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Interconnectedness in heliophysics

Carolus J. Schrijver and George L. Siscoe

1.1 Introduction

The volumes on heliophysics, of which this is the third, emphasize universal processes for which some basic physical phenomenon manifests itself in a variety of circumstances throughout the local cosmos and beyond. The topics range from the variability of the star next to which we live to the distant interstellar medium, via planetary environments including, in particular, geospace in which a magnetic field and atmosphere shield us from most of the dangerous consequences of solar variability – taking us from solar flares, coronal mass ejections, and their associated energetic particles, via the dynamic interplanetary medium, to magnetospheric, ionospheric, and tropospheric consequences. This volume in particular emphasizes interconnectedness, which manifests itself in three different guises that appear, often implicitly, throughout the text.

First, there is the interconnectedness by the universal processes themselves: magnetohydrodynamics, radiative transfer, networks of chemical reactions, magnetic-field dynamics and topology, particle acceleration, shocks, turbulence, etc., pervade all three volumes. Second, we see the interconnectedness in the very evolution of the solar system, from the formation of the central star and its orbiting planets, to the impact of the star on planetary habitability, and the eventual demise of the solar system as we know it (Fig. 1.1). Third, there are many connections between a variety of research disciplines, each of which is advanced by what is learned from other disciplines, thus providing mutual support in their quest for deeper understanding.

This introductory chapter lights up the stage upon which the stories in this volume unfold by introducing some of the key components of each of these three faces of interconnectedness. The extensive network of linkages from one scientific discipline to another emphasizes how important it is to have a systems point of view, both for the individual researchers (to which we hope these books on

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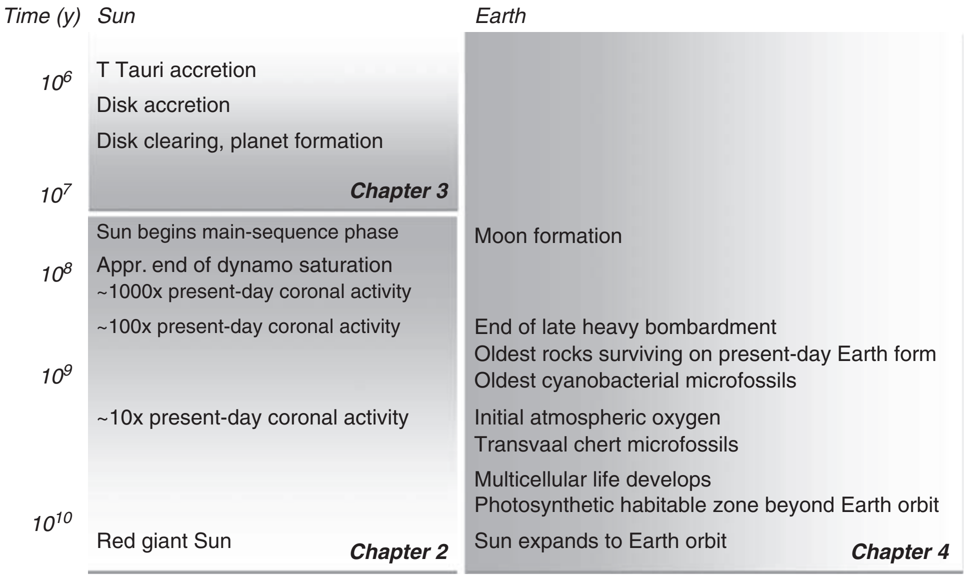

Fig. 1.1. Key events in the history of the Sun and Earth, pointing to the chapters in this volume in which these are discussed.

heliophysics will contribute) and for the various research disciplines and their supporting government agencies that must work together, recognizing that the advance of any one discipline occurs within the context of the combined activities in all of science and technology; a case for this was made eloquently by Stokes (1997), who pointed out that it is the combination of a broad spectrum of activities in pure science, applied engineering, and applied science that best stimulates societal advances.

We explore a few of the emerging themes in the sections below.

1.2 Field–plasma–neutral interaction

The interconnectedness of magnetic fields and ionized matter is pervasive throughout heliophysics. This field–plasma coupling is observable in many different domains, ranging from the Earth's ionosphere to the Sun's surface, and the effects reach even further from the deep interior of Sun and planets to the outermost reaches of the heliosphere. Substantial problems in this area continue to hamper progress in heliophysics, regardless of the ubiquity of field–plasma interactions, despite the possibility of both remote-sensing and *in-situ* observations (although by no means as ubiquitous as the processes themselves), and notwithstanding the rapid advances in computational (radiative) magnetohydrodynamics.

Some of the key problems in this research area involve the acceleration of ions and electrons to energies that vastly exceed the characteristic kinetic energies of the parent plasma population, and the role of a variety of waves in particle diffusion and acceleration (see Vol. II). Large solar flares and their associated coronal mass ejections, for example, appear to distribute energy over thermal, non-thermal, and bulk kinetic energies roughly equally in order of magnitude (see Vol. II, Chapter 5); clearly, particle acceleration is an integral part of the processes associated with destabilization and reconnection of magnetic field throughout heliophysics.

The coupling with neutral components within the plasma introduces complications not only in terms of electrical conductivity and drag forces (e.g. Vol. I, Chapter 12 and Vol. II, Chapter 12), but also can shift the ionization balance by collisions between the component species. The latter, of course, also leads to a network of chemical reactions that are well studied within the upper atmosphere of Earth and other planets (Chapters 13 and 16), in which non-local coupling by radiative transfer plays an important role (as it does in the solar near-surface layers).

Advances are being made by combining geospace and heliospheric studies (that offer at least some *in-situ* observing), solar remote-sensing observations, laboratory plasma physics, and many-particle or hybrid particle–MHD simulations with powerful computer facilities. Some of these connections are made in the *Heliophysics* series (particularly in Vol. II), but most of this area of interactions between scientific disciplines is beyond what can be covered in these few textbooks, having its own rich literature with branches connecting many of the physical sciences.

1.3 Transport of angular momentum and energy

Transport of angular momentum through the coupling of distant concentrations of mass occurs either through gravitational tides, by magnetic stresses, or by flows. Gravitational coupling has obviously played an important part in the spin-orbit synchronization of the Earth's single moon. This coupling continues to be important as a stabilizer for the direction of the Earth's spin axis (Chapter 4), even as it causes the precession of that axis with associated climatic effects (Chapters 11 and 12).

Tidal forces also act significantly on Jupiter's moon Europa and Saturn's moon Enceladus, in which they appear to result in liquid water in their interiors (Chapter 4), which makes these moons interesting objects to study from an exobiological perspective. Tidal spin-orbit coupling also leads to the formation of short-period, highly active binary stars (like the so-called RS CVn type binary systems; see Chapter 2). Gravitational tidal coupling is generally well understood, and thus the transfer of rotational energy can be estimated with reasonable accuracy.

Angular momentum transport via the magnetic field is important in the coupling of protostars and young T Tauri stars to their surrounding disks and magnetized

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stellar winds (Chapter 3 in this volume, and Vol. I, Chapter 9). After the early formation phases of a planetary system, the loss of stellar angular momentum continues through a stellar wind, leading to magnetic braking of the stellar rotation and the concomitant gradual decrease in stellar activity with age (Chapter 2). In tidally interacting binaries with one or more magnetically active components, the loss of spin angular momentum by a stellar wind drains the orbital angular momentum reservoir, eventually leading to the merger of the component stars, leaving an old but rapidly spinning single star (like FK Comae). The theory of the loss of angular momentum by a stellar wind is very much incomplete, but observations of stellar clusters and binary stars whose ages can be estimated from evolutionary phases of the component stars, measurements of the solar wind for several decades throughout the heliosphere, and data on the stellar equivalents of the heliospheric bow shock have established a fair level of empirical knowledge (Chapter 2).

