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The Inner Heliosphere at Fifty

Recent observations show that the Sun's magnetic field is flipping, marking one of the weakest sunspot cycle maxima in recent history. Many consequences have been observed and are under study, from a significant diminishing of the upper atmosphere's density [*Solomon et al.,* 2010] to record low levels of geomagnetic activity [*Richardson,* 2013] to the large increase of local galactic cosmic ray fluxes starting in the preceding solar minimum [*Mewaldt et al.,* 2010].

Yet as recently as the 1950s, there was little deep understanding of long-documented connections between the observed sunspot cycle, perturbations in the Earth's surface magnetic field, the occurrence of auroras, the appearance of the Sun's corona during total solar eclipses and in coronagraph images, and occasional white-light solar flares, with their associated radio emissions and ionospheric disturbances. Spectral line information had already indicated that the corona—the upper atmosphere of the Sun—is composed mostly of hydrogen at a temperature of about a million degrees Kelvin with a correspondingly high ionization state, but beyond that, researchers knew little of how the corona influenced Earth or the space around it.

The 1950s was also a period of postwar technological advancements and unprecedented growth of institutions of higher learning. Communications increasingly relied on ionosphere-dependent transmissions, which can be disrupted by solar events. The time had arrived for new investigations concerning our relationship to our star. Following the discovery by George Ellery Hale that sunspots were sites of magnetic fields [*Hale,* 1908], the development of the magnetograph by Horace Babcock and his son Harold was particularly important in spurring interest in solar astronomy in academic circles [*Babcock,* 1953]. Sunspots were established as sites of especially strong magnetic fields on the solar surface, but, in addition, the presence of fields outside of sunspots and their influences over the highly ionized solar atmosphere gained attention. While the emphasis in this era was mainly on the phenomenology observable within the limits of ground-based instrumentation, with colorful names of features such as "disparitions brusque" and "plages" introduced, the stage was set for the next phase in the space age.

The Parker Solar Wind and Emergence of the Field of Heliophysics

By the early 1960s, several theoreticians were using existing information to envision what was present between the Sun and Earth. Eugene Parker proposed that an ionized, mainly hydrogen gas or plasma continuously flowed out from the Sun like a fluid, carrying some of the Sun's magnetic field along with it [*Parker,* 1958]. He made the additional prediction that this "solar wind" was flowing at supersonic speeds (reaching hundreds of kilometers per second or more) because of its origins in the hot corona and the resulting physics of its pressure-driven escape from the Sun's gravitational well. A competing theory invoking a picture more similar to an ionized planetary upper atmosphere was developed around the same time by Joseph Chamberlain [*Chamberlain,* 1960]. Chamberlain's consideration of single particle or kinetic effects, together with the charge and mass differences between the protons and electrons, resulted in much lower outflow speeds. The essential difference between Parker's and Chamberlain's hypotheses concerned the applicability of the fluid theory to the space between the Sun and Earth, which was expected to be a highly rarefied, collisionless medium.

Then instruments successfully detected the solar wind particles and magnetic fields in interplanetary space on the Soviet Union's first three Luna missions and on the United States's Explorer 10 and Mariner 2 missions [*Neugebauer and von Steiger,* 2001]. These measurements established the existence of a solar wind and interplanetary field with properties much like those described by Parker's concept. In particular, the speed of the ionized gas (plasma) was about 400 kilometers per second, and the magnetic field exhibited behavior consistent with a "Parker spiral" configuration (Figure 1a) that arises naturally from picturing streams of fluid ejected from a rotating Sun—the flow is radially outward, but the fluid elements from a particular source location and the source field they carry make a spiral shape as the Sun rotates under them. While a greater appreciation of the nonfluid aspects of solar wind behavior developed later, Parker's picture is the first one that most students of space physics encounter and routinely use.

The field of heliospheric research was thus born and grew rapidly through the 1990s with much success, based on these early paradigms. Important advances made during this time included much more detailed descriptions of the coronal sources of solar wind. The bright, near-equatorial rays or streamers seen in eclipse and coronagraph images obtained during periods of low solar activity led to the first coronal models based on the assumption of a large-scale dipole magnetic field of the Sun (Figure 1b). Streamers were interpreted as sites where hot gas is trapped in topologically "closed" magnetic field arcades rooted in the Sun, which in the dipole case encircles the solar equator (Figure 1b). The solar wind flows out along "open" fields in the solar polar regions.

