Above it, temperature rises rapidly through the transition region before reaching the extremely hot corona. The atmospheric structure presents one of the most famous problems in solar physics: the coronal-heating problem.

The Coronal-Heating Problem:

A particularly counterintuitive feature of the Sun is that the corona is dramatically hotter than the photosphere. Coronal temperatures can reach approximately 1–2 million K or more, whereas the photosphere has a temperature near 5,500 K. A complete explanation of this temperature inversion remains unresolved.

Several mechanisms have been proposed, including:

- Alfvén-wave dissipation;
- magnetohydrodynamic turbulence;
- magnetic-field braiding;
- nanoflares;
- reconnection;
- plasma-wave heating; and
- combinations of these processes.

A comprehensive review by Cranmer and colleagues emphasizes that observations and three-dimensional numerical simulations have significantly advanced understanding of coronal heating and solar-wind formation, but no single mechanism has yet achieved definitive explanatory status. The problem is important beyond solar physics because the corona is the region from which the solar wind originates. Understanding coronal heating is therefore closely linked to understanding how the solar wind is accelerated.

Solar Magnetism and the Solar Dynamo:

The Sun's magnetic field controls much of its observable activity. Sunspots, prominences, flares, CMEs, coronal structures, and many aspects of the solar wind are fundamentally magnetic phenomena. The prevailing theoretical framework is the hydromagnetic dynamo. In simplified terms, a dynamo converts kinetic energy associated with conducting plasma motions into magnetic energy. The solar plasma is electrically conducting, allowing fluid motion to stretch, twist, and regenerate magnetic fields. Differential rotation is particularly important. Different latitudes of the Sun rotate at different angular velocities, causing magnetic field lines to be stretched and sheared. Turbulent convection and other large-scale flows further contribute to magnetic-field evolution. Charbonneau's influential reviews describe the solar cycle as the product of hydromagnetic dynamo action while emphasizing that the relative contributions of different inductive mechanisms remain uncertain.

The 11-Year Solar Cycle:

The most prominent manifestation of solar magnetism is the approximately 11-year solar activity cycle. During solar minimum, the Sun may have relatively few sunspots and a simpler large-scale magnetic configuration. Activity increases toward solar maximum, when sunspots, flares, CMEs, and other magnetic phenomena become substantially more frequent. Importantly, the complete magnetic cycle is approximately 22 years because the global magnetic polarity reverses during each approximately 11-year activity cycle. Sunspots are relatively dark regions produced by strong magnetic fields emerging through the photosphere. Their reduced brightness results primarily from the suppression of convective energy transport by intense magnetic fields. The spatial and temporal distribution of sunspots forms the famous butterfly diagram, which provides one of the principal observational constraints on dynamo models.

Contemporary Solar-Dynamo Debate:

One of the most important recent developments concerns the location of the dynamo responsible for the solar cycle. Traditional models have often emphasized the tachocline—the shear layer near the interface between the radiative interior and convection zone—as a critical region for magnetic-field generation. However, recent research has questioned whether the dominant dynamo must originate there. A 2024 *Nature* study by Cameron et al. and collaborators argued, based on helioseismic observations and dynamical considerations, that the solar dynamo may begin much closer to the surface. The study connected the observed low-latitude torsional oscillations and sunspot migration to the near-surface shear layer occupying roughly the outer 5–10% of the Sun. This represents an important conceptual development because it challenges models in which deep-seated magnetic processes are assumed to be solely responsible for the observed solar cycle. Nevertheless, the issue remains unresolved. Solar dynamo theory continues to include competing classes of models, including:

- mean-field dynamo models;
- flux-transport/Babcock–Leighton models;
- distributed dynamo models;
- near-surface dynamo models; and
- global three-dimensional MHD simulations.

The continuing disagreement illustrates the difficulty of inferring three-dimensional magnetic processes from limited observational diagnostics.

Sunspots, Flares, and Coronal Mass Ejections:

Sunspots:

Sunspots are manifestations of strong magnetic fields emerging through the photosphere. Their numbers and distributions change systematically during the solar cycle. They typically occur in bipolar groups and display magnetic polarity patterns that change systematically between cycles. These observations provide important constraints on models of magnetic-field generation and transport.

Solar Flares:

Solar flares are intense releases of electromagnetic energy associated with rapid changes in magnetic-field configuration. Magnetic reconnection is considered a central physical mechanism. Flares can emit radiation across a broad range of wavelengths, including:

- radio;
- optical;
- ultraviolet;
- extreme ultraviolet;
- X-rays; and
- gamma rays in the most energetic cases.

They can also accelerate particles to very high energies.

Coronal Mass Ejections:

CMEs are enormous expulsions of magnetized plasma from the solar corona. When directed toward Earth, they can interact strongly with the terrestrial magnetosphere. The resulting geomagnetic disturbances can produce aurorae but can also interfere with satellite operations, radio communication, navigation systems, and electrical infrastructure. The Sun's variable electromagnetic and particle environment therefore has direct technological consequences for modern civilization.

Critical Evaluation of the Literature:

The literature demonstrates substantial progress but also reveals several persistent limitations.

First, observations of the solar surface are significantly more complete than observations of the interior. Consequently, dynamo models necessarily involve assumptions concerning processes that cannot be directly observed. Second, numerical simulations remain constrained by computational resources. The enormous range of spatial and temporal scales in the solar plasma makes it impossible to reproduce every relevant physical process simultaneously.

Third, competing models can sometimes reproduce similar observational characteristics. For example, different dynamo mechanisms may reproduce aspects of the sunspot cycle while making different predictions about the underlying magnetic-field structure. Fourth, the corona represents a strongly nonlinear plasma environment in which turbulence, waves, reconnection, and kinetic processes interact. This makes it difficult to isolate a single mechanism responsible for heating and particle acceleration.

The literature therefore increasingly favors multi-observational and multi-scale approaches, combining helioseismology, photospheric magnetic measurements, coronal observations, in-situ solar-wind measurements, and numerical modelling.

Conclusion:

The Sun is a complex, dynamic plasma system whose apparent stability conceals a wide range of physical processes operating over enormous spatial and temporal scales. Nuclear fusion in the core supplies the energy that sustains the star, while radiative transport and convection redistribute that energy toward the surface. The interaction of convection, differential rotation, and magnetic fields generates the solar magnetic environment responsible for sunspots, flares, CMEs, the solar cycle, and the solar wind. Modern helioseismology has transformed understanding of the solar interior, while MHD simulations have

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provided increasingly sophisticated models of magnetic-field generation and atmospheric dynamics. Nevertheless, fundamental questions remain open. In particular, the precise origin of the solar dynamo, the physical mechanism responsible for coronal heating, and the acceleration of the solar wind remain active areas of research. Recent evidence suggesting that the near-surface shear layer may play a major role in the dynamo illustrates how contemporary observations can challenge established theoretical paradigms.

The importance of solar research extends beyond understanding one star. The Sun provides the most accessible laboratory for studying stellar magnetism, plasma astrophysics, and magnetic reconnection. Moreover, solar variability directly influences Earth's technological environment through space weather. A comprehensive understanding of the Sun is therefore simultaneously an astrophysical, plasma-physical, and practical scientific objective. Future progress will depend on combining high-resolution observations with advanced helioseismic inversions, global and local MHD simulations, and measurements of the solar wind and energetic particles. The continuing development of these approaches is likely to provide increasingly stringent tests of competing theories and move solar physics toward a predictive understanding of stellar magnetic activity.

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