HELIOPHYSICS

Active Stars, their Astrospheres, and Impacts on Planetary Environments

Heliophysics is a fast-developing scientific discipline that integrates studies of the Sun's variability, the surrounding heliosphere, and the environment and climate of planets. It encompasses all the variability that we know as space weather, but also enables us to understand the conditions leading to the relatively stable environment that supports life on Earth: our planet is in an orbit that has kept it within the habitable zone throughout the Sun's evolution, without overly detrimental effects of flares and coronal mass ejections, shielded well enough from galactic cosmic rays, and with the right amount of dynamo action.

This volume, the fourth in this series, explores what makes the conditions on Earth "just right" to sustain life, by comparing Earth to other solar-system planets, by comparing solar magnetic activity to that of other stars, and by looking at the properties of evolving exoplanet systems. By taking an interdisciplinary approach and using comparative heliophysics, the authors illustrate how we can learn about our local cosmos by looking beyond it, and, in doing so, also enable the converse.

Supplementary online resources are provided, including lecture presentations, problem sets, and exercise labs, making this ideal as a textbook for advanced undergraduate and graduate-level courses, as well as a foundational reference for researchers in the many subdisciplines of helio- and astrophysics.

The four volumes in the Heliophysics series are:

1. *Heliophysics – Plasma Physics of the Local Cosmos*
2. *Heliophysics – Space Storms and Radiation: Causes and Effects*
3. *Heliophysics – Evolving Solar Activity and the Climates of Space and Earth*
4. *Heliophysics – Active Stars, their Astrospheres, and Impacts on Planetary Environments*

CAROLUS J. SCHRIJVER is a Senior Fellow at Lockheed Martin Advanced Technology Center, California, where his work focuses primarily on the magnetic field in the solar atmosphere. His research includes the dynamics of magnetic field at and above the solar surface, how that shapes the heliosphere, and how it powers solar eruptions that are the drivers of space storms around Earth. Dr. Schrijver is involved in several NASA missions to better understand the Sun and the heliosphere. He is co-editor of the first three books in this series, and has published a popular science book entitled *Living with the Stars* on the multitude of connections between the human body, the Earth, the planets, and the stars.

FRANCES BAGENAL is Professor of Astrophysical and Planetary Sciences at the University of Colorado, Boulder. Her research comprises the synthesis of data analysis and theory in the study of space plasmas, and she has specialized in the fields of planetary magnetospheres and the solar corona. Professor Bagenal has been involved in NASA missions to planetary objects including Voyager, Galileo, and Deep Space 1, and she is an investigator on the New Horizons mission to Pluto, and the Juno mission to Jupiter.

JAN J. SOJKA is Department Head in the Department of Physics at Utah State University. His research explores how our upper atmosphere and its ionosphere are coupled with the magnetosphere and driven by the Sun and solar wind in an effort to unravel impacts on our technologies, focusing particularly on the modeling of the ionosphere and its couplings and drivers, to enable assessments of how well our theories conform to reality. For over four decades, Professor Sojka has been involved with sounding rockets, magnetospheric and ionospheric satellite missions, as well as numerous groundbased facilities. He is currently Co-Investigator on the NASA SDOs EVE instrument observing the X-EUV solar irradiance.

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Preface

Anyone who has ever seen a picture of Earth taken from deep space can be forgiven for thinking of these two words: "splendid isolation." Surrounded by millions of miles of uninterrupted black, the fragile blue globe seems profoundly alone, disconnected from anything else.

Nothing could be further from the truth: Earth is profoundly connected to our star.

The bright blue disk is just the most obvious evidence. A non-stop flood of sunlight warms the planet, simultaneously allowing us to live and to see. Invisible connections are equally profound. Solar radiation puffs up our atmosphere, altering its structure and chemistry. Solar winds buffet our magnetosphere, lighting up polar skies with curtains of light, and driving currents of electricity through the soil below. Solar magnetism deflects cosmic rays, moderating the effect of the Galaxy on our tiny home in space.