This picture neatly explained the "magnetic sector" structure observed in the solar wind where alternating outward and inward Parker spiral fields were detected—with sometimes repeating patterns on the approximately 27-day time scale of the solar rotation. A tilt or warp of the coronal dipole equator with respect to the ecliptic plane could easily produce such patterns.

By J. G. Luhmann

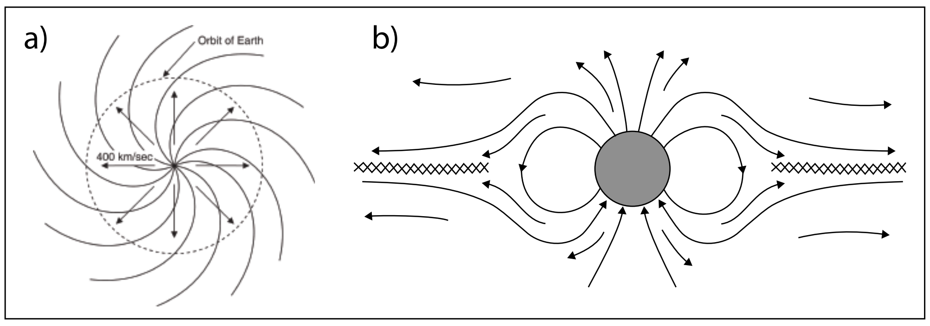

Fig. 1. Depictions of early ideas of heliophysics. (a) The original Parker solar wind and interplanetary magnetic field concepts. (b) The early dipolar corona model with polar coronal hole sources of the solar wind.

Insights From Space-Based Platforms and the Emerging Field of Space Weather

Parallel developments of still newer technologies and increasing access to space-based platforms then led to the next major paradigm shifts. In particular, the soft X-ray telescopes on Skylab (NASA's first space station [see *Eddy,* 1979, and references therein]) had a particularly important impact on heliospheric research because they allowed scientists to observe coronal holes, areas dark in X-ray images that are seen on the solar disk nestled between the arcades of the bright streamers. Moreover, these features changed with time, and the magnetically closed arcades sometimes erupted. These eruptions, a newly defined form of solar activity distinct from flares, were termed coronal mass ejections (CMEs).

Space-based in situ measurements of plasma and field features at both quiet and active times could now be associated with what was observed at the Sun in remarkable detail. For example, a large coronal hole present near the central disk of the Sun would often be followed several days later by especially fast solar wind at Earth. The dark areas were therefore recognized as the footprints of open coronal field channels out of which fast solar wind easily escaped. Notably, these were often not confined to the solar polar regions associated with the dipole corona picture. Instead, coronal holes were often highly irregular in shape and present over a range of solar latitudes (Figure 2). Moreover, their spatial distribution, like that of the bright streamers, changed with the phase of the 11-year sunspot cycle. Computational advances enabled the development of models of the coronal magnetic field based on the solar surface field observations. These often reproduced features resembling both streamers and coronal holes seen in the eclipse, coronagraph, and soft X-ray images, establishing once and for all that the solar magnetic field exerts major control over the structure of the heliosphere.

The identification of CMEs ushered in a new era of space weather research and the possibility of forecasting it. A European twin-spacecraft mission called Helios, which orbited the Sun between the heliocentric distance of Mercury's and Earth's orbits from the mid-1970s to the mid-1980s, captured the plasma and field signatures of CMEs and their effects on the surrounding solar wind as they evolved along their outward paths.

By the late 1990s, *Gosling* [1993] had convinced the research community to accept that the flares observed at the Sun were not the most direct cause of the geomagnetic storms that sometimes followed. If a coronal mass ejection occurred in association with a central or western disk flare, it could be followed within a few days by a shock wave and then several days of enhanced solar wind parameters (density, velocity, and magnetic field) upstream of Earth. Around this time, the first phenomenological models of the proposed coronal eruption process and its interplanetary consequences were introduced (Figure 2).

Detailed Observations of the Heliosphere

In the 1970s, a number of planetary missions traveling away from the Sun, in particular the Pioneer 10 mission to explore Jupiter's space environment followed by the twin Voyager spacecraft, made interplanetary measurements of the solar wind and its variations beyond Earth's orbit that extended Parker's basic picture as far as human-made robots ventured in space. During this period the practical aspects of this science of heliospheric physics were also realized in the support of the human space exploration program because flare watching was no longer sufficient to ensure astronaut safety. Potential solar energetic particle radiation hazards related to CME-driven shocks were recognized as something to be considered in both human and robotic mission design and operations. It would have seemed to many an outside observer that the understanding of the heliosphere and its connections to the Sun were nearly complete.

