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Perspective on heliophysics

GEORGE L. SISCOE AND CAROLUS J. SCHRIJVER

1.1 Universal processes: "laws" of space weather

Heliophysics is concerned with laws that give rise to structures and processes that occur in magnetized plasmas and in neutral environments in the local cosmos, both temporal (weather-like) and persistent (climate-like). These laws systematize the results of half a century of exploring space that followed centuries of ground-based observations. During this time spacecraft have imaged the Sun over many wavelengths and resolutions. They have visited every planet, all major satellites and many minor ones, and a selection of comets and asteroids. Beyond this they have traversed the expanse of the heliosphere itself. Out of the vast store of data so accumulated, the laws and principles of heliophysics are emerging to describe structures that are natural to magnetized plasmas and neutrals in cosmic settings and to specify principles that make the heliosphere a realm of numerous, original dynamical modes.

By "the laws of heliophysics" we are not here referring to a subset of the laws of physics that apply to all things everywhere. A discipline that needs to refer back to the fundamental laws of physics to explain its phenomena would be totally derivative, having no synthesizing laws of its own, no regularities peculiar to it, no inherent principles with explanatory power sufficient to link its own distinctive phenomena; in short, no paradigms. To help fix this idea, we list here a few familiar examples from other fields of discipline-specific general laws or principles: chemistry – the periodic table, valence, Le Chatelier–Braun principle; biology – evolution, double helix; geology – "deep time", plate tectonics; astronomy – Kepler's laws, Hertzsprung–Russell diagram, expanding universe; meteorology – Hadley cell, baroclinic instability.

In the case of heliophysics, probably most of its laws have yet to be discovered, since the project of finding them is young. Moreover, heliophysics is a unique hybrid between meteorology and astrophysics with substantial components

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of physics and chemistry. Thus, many of the laws of heliophysics that we can list at this time might be subjects for research in meteorology (e.g. the field of aeronomy), astrophysics (e.g. shock waves and cosmic rays), physics (e.g. magnetic reconnection and particle energization), or chemistry (e.g. reaction rates in planetary ionospheres and thermospheres). Other laws are still hiding their full relevance, even as they hint at their existence through the (self-)similarity of processes and scale-free power-law spectra of a wide range of phenomena, in energies of solar flares, coronal mass ejections, and energetic particles, and from geomagnetic storm occurrences to solar-wind turbulence spectra.

Our three volumes on heliophysics, of which this is the second, are intended to lay out the structures and phenomena with which heliophysics is concerned that might be organized under general laws and principles and to indicate how far the field has progressed toward uncovering them. In particular, the present volume is concerned with energy-conversion phenomena with emphasis on the explosive kind that produce solar eruptions and the storms of energetic particles, which on occasion render space a hostile environment for technological, space-faring humanity. These phenomena are, of course, of special interest to space weather.

1.2 Pressure, gravity, and electromagnetism

This volume's emphasis on time-dependent phenomena (commonly captured under the term space weather) follows an emphasis in Volume I on structures and processes that persist over time and that at any time can be seen at one or more places in the heliosphere (examples of which include the solar wind and planetary magnetospheres and ionospheres). In Volume I the emphasis was on the rich variety of such structures and processes, as illustrated in its first chapter by following a wandering proton on an odyssey that began beneath the solar surface and ended in the interstellar medium. In its struggle upward to the photosphere and chromosphere it shuffled through numerous solar structures and processes. Upon reaching the corona it passed through sites of dissipation where, being energized enough to escape the Sun's gravitational hold, it joined the solar wind, only to be caught a few days later by the Earth's magnetic field. Entrained as a member of the magnetosphere's high-pressure plasma, it experienced a tour of ionospherically ruled inner chambers before escaping again to continue its journey to freedom. Eventually it exited through the termination shock and ultimately returned to the interstellar medium from which it had been captured by the proto-heliosphere 4.5 billion years earlier (which is part of the story told in Volume III).

