SOLAR JOURNEY: THE SIGNIFICANCE OF OUR GALACTIC ENVIRONMENT
FOR THE HELIOSPHERE AND EARTH

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SOLAR JOURNEY: THE SIGNIFICANCE OF OUR GALACTIC ENVIRONMENT FOR THE HELIOSPHERE AND EARTH

Edited by

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Dedicated to the memory of Professor John Alexander Simpson, whose contributions to science, and dedication to the peaceful use of that science, were longstanding and far-reaching.

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Preface

The distinction between geophysics and astronomy was once clear. Events on Earth constituted the realm of geophysics, while astronomy encompassed objects that are located many light years from the Sun and Earth. Interstellar clouds were "out there", where they could be observed from isolated observatories nestled under the starry skies of the world's deserts. Geology relied on shovels and drill bits to obtain samples of mud and ice that contained clues to the paleoclimate. The space age changed all of this, with the discovery of interstellar gas and dust inside of the heliosphere. Mankind now looks out on the Universe from our vantage point on the spaceship Earth, and the scientific continuum that starts with the mineral and isotope composition on Earth extends back to the creation of the elements and isotopes at the beginning of the Universe. Through geological traces of radioisotopes and interplanetary material with a cosmic origin, the planetary system of the Sun provides a living record of the journey of the Sun through the Milky Way Galaxy. It is this living record, of which we are a part, that makes the discussions of the influence of interstellar matter on the heliosphere and Earth a compelling topic.

The Sun experiences many kinds of Galactic environments on its journey through space. The solar wind bubble, or heliosphere, acts as a buffer between the broad range of interstellar cloud types that are encountered, and the inner portion of the solar system where the Earth is located. The goal of this book is to show how changes in the galactic environment of the Sun affect the heliosphere, solar system, and Earth. It is partly motivated by what may be a purely happenstance coincidence. When I first plotted the solar space trajectory on a map of the Local Bubble,[1] it occurred to me that it may not be a coincidence that our Earth was in the deep vacuum of the Local Bubble during the past $\sim$2.5 million years when the genus *homo* emerged.

Professor John A. Simpson gave me a desk with his group after we moved to Chicago from Berkeley, and I learned about the heliosphere. Convinced that the interstellar hydrogen and helium observed inside of the heliosphere were part of the interstellar cloud seen towards Rasalhague, 14 pc away, I proposed to use the ultraviolet spectrometers on the *Copernicus* satellite to acquire high-resolution data on solar Lyman-alpha photons fluorescing off of interstellar hydrogen inside of the heliosphere[2]. In the world of astronomy, interstellar matter was between distant stars such as Scorpius and Orion, so this may have been the first observational effort to relate interstellar gas inside and outside of the heliosphere.

This book is dedicated to the memory of Professor John Simpson, who helped make the space age a reality. He played an important role in bringing a full-fledged space physics program to fruition at NASA, and was a leader in promoting healthy international scientific collaborations. John was the Principal Investigator for instruments on 10 interplanetary spacecraft and twenty Earth-orbiting satellites. He was an author or coauthor of over 330 scientific papers published between the years 1940–2000. His group made many major scientific contributions, including the discovery of the anomalous cosmic ray component[3]. John also played a vital role in founding and supporting *The Bulletin of the Atomic Scientists*, a periodical dedicated to the peaceful use of nuclear energy. His influence on the world has been profound. This volume is dedicated to John in honor of his scientific and policy contributions.

Notes

1. Frisch, P. and York, D. G. (1986). Interstellar Clouds Near the Sun. In *The Galaxy and the Solar System*, pages 83–100. Eds. R. Smoluchowski, J. Bahcall, and M. Matthews (University of Arizona Press).
2. Adams, T. F. and Frisch, P. C. (1977). High-resolution Observations of the Lyman Alpha Sky Background. *Astrophys. J.*, 212:300–308.
3. Garcia-Munoz, M., Mason, G. M., and Simpson, J. A. (1973). A New Test for Solar Modulation Theory: the 1972 May-July Low-Energy Galactic Cosmic-Ray Proton and Helium Spectra. *Astrophys. J. Lett.*, 182:L81–L84.

PRISCILLA C. FRISCH

Foreword

"An unusual display of the Aurora Borealis was witnessed here on the evening of Oct. 22, 1804...where a luminous cloud was formed, curling and rolling like smoke, and soon after dissipated in quick and repeated coruscations. .... On the 16th of June, 1806, there occurred a remarkable eclipse of the sun, which, at Boston and places farther south, was total. ... This eclipse formed an epoch among farmers, who used to date from it the commencement of those cold seasons, which, with some exceptions, continued with increasing severity, for 10 years."

