A Detailed Examination of Solar Magnetism and Its Dynamo: Space Education and Strategic Applications 2023 Conference Proceeding

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Magnetism is at the heart of all solar activity, which affects our magnetosphere as well as the outermost boundaries of our Solar System. This is especially important as we have become a technology-dependent society and develop our space exploration efforts to reach new heights by returning to the Moon and setting the first foot on Mars. This summary aims to present a brief overview of the solar dynamo by discussing the generation, propagation, and emergence of magnetic fields gathered by historical and helioseismic data exhibited by sunspots.

Early Observations of Sunspots

The early 1800s began our understanding of sunspot behavior, starting with Samuel Schwabe. He was convinced a planet closer than Mercury was orbiting the Sun. During his seventeen-year search, he tracked sunspots as they crossed the solar disk and observed periods of high and low sunspot activity. This became the basis for the 11-year cycle. Next, Richard Carrington was one of the first to make the correlation that solar activity can affect Earth's magnetosphere via geomagnetic storms due to the infamous Carrington Event. After recording the movement of sunspots at various latitudes, he also concluded that the surface does not rotate as one body. It exhibits differential rotation in which it rotates faster around the equator than at the poles.

Gustav Spörer worked with Carrington and noticed the migratory motions of these sunspots throughout the solar cycle. Sunspots emerged at higher latitudes at the start of a cycle and then developed closer to the equator throughout the progression. At the turn of the century, George Hale progressed the field further by concluding that sunspots were areas of high magnetism with a bipolar nature and changes its orientation from one cycle to the next. He used new techniques, like the Zeeman effect, to calculate the strength of sunspots and built his own spectroheliograph to observe the Sun one wavelength at a time. A colleague of Hale, Alfred Joy, took note of the inclination

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angle of sunspots in association with their latitudes. The further away from the equator, the larger the tilt among sunspot pairs. The collection of observational evidence gathered from these scientists began our modern understanding of the solar dynamo.

Beginnings of a New Field

Sunspot magnetism was revisited in the 1960s with Horace Babcock. He invented the solar magnetograph to measure the overall magnetic strength of the Sun. During the same time frame, Robert Leighton was applying new procedures, like the subtraction method to "spot the difference" and measure its magnitude. His method, along with Babcock's magnetograph, allowed photographing entire active regions, discover supergranulation, and detect small-scale oscillations with an average time interval of 300 seconds (Leighton et al., 1961, p. 488). The latter opened the door to a new field … helioseismology.

Listening to the Sun

Helioseismology is the study of solar oscillations. If one were to listen to the Sun, it would sound like a constant humming noise because millions of wavelengths are traveling throughout simultaneously. Helioseismologists track one wavelength at a time and determine how long it takes for each one to return to the surface. The path of each wavelength reveals characteristics of the solar interior, with each layer changing the wavelength's speed and refraction angle.

Each wavelength has varying periods from a couple of days to a few months, and observing them requires long, uninterrupted sessions. These paths reveal internal motions, composition, temperatures, and layering, i.e., the core, radiative zone, and convection zone. A notable discovery showed that differential rotation continues throughout the convection zone and is halted at the radiative zone boundary. The turbulence from the convection zone against the rigid radiative zone generates a current within the electrically conductive plasma. The tachocline sits at this boundary, generating the magnetic field and powering the large-scale solar dynamo.

The Solar Dynamo

Babcock expressed that the solar dynamo occurs in five stages, beginning with the initial poloidal field. At the start of a cycle, magnetic field lines are organized in an orderly north-south direction. Differential rotation pulls and stretches them around the Sun due to the frozen flux theorem to become a toroidal field. The pulling of these field lines causes them to become intensified, and at the same time, the motions of the convection zone twist them, further strengthening them and turning them into flux ropes. Helicity within these ropes is a conservation mechanism, which allows them to remain intact as they travel through the convection zone.

Magnetic buoyancy is achieved when magnetic pressure within the ropes equals the surrounding gas pressure, allowing them to rise. The strongest flux ropes propagate through the convection zone and emerge out the photosphere, forming bipolar magnetic regions or sunspots. Meridional circulation expands the flux ropes to reach higher and higher into the corona. As the spots migrate closer to the equator, the leading spot in one hemisphere will connect with the leading spot of opposite polarity in the other hemisphere, initiating a neutralization stage and the magnetic reversal process. The final stage is the reversed dipolar field, where the overall magnetic polarity of the Sun is reversed and starts a new cycle.

Leighton's contribution took a mathematical approach and factored in supergranulation to influence the field's migration, leading the ropes to randomly stray further from their initial points. He matched the size and frequency rate to equal the same rate needed to neutralize the polarity fields across the equator. The Babcock-Leighton model is a fantastic representation of how the dynamo works and remains a staple in solar dynamo theory.

Delving into dynamo specifics, the structure of the convection zone is a complex entity. The types of convection cells vary from granulation to mesogranulation to supergranulation, all leading to giant cells. Each convection cell exhibits large, slow upflows and fast, narrow downflows. These downflows create superplumes that penetrate deeper into the convection zone, reaching all the way down to giant cells. The entire convection zone acts like a filter for only the strongest flux ropes, considering the average magnetic strength of a sunspot is around 3,000 Gauss (High Altitude Observatory, 2023). In addition to the large-scale dynamo that encompasses the Sun in its entirety, there's also the small-scale dynamo.

An attribute of fast dynamo theory suggests that all types of turbulent motion in a conductive fluid can create a dynamo, making it plausible for granulation, mesogranulation, and supergranulation to act as magnetic field generators. This magnetic field is expelled between granules and is more noticeable when the Sun is quiet. A mechanism typically seen during this time is convective collapse, which is when instabilities form within the flux tubes and cause them to shrink rapidly. This increases their magnetic pressure until it matches the surrounding gas pressure, thus reaching up to two kilogausses in strength (Nagata et al., 2008, p. L145).

The generation, propagation, and emergence of magnetic fields through historical and helioseismic data exhibited by sunspots have been explored throughout this summary. Significant contributions by Schwabe, Carrington, Spörer, Hale, and Joy commenced our modern understanding of the solar magnetic cycle. The individual workings of Babcock and Leighton were brought together to refine the dynamo model, which became integral in heliophysics. Helioseismology bridged the gap between what scientists observed on the photosphere and the mechanisms involved within the interior, including the crucial tachocline. The cohesion of large-scale and small-scale dynamos shows the dynamic nature of our Sun, with the multitude of forces, flows, and motions that participate. Heliophysicists, solar astronomers, and helioseismologists will continue to unify each piece in hopes of fully understanding the heart of all solar activity.

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