In Volume I we noted that although narrating the odyssey of a proton illustrates well the variety of heliospheric structures and processes, a corresponding narrative exists for the magnetic field – a narrative that features the magnetic field's

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role in generating space weather. Indeed the magnetic field is the *sine qua non* – "that without which nothing" – of space weather. Without the magnetic field, neither solar activity nor magnetic storms – the solar and terrestrial sources of space weather – would exist. Two properties of the magnetic field initiate its career as a generator of space weather: (1) it has no conserved sources, and (2) it is buoyant. The first of these properties means that the magnetic field must be continually generated. Although in principle fossil magnetic fields could have remained from the creation of the solar system, this appears not to be the case (see Vol. III). Witness the 22-year magnetic cycle of the Sun and the reversals of the Earth's magnetic field. On shorter time scales, the magnetic topography of the solar surface changes so rapidly that it must be monitored constantly as input for space weather forecasts.

The telling comparison is with the gravitational field, **g**, which unlike the magnetic field, **B**, has a conserved source. The conserved source of the gravitational field is mass, as can be seen in the field equations that apply to the gravitational field:

$$\nabla \cdot \mathbf{g} = -4\pi G\rho, \tag{1.1}$$

$$\nabla \times \mathbf{g} = \mathbf{0}, \tag{1.2}$$

where G is the gravitational constant and ρ is the mass density. Thus, gravity is determined by the amount of mass present and its distribution. Since mass is conserved and the gravitational force causes matter to collapse into systems in which the gravitational force is almost perfectly balanced by thermal or inertial forces, gravitationally organized matter tends to be stable over eons (thermally driven instabilities in gravitationally bound gases form an important exception to this generalization, to which we return below). In contrast, the pertinent field equations for the magnetic field are

$$\nabla \cdot \mathbf{B} = 0, \tag{1.3}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}. \tag{1.4}$$

The source term for the magnetic field in these equations is electrical current, **J**, which, unlike mass, is not a conserved quantity. Thus we see that **B** is a product of dynamo or other magnetohydrodynamic (MHD) processes that generate current in real time. The crucial distinction is that unlike the gravitational field, which is in effect a byproduct of a conserved, definite quantity of mass and so is inherently persistent, the magnetic field is generated by a variety of plasma motions in the Sun, in the solar wind, and in planetary magnetospheres on time scales shorter than what would be needed to reach an equilibrated state. Hence, the local cosmos is constantly adjusting and attempting to relax, but it never gets to such a

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quasi-stationary state. The consequence of this is what we call weather, including the focus of this volume: space weather.

The non-steadiness of space weather arises from the dynamical properties of the magnetic force and its interaction with the other force fields – gravity, pressure, and inertia – as given by the MHD momentum equation (see Vol. I, Chapter 3):

$$\rho \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} + \nabla p = \rho \mathbf{g} + \mathbf{J} \times \mathbf{B}. \tag{1.5}$$

For a time-independent equilibrium to be possible, or at least one without motion, solutions without the $\mathrm{d}\mathbf{v}/\mathrm{d}t$ term must exist. But there can be no such equilibrium involving the magnetic field because of the different makeup of the stress tensors of the three forces. On this point, Eugene Parker states in his book *Cosmical Magnetic Fields* (1979): “When there is a magnetic field present in a compressible fluid, there can be no equilibrium unless the gravitational force is parallel to the magnetic force” (p. 298), which of course is not possible everywhere within a naturally occurring, autonomous, gravitationally bound magnetized plasma. The role that the gravitational force plays in establishing an equilibrium can be stated in terms of the stress tensors of the three forces: thermal pressure, gravity, and magnetism. Whereas the pressure terms in the stress tensors of the thermal pressure force and magnetic field force are positive definite – they act to force the plasma to expand – the corresponding term for the gravitational force is negative definite – it acts to force the plasma to contract. Therefore, unless restrained by gravity, hot plasmas and magnetic fields would expand indefinitely (note that because of the specific form of the gravitational field equations it is not the pressure term in the gravitational stress tensor that causes matter to contract, it is the tension term – gravity really does pull). That it is the nature of hot plasmas and magnetic fields to expand and of gravitational fields to contract can also be seen from the virial theorem for an isolated system (e.g. Rossi and Olbert, 1970, p. 305):

$$\frac{1}{2} \frac{\mathrm{d}^2 I}{\mathrm{d}t^2} = 2T + M - G, \tag{1.6}$$

where I is the trace of the moment-of-inertia tensor of the system, T is the total kinetic energy (bulk plus thermal), M is the total magnetic energy, and G is the gravitational energy (taken to be positive definite like the other energies). Thus, equilibrium is possible only if the gravitational energy term balances the kinetic and magnetic energy terms, which act to make the system expand, thereby increasing the system’s moment of inertia.

Taken together, as in the Sun, the three forces – thermal pressure, gravity, and magnetism – produce a situation in which gravity and pressure are in quasi-equilibrium, but the magnetic field with its positive pressure expands and, being massless, becomes buoyant in the pressure gradient set up by the pressure–gravity

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equilibrium. Thus begins the odyssey of a magnetic flux tube newly generated in the subsurface solar dynamo. But this story is complex and is better told in chapters dedicated to it (Vol. I, Chapters 4 and 8; and Vol. III).

For the present purpose, the point is that in the Sun the magnetic field necessarily introduces motion, and this motion is subject to instabilities that result in magnetic structures with a wide range of scale sizes. The situation is further complicated by thermally driven motion fields, such as convection cells and differential rotation, that redistribute and concentrate magnetic flux. What, on occasion, raises this interesting but esoteric behavior to a level of importance to space weather is that magnetic structures sometimes reach a dimension so large that the amount of ambient energy that can be tapped explosively by an instability (the nature of which is the subject of ongoing research, see this volume, Chapter 6) is huge enough to disrupt the space between Sun and Earth and beyond.

1.3 Structure and dynamics of the local cosmos

The magnetic field's inherent tendency to expand does not by itself account for its space weather effectiveness. If expansion were enough then the expanding corona unassisted by the magnetic field would manifest storms, which it does not do. An additional property of the magnetic field that adds to its space weather effectiveness is tension. Tension is not a property of thermal pressure but, as noted above, it is a property of gravity. Tension allows gravity and the magnetic field to organize matter into coherent volumes. In the case of gravity, one such volume is called the Sun. As for the magnetic field, tension gives spatial coherence to magnetic flux tubes through transmission of Alfvén waves (a statement that assumes the validity of the MHD condition, i.e. the "freezing" of magnetic flux to the plasma). There is an important difference regarding the types of volumes that the gravitational and magnetic tension forces organize. The gravitational field has no shielding currents ($\nabla \times \mathbf{g} = \mathbf{0}$), and since its source is mass density ($\nabla \cdot \mathbf{g} = -4\pi G\rho$), it has no discontinuities because that would require an infinite mass density. Hence, the gravitational field is relatively homogeneous; it varies smoothly and continuously in space. On the other hand, the magnetic field has shielding currents ($\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$) which spontaneously form discontinuities, called current sheets (Parker, 1994). Therefore the flux tubes into which the magnetic field organizes plasma by tension can have relatively well-defined outer boundaries.

In fact one may picture the heliosphere as being filled rim to rim with more-or-less discrete magnetic flux tubes (Vol. I, Chapters 4 and 6). On the Sun these take the form of filaments, fibrils, and sunspots, to name a few. In the heliosphere flux tubes range in size from the dissipation scale of solar wind turbulence