New England agricultural records during the Little Ice Age, from "Annals of the Town of Warren", by Cyrus Eaton (Hallowell, Masters, Smith & Co.)

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The editor thanks Andrew Hanson, Phillip Fu and Indiana University, for allowing the use of the cover figure, which shows a heliosphere visualization from the DVD "Solar Journey". The heliosphere model is based on Timur Linde's Ph.D. thesis. The film clip containing this visualization, which was produced with support from NASA Grant NAG5-11999, can be downloaded from *http://cs.indiana.edu/∼soljourn*.

The editor is grateful to Sarah Frisch for her valuable assistance in editing these articles, and to Henry Frisch for his continuous support of this project.

Chapter 1

INTRODUCTION: PALEOHELIOSPHERE VERSUS PALEOLISM

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Abstract Speculations that encounters with interstellar clouds modify the terrestrial climate have appeared in the scientific literature for over 85 years. The articles in this volume seek to give substance to these speculations by examining the exact mechanisms that link the pressure and composition of the interstellar medium surrounding the Sun to the physical properties of the inner heliosphere at the Earth.

Keywords: Heliosphere, interstellar clouds, interstellar medium, cosmic rays, magnetosphere, atmosphere, climate, solar wind, paleoclimate

1.1 The Underlying Query

If the solar galactic environment is to have a discernible effect on events on the surface of the Earth, it must be through a subtle and indirect influence on the terrestrial climate. The scientific and philosophical literature of the 18th, 19th and 20th centuries all include discussions of possible cosmic influences on the terrestrial climate, including the effect of cometary impacts on Earth (Halley, 1724), and the diminished solar radiation from sunspots, which Herschel attributed to "holes" in the luminous fluid on the surface of the Sun[1] (Herschel, 1795). The discovery of interstellar material in the 20th century led to speculations that encounters with dense clouds initiated the ice ages (Shapley, 1921), and many papers appeared that explored the implications of such encounters, including the influence of interstellar material (ISM) on the interplanetary medium and planetary atmospheres (e.g. Fahr, 1968, Begelman and

P. C. Frisch (ed.), Solar Journey: The Significance of our Galactic Environment for the Heliosphere and Earth, 1–22.

Rees, 1976, McKay and Thomas, 1978, Thomas, 1978, McCrea, 1975, Talbot and Newman, 1977, Willis, 1978, Butler et al., 1978). The ISM-modulated heliosphere was also believed to affect climate stability and astrospheres (e.g. Frisch, 1993, Frisch, 1997, Zank and Frisch, 1999). Recent advances in our understanding of the solar wind and heliosphere (e.g. Wang and Richardson, 2005, Fahr, 2004) justify a new look at this age-old issue. This book addresses the underlying question:

How does the heliospheric interaction with the interstellar medium affect the heliosphere, interplanetary medium, and Earth?

The heliosphere is the cavity in the interstellar medium created by the dynamic ram pressure of the radially expanding solar wind, a halo of plasma around the Sun and planets, dancing like a candle in the wind and regulating the flux of cosmic rays and interstellar material at the Earth. Neutral interstellar gas and large interstellar dust grains penetrate the heliosphere, but the solar wind acts as a buffer between the Earth and most other interstellar material and low energy galactic cosmic rays (GCR). Together the solar wind and interstellar medium determine the properties of the heliosphere. In the present epoch the densities of the solar wind and interstellar neutrals are approximately equal outside of the Jupiter orbit. Solar activity levels drive the heliosphere from within, and the physical properties of the surrounding interstellar cloud constrain the heliosphere from without, so that the boundary conditions of the heliosphere are set by interstellar material. Figure 1.1 shows the Sun and heliosphere in the setting of the Milky Way Galaxy.

The answer to the question posed above lies in an interdisciplinary study of the coupling between the interstellar medium and the solar wind, and the effects that ISM variations have on the 1 AU environment of the Earth through this coupling. The articles in this book explore different viewpoints, including *gedanken* experiments, as well as data-rich summaries of variations in the solar environment and paleoclimate data on cosmic ray flux variations at Earth.

The book begins with the development of theoretical models of the heliosphere that demonstrate the sensitivity of the heliosphere to the variations in boundary conditions caused by the passage of the Sun through interstellar clouds. A series of *gedanken* experiments then yield the response of planetary magnetospheres to encounters with denser ISM. Variations in the galactic environment of the Sun, caused by the motions of the Sun and clouds through the Galaxy, are shown to occur for both long and short timescales.

The heliosphere acts as a buffer between the Earth and interstellar medium, so that dust and particle populations inside of the heliosphere, which have an interstellar origin, vary as the Sun traverses interstellar clouds. These buffering mechanisms determine the interplanetary medium[2]. The properties of these buffering interactions are evaluated for heliosphere models that have been developed using boundary conditions appropriate for when the Sun traverses different types of interstellar clouds.

The consequences of Sun-cloud encounters are then discussed in terms of the accretion of ISM onto the terrestrial atmosphere for dense cloud encounters, and the possibly extreme variations expected for cosmic ray modulation when interstellar densities vary substantially. Radioisotope records on Earth extending backwards in time for over $\sim$0.5 Myrs, together with paleoclimate data, suggest that cosmic ray fluxes are related to climate. The galactic environment of the Sun must have left an imprint on the geological record through variations in the concentrations of radioactive isotopes.

The selection of topics in this book is based partly on scientific areas that have already been discussed in the literature. The authors who were invited to contribute chapters have previously studied the heliosphere response to variable ISM conditions.

Figure 1.1 shows the heliosphere in our setting of the Milky Way Galaxy. A postscript at the end of this chapter lists basic useful information. I introduce the term "paleoheliosphere" to represent the heliosphere in the past, when the boundary conditions set by the local interstellar material (LISM) may have differed substantially from the boundary conditions for the present-day heliosphere. The "paleolism" is the local ISM that once surrounded the heliosphere.

1.2 Addressing the Query: The Heliosphere and Particle Populations for Different Interstellar Environments

The solar wind drives the heliosphere from the inside, with the properties of the solar wind varying with ecliptic latitude and the phase of the 11-year solar activity cycle. The global heliosphere is the volume of space occupied by the supersonic and subsonic solar wind. Interstellar material forms the boundary conditions of the heliosphere, and the windward side of the heliosphere, or the "upwind direction", is defined by the interstellar velocity vector with respect to the Sun. The leeward side of the heliosphere is the "downwind direction". Figure 1.1 shows a cartoon of the present-day heliosphere, with labels for the major landmarks such as the termination shock, heliopause, and bow shock.

In the present-day heliosphere, the transition from solar wind to interstellar plasma occurs at a contact discontinuity known as the "heliopause", which is formed where the total solar wind and interstellar pressures equilibrate (Holzer, 1989). For a non-zero interstellar cloud velocity in the solar rest frame, the solar wind turns around at the heliopause and flows around the flanks of the heliosphere and into the downwind heliotail. Before reaching the heliopause, the supersonic solar wind slows to subsonic velocities at the "termination shock", where kinetic energy is converted to thermal energy.

The subsonic solar wind region between the termination shock and heliopause is called the inner "heliosheath". The outer heliosheath lies just beyond the heliopause, where the pristine ISM is distorted by the ram pressure of the