With the 1990s came the European-led Ulysses mission, the first opportunity to venture far out of the ecliptic plane and observe the Sun. At the same time, major developments in computing and numerical simulation techniques began to allow increasingly sophisticated physics-based modeling of the corona and heliosphere. The possibilities for space weather prediction from the Sun to Earth became more realistic. In addition, progress in helioseismology, the diagnosis of the Sun's internal structure and dynamics from its surface oscillations, opened minds to the connections of the solar interior to the structure of, and events in, the corona.

In a somewhat ironic twist, the limitations of the Parker picture of the heliosphere also became more apparent. The heliolatitude gradients in solar wind properties inferred earlier from interplanetary scintillation measurements that were confirmed by Ulysses, combined with continuous imaging of the corona on the European Space Agency (ESA)/NASA Solar and Heliospheric Observatory (SOHO) spacecraft, found that the Parker wind concept most closely applies to solar wind coming from the central portions of coronal holes. However, a large fraction of the ecliptic solar wind, and much of the solar wind at all latitudes during active periods of the solar cycle, is much more complicated in its origins and characteristics. Even at quiet times, some of the solar wind that is experienced at Earth consists of CMEs that leave the Sun at speeds less than typical solar wind speeds and are caught up in the flow but are not distinguishable as specific events or disturbances.

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ABOUT AGU

Slingerland Receives 2012 G. K. Gilbert Award

Rudy L. Slingerland received the 2012 G. K. Gilbert Award at the 2012 AGU Fall Meeting, held 3–7 December in San Francisco, Calif. The award recognizes "a scientist who has either made a single significant advance or sustained significant contributions to the field of Earth and planetary surface processes, and who has in addition promoted an environment of unselfish cooperation in research and the inclusion of young scientists into the field."

Citation

It is a tremendous pleasure to see the 2012 G. K. Gilbert Award presented to Professor Rudy Slingerland, of Penn State University. Rudy has been serving the Earth sciences for more than 3 decades. He has done so through his own research contributions; through research that he has inspired in his students, postdocs, and colleagues; and through his many efforts on behalf of the larger community. These include dedication to organizations like the Community Surface Dynamics Modeling System, for which he ably chaired the steering committee during its critical first 5 years.

In terms of his own scientific contributions, the list of scientific topics that have drawn Rudy's curiosity is quite impressive. To stratigraphers and sedimentologists, he is known as a founder, practitioner, and lifelong champion for quantitative dynamic stratigraphy. He is known among paleoceanographers for having pioneered the computational study of circulation patterns in ancient epeiric seaways. Tectonicists may know Rudy best for his work on ancient and modern fold-and-thrust belts. Geomorphologists, on the other hand, are most attuned to his work on landscape evolution and river dynamics. It is noteworthy, for example, that his work with Scott Snow on modeling river profile evolution, beginning in the late 1980s, helped to set the stage for the recent surge of interest in that topic.

Across this diverse body of work, Rudy's contributions have always been notable for their insistence on posing clear, precise, and carefully phrased questions—questions that cut through the seeming complexity of the natural world. In a similar way, this award's namesake was renowned for his ability to see through the richness of the natural landscape and recognize the underlying core principles at work. Thus, it is fitting that Rudy should be recognized with an award named in Gilbert's honor.

—GREGORY E. TUCKER, Department of Geological Sciences, University of Colorado, Boulder

Response

I'm deeply honored to receive the Earth and Planetary Surface Processes G. K. Gilbert Award, in no small part because Gilbert's application of simple physical principles to Earth surface processes has always been an inspiration to me. My desire to study the transportation of debris by running water started a long time ago on our family farm, where re-engineering the local stream with a backhoe was a rewarding afternoon activity.

After a Geology B.Sc. degree and 2 years in the U.S. Navy Seabees, I knew that I wanted to study with Professor Gene Williams, an intense sedimentary geologist on the graduate faculty at Penn State. His philosophical and quantitative style influenced me more than he can ever know. Five years later and armed with a fresh Ph.D., I was hired by the Department of Geosciences at Penn State to replace Gene. During the next 36 years, I never saw a job that looked better.

Rudy L. Slingerland

I know that I am accepting this award on behalf of all of my students and colleagues with whom I have worked. To all of you I give my heartfelt thanks for good times in the field, good scientific discussions, and the chance to participate with you in such a noble enterprise as geology.