(Vol. I, Chapter 7) up to global-scale spiral flux tubes that emerge from coronal holes. Planetary magnetospheres are composites of magnetic flux tubes with dimensions from flux-transfer events – small tubes that adhere like parasites to a magnetosphere's "skin" – up to the open-field-line lobes that constitute the magnetotail. The heliosphere's menagerie of flux tubes is tightly packed since a magnetic flux tube expands until stopped by another flux tube expanding in the other direction. For example, magnetospheres are magnetic flux tubes anchored in gravitating planets, which expand until stopped by the momentum-bearing, plasma-filled flux tubes of the solar wind. The dynamics of expanding magnetic flux tubes results in a network of flux tubes separated by current sheets and filling the heliosphere. Current sheets so formed play an important role in space weather by being sites of magnetic dissipation known generally as magnetic reconnection (Vol. I, Chapter 5). Manifestations of magnetic reconnection at current sheets – in some cases quite dramatic manifestations – have been observed on the Sun, in the solar wind, and at various places around magnetospheres.

To recount briefly, from the structure of the stress tensors of the three forces that act on magnetized plasmas in cosmic settings one can deduce these general properties:

(i) On time scales relevant to space weather, gravitational fields are smoothly varying fixtures of space that do not change in time. In contrast, the magnetic field forms a discontinuous, space-filling network of flux tubes that are for the most part in a continual process of non-steady creation and dissipation.
(ii) Plasmas and magnetic fields will expand indefinitely unless held down by a gravitational field or, at a local level, unless restrained by opposing expansions.
(iii) Gravity and pressure create stable, static structures (thermally driven convection and circulation excepted and discussed separately) whereas magnetic fields do not form stable, static structures with gravity or pressure, but in a fluid medium like the Sun form buoyant flux tubes that shred on rising and (passing here from deduction to observation) reform on the surface into filaments, tubes, and loops that cover a great range of sizes.

The manifold sizes, forms, and temporal modes of magnetically derived structures (described here in Chapter 5) are not deducible merely from the structure of the stress tensors of the participating forces. To understand these – indeed, not just the extremes but all space weather phenomena – is part of the business of heliophysical research as covered in these volumes.

Creation, buoyant rise, surface transport, flux-tube formation, stretching, expansion, and dissipation-assisted expulsion name events in the lives of magnetic field structures that at any time and at all times traffic in their thousands from the Sun to the heliopause and create the time-dependent conditions that constitute the solar manifestations of space weather. These magnetic structures are, of course, plasma filled. They form a continuous network of moving magnetic plasma carriers that stretches about 100 AU from the Sun to the border of the heliosphere. The geometry and topology of the network of magnetic plasma carriers reflects the distribution of closed magnetic structures on the Sun and thus changes with the phase of the solar cycle. At solar minimum it usually forms a singly connected wavy sheet, called the streamer belt, forming a low-latitude, Sun-circling band. By the time of solar maximum it has evolved into a multiply connected, pole-to-pole honeycomb-like network. If one could see it, the network would be streaked with flux tubes of variable density and spotted with magnetized plasma blobs of many sizes, mostly advecting outward with the solar wind. Within the heliosphere, but outside the network, we have the domain of the fast, more-or-less unstructured solar wind that emanates from coronal holes and fills most of the three-dimensional heliosphere. Typically one to a few times per day, this picture of orderly outward transport through 3D volumes of fast solar wind interlaced with 2D-like sheets of magnetically structured slow solar wind is disrupted by explosive ejections of quasi-spherical magnetic clouds that expand rapidly and shoot outward. These are coronal mass ejections, CMEs, the bringers of space storms.

CMEs are macroscale magnetic flux tubes that can suddenly, coherently form low in the corona and accelerate to speeds sometimes in excess of 2000 km/s before leaving the Sun (Chapter 5). As presently understood, their high speed is a consequence of unbalanced magnetic forces operating on magnetically organized volumes of plasma (Chapter 6). By contrast – to emphasize again the magnetic field's role as the prime generator of space weather events – the pressure gradient force (aided by waves) is able to propel the solar wind to peak speeds of only about 800 km/s, as measured by the Ulysses spacecraft over the solar poles. The storm that follows a CME's arrival at Earth – a magnetic storm as it has been called since before CMEs were discovered – disturbs the magnetic field everywhere in the magnetosphere and at ground level, sometimes enough to disrupt power and communications systems (Chapter 2). The radiation belts in the magnetosphere are pumped up and become more than usually hazardous to satellites and astronauts (Chapters 13 and 14).

As mentioned, CMEs often move faster than the prevailing solar wind and thus plow through it, sweeping it up and compressing it to form shock waves. CME shock waves can claim importance not just because they signal the arrival of the storm (and so predicting their time of arrival is a high-priority activity of space weather forecasters), but also because they themselves are the generators of one of the most serious hazards of space: solar cosmic rays, or as they are more conventionally called, solar energetic particles (Chapter 8). In the rarefied solar wind,

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shock waves, viewed at the microscale, are not the result of particles impacting particles with consequent rapid thermalization, as happens in dense media, but rather of waves impacting particles that in turn stimulate the impacting waves through a positive feedback process. Here a subset of the particles can experience multiple, energy-increasing wave encounters before leaving the energy-exchanging shock layer and end up with energies high enough to be of concern to humans who would otherwise have no interest in CMEs. These subjects fall under the headings of particle acceleration in shocks, which Chapter 8 treats in substantial detail, and of the radiation effects on biological materials and spacecraft hardware, which are reviewed in Chapters 13 and 14.

CME shock waves occupy a special place in heliophysical studies because of their sometimes harmful effect on human enterprises outside of heliophysics. But within heliophysics they represent just one example, not especially exceptional, of a large population of shock waves. Shock waves form not only in front of fast CMEs but wherever the solar wind impacts relatively stationary objects, such as planets and the interstellar medium, and where fast solar wind streams are brought into contact with slow solar wind streams by the spiral geometry that the Sun's rotation imparts to all long-lived solar wind structures, so-called corotating interaction regions (CIRs). The frequent occurrences of CMEs, CIRs, and the multitude of planets result in a collection of shock waves that are accessible by spacecraft for detailed study, which is an advantage that puts heliophysics at the forefront in the study of collisionless shocks and particle acceleration at shocks. In this regard Eugene Parker in his *Cosmical Magnetic Fields* has stressed the value of the broader role that heliophysical research plays: "It cannot be emphasized too strongly that understanding of the magnetic activity in the astronomical universe can be achieved only by coordinated study of the various forms of activity that are accessible to quantitative observation in the solar system." Accordingly, Chapter 7 treats shock waves in their heliophysical varieties and, as already noted, Chapter 8 treats particle energization at shocks generally. The heliosphere serves as a laboratory not only to study energization of particles at shocks, but also to look into their transport within the heliosphere once energized, as Chapter 9 describes. Here the coverage includes galactic cosmic rays as well as locally produced energetic particles.

1.4 Energetic particles

On the topic of energetic particles we may segue from the Sun and the solar wind as places where the elements of space weather are generated to magnetospheres as places that lie at the receiving end of all this generation. But not passively – magnetospheres also generate space hazards, especially energetic particles, which,

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magnetically trapped, fill reservoirs known as radiation belts because they circle the planet equatorially. Earth's radiation belts (also known as the Van Allen belts) are best known, but all magnetized planets have them. They reach their acme of damage potential at Jupiter. The origins and properties of radiation belts are related in Chapter 11, and this concludes the book's description of hazardous space weather elements as such. But recall that all space weather elements entail the conversion of energy between the kinetic and the magnetic forms – kinetic energy of subsurface flows in the dynamo region of the Sun creates magnetic energy, some of which eventually converts explosively into the kinetic energy of CMEs, and some of which drives hydromagnetic shock waves (creating magnetic energy), the dissipation mechanism for which entails the energization of particles (creating kinetic energy). Once CMEs reach Earth and create magnetic storms, the swapping of energy back and forth, starting with the kinetic energy of the CME and ending in part in the radiation belts, becomes even more involved. This story merits its own treatment in Chapter 10, which considers energy conversion at planetary magnetospheres in a fully general way.