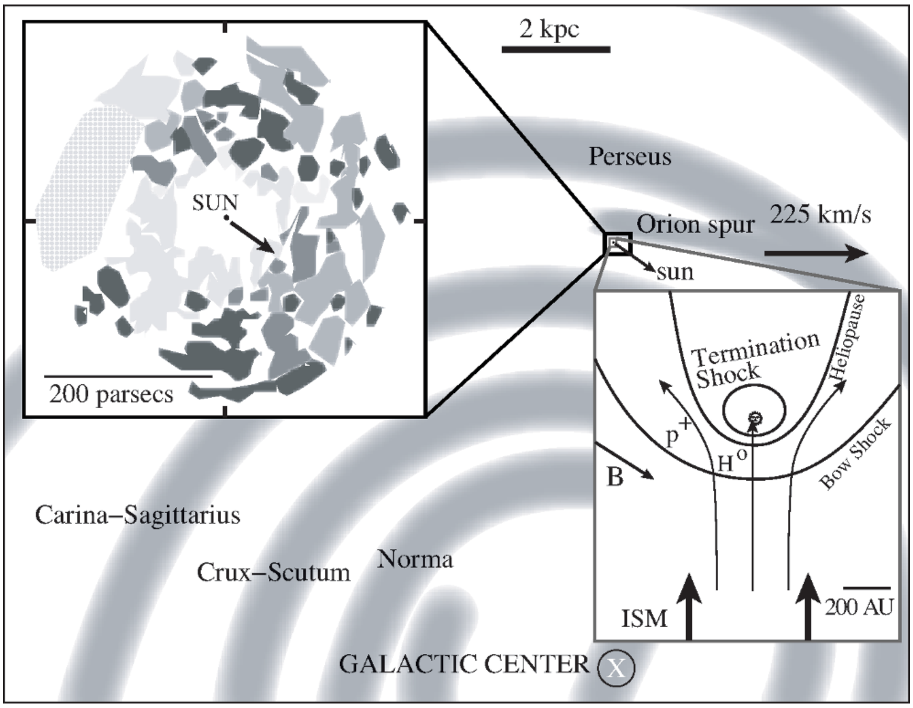

Figure 1.1. The solar location and vector motion are identified for the kiloparsec scale sizes of the Milky Way Galaxy (large image), and for the ∼500 parsec scale size of the Local Bubble (medium sized image, inset in upper left hand corner). A schematic drawing of the heliosphere (small image, inset in lower right hand corner) shows the upwind velocity of the interstellar wind ("ISM") as observed in the rest frame of the Sun. Coincidently, this direction, which determines the heliosphere nose, is close to the galactic center direction. The orientation of the plane in the small inset differs from the planes of the large and medium figures, since the ecliptic plane is tilted by 60° with respect to the galactic plane. The Sun is 8 kpc from the center of the Milky Way Galaxy, and the solar neighborhood moves towards the direction $\ell = 90^\circ$ at a velocity of 225 km s^{-1}. The spiral arm positions are drawn from Vallee (2005), except for the Orion spur. The Local Bubble configuration is based on measurements of starlight reddening by interstellar dust (Chapter 6). The lowest level of shading corresponds to color excess values E(B-V) $=$ 0.051 mag, or column densities log N(H) (cm^{-2}) $=$ 20.40 dex. The dotted region shows the widespread ionized gas associated with the Gum Nebula. The heliosphere cartoon shows interstellar protons deflected in the plasma flow in the outer heliosheath regions, compared to the interstellar neutrals that penetrate the heliopause.

heliosphere. A bow shock, where the interstellar gas becomes subsonic, is expected to form ahead of the present-day heliosphere in the observed upwind direction of the ISM flow through the solar system.

Large interstellar dust grains and interstellar atoms that remain neutral inside of the orbit of Earth, such as He, are gravitationally focused in the downwind direction. This "focusing cone" is traversed by the Earth every year in early December, and extends many AU from the Sun in the leeward direction (e.g. Landgraf, 2000, Möbius et al., 2004, Frisch, 2000). The heliotail itself extends $>10^3$ AU from the Sun in the downwind direction, forming a cosmic wake for the solar system.

Of significance when considering the interaction of the heliosphere with an interstellar cloud is that neutral particles enter the heliosphere relatively unimpeded, after which they are ionized and convected outwards with the solar wind. Ions and small charged dust grains are magnetically deflected in the heliosheath around the flanks of the heliosphere (see Figure 1.1).

Space and astronomical data now confirm the basic milestones of the outer heliosphere. Voyager 1 crossed the termination shock at 94 AU on 16 December, 2004 (UT), and observed the signature of the termination shock on low-energy particle populations, the solar wind magnetic field, low-energy electrons and protons, and Langmuir radio emission (Stone et al., 2005, Burlaga et al., 2005, Gurnett and Kurth, 2005, Decker et al., 2005). The present-day termination shock appears to be weak, with a solar wind velocity jump ratio (the ratio of upstream to downstream values) of $\sim$2.6 and a magnetic field compression ratio of $\sim$3. The magnetic wall that is predicted for the heliosphere (Linde, 1998, Ratkiewicz et al., 1998, Chapter 3 by Pogorelov and Zank) appears to have been detected through observations of magnetically aligned dust grains (Frisch, 2005), and the offset between upwind directions of interstellar H° and He° (Lallement et al., 2005). The compressed and heated H° in the hydrogen wall region of the outer heliosheath has now been detected around a number of stars (Wood et al., 2005).

The present-day solar wind is the baseline for evaluating the heliosphere response to ISM variations in the following articles, so a short review of the solar wind is first presented. The remaining part of §1.2 introduces the topics in the following articles in terms of the underlying query of the book.

