Chapter 1

INTRODUCTION: PALEOHELIOSPHERE VERSUS PALEOLISM

Priscilla C. Frisch
University of Chicago
frisch@oddjob.uchicago.edu

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

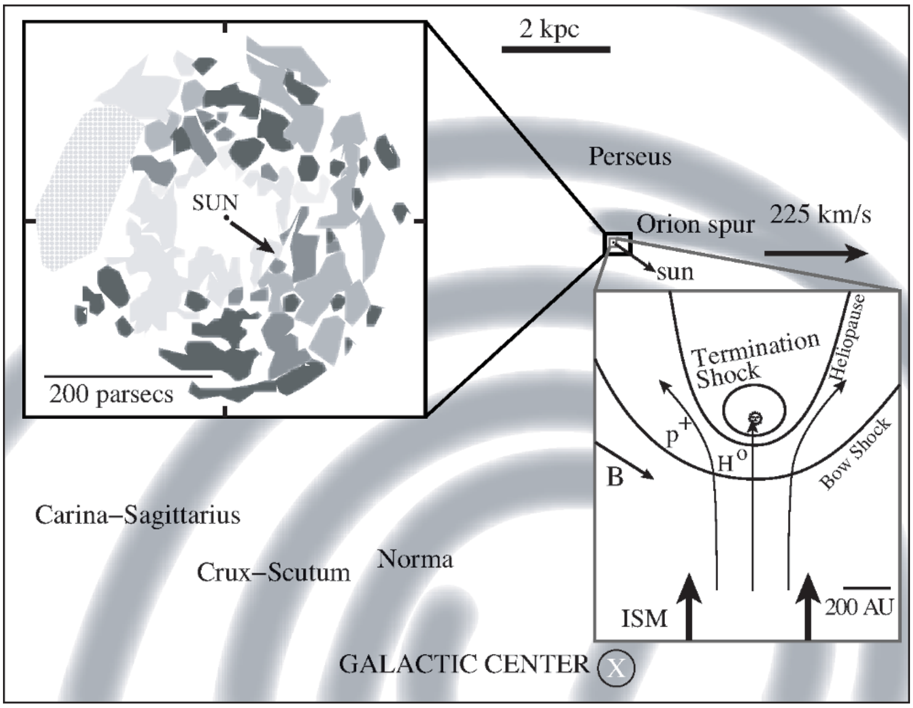

Figure 1.1. The solar location and vector motion are identified for the kiloparsec scale sizes of the Milky Way Galaxy (large image), and for the ∼500 parsec scale size of the Local Bubble (medium sized image, inset in upper left hand corner). A schematic drawing of the heliosphere (small image, inset 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°$) 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 $\leq 40°$ (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(H^{o})$\sim$0.2 cm^{-3}, and n(H^{+})$\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, $P_{\rm SW}$, 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 $P_{\rm SW,1AU}\sim\rho\, v^2$ so the heliosphere distance, $R_{\rm HP}$, is given by:

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

The interstellar pressure terms include the magnetic pressure $P_{\rm B}$, the thermal, $P_{\rm Ions,thermal}$, and the ram, $P_{\rm Ions,ram}$, pressures of the charged gas, and the pressures of dust grains, $P_{\rm Dust}$, and cosmic rays, $P_{\rm CR}$, 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 arm regions where active star formation occurs, a range of interstellar magnetic field strengths and orientations are expected over the solar lifetime (Shaviv, Chapter 5, and Frisch and Slavin, Chapter 6).

1.2.3 Planetary Magnetospheres

The Earth's magnetosphere acts as a buffer between the solar wind and atmosphere, and as such is an ingredient in understanding the effect of our galactic environment on the Earth. The decreasing solar wind density in the outer heliosphere results in an interplanetary medium around outer planets that is more sensitive to ISM variations than for inner planets, with implications for the magnetospheres of Jupiter, Neptune, and Uranus. Most topics in this book are already considered in the scientific literature, but questions about magnetosphere variations from an ISM-modulated heliosphere have received scant attention. In a quintessential *gedanken* experiment, Parker explores the interaction between magnetospheres and the solar wind for variations in the interstellar density, and for inner versus outer planets (Chapter 4).

1.2.4 Short and Long Term Variations in the Galactic Environment

There is every reason to expect that the galactic environment of the Sun varies over geological timescales. The Sun moves through space at a velocity of 13–20 km s^{-1}, and interstellar clouds have velocities ranging up to hundreds of km s^{-1}. The Arecibo Millennium survey showed that $\sim$25% of the mass contained in interstellar H°, including both warm and cold ISM, is in clouds traveling with velocities $\geq$10 km s^{-1} through the local standard of rest (Heiles and Troland, 2003). Thus Sun-cloud encounters with relative velocities exceeding 25 km s^{-1} are quite likely, and for a typical cloud length of $\sim$1 pc the cloud transit time would be $\sim$40,000 years. The many types of ISM traversed by the Sun during the past several million years have affected the heliosphere, the inner solar system, and the flux of anomalous and galactic cosmic rays at Earth (Frisch and York, 1986, Frisch, 1997, Frisch, 1998).

For the past $\sim$3 Myrs the Sun has been in a nearly empty region of space, the "Local Bubble", with very low densities of $<10^{-26}$ gr cm^{-3}. Within the past 44,000–150,000 years the Sun entered a flow of tenuous, partly neutral ISM, nick-named the "Local Fluff", with density $\sim$60 times higher (Chapter 6). This transition was accompanied by the appearance of interstellar dust and neutrals in the heliosphere, along with the pickup ion and anomalous cosmic ray populations. Galactic cosmic ray modulation was affected, providing a possible link between our galactic environment and climate. Intriguingly, the averaged cosmic ray flux at Earth, as traced by ^{10}Be records, was lower in the past $\sim$135 kyrs than for earlier times (Chapter 12). Was the decrease in the galactic cosmic ray flux $\sim$135 kyrs ago caused by an increase in modulation as the Sun entered the Local Fluff?

The galactic environment of the Sun also varies quite dramatically over long time scales, as discussed by Shaviv (Chapter 5). Over its 4.5 billion year lifetime, the Sun traverses spiral arm and interarm regions, with atomic densities varying from less than $10^{-26.1}$ g cm^{-3} to over $10^{-20.1}$ g cm^{-3}, and temperatures ranging over 7 orders of magnitude, 10–10^7 K. The Sun is now in low density space between the Perseus and Sagittarius spiral arms, and on the inner edge of what is known as the Orion spur on the Local Arm. The Local Arm is not shown in Figure 1.1, as is consistent with the usual Galaxy depictions. The Local Arm does not appear to be a grand design spiral shock (Bochkarev, 1984). The Sun has a systematic motion of 13–20 km s^{-1} with respect to the nearest stars, corresponding to $\sim$3–4 AU per year. The Local Interstellar Cloud (LIC) now surrounding the Sun traverses the heliosphere at $\sim$5.5 AU per year. The Sun oscillates vertically through the galactic plane once every $\sim$34 Myrs, and orbits the center of the Milky Way Galaxy once per $\sim$220 Myrs.

Shaviv evaluates variations in the galactic environment of the Sun over long timescales. This bold discussion compares various geologic records of cosmic ray flux variations, based on radioisotope data that sample timescales of $\sim 10^8$ years, with models of the Milky Way Galaxy spiral arm pattern to reconstruct the timing of the Sun's passage through spiral arms. The chapter concludes that star formation in spiral arms leaves a signature on the radioisotope records of the solar system.

Frisch and Slavin (Chapter 6) reconstruct short-term variations of the galactic environment of the Sun using observations of interstellar matter towards nearby stars and inside of the solar system. Radiative transfer models of the LIC show that ionization varies across this low density cloud, so that the heliosphere boundary conditions vary from radiative transfer considerations alone as the Sun traverses the LIC. Cloud transitions are predicted for the past $\sim$3 Myrs, including the departure of the Sun from the Local Bubble interior 44,000–150,000 years ago.

1.2.5 Interstellar Dust

The particle populations formed by the interactions between the solar wind and interstellar dust, gas, and cosmic rays are emissaries between the cosmos and inner heliosphere, varying as the Sun moves through clouds.

About $\sim$1% of the mass of the cloud surrounding the Sun is contained in interstellar dust grains. The largest of these charged grains, mass $>10^{-13}$ g, have large magnetic Larmor radii of $>$500 AU at the heliopause for an interstellar field of $\sim$1.5 μG, and flow into the solar system. The Earth passes through the gravitational focusing cone formed by these grains early each December. The smallest charged grains, mass $<10^{-14.5}$ g and radii <0.01 μm, have Larmor radii of $\sim$20 AU, depending on the magnetic field strength and radiation field, and are deflected around the heliosheath (Frisch et al., 1999). Interstellar dust grains are measured in the inner heliosphere within $\sim$5 AU of the Sun, and over the solar poles, by satellites such as Ulysses, Galileo and Cassini. Landgraf (Chapter 7) reviews the properties of the interaction between interstellar dust and the solar wind, and speculates on the changes that might be expected from an encounter with a dense interstellar cloud.

Should it some day be possible to compare the ratio of large to small interstellar dust grains on the surfaces of the inner versus outer planets, it would become possible to disentangle cloud encounters from solar activity effects.

At the very large end of the dust population mass spectrum we find interstellar micrometeorites, with masses $\sim 3 \times 10^{-7}$ g, open orbits, and inflow velocities greater than the 42 km s^{-1} escape velocity from the solar system at 1 AU. These interstellar objects, detected by radar as they impact the atmosphere, evidently originate in circumstellar disks such as that around β Pictoris, and in the interior of the Local Bubble (Baggaley, 2000, Meisel et al., 2002). These objects do not collisionally couple to the interstellar gas (Gruen and Landgraf, 2000), and should not vary with the type of ISM surrounding the Sun.

1.2.6 Particle Populations in the Inner and Outer Heliosphere

Presently, low energy interstellar neutrals, high energy galactic cosmic rays, and interstellar dust all enter the heliosphere. The characteristics of each of these populations and their secondary products are modified as the Sun transits the ISM, or the cloud ionization changes. The first ionization potential (FIP) of H$^\circ$ is 13.6 eV. Neutral interstellar atoms with FIP $<$ 13.6 eV are ionized in nearly all interstellar clouds because the main source of interstellar opacity is H$^\circ$. Interstellar ions are deflected around the heliosheath, so the result is that only interstellar atoms with FIP $>$ 13.6 eV enter the heliosphere where they are then destroyed, primarily by charge exchange with solar wind ions.