The properties of space weather elements that render them hazardous aid in their detection and measurement. Energetic particles can be detected and measured directly *in situ* with instruments carried on spacecraft. *In-situ* measurements have sampled the heliosphere's energetic particles from its inner region around Mercury to its border with the interstellar medium. As Chapter 3 describes, such measurements have determined how electrons and ions from protons to multiply ionized iron are distributed over multiple decades of energy, revealing long tails extending to high energies (the space weather hazardous range) ending finally in cutoffs. These data have led to the discovery that the high-energy tails have a universal slope, instancing Parker's pronouncement on the value of quantitative heliophysical studies. What cannot be measured directly *in situ*, as near the Sun or in the heart of Jupiter's radiation belts, can often be inferred through X-rays and synchrotron radiation and other emissions that energetic electrons cause. Chapter 4 reviews these techniques and shows how the radiative signatures of energetic particles have proven invaluable in probing unreachable environments and, with the advantage of global monitoring of the space environment, of continuously documenting the occurrence of explosive energy conversion events.

1.5 Weather and climate in space

We have named many of the main players in magnetically induced space weather: networks of advecting blobs and ropes of magnetized plasma, CMEs, magnetic storms, shock waves, solar energetic particles, cosmic rays, and radiation belts. As

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a prelude to this cataloging of space weather elements we emphasized the difference in the behavior of gravitationally organized matter and magnetically organized matter. We return here to this difference as it shows up in time-dependent (weather-like) phenomena; that is, we compare gravitationally organized weather with the magnetically organized type in terms of energy conversions.

Gravitationally organized weather is the kind of weather that occurs in the atmospheres of the Sun and the planets. Weather arises in response to a need to move energy from a source to a sink. On the Sun the source is thermonuclear reactions in the core and the sink is electromagnetic radiation from the photosphere. A small fraction of this energy flow is diverted into the generation of magnetic fields, which is the source of energy for space weather, as already narrated. To represent weather on planets, we will look at the Earth. Here the source of energy is incoming solar radiation, mostly in the visible band of wavelengths, and the sink is outgoing terrestrial radiation, mostly in the infrared (a small amount of energy enters the atmosphere from below, but it is negligible as a source of weather; this is not the case for the Sun, of course, or for the giant planets, which have a significant internal energy source that we are not considering).

The flow of energy from source to sink at both the Sun and the Earth is conveyed in part by the atmosphere carrying the energy from a hot region to a relatively cold region. However, in the case of the Sun, energy is transported mainly by means of radiative diffusion from the core to about 70% of the way to the photosphere. In the outer 30% of the Sun's atmosphere, radiative energy transport gives way to convective transport, the motion field of which takes the form of convection cells, which can be seen as a granular pattern in the photosphere. The photospheric granular pattern is more-or-less homogeneous since there is little variation in the rate of energy outflow over the solar surface to give a variation in the sizes and shapes of the granules; in magnetically active regions, granulation is deformed with little impact on the brightness, but in sunspots it is strongly suppressed, resulting in a pronounced drop in brightness.

A pattern of homogeneous convection cells is not a description that applies to the situation at Earth, where the rates of incoming and outgoing radiative energy vary significantly from equator to pole. Here, atmospheric transport acts to reduce the equator-to-pole temperature difference that would result from local radiative equilibrium. If the Earth did not rotate and solar radiation were nonetheless distributed uniformly in longitude (a highly artificial situation to make a point), there would be one global convection cell rising at the equator and sinking at the pole. But Earth's rotation does not allow an energy conveyor belt to stretch from equator to pole in one loop. Instead it takes three loops, like a gear chain with three gears. The gears are called cells, the Hadley cell in the tropics, the Ferrell cell at mid-latitude, and the polar cell on top. The Hadley cell drives them all. Each hemisphere (north and south) has such a three-celled conveyor belt carrying energy from