—RUDY L. SLINGERLAND, The Pennsylvania State University, University Park

Lamb Receives 2012 Luna B. Leopold Young Scientist Award

Michael Lamb received the 2012 Luna B. Leopold Young Scientist Award at the 2012 AGU Fall Meeting, held 3–7 December in San Francisco, Calif. The award recognizes "a young scientist for making a significant and outstanding contribution that advances the field of Earth and planetary surface processes."

Citation

Mike Lamb is an accomplished field scientist, numerical modeler, and experimentalist who has established himself as a leader in the fields of geomorphology, sedimentology, marine geology, and planetary geology. His diversity of accomplishments and interests sets him apart from his peers. Mike has worked on net erosional and net depositional terrains in both terrestrial and submarine environments on Earth, as well as the surfaces of other planets and moons. His publication record is very substantial, and his research is rigorous and quantitative.

Mike's work is groundbreaking and attests to a remarkable scientific range and creativity. Among his accomplishments is his demonstration that the critical Shields number *increases* significantly with increasing slope, even for very low slopes. Mike's work on bedrock canyons shows that they are not solely produced by groundwater sapping, but also by surface runoff, which has direct implications for the interpretation of similar geomorphological features on Mars and Titan. His experimental and theoretical work on hyperpycnal flows is seminal and an important contribution to our understanding of the processes that control delivery of river sediment to coastlines and oceans. This work reveals the processes that link the terrestrial and marine realms with regard to sediment transport and deposition. Overall, the cumulative impact of this work extends well beyond geomorphology.

Mike is carrying on three of the most important threads of Luna Leopold's research: a rigorous, quantitative approach, great scientific range, and creativity. This combination of traits is allowing Mike to quickly become a leader in his field and makes him a fitting recipient of the Luna B. Leopold Young Scientist Award.

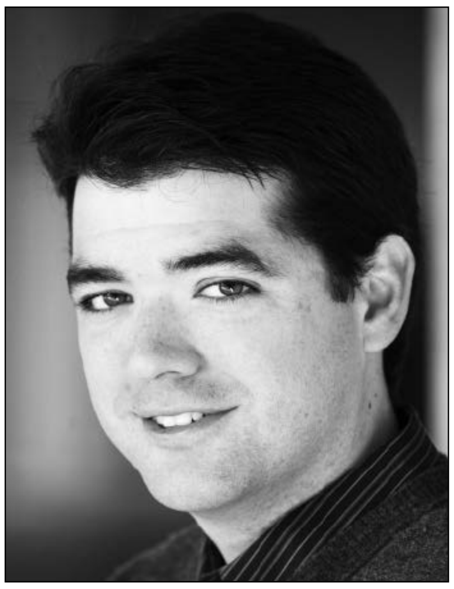
—PAUL MYROW, Department of Geology, Colorado College, Colorado Springs

Response

It is my pleasure to be a part of the exciting community of Earth and planetary surface processes. In addition to the opportunities to participate in engaging and fundamental science, I enjoy our field because of collaborations with bright and fun people. In my short career I have had the pleasure to work with a number of colleagues, and I share this award with you.

A few people deserve particular mention for impacting my career. Chris Paola inspired me to the field of Earth and Planetary Surface Processes. Gary Parker pushed me to conduct my first independent project and introduced me to flume experiments. Jeff Parsons advised my master's work. Bill Dietrich, my Ph.D. advisor, opened my eyes to fascinating problems and approaches in geomorphology. David Mohrig advised my postdoctoral work, and his cross-disciplinary science has been an inspiration since I was an undergraduate student. Alan Howard and Paul Myrow have been unofficial advisors who have generously guided me through a number of projects, including introducing me to Mars and the sedimentary record. In the past 4 years at Caltech, I have had the pleasure to work with Ryan Ewing, Ben Mackey, Phairot Chatanantavet, Roman DiBiase, Adam Booth, Vamsi Ganti, and Edwin Kite as postdocs. In addition, I thank graduate students Ajay Limaye, Joel Scheingross, Jeff Prancevic, and Mathieu Lapotre. Brian Fuller helped me build a new flume laboratory at Caltech. Thank you to John Grotzinger, Woody Fischer, Ken Farley, Jean-Philippe Avouac, and the rest of the Caltech community for support and mentorship.

Thank you for this award.



Michael P. Lamb

—MICHAEL P. LAMB, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena