1

Introduction

CAROLUS J. SCHRIJVER, FRANCES BAGENAL,
AND JAN J. SOJKA

1.1 Comparative heliophysics

Our knowledge of conditions – past, present, and future – throughout the solar system is rapidly advancing. We can specify the details of the evolution of the Sun, and can represent the conditions of its magnetic activity over time with fair certainty. We have explored – both remotely and in situ – many of the "worlds" throughout the solar system, from Mercury to Pluto, including asteroids and comets. Along with an appreciation of the diversity of conditions in space around all these environments comes the realization that the conditions here on Earth are remarkably just right for the only world that we know to sustain life. Specifically, Earth is in an orbit that has kept it within the range in orbital distances within which the planet has maintained liquid water at its surface throughout the past several billions of years. It orbits far enough from the Sun that tidal forces could not lock Earth's rotation to its orbital motion, thus allowing solar irradiance to be effectively distributed over the sphere on the relatively short time scale of the terrestrial day. Moreover, since the Late Heavy Bombardment some 4 billion years ago, Earth has received limited environmental debris (asteroids, comets, . . .). The impacts of the Sun's magnetic activity on the Earth have also been relatively benign, without overly detrimental effects of flares and coronal mass ejections. Moreover, the Earth is shielded well enough from galactic cosmic rays by both solar wind and terrestrial magnetism. And then there are the added conditions related to the internal properties of the planet that contribute to its ability to sustain life, including plate tectonics and dynamo action. In short, the Earth's characteristics are "just right" (see, e.g., Ch. 4 in Vol. III, and Ward and Brownlee, 2000, and also Vidotto *et al.*, 2014, and references therein, for select topics on cool stars and space weather and planetary habitability).

All of these circumstances conspire to a relatively stable environment, both in terms of the terrestrial climate and in terms of what we nowadays call "space weather". In order to understand the processes that create these environmental

Cambridge University Press
978-1-107-09047-7 - Heliophysics: Active Stars, their Astrospheres, and Impacts on Planetary Environments
Edited by Carolus J. Schrijver, Frances Bagenal and Jan J. Sojka
Excerpt
More information

conditions, and to appreciate the influences of space weather on the planet that is our only known compatible habitat, we need to advance a field of science called “heliophysics”. Heliophysics is the field that encompasses the Sun–solar system connections, and that therefore concentrates on the Sun and on its effects on Earth, the other planets of the solar system, and the changing conditions in space. As such, heliophysics has to cover an extraordinary range of topics, essentially being equivalent to ecology in attempting to describe a complex web of often non-linear interactions that certainly do not stop at the boundaries of the traditional scientific (sub-)disciplines or at the perimeters of domains maintained by funding agencies.

Heliophysics tackles the workings of an interconnected system of magnetic field and plasma that couples the Sun with her entourage that forms the solar system. Indeed, it is the commonality of plasma physics of this solar system family that has enabled the amalgamation of solar physics, cosmic ray physics, solar wind physics, magnetospheric physics, ionospheric physics, and more into heliophysics. What plasma physics does on the Sun to generate huge bursts of energy as photons, solar wind structures, and energetic particles, plasma physics also does on the planets, in effect protecting them from these energetic outbursts via magnetospheres and ionospheres, whose activity at times interferes with our technological tools on and near Earth.

The “habitable zone” of a planetary system is commonly defined loosely as the range of distances of planets relative to their parent star within which water can exist at the planet surface as a liquid. But from a heliophysics point of view, the definition of “habitable” also includes how well the planet is shielded from what the nearby star or the surrounding galaxy throws at it. In that sense, a habitable planet is one that provides a magnetic shield that stalls and deflects the energetic solar wind structures and cosmic rays respectively. The upper atmosphere of a habitable planet similarly plays the role of absorbing harmful radiations, in the process creating the planet’s ionosphere. The ionospheric shield also safely dissipates the energy carried by huge currents generated in the magnetosphere as the planet’s magnetic field stalls the solar wind structures. Heliophysics can thus be viewed as the integrating science that will determine which exoplanets are habitable to a technologically advanced life form. In fact, the aspects of this definition of “habitable planet” require understanding of space weather.

This is the fourth volume in a series that introduces the rich spectrum of topics covered in heliophysics (see Table 1.1 for the volume titles and Table 1.2 for thematically sorted chapter titles). Where the preceding three volumes focus on describing and understanding the conditions in our local cosmos, particularly where the Sun and its planets are concerned, here we take a somewhat different perspective. The focus of this volume is what we can learn from other stars, from

Cambridge University Press
978-1-107-09047-7 - Heliophysics: Active Stars, their Astrospheres, and Impacts on Planetary Environments
Edited by Carolus J. Schrijver, Frances Bagenal and Jan J. Sojka
Excerpt
More information

Table 1.1 *Titles of the volumes in the Heliophysics series. References in this volume to chapters in other volumes use the numbering as in this table.*

Volume	Title and focus
I	Plasma physics of the local cosmos
II	Space storms and radiation: causes and effects
III	Evolving solar activity and the climates of space and Earth
IV	Active stars, their astrospheres, and impacts on planetary environments
V[a]	Space weather and society

[a] Available online at http://www.vsp.ucar.edu/Heliophysics/science-resources-textbooks.shtml

Table 1.2 *Chapters and their authors in the Heliophysics series sorted by theme (continued on the next page), not showing introductory chapters.*

Universal and fundamental processes, diagnostics, and methods	
I.2. Introduction to heliophysics	*T. Bogdan*
I.3. Creation and destruction of magnetic field	*M. Rempel*
I.4. Magnetic field topology	*D. Longcope*
I.5. Magnetic reconnection	*T. Forbes*
I.6. Structures of the magnetic field	*M. Moldwin* et al.
II.3 In-situ detection of energetic particles	*G. Gloeckler*
II.4 Radiative signatures of energetic particles	*T. Bastian*
II.7 Shocks in heliophysics	*M. Opher*
II.8 Particle acceleration in shocks	*D. Krauss-Varban*
II.9 Energetic particle transport	*J. Giacalone*
II.11 Energization of trapped particles	*J. Green*
IV.11 Dusty plasmas	*M. Horányi*
IV.12 Energetic-particle environments in the solar system	*N. Krupp*
IV.13 Heliophysics with radio scintillation and occultation	*M. Bisi*
Stars, their planetary systems, planetary habitability, and climates	
III.3 Formation and early evol. of stars and proto-planetary disks	*L. Hartmann*
III.4 Planetary habitability on astronomical time scales	*D. Brownlee*
III.11 Astrophysical influences on planetary climate systems	*J. Beer*
III.12 Assessing the Sun-climate relationship in paleoclimate records	*T. Crowley*
III.14 Long-term evolution of the geospace climate	*J. Sojka*
III.15 Waves and transport processes in atmosph. and oceans	*R. Walterscheid*
IV.5 Characteristics of planetary systems	*D. Fischer & J. Wang*
IV.7 Climates of terrestrial planets	*D. Brain*

Table 1.2 *(Continued from the previous page)*

The Sun, its dynamo, and its magnetic activity; past, present, and future	
I.8. The solar atmosphere	*V. Hansteen*
II.5 Observations of solar and stellar eruptions, flares, and jets	*H. Hudson*
II.6 Models of coronal mass ejections and flares	*T. Forbes*
III.2 Long-term evolution of magnetic activity of Sun-like stars	*C. Schrijver*
III.5 Solar internal flows and dynamo action	*M. Miesch*
III.6 Modeling solar and stellar dynamos	*P. Charbonneau*
III.10 Solar irradiance: measurements and models	*J. Lean & T. Woods*
IV.2 Solar explosive activity throughout the evol. of the solar system	*R. Osten*
Astro-/heliospheres, the interstellar environment, and galactic cosmic rays	
I.7. Turbulence in space plasmas	*C. Smith*
I.9. Stellar winds and magnetic fields	*V. Hansteen*
III.8 The structure and evolution of the 3D solar wind	*J. Gosling*
III.9 The heliosphere and cosmic rays	*J. Jokipii*
IV.3 Astrospheres, stellar winds, and the interst. medium	*B. Wood & J. Linsky*
IV.4 Effects of stellar eruptions throughout astrospheres	*O. Cohen*
Dynamos and environments of planets, moons, asteroids, and comets	
I.10. Fundamentals of planetary magnetospheres	*V. Vasyliūnas*
I.11. Solar-wind magnetosphere coupling	*F. Toffoletto & G. Siscoe*
I.13. Comparative planetary environments	*F. Bagenal*
II.10 Energy conversion in planetary magnetospheres	*V. Vasyliūnas*
III.7 Planetary fields and dynamos	*U. Christensen*
IV.6 Planetary dynamos: updates and new frontiers	*S. Stanley*
IV.10 Moons, asteroids, and comets interact. with their surround.	*M. Kivelson*
Planetary upper atmospheres	
I.12. On the ionosphere and chromosphere	*T. Fuller-Rowell & C. Schrijver*
II.12 Flares, CMEs, and atmospheric responses	*T. Fuller-Rowell & S. Solomon*
III.13 Ionospheres of the terrestrial planets	*S. Solomon*
III.16 Solar variability, climate, and atmosph. photochemistry	*G. Brasseur* et al.
IV.8 Upper atmospheres of the giant planets	*L. Moore* et al.
IV.9 Aeronomy of terrestrial upper atmospheres	*D. Siskind & S. Bougher*
Technological and societal impacts of space weather phenomena	
II.2 Introduction to space storms and radiation	*S. Odenwald*
II.13 Energetic particles and manned spaceflight	*S. Guetersloh & N. Zapp*
II.14 Energetic particles and technology	*A. Tribble*
V.2 Space weather: impacts, mitigation, forecasting	*S. Odenwald*
V.3 Commercial space weather in response to societal needs	*W. Tobiska*
V.4 The impact of space weather on the electric power grid	*D. Boteler*
V.5 Radio waves for communication and ionospheric probing	*N. Jakowski*

other planetary systems, and from non-planetary bodies within the solar system. With this, we attempt to open up a view of what could be termed "comparative heliophysics" that aims to learn about our local cosmos by looking beyond it, and in doing so also enables the converse.

Cambridge University Press
978-1-107-09047-7 - Heliophysics: Active Stars, their Astrospheres, and Impacts on Planetary Environments
Edited by Carolus J. Schrijver, Frances Bagenal and Jan J. Sojka
Excerpt
More information

Where experimental physics offers researchers the possibility to set key parameters to desired values, albeit to a range of values generally limited by the instrumental setup, heliophysics does not offer that valuable option to study the dependence of processes on any one of the environmental parameters. We cannot change the mass, age, spin rate, or chemical composition of the Sun or of the Earth. Nor can we change the distance at which our home planet orbits its parent star. This is a major complication not only in quantifying how these and other parameters affect the Sun–Earth connections, but even in determining which parameters are of critical importance in shaping the climate of space throughout the solar system.

As our observational technologies advance, and as our observational archives grow, however, even heliophysics can approximate an experimental science by looking not only at the present-day Sun, Earth, and other planets, but by studying conditions of a multitude of Sun-like stars, of the other bodies within the solar system, and increasingly of other planetary (or exoplanet) systems.

1.2 Exoplanets

Until the mid 1990s, no planets were known to orbit Sun-like stars other than those orbiting the Sun. Within the following two decades, our capabilities and knowledge advanced to the estimate – using statistical arguments based on the observed sample – that most stars that we see in the sky have a planetary system with one or more planets; even binary stars show evidence of circumbinary planets in at least 1 in 10 cases (note that roughly 1 in 2 “stars” in the sky is actually a binary system composed of two, often quite dissimilar, stars). Chapter 5 outlines the observational instrumentation and techniques that enabled this dramatic shift in our knowledge.

Instrumental limitations and the properties and orbital parameters of exoplanets have thus far kept the number of detected exoplanet systems at several thousand. But that number suffices to enable us to learn much about the formation and evolution of planetary systems and their planets, as discussed in Ch. 5.

For example, the combination of observations and numerical experiments suggests that gas giants accumulate up to a few hundred Earth masses of material – first the solids and then increasingly rapidly gases – within a matter of a few million years. This process is aided in its efficiency by the migration of growing planets within the young planetary system: planets are not bound to their initial orbits, but can migrate either inward or outward, subject to gravitational interactions, thus having access to a large volume of the primordial disk from which to collect material. Interestingly, it appears that it is the very collection process of matter onto the growing planet that causes mass redistributions within the disk so that their tidal effects can make planets migrate, particularly if other planets are forming elsewhere in the system, while the gravitational coupling between multiple young

Cambridge University Press
978-1-107-09047-7 - Heliophysics: Active Stars, their Astrospheres, and Impacts on Planetary Environments
Edited by Carolus J. Schrijver, Frances Bagenal and Jan J. Sojka
Excerpt
More information

planets in eccentric orbits can scatter bodies around (both in distance from their central star and in orbital inclination).

Planets may form into three distinct categories: terrestrial planets with radii up to about $1.7R_{\oplus}$, dwarf gas planets up to about $4R_{\oplus}$, and giant gas planets beyond that. Their radii and their atmospheric constituents appear to reflect their migration history within the primordial disk, but the details of these dependencies continue to be uncovered. The lower-radius group looks to be mostly rocky, while the intermediate-radius group shows evidence of an increasingly large gaseous envelope with increasing radius.

1.3 Cool stars and their space weather

Many stars exhibit signatures of stellar magnetism resembling what we see on the Sun. Even if spectroscopy does not provide direct evidence for a complex, evolving surface magnetic field, many stars do display one or more of a variety of tell-tale signatures: cool starspots that modulate the brightness as the stars rotate and the spots evolve, a warm chromosphere enveloping the star, a hot corona glowing in the EUV or in X-rays, or flaring. All this activity is rooted in the stellar dynamo process (see, e.g., Chs. 3 and 4 in Vol. I, and Chs. 2, 5, and 6 in Vol. III) that converts mechanical energy in 3D convective plasma motions of sufficient complexity into electromagnetic energy, directed into large-scale organization by the Coriolis forces acting within the rotating star.

Magnetically dominated phenomena in the atmospheres of stars bear similarities to what we observe on the Sun in a class of stars that we refer to as “cool stars”. Whether old or young, more or less massive than the Sun, these stars have two characteristics that set them apart from other stars. The first, as can be inferred from their name, is that they all have surface temperatures that are relatively low, making them yellow, orange, or red in appearance. It is another, related common characteristic that is directly responsible for making all cool stars exhibit solar-like magnetic activity: they all have a zone that extends up to their surfaces – i.e., an envelope – in which convective energy transport (through overturning bulk plasma motions) carries most of the energy outward.

This convection zone may be a shallow layer (as in mid-F type main-sequence stars of 1.2 solar masses) around a “radiative interior” (in which energy is transported primarily by a random walk of photons) or it may reach all the way to the very center (for main-sequence stars much cooler than the Sun, of spectral type late-M or cooler, around 0.3 solar masses or less). In the long-lived phase of stellar adulthood – when we characterize them as “main-sequence stars” – stellar mass may be used as differentiator: stars with masses below roughly 1.2 solar masses are cool stars. But stars in their infancy (prior to reaching hydrostatic stability

Cambridge University Press
978-1-107-09047-7 - Heliophysics: Active Stars, their Astrospheres, and Impacts on Planetary Environments
Edited by Carolus J. Schrijver, Frances Bagenal and Jan J. Sojka
Excerpt
More information

that follows initiation of nuclear fusion of hydrogen) or in their old age (after running out of most of the fusible hydrogen) have convective envelopes regardless of their mass, making it unambiguously clear that it is the convection that powers the stellar dynamo. We know from stellar population studies that the characteristics of the convective motions and their response to stellar rotation (through the Coriolis force) are the controlling parameters that set stellar magnetic activity levels.

The evolution of stars like the Sun and of their magnetic activity was summarized in Chs. 2 and 3 of Vol. III (for other introductory discussions of solar and stellar magnetism, see, e.g., Schrijver and Zwaan, 2000, and Reiners, 2012). In this volume, Ch. 2 uses observations of stellar flaring to piece together the history of impulsive activity of the Sun from its pre-main-sequence phase to old age. Observations of many stars and with different instruments sensitive to different energy ranges along the electromagnetic spectrum suggest that observable stellar flares (which are typically much more energetic than even the largest solar flares simply because smaller ones hide below present-day detection thresholds or within the quiescent background glow of the corona) have many properties in common, supporting the assumption that stellar and solar flares share the basic picture that was developed for magnetically driven, reconnection-powered solar impulsive events. Although that general picture appears to be widely applicable, we note that observations of stellar flares, and indeed also of solar flares, generally occur in narrow spectral bands that can range from hard X-rays to radio, or in broad spectral windows without spectral information. The result is that it remains a challenge to put solar and stellar flare observations on a common energy scale (preferably the bolometric scale that measures all of the temporary, sudden increase in photon output from stars that is the definition of flaring; see, e.g., Schrijver *et al.*, 2012).

The young Sun, in the first hundreds of millions of years of its main-sequence life, would most likely have exhibited flaring with energies exceeding 100 up to perhaps 1000 times the total energy involved in the largest recent flares, and would have displayed even these major events as frequently as roughly once a week. Over time, the frequency of flaring dropped sharply as the Sun lost angular momentum through the magnetized solar wind, a process that continues today albeit at a much reduced rate. This decrease in flare frequency would have been rapid over the first billion years or so of solar history, likely having slowed considerably over the most recent few Gyr. Whether there is an upper cutoff energy to solar flares that might also have dropped over time remains to be established: we do not know if the present-day Sun can still generate such enormous flares, albeit at vastly reduced frequency. On the one hand, we have no evidence that it did so in any available record, be it written or geological. On the other hand, there are observations of stars that look to be quite like the Sun in terms of internal structure and rotation rate that

Cambridge University Press
978-1-107-09047-7 - Heliophysics: Active Stars, their Astrospheres, and Impacts on Planetary Environments
Edited by Carolus J. Schrijver, Frances Bagenal and Jan J. Sojka
Excerpt
More information

have been observed to produce flares with energies hundreds of times larger than the largest flare recorded for the Sun in the past half century (see Sect. 2.2.3, and Schrijver and Beer, 2014).

Binary stars (in particular the tidally interacting compact ones) provide yet another experimental environment, both on dynamo activity and on flaring: in such stars, flare energies can reach up to 100 000 times those seen for the most energetic solar flares, possibly through tidal effects on dynamo action or through magnetic coupling between the stars. Although such large flares attract observers for the obvious reason that they stand out from the background emission of the stellar system and that they occur so often that they are readily captured within the limits of observing windows, it remains to be seen whether such enormous energies could ever have been released from flaring from the single star that we call the Sun at any phase of its evolution.

Although energetic flares can be observed on other stars throughout the electromagnetic spectrum, there are no unambiguous indicators of coronal mass ejections or energetic particle populations in the astrospheres of those stars; for those properties, we need to rely on solar and solar-system observations combined with numerical experimentation at least until detection techniques are developed that are far more sensitive than we have access to today.

1.4 Astrospheres, stellar winds, and cosmic rays

The interaction of the solar wind and the interstellar medium is discussed in Ch. 3. One of the effects of the solar wind is that Galactic Cosmic Rays (GCRs) are held at bay fairly effectively (e.g., Ch. 9 in Vol. II, and Ch. 9 in Vol. III). Changes in the solar wind and its embedded magnetic field over evolutionary to short-term time scales are associated with changes in the spectrum of the GCRs that can penetrate into the solar system to reach Earth orbit, because they affect the propagation of the GCRs into the inner solar system and also because these changes move the very boundary of the solar wind from where GCRs start their random-walk diffusive penetration of the solar system.

Over the billions of years in the history of the Sun, the solar system will have encountered very different interstellar medium (ISM) environments. ISM density contrasts reach up to a factor of a million, with densities ranging from some $0.005\,\mathrm{cm}^{-3}$ in tenuous, warm clouds to $10^4\,\mathrm{cm}^{-3}$ in dense, cool molecular clouds. Increasingly dense ISM environments would decrease the size of the heliosphere by pushing the heliopause – that separates the solar wind from the ISM with its GCRs – inward. Chapter 3 discusses how the heliosphere would vary with the properties of the solar wind and of the interstellar medium. Models suggest that the Earth would be shielded from the full effect of GCRs under almost all

Cambridge University Press
978-1-107-09047-7 - Heliophysics: Active Stars, their Astrospheres, and Impacts on Planetary Environments
Edited by Carolus J. Schrijver, Frances Bagenal and Jan J. Sojka
Excerpt
More information

circumstances. Even at an ISM density 100 times higher than in the local interstellar cloud (LIC), the termination shock (TS) would still be at about 10 Sun–Earth distances (astronomical units, or AU). Only at a density of multiple hundreds of times that in the LIC would the TS move inside of the Sun's present-day habitable zone (cf., Ch. 4 in Vol. III), exposing Earth to the full intensity of GCRs as well as to interstellar dust. A nearby supernova would do the same, plus expose Earth to the remnants of the stellar explosion themselves; this may have happened a mere 3 Myr ago, leaving a signature in the ^{60}Fe radioisotope in the Earth's crust (see Sect. 3.5).

When the Sun was younger, it most likely had a larger mass loss. How much larger remains to be established, but observations of Sun-like stars (Sect. 3.7.2) suggest the mass-loss rate may have been at least some 50 times higher than at present. For the present ISM conditions, that would have meant a heliosphere some seven time larger, with correspondingly much lower GCR intensities (cf., Ch. 11 in Vol. III). In the distant future, with weakening solar activity, the Sun's mass-loss rate is expected to decrease by a factor somewhere between 4 and 7 prior to the beginning of the subgiant and giant phases (Eq. (3.2)), and the heliosphere will correspondingly gradually shrink to about half its present size (to roughly Pluto's orbital radius; assuming present-day ISM conditions), and the GCR population in the inner solar system will thereby gradually increase.

Chapter 4 shows how models suggest that the GCR intensity around 1 GeV has likely increased by more than a factor of 100 since the Archean era (ending some 2.5 billion years ago) after the Late Heavy Bombardment when evidence for single-celled life is first seen on Earth (cf., Ch. 4 in Vol. III). Whether energetic particles originating from the more active young Sun would have compensated for the low GCR intensities around the young Earth remains to be seen: although young stars flare much more intensely and frequently (Ch. 2), we simply do not know enough about any associated coronal mass ejection (CME) activity to usefully constrain "SEP" events for the young Sun: whereas radio observations of stars may give some information on energetic particles trapped within coronae, no techniques are currently available to reveal energetic particles moving outward through astrospheres.

1.5 Astrophysical dynamos and space weather

Computer simulations provide us with glimpses of what space-weather phenomena may be like if the orbit of the planet is changed, or if the level of activity of the star is changed. Chapter 4 discusses, among other things, the effect of a variable stellar wind on a hypothetical magnetized planet at about a fraction of only a few tenths of the Sun–Earth distance. First, the rapid orbital motion would cause the planet's magnetotail to persistently be driven away from the essentially radial direction relative to the Sun–planet line that it has for Earth, by many tens of degrees. When coronal mass ejections (CMEs) would hit this planet, the magnetotail would be forced into the near-radial direction, thus shifting the associated auroral zones and the range of impacts of magnetospheric storms.

Planetary magnetism appears to be an important ingredient in the evolution of a planetary atmosphere, in part by setting the stripping effects of stellar winds. It also keeps energetic particles largely away from these atmospheres. As in the case of stellar dynamos, planetary dynamos require the combination of overturning motions in a conducting fluid and a deep-seated driver of such motions (see Ch. 6). The fluid in this case is indeed a liquid, of a viscosity that is considerable compared to that of the stellar gaseous plasma. The driver of the flows can be heat from impacts onto the planet (or smaller body), or released from nuclear fission of radio-active elements deep inside the planet, or from tidal forces. Or the driver of the flow may be a gradient in chemical composition maintained by a chemically differentiating phase transition from fluid to solid as the planet cools.

Astrophysical dynamos persist for a long time in bodies of sufficient size. Earth's magnetic field, for example, although variable in its detailed pattern and dominant directionality (i.e., polarity), appears to have maintained a roughly constant net strength over at least the past 3 billion years (Ch. 6) despite the fact that the dominant driver of the internal convective motions switched from thermal (nuclear decay) to compositional (chemical differentiation driven by Ni and Fe condensation onto the core, releasing lighter elements including Si, S, and O) about a billion years ago.

Astrophysical dynamos appear to generate structures in the magnetic field on a wide range of scales. This is immediately evident on the Sun, where we see bipolar regions emerge and evolve that span a range from the observational resolution limit (of order 100 km) up the full solar diameter (1.4 million km). For Earth, we cannot directly measure the small-scale structures, because the top of the dynamo region is deep inside the Earth, so that only the lower orders are readily measurable at the surface (see, e.g., Ch. 7 in Vol. III). If we look away from the solar surface by the same relative distance, we see a similarly "simple" structure, dominated by the dipole and quadrupole terms that shape the heliospheric magnetic field.

In smaller bodies, one key problem for exciting and maintaining a magnetic field is simply that their size lowers the magnetic Reynolds number by making the diffusion of magnetic field more effective relative to the motions shaping that field, all other things being equal (cf., Eq. (6.3)). In those smaller bodies with limited available primordial thermal energy or nuclear fission energy, and larger surface-to-volume ratios that speed up cooling, dynamos that do manage to operate should