1.2.1 The Present Day Solar Wind

The solar wind originates in the million degree solar corona that expands radially outwards, with a density $\sim 1/R_{\rm S}^2$ where $R_{\rm S}$ is the distance to the Sun, and contains both features that corotate with the Sun, and transient structures (e.g. Gosling, 1996). The properties of the solar wind vary with the phase of the solar magnetic activity cycle and with ecliptic latitude. The best historical indicator of solar magnetic activity levels is the number of sunspots, first detected by Galileo in 1610, which are magnetic storms in the convective zone of the Sun. Sunspot numbers indicate that the magnetic activity levels fluctuate with a $\sim$11 year cycle, or the "solar cycle", and solar maximum/minimum corresponds to the maximum/minimum of sunspot numbers. The magnetic polarity of the Sun varies with a $\sim$22 year cycle. During solar maximum, a low-speed wind, with velocity $\sim$300–600 km s^{-1} and density $\sim$6–10 particles cm^{-3} at 1 AU, extends over most of the solar disk. Open magnetic field lines[3] are limited to solar pole regions. A neutral current sheet $\sim$0.4 AU thick forms between the solar wind containing negative magnetic polarity fields and the solar wind that contains positive magnetic polarity fields. The neutral current sheet reaches its largest inclination ($\geq 70^\circ$) during solar maximum. During the conditions of solar minimum, a high speed wind with velocity $\sim$600–800 km s^{-1} and density $\sim$5 cm^{-3} is accelerated in the open magnetic flux lines in coronal holes. During mininum, the high speed wind and open field lines extend from the polar regions down to latitudes of $\leq 40^\circ$ (Smith et al., 2003, Richardson et al., 1995). The higher solar wind momentum flux associated with solar minimum conditions produces an upwind termination shock that is $\sim$5–40 AU more distant in the upwind direction than during solar maximum conditions (e.g. Scherer and Fahr, 2003, Zank and Müller, 2003, Whang, 2004).

During solar minimum conditions, the magnetic field is dominated by the dipole and hexapole moments, with a small contribution from a quadrupole moment. The alignment and strength of the multipoles depend on the phase of the solar cycle (Bravo et al., 1998). The solar dipole moment is strongest during solar minimum, when it is generally aligned with the solar rotation axis. Sunspots migrate from high to low heliographic latitudes. The magnetic poles follow the coronal holes to the solar equator as solar activity increases. During the solar maximum period, the galactic cosmic rays undergo their maximum modulation, the dipole component of the magnetic field is minimized, and the polarity of the solar magnetic field reverses (Lockwood and Webber, 2005, Figure 1.2). Over historic times, the cosmic ray modulation by the heliosphere correlates better with the open magnetic flux line coverage than with sunspot numbers (McCracken et al., 2004).

Variable cosmic ray modulation produced by a variable heliosphere may be a primary factor in both solar and ISM forcing of the terrestrial climate. The heliosphere modulation of cosmic rays is well established. John Simpson, to whom this book is dedicated, initiated a program 5 solar cycles ago in 1951 to monitor cosmic ray fluxes on Earth using high-altitude neutron detectors (Simpson, 2001). The results show a pronounced anticorrelation between cosmic ray flux levels and solar sunspot numbers, which trace the 11-year Schwabe magnetic activity cycle, and which also show that the polarity of the solar magnetic field affects cosmic ray modulation (see Figure 1.2). The articles in this book show convincingly that the ISM also modulates the heliosphere, and the effect of the solar wind on the heliosphere must be differentiated from the influence of interstellar matter.

Variations in solar activity levels are also seen over $\sim$100–200 year timescales, such as the absence of sunspots during the Maunder Minimum in the 17th century. Modern climate records show that the Maunder Minimum corresponded to extremely cold weather, and radioisotope records show that the flux of cosmic rays was unusually high at this time (see Kirkby and Carslaw, Chapter 12). Similar effects will occur from the modulation of galactic cosmic rays by the passage of the Sun through an interstellar cloud.

These temporal and latitudinal variations in the solar wind momentum flux produce an asymmetric heliosphere, which varies with time. Any possible historical signature of the ISM on the heliosphere must first be distinguished from variations driven by the solar wind itself.