Angular momentum transport by flows inside astrophysical bodies is the cause of their near-rigid rotation with latitude and depth of the solar interior (e.g. Chapter 5). But the models of the full convective envelopes of stars and giant planets need to advance significantly before we can use their results in, for example, magnetohydrodynamic dynamo models in which the non-rigid rotation and other large-scale circulations appear to be crucial (Chapters 5 and 7).

Transport of kinetic and electromagnetic energy is of such obvious importance throughout heliophysics that it needs no mention here. Understanding it well enough that we can formulate accurate self-consistent models of, for example, photosphere-to-corona, stratosphere-to-magnetosphere, or Sun-to-planet energy transfer is, of course, another matter that is only partially discussed in these volumes.

1.4 Dynamo action

Dynamo action or, more specifically, the generation and maintenance of a (generally varying) magnetic field against diffusive decay (see Vol. I, Chapter 3 and Chapters 5, 6, and 7 in this volume), is a widespread phenomenon throughout the universe, from entire galaxies to the scale of planets, spanning a range of scales of $\mathcal{O}(10^{14})$. The stellar dynamo is critical to the very formation of stars and their planetary systems (Chapter 3) and to the shielding of planetary atmospheres against, for instance, ablation by stellar winds (Chapter 4) and the effects of energetic particles (galactic cosmic rays and solar energetic particles), and interplanetary manifestations of coronal mass ejections (see Chapter 9 and various chapters in Vols. I and II).

Astrophysical and planetary dynamo theory and modeling (Chapters 5, 6, and 7) clearly have much in common, both in their basic processes and – at least in the most active stars – perhaps even in the domains of their characteristic magnetic Reynolds numbers, as argued in Chapter 7. The latter suggests a universal scaling property (Section 7.6.5) that measures “saturated” dynamo action (Section 2.3.2) in terms of the available energy from either nuclear fusion in stellar cores or nuclear fission and residual thermal energy in planetary interiors. This similarity in astrophysical theaters of dynamo action enables the direct application of numerical magnetohydrodynamic models at currently achievable magnetic Reynolds numbers to planets and at least some types of stars alike; such a direct comparison between models and observations may lead to an explanation of the generally dipolar field of the coolest dwarf stars (Section 2.7) and it raises the possibility of irregular field reversals in such stars similar to what is found for the geodynamo and its models (Section 7.2.2.3).

Despite remarkable advances in the numerical modeling of astrophysical dynamos, a comprehensive dynamo theory with predictive capabilities has yet to be developed: describing the Sun’s decadal and multi-decadal patterns in its magnetic activity, or the characterization of stellar activity levels based on the stars’ fundamental properties, remain beyond current capabilities. Here, both astrophysical and geophysical empirical data provide critical input. Studies of populations of Sun-like stars have revealed the scaling of stellar magnetic activity with rotation rate, multi-decade observations of stars like the Sun are beginning to reveal a richness of long-term variability well beyond the historical records of solar variability, and analysis of the stratification of isotope abundances and chemical composition of ice deposits spanning multiple centuries are expanding our view of solar–heliospheric activity by hundreds of years up to possibly hundreds of thousands of years beyond historical records (Chapters 2, 7, 11, and 12). Moreover, understanding the formation history of stars, as described in Chapter 3, relies on improved understanding of stellar dynamos (and, likely, dynamos within the innermost, warm parts of accretion disks).

Improved understanding of all these areas – star formation, stellar activity, star–planet connections, magnetospheric shielding, . . . , and the underlying dynamo action – are advancing jointly through their interconnectedness. The need for a correct interpretation of the empirical data that are in principle available reaches even further into apparently distant scientific disciplines: e.g. the proper reading of ^{10}Be (half life of 1.5 Myr) concentrations found in arctic and antarctic ice sheets (Chapter 11), or ^{14}C (half life 5.7 kyr) to ^{12}C isotope ratios used in tree-ring studies, requires that one also understand how these isotopes are formed (which involves cosmic-ray physics, discussed in Chapter 9, and nuclear physics) and how they are transported and deposited (bringing in atmospheric transport processes, paleoclimatology, and the geological and atmospheric processes involved in precipitation of the ejecta from volcanic eruptions – discussed in Chapters 4, 15, 11, and 12 – as well as the meandering transport of galactic cosmic rays against the turbulent outflowing solar wind – discussed in Chapters 8 and 9): just imagine, as you read this volume, the chain of processes from the acceleration of, say, a proton to become a member of the high-energy galactic cosmic-ray population to the storage of the ^{14}C isotope in living tissue, including yours, and how the use of the ^{14}C to ^{12}C isotope ratio in archeological dating studies is entangled with understanding of the variability of solar activity over the past millennia.

1.5 Extreme events and habitability

We encounter power laws throughout heliophysics, such as in the energy distribution of solar and stellar flares (Vol. II, Chapter 5, and Chapter 2 in this volume), solar coronal mass ejections (Vol. II, Chapter 6), energetic particles and galactic cosmic rays (Vol. II, Chapter 9, and Chapter 9 in this volume), and in the flux distribution of solar active regions (Chapter 2). In many of these cases, there is insufficient empirical statistical knowledge to establish whether there are cutoffs to these distributions for the largest or most-energetic events. Yet, although very large events are rare, they may not be rare enough to ignore their potential effects on evolutionary time scales of planets or even on the more ephemeral manifestation of life on planets. For example, the energy distribution of flares on active stars (Section 2.3.3) continues up to at least three orders of magnitude larger than the largest solar flares documented historically. One observation suggests that events another three orders of magnitude larger are possible on what appears to be a run-of-the-mill G1.5 V star, i.e. a star very much like our own Sun, at least in spectral type.

Extrapolation of the observed power-law frequency distribution of energies, and estimation of the equivalent radiation dose at ground level by energetic particles associated with such events, suggests that if such extreme events occur on a star of solar-like activity, they could have impacts on life on Earth on geological time scales. We do not currently know what limits the upper end of the spectrum of flare energies, how the energy spectrum of solar energetic particles changes towards extreme events, or how to reliably convert the energy in energetic particles to damage potential in biological tissue. But that flares can be larger than observed by our present-day instrumentation seems very likely, if only because of the estimated magnitude of the large white-light flare reported on in 1859 by Carrington and Hodgson (see Vol. II, Chapters 2 and 5). Such flares, and their associated coronal mass ejections (suggested by sporadic reports made centuries ago of what could be aurorae at unusually low latitudes), would have substantial impact on our infrastructure in space (see Vol. II, Chapter 2).

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It appears both possible and instructive to find records of such large events in, for example, isotope ratios and chemical abundances in ice cores, or perhaps in sediment layers with unusually stable stratifications (see e.g. Usoskin, 2008, and McCracken *et al.*, 2001, for a discussion of past solar energetic particle events based on lunar samples and ice cores, which suggests a break in the power-law spectrum that would make extremely large events very rare, if not absent altogether). The combination of radiological studies of geological and snow-precipitation records, continued stellar observations of an ensemble of Sun-like stars, and advancing the modeling of active-region generation, magnetic destabilization, particle acceleration mechanisms, etc., likely will provide better constraints on such large events of importance to the habitability of planets and, in particular, to the protection of humanity's space assets by improved forecasting of extreme events.

Other "extreme events" described in this volume include the destabilization of the Kuiper belt leading to heavy bombardment and orbital modifications for the planets (Chapters 3, 4, and 11); rapid global climate changes subject to changes in atmospheric greenhouse conditions (Chapters 4 and 12); impacts of large comets (such as the large impact off the Yucatan peninsula some 65 Myr in Earth's past, or those observed on Jupiter in 1994 and 2009); and, of course, large volcanic eruptions (Chapter 12). We do not discuss potential events external to the heliosphere here, but refer to Vol. II, Section 2.6, for a brief discussion of some types of such events.

1.6 Our remarkable, remarkably sensitive environment

In 1960, Frank Drake devised an expression to estimate the number $N_{\rm C}$ of advanced civilizations within our galaxy, here shown relative to the number of stars N_* in the galaxy:

$$n_{\rm C} \equiv \frac{N_{\rm C}}{N_*} = \left(\frac{r_* \tau_{\rm C} f_{\rm i}}{N_*} \right) f_{\rm p} N_{\rm p} f_\ell, \tag{1.1}$$

where r_* is the characteristic rate of star formation within the galaxy (estimated to be $\mathcal{O}(10\,{\rm yr}^{-1})$), $f_{\rm p}$ is the fraction of stars with planets of which $N_{\rm p}$ per star might be able to support life, f_ℓ is the fraction of those planets that actually will develop life during the life time of the star, of which a fraction $f_{\rm i}$ develop intelligent life that persists for a time $\tau_{\rm C}$. Here, we omit a factor that quantifies how likely such civilizations would in principle be able to communicate with other such civilizations.

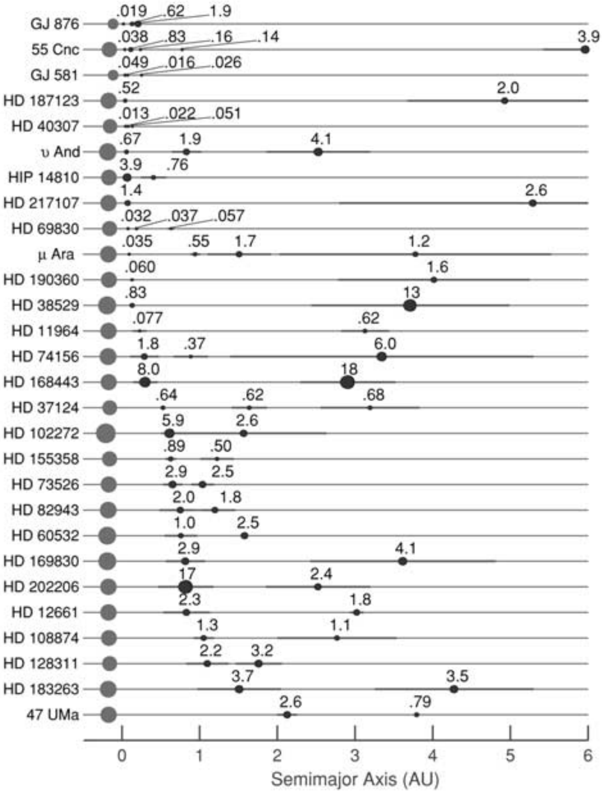

Fig. 1.2. Of some three hundred known planetary systems by 2009, at least 30% are known to contain more than one planet. This diagram shows the semimajor axes (relative to the radius of the Earth's orbit around the Sun) and minimum masses (in units of Jupiter masses) for the planets in multi-planet systems. The diameters of the symbols for the central stars scale with the cube root of stellar mass. (From Wright *et al.*, 2009. Reproduced by permission of the AAS.)

The recent and continuing rapid advances in instrumentation have led to the discovery of hundreds of exoplanets to date (Fig. 1.2),[†] and we can anticipate many more discoveries in the near future by, for example, NASA's Kepler mission that was launched in March of 2009. These studies suggest that $f_\mathrm{p} = \mathcal{O}(1)$.

Chapter 4 argues that because microbial life started so soon after the Late Heavy Bombardment of the Earth (Fig. 1.1), the fraction f_ℓ of planets that are in principle capable of supporting terrestrial-like life and that develop such life is also likely to be, very roughly – to astronomical standards – of order unity.

The characteristic number of planets per star that are capable in principle of supporting Earth-like life, N_p, at some time in its history is hard to estimate with our

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[†] See www.exoplanets.eu for a comprehensive list.

present-day knowledge. But because the width of the habitable zone (Chapter 4) is fairly large – at least in order of magnitude – compared to the size of a planetary system, we may not be too far off if we set $N_{\rm p} = \mathcal{O}(1)$.

In view of these arguments, many of which are discussed within this volume, we may argue that the product $f_{\rm p} N_{\rm p} f_\ell$ is likely not to be very much smaller than unity. Making even a very rough estimate of $n_{\rm C}$ is, however, subject to the very large uncertainty on the value of $\tau_{\rm C} f_{\rm i}$. This estimate for the characteristic lifetime of intelligent civilizations that form on a fraction of all life-bearing planets is the most uncertain number in Eq. (1.1). We have no basis in either statistical empirical knowledge or in validated social–biological–ecological studies to have much confidence in any number we assign to $\tau_{\rm C} f_{\rm i}$. Thinking about this number is of interest from a heliophysical perspective, though, because upper limits to $\tau_{\rm C}$ are likely dictated by events of extraterrestrial origin: impacts by large bodies, major stellar flares and mass ejections, destabilization of planetary orbits, atmospheric ablation, planetary drift relative to the habitable zone, and more exotic, extra-heliospheric phenomena such as supernovae; these and other processes that contribute to the long-term habitability of the Earth led to the title of a book that reviews these and other processes: *Rare Earth* by Ward and Brownlee (2000).

If we are pessimistic about the longevity of civilizations, and set $\tau_{\rm C} \sim 10^3$ yr, or if alternatively we take a characteristic time scale between disastrous impacts of $\tau_{\rm C} \sim 10^8$ yr, estimates for $n_{\rm C}$ would have upper limits spanning values of 1 in $3 \times 10^7/f_{\rm i}$ to 1 in $300/f_{\rm i}$. This vast range of values for $n_{\rm C}$ has obviously profound consequences for our likelihood of finding intelligent life in Earth's vicinity, compounded by the problem of establishing a realistic value for the fraction $f_{\rm i}$ of planets on which intelligent life develops in the first place.

1.7 System complexity

Before we end this introductory chapter, we point out one more thing: heliophysics is a discipline filled with sensitive non-linear interdependencies and feedback pathways. One example of that is found in the modeling of climate responses to the ~0.1% variability in total solar irradiance (Chapter 12), in which it may be that the effect of the variable radiative energy deposited within the stratosphere (a very small fraction of the total; Chapters 10 and 14) is amplified to have consequences throughout the troposphere and even the global ocean circulation. Another minute effect is found in the modeling of the differential rotation profile within the solar convective envelope, where pole–equator temperature differences of ~10 K are discussed for a region with a characteristic temperature of one million kelvin (Chapter 5).

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These effects sometimes occur where large opposing effects very nearly, but not quite, cancel out, as in a planetary climate system where energy input and output very nearly balance through a variety of channels that involve a range of time scales (from the near-immediate balance in the troposphere to the slow response of the deep oceans). This presents validation problems for such models requiring high fidelity of the codes, intercomparison of multiple codes or multiple realizations of the system in the real world, either by intercomparing multiple planets or many stars, or by comparison with long records of one system preferably under a variety of conditions of internal and external drivers (see Chapters 2 and 12). These problems go hand in hand with opportunities for discovery, because the near-cancellation of effects generally depends on time and place. High-resolution climate modeling, for example, suggests that, whereas solar driving may play a relatively minor role in global climate change in the past half century, the 11-year fingerprint of this driving may be more (or less) pronounced in any given local record than in globally averaged records (see Chapter 16).

Heliophysics is the science of all the processes within the local cosmos, from distant past to distant future, that govern the evolution of the Earth, the Sun, and the planet-bearing heliosphere in its entirety. Whereas heliophysics is not, per se, aiming to evaluate the Drake expression, it is interesting to contemplate how much of the physics discussed in this volume and in the preceding two needs to be combined into setting a heliophysical upper limit to $\tau_C f_i$ or in validation of highly complex non-linear numerical models.

We hope you enjoy the voyage through space and time offered in this volume, and invite you to think how to optimize the interaction of the many scientific disciplines that are explicitly mentioned and implicitly required in the making of this story.