The density of interstellar neutrals in the inner heliosphere depends on the density and ionization of the surrounding cloud, the ionization (or “filtration”) of those neutrals by the heliosheath, and the subsequent interactions with the solar wind inside of the heliosphere. Secondary products produced by solar wind interactions with interstellar neutrals inside of the heliosphere include pickup ions[4], energetic neutral atoms, the gravitational focusing cone formed by helium (also seen in dust), and the anomalous cosmic ray population with energies $<$1 GeV. Interstellar neutrals inside of the heliosphere, and the heliosphere itself, form a coupled system that together respond to variations in the heliosphere boundary conditions.

Moebius et al. (Chapter 8) model the heliosphere for several different conditions, and then probe the response of the inner heliosphere to the density of interstellar neutrals flowing into this ISM-modified heliosphere. At 1 AU, the neutral densities, particle populations derived from interstellar neutrals, and characteristics of the helium focusing cone all respond to variations in the interstellar boundary conditions. For some cases, increased neutral fluxes fall on the atmosphere of Earth (also see Yeghikyan and Fahr, Chapter 11).

The velocity structure of the ISM appears to vary on subparsec scale lengths (Frisch and Slavin, Chapter 6), and these variations may in some cases result in significant modifications of the inner heliosphere, particularly the gravitational focusing cone, when all other interstellar parameters such as thermal pressure are invariant (Zank et al., Chapter 2, Moebius et al., Chapter 8).

The most readily available diagnostics of the paleoheliosphere are radioisotopes, formed by cosmic ray spallation on the atmosphere, interplanetary and interstellar dust, and meteorites. Thus, the evaluation of cosmic ray modulation for various types of interstellar cloud boundary conditions is a key part of understanding the paleoclimate records that might trace the solar journey through the Milky Way Galaxy. Fahr et al. (Chapter 9) and Florinski and Zank (Chapter 10) use our understanding of galactic cosmic ray modulation in the modern-day heliosphere as a basis for making detailed calculations of the response of the paleoheliosphere, or the heliosphere as it once was, to the paleolism, or the local interstellar medium that once surrounded the Sun. The predictions of these calculations are quite intriguing. Both the termination shock compression ratio and the solar wind turbulence spectrum may vary dramatically with different environments, as mass-loading by pickup ions and the heliosphere properties vary. The problem of galactic cosmic ray modulation in an ISM-forced heliosphere is extremely important to understanding the paleoheliosphere signature in the terrestrial isotope record.

Today, galactic cosmic rays (GCR) with energies ≥ 0.25 GeV penetrate the solar system, and anomalous cosmic rays (energies <1 GeV) are formed from accelerated pickup ions. The cosmic ray flux at Earth is sampled by geological radioisotope records, as reviewed Kirkby and Carslaw (Chapter 12, also see Florinski and Zank, Chapter 10). Astronomical data indicates that the Sun has emerged from a region of space with virtually no neutral ISM within the past $\sim$0.4–1.5 10^5 years, and entered the Local Fluff (Chapter 6). The GCR modulation discontinuity that accompanied this transition may be in the geologic record, which show lower cosmic ray fluxes at Earth, on the average, for the past 135 kyrs years than the 135 kyrs before that (Christl et al., 2004).

1.2.7 Atmosphere Accretion from Dense Cloud Encounters

Harlow Shapley (1921) suggested that an encounter between the Sun and giant dust clouds in Orion may have perturbed the terrestrial climate and caused ice ages. The discovery of interstellar H° and He° inside the heliosphere was soon followed by studies of the ISM influence on the atmosphere for dense cloud conditions (Fahr, 1968, Begelman and Rees, 1976, McKay and Thomas, 1978, Thomas, 1978, McCrea, 1975, Talbot and Newman, 1977, Willis, 1978, Butler et al., 1978). Yeghikyan and Fahr (Chapter 11), evaluate the density of ISM at the Earth based on models describing the heliosphere inside of an dense cloud, and the interactions between the solar wind and ISM for these dense cloud conditions (also see Chapter 9, by Fahr et al.). These models then yield the concentration of interstellar hydrogen at the Earth, and the flow of water downward towards the Earth's surface, as a function of the dense cloud density. Significant atmosphere modifications are predicted in some cases. Enhanced neutral populations at 1 AU for a somewhat lower interstellar cloud density regime are discussed in Chapter 8, by Moebius et al.

1.2.8 Possible Effects of Cosmic Rays

Both solar activity cycles (Figure 1.2) and ISM variations modulate the cosmic ray flux in the heliosphere, and Kirkby and Carslaw (Chapter 12) compare galactic cosmic ray records with paleoclimate archives. They examine sources of climate forcing such as solar irradiance and cosmic ray fluxes, and conclude that arguments in favor of cosmic ray climate forcing are strong although the mechanism is uncertain. This relation between cosmic ray flux levels and the climate is shown by radioisotope records and climate archives, such as ice cores, stalagmites, and ice-rafted debris, and for modern times, by historical records. Paleoclimate archives include terrestrial records of cosmic ray spallation in the atmosphere, as traced by radioisotopes with short half-lives ($\tau_{1/2}$), e.g. ^{14}C ($\tau_{1/2} = 5,730$ yrs) and ^{10}Be ($\tau_{1/2} = 1.6$ Myrs). Possible mechanisms linking the cosmic ray flux at 1 AU and the climate include cloud nucleation by cosmic rays, and the global electrical circuit (see Chapter 12 and Roble and Hays, 1979). The discussion in Chapter 12 provides persuasive evidence linking the surface temperature to cosmic ray fluxes at Earth. The anti-correlation between sunspot number and cosmic ray fluxes in Figure 1.2 shows the heliosphere role in cosmic ray modulation; this mechanism must have also been a prominent mechanism for relating the ISM-modulated heliosphere with the climate. Fortunately this hypothesis is also verifiable by comparing paleoclimate data with astronomical data on the timing of cloud transitions.

The radioisotope records also indicate that cosmic ray fluctuations have occurred over longer timescales of many 10^8 years. Shaviv compares the ^{36}Cl

($\tau_{1/2}$~0.3 Myrs) and ^{40}K ($\tau_{1/2}$~1.3 Gyr) cosmic ray exposure records in iron meteorites (Chapter 5), but in this case to obtain cosmic ray flux increases due to the Sun's location in spiral arms where active star formation occurs.

A number of studies, none convincing, have invoked the geological ^{10}Be record, as a proxy for cosmic ray fluxes at Earth, to infer historical encounters with interstellar clouds. As a way of dating the Loop I supernova remnant, it was suggested that the relative constancy of ^{10}Be in sea sediments precluded a strong nearby X-ray source within the past $\sim$2 Myrs (Frisch, 1981). Sonett (1992) suggested that peaks in ^{10}Be layers 35,000 and 65,000 years ago resulted from a compressed heliosphere caused by the passage of a high-velocity interstellar shock. This extreme heliosphere compression expected for a rapidly moving cloud is supported by heliosphere models (Chapter 2). Structure in the ^{10}Be peaks has also been related to spatial structure in the local ISM (Frisch, 1997), and solar wind turbulence caused by mass-loading of interstellar neutrals may supply the required mechanism. Global geomagnetic excursions such as the events $\sim$32 kyr and $\sim$40 kyr ago also affect the ^{10}Be record, and can not be ignored (Christl et al., 2004). Indeed, Figure 1.2 shows the sensitivity of galactic cosmic ray fluxes on Earth to geomagnetic latitude.

1.3 Closing Comments

This brief summary of the scientific question motivating this book does not relay the full significance of the galactic environment of the Sun to the heliosphere and Earth; the following chapters provide deeper insights into this question.

Historical and paleoclimate data show a correspondence between high cosmic ray flux levels and cool temperatures on Earth (Parker, 1996). The disappearance of sunspots for extended periods of time, such as the Maunder Minimum in the years 1645 to 1715, shows up in terrestrial radioisotope records such as ^{10}Be in ice cores (Chapter 12). The solar magnetic activity cycle was present during this period, and cosmic ray modulation by the heliosphere was still evident (McCracken et al., 2004). The ^{10}Be record now extends to $\sim 10^5$ years before present, raising the hope that encounters between the Sun and interstellar clouds can be separated from solar activity effects, and from the global signature of geomagnetic pole wandering.

Sunspots have long been controversial as an influence on the terrestrial climate. Sir William Herschel carefully observed them, and postulated that diminished solar radiation at Earth during sunspot maximum affected the terrestrial climate (1801). Prof. Langley (1876) measured the radiative heat from sunspot umbral and penumbral regions, and concluded the $< 0.1\%$ solar radiation decrease associated with sunspots was inadequate to affect the climate. Climate records show that the Maunder Minimum and other periods of low solar activity levels have been exceptionally cold, which implicates high cosmic ray fluxes with cold climate conditions. Solar activity levels have returned to historic highs in the past few decades (Caballero-Lopez et al., 2004), and the historic correlations indicate these high levels also yield warm climate conditions. Unfortunately, these scientific conclusions also impact the politically loaded issue of global warming.

The possibility that the cosmos has affected the terrestrial climate is a long-time source of speculation, with many of the first discussions focused on explaining the "Universal Deluge". In 1694 Edmond Halley presented his thoughts to the Royal Society as to whether the "casual Shock of a Comet, or other transient Body" might instantly alter the axis orientation or diurnal rotation of the Earth, thus disturbing sea levels, or whether the impact of a comet could explain the presence of "vast Quantities of Earth and high Cliffs upon Beds of Shells, which once were the Bottom of the Sea" (Halley, 1724). Halley's speculation has resurfaced in the hypothesis that the impact of a comet led to the extinction of dinosaurs 65 Myrs ago at the Cretaceous-Tertiary boundary (Alvarez, 1982). The common sense disclaimer that accompanied Halley's discussion is timeless: *"... the Almighty generally making us of Natural Means to bring about his Will, I thought it not amiss to give this Honourable Society an Account of some Thoughts that occurr'd to me on this Subject; wherein, if I err, I shall find myself in very good Company."*

The articles in this volume show firmly that the interaction between the heliosphere and ISM depends on the detailed boundary conditions set for the heliosphere by each type of interstellar cloud encountered by the Sun, and that the galactic environment of the Sun changes over both geologically short time scales of $<10^5$ years, and long time scales of $>10^7$ years. This interaction, in turn, affects the flux of gas, dust, and energetic particles in the inner heliosphere.

The discussions in this book also apply to the study of astrospheres around cool stars, which are expected to have similar properties as the heliosphere. Is the historical astrosphere of a star a factor in climate stability for planetary systems? I think so (Frisch and York, 1986). If so, then the sample of $\sim$100 detected extrasolar planetary systems can be narrowed to those that are the most likely to harbor technological civilizations by evaluating the astrosphere characteristics suitable to the space trajectory of each star (Frisch, 1993). Astrospheres have now been detected towards $\sim$60% of the observed cool stars within 10 pc (Wood et al., 2005), and extensive efforts to detect Earth-sized exoplanets are underway. Perhaps some day these questions will be answered.

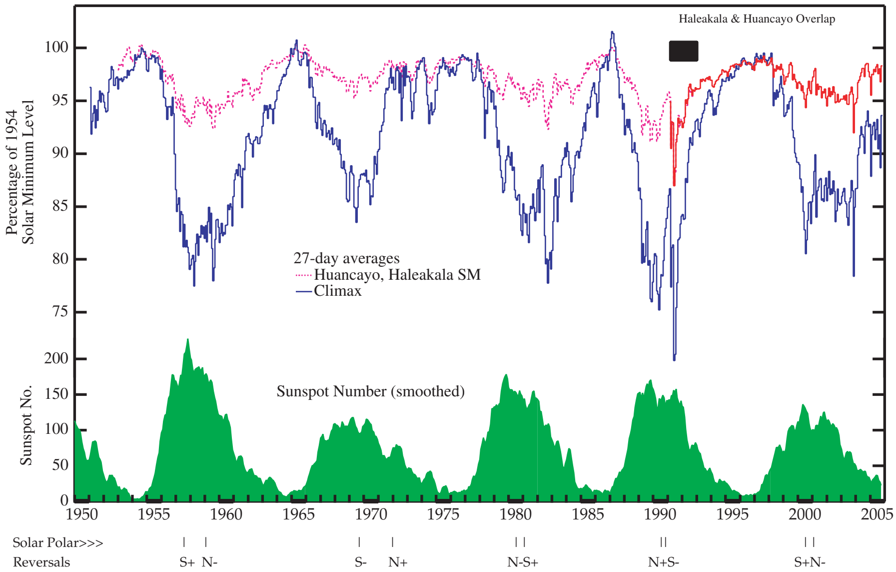

Figure 1.2. Galactic cosmic ray fluxes on Earth versus solar activity levels for sunspot cycles 18–23. Depicted are 27-day averages of the Climax (blue), and Huancayo/Haleakala (pink/red) neutron monitor rates as a percentage of their respective 1954 solar minimum levels. The running averages of the monthly mean sunspot number (green) are a proxy for the level of turbulence in the heliosphere as a function of solar activity. There is a clear anti-correlation between the neutron monitor rates and the sunspot number. The flat-topped versus peaked-top neutron monitor rates seen at successive 11-year solar minimum periods are a function of the polarity of the heliospheric magnetic field, noted at the bottom. The Climax data show solar cycle modulation for >3 GeV GCRs, while the Huancayo/Haleakala data show solar cycle modulation for >13 GeV GCRs (for additional detail please see Lopate, 2005). The geomagnetic latitudes of Climax and Huancayo/Haleakala are 48° and $\sim 0.5^\circ/20^\circ$. The poles are given as N and S, for north and south poles. The terms N+/S- indicate the times when the polarities of the north/south poles became positive/negative, while N-/S+ indicates they became negative/positive instead. The N/S poles do not appear to switch polarities simultaneously. The author thanks Dr. Clifford Lopate for providing this figure, and for maintaining a valuable data stream from an experiment begun by John Simpson in 1950.

Acknowledgments: The author thanks Dr. Clifford Lopate, of the University of New Hampshire, for providing Figure 1.2, and Dr. Lopate thanks NSF Grant 03-39527 for supporting the research displayed in this figure. The author thanks NASA for supporting her research, including grants NAG5-13107 and NNG05GD36G.

Postscript: Definitions

The nine planets of the solar system (including Pluto as a planet) extend out to 39 AU, compared to the distance of the solar wind termination shock in the

Table 1.1. Commonly Used Terms and Acronyms.

Object	Description
Interstellar:	
Interstellar Material, ISM	Atoms in the space between stars
Local Fluff or CLIC	ISM within ~30 pc, density $10^{-24.3}$ g cm^{-3}
	CLIC = Cluster of Local Interstellar Clouds
Local Interstellar Cloud, LIC	The cloud feeding ISM into the solar system
Local Bubble, LB	Nearby ISM with density $<10^{-26.1}$ g cm^{-3}
Heliosphere:	
Solar Wind, SW	Solar plasma expanding to form heliosphere
	Density ~5 ions cm^{-3}, velocity ~450 km s^{-1}
	at Earth
Neutral Current Sheet	Thin neutral region separating SW
	with opposite magnetic polarities
Heliosphere, HS	Region of space containing the solar wind
Termination Shock, TS	Shock where solar wind becomes subsonic
	TS at ~94 AU on 16 December, 2004
Heliosheath	Subsonic solar wind, outside TS
Heliosphere Bow Shock	Shock where LIC becomes subsonic
Focusing Cone	Gravitationally focused ISM dust
	and helium gas downwind of the Sun
Interstellar Products in the Heliosphere:	
Pickup Ions, PUI	Ions from SW-ISM charge exchange
Energetic Neutral Atoms	ENAs, Energetic atoms formed by
	charge exchange with ions
Cosmic Rays:	
Anomalous, ACR	Accelerated pickup ions, energy <1 GeV
Galactic, GCR	From supernova, energy >1 GeV at Earth

upwind direction of 94 AU. The Earth is 8.3 light minutes from the Sun, versus the ~0.5 light day distance to the upwind termination shock of the solar wind. The ecliptic and galactic planes are tilted with respect to each other by ~60°, and the north ecliptic pole points towards the galactic coordinates $\ell = 96.4°$ and $b = +29.8°$. This tilt allows the separation of large scale ecliptic and large scale galactic phenomena by geometric considerations.

Acronyms are used throughout this book, and some of these are listed in Table 1. For those new to this subject, an astronomical unit, AU, is the distance between the Earth and Sun. A parsec, pc, is 206,000 AU, 3.3 light years (ly), or 3.1 $\times$ 10^{18} cm. For comparison, the nearest star, α Cen, is 1.3 pc from the Sun.

Notes

1. In this same paper Herschel commented that "Whatever fanciful poets might say, in making the sun the abode of blessed spirits, or angry moralists devise, in pointing it out as a fit place for the punishment of the wicked, it does not appear that they had any other foundation for their assertions than mere opinion and vague surmise; but now I think myself authorized, *upon astronomical principles,* to propose the sun as an inhabitable world, and am persuaded that the foregoing observations, with the conclusions I have drawn from them, are fully sufficient to answer every objection that may be made against it." These comments show that valuable data are not always interpreted correctly.

2. The buffering processes convert interstellar neutrals into low energy ions, which are convected outwards with the solar wind and accelerated to low cosmic ray energies that have an anomalous composition, including abundant elements with FIP $>$ 13.6 eV. The high energy galactic cosmic ray population incident on the heliosphere is also modulated.

3. Open magnetic field lines are formed in coronal holes that reconnect in the outer heliosphere and contain low density and very high speed, $\sim$700 km s^{-1}, solar wind.

4. The pickup ions are interstellar neutrals formed by charge exchange with the solar wind. Energetic neutral atoms are formed by energetic ions that capture an electron from a low energy neutral by charge exchange. The gravitational focusing cone contains heavy elements (mainly He) that are predominantly ionized inside of 1 AU and therefore gravitationally focused downwind of the Sun (Chapter 8). Large interstellar dust grains are also gravitational focused (Chapter 7). The anomalous cosmic ray population is formed from pickup ions accelerated to low cosmic ray energies, $<$1 GeV, in the solar wind and at the termination shock, and then subjected to the same modulation and propagation processes as galactic cosmic rays (Jokipii, 2004).

References

Alvarez, L. W. (1982). Experimental Evidence that an Asteroid Impact Led to the Extinction of many Species 65 Million Years Ago. *NASA STI/Recon Technical Report N*, 83:33813.

Baggaley, W. J. (2000). Advanced Meteor Orbit Radar Observations of Interstellar Meteoroids. *J. Geophys. Res.*, 105:10353–10362.

Begelman, M. C. and Rees, M. J. (1976). Can Cosmic Clouds Cause Climatic Catastrophes. *Nature*, 261:298.

Bochkarev, N. G. (1984). Large-Scale Bubble Structure of the Interstellar Medium and Properties of the Local Spiral Arm. In *Local Interstellar Medium*, Eds. Y. Kondo, F. Bruhweiler, and B. Savage

Bravo, S., Stewart, G. A., and Blanco-Cano, X. (1998). The Varying Multipolar Structure of the Sun's Magnetic Field and the Evolution of the Solar Magnetosphere Through the Solar Cycle. *Sol. Phys.*, 179:223–235.

Burlaga, L. F., Ness, N. F., Acuña, M. H., Lepping, R. P., Connerney, J. E. P., Stone, E. C., and McDonald, F. B. (2005). Crossing the Termination Shock into the Heliosheath: Magnetic Fields. *Science*, 309:2027–2029.

Butler, D. M., Newman, M. J., and Talbot, R. J. (1978). Interstellar Cloud Material - Contribution to Planetary Atmospheres. *Science*, 201:522–525.

Caballero-Lopez, R. A., Moraal, H., McCracken, K. G., and McDonald, F. B. (2004). The Heliospheric Magnetic Field from 850 to 2000 AD Inferred from ^{10}Be Records. *J. Geophys. Res. (Space Physics)*, 109:12102.

Christl, M., Mangini, A., Holzkämper, S., and Spötl, C. (2004). Evidence for a Link between the Flux of Galactic Cosmic Rays and Earth's Climate during the past 200,000 years. *J. Atmos. Terres. Phys.*, 66:313–322.

Decker, R. B., Krimigis, S. M., Roelof, E. C., Hill, M. E., Armstrong, T. P., Gloeckler, G., Hamilton, D. C., and Lanzerotti, L. J. (2005). Voyager 1 in the Foreshock, Termination Shock, and Heliosheath. *Science*, 309:2020–2024.

Fahr, H. J. (1968). On the Influence of Neutral Interstellar Matter on the Upper Atmosphere. *Astrophys. & Space Sci.*, 2:474.

Fahr, H.-J. (2004). Global Structure of the Heliosphere and Interaction with the Local Interstellar Medium: Three Decades of Growing Knowledge. *Adv. Space Res.*, 34:3–13.

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).

Frisch, P. C. (1981). The Nearby Interstellar Medium. *Nature*, 293:377–379.

Frisch, P. C. (1993). G-star Astropauses - A Test for Interstellar Pressure. *Astrophys. J.*, 407:198–206.

Frisch, P. C. (1997). Journey of the Sun. *http://xxx.lanl.gov/*, astroph/9705231.

Frisch, P. C. (1998). Interstellar Matter and the Boundary Conditions of the Heliosphere. *Space Sci. Rev.*, 86:107–126.

Frisch, P. C. (2000). The Galactic Environment of the Sun. *American Scientist*, 88:52–59.

Frisch, P. C. (2005). Tentative Identification of Interstellar Dust in the Magnetic Wall of the Heliosphere. *Astrophys. J. Let.*, 632:L143–L146.

Frisch, P. C., Dorschner, J. M., Geiss, J., Greenberg, J. M., Grün, E., Landgraf, M., Hoppe, P., Jones, A. P., Krätschmer, W., Linde, T. J., Morfill, G. E., Reach, W., Slavin, J. D., Svestka, J., Witt, A. N., and Zank, G. P. (1999). Dust in the Local Interstellar Wind. *Astrophys. J.*, 525:492–516.

Gosling, J. T. (1996). Corotating and Transient Solar Wind Flows in Three Dimensions. *Ann. Rev. Astron. & Astrophys.*, 34:35–74.

Gruen, E. and Landgraf, M. (2000). Collisional Consequences of Big Interstellar Grains. *J. Geophys. Res.*, 105:10291–10298.

Gurnett, D. A. and Kurth, W. S. (2005). Electron Plasma Oscillations Upstream of the Solar Wind Termination Shock. *Science*, 309:2025–2027.

Halley, E. (1724). Some Considerations about the Cause of the Universal Deluge, Laid before the Royal Society, on the 12th of December 1694. By Dr. Edmond Halley, R. S. S. *Philosophical Transactions Series I*, 33:118–123.

Heiles, C. and Troland, T. H. (2003). The Millennium Arecibo 21 Centimeter Absorption-Line Survey. I. Techniques and Gaussian Fits. *Astrophys. J. Supl.*, 145:329–354.

Herschel, W. (1795). On the Nature and Construction of the Sun and Fixed Stars. By William Herschel, LL.D. F. R. S. *Philosophical Transactions Series I*, 85:46–72.

Herschel, W. (1801). Observations Tending to Investigate the Nature of the Sun, in Order to Find the Causes or Symptoms of Its Variable Emission of Light and Heat; With Remarks on the Use That May Possibly Be Drawn from Solar Observations. *Philosophical Transactions Series I*, 91:265–318.

Holzer, T. E. (1989). Interaction between the Solar Wind and the Interstellar Medium. *Ann. Rev. Astron. & Astrophys.*, 27:199–234.

Jokipii, J. R. (2004). Transport of Cosmic Rays in the Heliosphere. In *AIP Conf. Proc. 719: Physics of the Outer Heliosphere*, pages 249–259.

Lallement, R., Quémerais, E., Bertaux, J. L., Ferron, S., Koutroumpa, D., and Pellinen, R. (2005). Deflection of the Interstellar Neutral Hydrogen Flow Across the Heliospheric Interface. *Science*, 307:1447–1449.

Landgraf, M. (2000). Modeling the Motion and Distribution of Interstellar Dust inside the Heliosphere. *J. Geophys. Res.*, 105:10303–10316.

Langley, S. P. (1876). Measurement of the Direct effect of Sun-Spots on Terrestrial Climates. *Mon. Not. Roy. Astron. Soc.*, 37:5.

Linde, T. J. (1998). *A Three-Dimensional Adaptive Multifluid MHD Model of the Heliosphere*. PhD thesis, Univ. of Michigan, Ann Arbor. *http://hpcc.engin.umich.edu/CFD/publications*.

Lockwood, J. A. and Webber, W. R. (2005). Intensities of Galactic Cosmic Rays of 1.5 GeV Rigidity versus Heliospheric Current Sheet Tilt. *J. Geophys. Res. (Space Physics)*, 110:4102.