1.2.2 Present Day Heliosphere and Sensitivity to ISM

The ISM forms the boundary conditions of the heliosphere, so that encounters with interstellar clouds will affect the global heliosphere, the interplanetary medium, and the inner heliosphere region where the Earth is located. Today an interstellar wind passes through the solar system at –26.3 km s^{-1} (Witte, 2004). An entering parcel of ISM takes about 20 years to reach the inner heliosphere, so that ISM near the Earth is constantly replenished with new inflowing material. This warm gas is low density and partially ionized, with temperature $T\sim$ 6,300 K, and densities of neutral and ionized matter of $n(\mathrm{H}^{\circ})\sim 0.2$ cm^{-3}, and $n(\mathrm{H}^{+})\sim 0.1$ cm^{-3}.

An elementary perspective of the response of the heliosphere to interstellar pressures is given by an analytical expression for the heliopause distance based on the locus of positions where the solar wind ram pressure, P_{SW}, and the total interstellar pressure equilibrate (Holzer, 1989). The solar wind density ρ falls off as $\sim 1/R^2$, where R is the distance to the Sun, while the velocity v is relatively constant. At 1 AU the solar wind ram pressure is $P_{\mathrm{SW,1AU}}\sim\rho\, v^2$ so the heliosphere distance, R_{HP}, is given by:

$$P_{\mathrm{SW,1AU}}/R_{\mathrm{HP}}^2 \sim P_{\mathrm{B}} + P_{\mathrm{Ions,thermal}} + P_{\mathrm{Ions,ram}} + P_{\mathrm{Dust}} + P_{\mathrm{CR}}$$

The interstellar pressure terms include the magnetic pressure P_{B}, the thermal, $P_{\mathrm{Ions,thermal}}$, and the ram, $P_{\mathrm{Ions,ram}}$, pressures of the charged gas, and the pressures of dust grains, P_{Dust}, and cosmic rays, P_{CR}, which are excluded by heliosphere magnetic fields and plasma. Some interstellar neutrals convert to ions through charge exchange with compressed interstellar proton gas in heliosheath regions, adding to the confining pressure. An important response characteristic is that, for many clouds, the encounter will be ram-pressure dominated, where $P_{\rm ram} \sim mv^2$ for interstellar cloud mass density m and relative Sun-cloud velocity v, so that variations in the cloud velocity perturb the heliosphere even if the thermal pressures remain constant.

The multifluid, magnetohydrodynamic (MHD), hydrodynamic and hybrid approaches used in the following chapters provide much more substantial models for the heliosphere, and include the coupling between neutrals and plasma, and field-particle interactions. These sophisticated models predict variations in the global heliosphere in the face of changing interstellar boundary conditions, and for a range of different cloud types. Although impossible to model a solar encounter with every type of interstellar cloud, the following articles include discussions of many of the extremes of the interstellar parameter space, including low density gas with a range of velocities, very tenuous plasma, high velocity clouds, dense ISM, and magnetized material for a range of field orientations and strengths. The discussions in these chapters extrapolate from our best theoretical understanding of the heliosphere boundary conditions today to values that differ, in some cases dramatically, from the boundary conditions that prevailed at the beginning of the third millennium in the Gregorian calendar.

The Sun has been, and will be, subjected to many different physical environments over its lifetime. Theoretical heliosphere models yield the properties of the solar wind-ISM interaction for these different environments, which in turn determine the nature and properties of interstellar populations inside of the heliosphere for a range of galactic environments. These models form the foundation for understanding the significance of our galactic environment for the Earth.

The interstellar parameter space is explored by Zank et al. (Chapter 2), where 28 sets of boundary conditions are evaluated with computationally efficient multifluid models. Moebius et al. (Chapter 8), Fahr et al. (Chapter 9), Florinski and Zank (Chapter 10), and Yeghikyan and Fahr (Chapter 11) also develop heliosphere models for a range of interstellar conditions. Together these models evaluate the heliosphere response to interstellar density, temperature, and velocity variations of factors of $\sim 10^9$, $\sim 10^5$, and $\sim 10^2$, respectively.

The interstellar magnetic field introduces an asymmetric pressure on the heliosphere, affecting the heliosphere current sheet and cosmic ray modulation. Pogorelov and Zank (Chapter 3) use MHD models to probe the heliosphere response to the interstellar magnetic field, including charge exchange between the neutrals and solar wind. The resulting asymmetry provides a test of the magnetic field direction, and shows strong differences between cases where the interstellar flow is parallel, instead of perpendicular, to the interstellar magnetic field direction. Since the random component of the interstellar magnetic field is stronger, on the average, than the ordered component, particularly in spiral