Years ago, the study of the Sun–Earth connection was edgy stuff. Big Thinkers held the planet and the star to be a system. From this synthesis emerged many new ideas and a new discipline called "heliophysics."

Now we know that they weren't thinking big enough. Like Earth, every world in the solar system is connected to its star. From the surface chemistry of Mercury, to the tattered atmosphere of Mars, to the flowing ices of Pluto, the fingerprints of solar activity may be found in all corners of the heliosphere.

In pop culture, people trace the "seven degrees of separation" between themselves and actor Kevin Bacon. Earth is connected much more closely to alien worlds. The central role of the Sun puts us just *one* degree of separation away from scores of planets, dwarf planets, moons, asteroids, and comets throughout the solar system. This proximity tells us something important: what we learn about those strange places, we also learn about ourselves.

The connectedness of things is the subject of this book: *Active Stars, their Astrospheres, and Impacts on Planetary Environments*. In 13 graduate-level chapters, experts lay out new ideas about how stars carve out a place in the galaxy to shape their own solar systems. The chapters touch on subjects ranging from magnetic reconnection and magnetohydrodynamics to climate and aeronomy. It may be one of the most interdisciplinary textbooks ever written – at least in the physical sciences.

Indeed, the themes laid out in this text are so interdisciplinary that their proper synthesis requires more than one book. This fourth volume of the Heliophysics series implicitly makes the case for a new research discipline: comparative heliophysics. As humans and their robots spread throughout the solar system, we will need this kind of interdisciplinary approach to understand the places we visit and to anticipate the dangers. What is the weather like on Titan today? How will a solar storm affect the ices of Europe? Is it safe to land on that comet?

These questions cannot be answered in "splendid isolation." Indeed, there really is no such thing . . . under the Sun.

Madhulika Guhathakurta, NASA/LWS program scientist,
Heliophysics Division,
Science Mission Directorate

Editors' notes

The Heliophysics series focuses on the physics of space weather events that start at the Sun and influence the Earth's environment and society's susceptibility to these processes. The Sun's variability affects not only Earth, but also the atmospheres, ionospheres, and magnetospheres of all other bodies throughout the solar system. The solar system offers a wider variety of conditions under which the interaction of bodies with a plasma environment can be studied than are encountered around Earth alone: there are planets with and without large-scale magnetic fields and associated magnetospheres; planetary atmospheres display a variety of thicknesses and compositions; satellites of the giant planets reveal how interactions occur with subsonic and sub-Alfvénic flows whereas the solar wind interacts with supersonic and super-Alfvénic impacts.

Analogous to the use of other environments in our own planetary system to learn more about Earth's environmental conditions we can look at the variety of other stars to learn more about our own Sun and its magnetism. With the realization that most stars support some form of planetary system, the variety of star–planet interactions to be considered also reaches far beyond our own present-day solar system: we can learn about the history and future of heliophysical processes throughout the life of the solar system by considering exoplanet systems, and we can envision environments elsewhere in the Galaxy by studying our solar system. Hence, the theme of this volume: comparative heliophysics.

The chapters in this volume, as in the others in this series, generally adhere to common practices in the disciplines that they primarily cover in their uses of symbols and units. We intentionally did not attempt to homogenize these across the contents to make it easier for the reader to connect the various chapters to the more detailed professional literature.

Additional resources

The texts were developed during a summer school series for heliophysics, taught at the facilities of the University Corporation for Atmospheric Research, in Boulder, Colorado, funded by the NASA Living With a Star program. Additional information, including text updates, lecture materials, (color) figures and movies, and teaching materials developed for the school can be found at http://www.vsp.ucar.edu/Heliophysics.

An online volume (Heliophysics V) describing the impacts of space weather on society in chapters looking into economic impacts, business opportunities, impacts on the electric power grid, and consequences of space weather for radio waves used in, e.g., navigation, can be accessed freely via the web.[1]

Definitions of many solar–terrestrial terms can be found via the index of each volume; a comprehensive list can be found at a web page maintained by NOAA's Space Weather Prediction Center.[2]

A note on star names and spectral designations

In this volume, several chapters refer to stars other than the Sun, using a variety of different naming conventions.[3] Here is a selective summary that covers most of what the reader will encounter in this volume. Stars that are relatively bright in the sky are often named after the constellation in which they occur, of which the Latin name is commonly abbreviated using three letters taken from the beginning of the word or words in their name, preceded by a Greek letter, starting with α for the brightest (e.g., α Cen for the brightest star in the constellation Centaurus) and continuing through the Greek alphabet, and continuing with numbers after the letters are all used. Alternative names include (1) old Arabic names (modified over time, such as Betelgeuse), (2) catalog numbers (such as the Henry Draper catalog numbers, e.g., HD 114762), (3) a letter combination preceding the constellation abbreviation which often designates a member of a variable star catalog (e.g., EK Dra), or (4) a rather unimaginative but straightforward combination of right ascension and declination that specifies the location in the sky, sometimes preceded

[1] http://www.vsp.ucar.edu/Heliophysics/science-resources-textbooks.shtml
[2] http://www.swpc.noaa.gov/content/space-weather-glossary
[3] See a summary at http://en.wikipedia.org/wiki/Star_designation

by a group of letters that specifies the type of star (e.g., the pulsar PSR 1257+12). Stars are often known by multiple names (users of, e.g., the Astrophysics Data System, ADS, can hunt through the literature by using databases of synonyms to search for studies on stars using multiple names simultaneously). In case of multiple stars, a capital following the name indicates which component is meant, most commonly differentiating between the brightest and next-brightest one as “A” and “B”. When a lower-case letter follows a star name, the designation refers to a planet orbiting the star.

Spectral types of stars are a measure of their spectral properties, long since resequenced in order of decreasing effective temperature (and thus in order of color from blue to red): O, B, A, F, G, K, M, L, T, Y, followed by a number from 1 to 9 as a subdivision. The Roman numeral that follows it is a measure for stellar radius or surface gravity, and indirectly of relative age: V for a mature main-sequence star (such as our Sun), IV for a slightly evolved star, and then III, II, and I for evolved giant, bright giant, and supergiant stars.

Stellar astronomers characterize spectral lines by the abbreviated Latin name of the element followed by a Roman numeral that designates the ionization stage of the element, e.g., the designation “Mg II” refers to a spectral line (or, if no particular name or wavelength follows, the entire set of spectral lines) of singly ionized magnesium. Sometimes, authors may use the spectral designation to characterize the population of the emitting atoms (e.g., “D I atoms” for neutral deuterium). Particularly strong spectral lines may have names followed by a Greek letter (such as “Lyman α”, the first in the Lyman series), or a capital letter which refers to a strong line identified in the solar spectrum (such as the Ca II H and K lines) or their equivalent transition in another element when indicated in lower case (e.g., for the H and K lines: the Mg II h and k lines).

Heliophysics

helio-, pref., on the Sun and environs, from the Greek helios.
physics, n., the science of matter and energy and their interactions.

Heliophysics is the

- *comprehensive new term for the science of the Sun–Solar System Connection.*
- *exploration, discovery, and understanding of our space environment.*
- *system science that unites all of the linked phenomena in the region of the cosmos influenced by a star like our Sun.*

Heliophysics concentrates on the Sun and its effects on Earth, the other planets of the solar system, and the changing conditions in space. Heliophysics studies the magnetosphere, ionosphere, thermosphere, mesosphere, and upper atmosphere of the Earth and other planets. Heliophysics combines the science of the Sun, corona, heliosphere and geospace. Heliophysics encompasses cosmic rays and particle acceleration, space weather and radiation, dust and magnetic reconnection, solar activity and stellar cycles, aeronomy and space plasmas, magnetic fields and global change, and the interactions of the solar system with our galaxy.

From NASA's "Heliophysics. The New Science of the Sun–Solar System Connection: Recommended Roadmap for Science and Technology 2005–2035."