Lopate, C. (2005). Fifty Years of Ground Level Solar Particle Event Observations, In *Solar Eruptions and Energetic Particles*. *J. Geophys. Res.*

Möbius, E., Bzowski, M., Chalov, S., Fahr, H.-J., Gloeckler, G., Izmodenov, V., Kallenbach, R., Lallement, R., McMullin, D., Noda, H., Oka, M., Pauluhn, A., Raymond, J., Ruciński, D., Skoug, R., Terasawa, T., Thompson, W., Vallerga, J., von Steiger, R., and Witte, M. (2004). Synopsis of the Interstellar He Parameters from Combined Neutral Gas, Pickup Ion and UV Scattering Observations. *Astron. & Astrophys.*, 426:897–907.

McCracken, K. G., McDonald, F. B., Beer, J., Raisbeck, G., and Yiou, F. (2004). A Phenomenological Study of the Long-Term Cosmic Ray Modulation, 850-1958 AD. *J. Geophys. Res. (Space Physics)*, 109:12103.

McCrea, W. H. (1975). Ice Ages and the Galaxy. *Nature*, 255:607–609.

McKay, C. P. and Thomas, G. E. (1978). Consequences of a Past Encounter of the Earth with an Interstellar Cloud. *Geophys. Res. Lett.*, 5:215–218.

Meisel, D. D., Janches, D., and Mathews, J. D. (2002). Extrasolar Micrometeors Radiating from the Vicinity of the Local Interstellar Bubble. *Astrophys. J.*, 567:323–341.

Parker, E. N. (1996). Solar Variability and Terrestrial Climate. In *The Sun and Beyond*, pages 117.

Ratkiewicz, R., Barnes, A., Molvik, G. A., Spreiter, J. R., Stahara, S. S., Vinokur, M., and Venkateswaran, S. (1998). Effect of Varying Strength and Orientation of Local Interstellar Magnetic Field on Configuration of Exterior Heliosphere. *Astron. & Astrophys.*, 335:363–369.

Richardson, J. D., Paularena, K. I., Lazarus, A. J., and Belcher, J. W. (1995). Radial Evolution of the Solar Wind from IMP 8 to Voyager 2. *Geophys. Res. Lett.*, 22:325–328.

Roble, R. G. and Hays, P. B. (1979). A Quasi-Static Model of Global Atmospheric Electricity. II - Electrical Coupling between the Upper and Lower Atmosphere. *J. Geophys. Res.*, 84:7247–7256.

Scherer, K. and Fahr, H. J. (2003). Breathing of Heliospheric Structures Triggered by the Solar-cycle Activity. *Annales Geophysicae*, 21:1303–1313.

Shapley, H. (1921). Note on a Possible Factor in Changes of Geological Climate. *J. Geology*, 29.

Simpson, J. A. (2001). *The Cosmic Radiation*, pages 117–152. Century of Space Science, Volume I (Kluwer Academic Publishers).

Smith, E. J., Marsden, R. G., Balogh, A., Gloeckler, G., Geiss, J., McComas, D. J., McKibben, R. B., MacDowall, R. J., Lanzerotti, L. J., Krupp, N., Krueger, H., and Landgraf, M. (2003). The Sun and Heliosphere at Solar Maximum. *Science*, 302:1165–1169.

Sonett, C. P. (1992). A Supernova Shock Ensemble Model using Vostok ^{10}Be Radioactivity. *Radiocarbon*, 34:239–245.

Stone, E. C., Cummings, A. C., McDonald, F. B., Heikkila, B. C., Lal, N., and Webber, W. R. (2005). Voyager 1 Explores the Termination Shock Region and the Heliosheath Beyond. *Science*, 309:2017–2020.

Talbot, R. J. and Newman, M. J. (1977). Encounters Between Stars and Dense Interstellar Clouds. *Astrophys. J. Supl.*, 34:295–308.

Thomas, G. E. (1978). The Interstellar Wind and Its Influence on the Interplanetary Environment. *Annual Review of Earth and Planetary Sciences*, 6:173–204.

Vallée, J. P. (2005). The Spiral Arms and Interarm Separation of the Milky Way: An Updated Statistical Study. *Astron. J.*, 130:569–575.

Wang, C. and Richardson, J. D. (2005). Dynamic Processes in the Outer Heliosphere: Voyager Observations and Models. *Adv. Space Res.*, 35:2102–2105.

Whang, Y. C. (2004). Solar Cycle Variation of the Termination Shock. In *AIP Conf. Proc. 719: Physics of the Outer Heliosphere*, pages 22–27.

Willis, D. M. (1978). Atmospheric Water Vapour of Extraterrestrial Origin - Possible Role in Sun-Weather Relationships. *J. Atmos. Terres. Phys.*, 40: 513–528.

Witte, M. (2004). Kinetic Parameters of Interstellar Neutral Helium. Review of Results obtained During One Solar Cycle with the Ulysses/GAS-Instrument. *Astron. & Astrophys.*, 426:835–844.

Wood, B. E., Redfield, S., Linsky, J. L., Müller, H.-R., and Zank, G. P. (2005). Stellar Lyα Emission Lines in the Hubble Space Telescope Archive. *Astrophys. J. Supl.*, 159:118–140.

Zank, G. P. and Frisch, P. C. (1999). Consequences of a Change in the Galactic environment of the Sun. *Astrophys. J.*, 518:965–973.

Zank, G. P. and Müller, H.-R. (2003). The Dynamical Heliosphere. *J. Geophys. Res.(Space Physics)*, 108:7–1.