Galactic Environment of the Sun and Stars: Interstellar and Interplanetary Material

By Priscilla C. Frisch and Hans R. Müller and Gary P. Zank and C. Lopate

1University of Chicago, Chicago, IL
2Bartol Research Institute, University of Delaware, Newark, DE
3IGPP, University of California, Riverside, CA
4University of Chicago, Chicago, IL

Interstellar material surrounding an extrasolar planetary system interacts with the stellar wind to form the stellar atmosphere, and regulates the properties of the interplanetary medium and cosmic ray fluxes throughout the system. Advanced life and civilization developed on Earth during the time interval when the Sun was immersed in the vacuum of the Local Bubble and the heliosphere was large, and probably devoid of most anomalous and galactic cosmic rays. The Sun entered an outflow of diffuse cloud material from the Sco-Cen Association within the past several thousand years. By analogy with the Sun and solar system, the Galactic environment of an extrasolar planetary system must be a key component in understanding the distribution of systems with stable interplanetary environments, and inner planets which are shielded by stellar winds from interstellar matter (ISM), such as might be expected for stable planetary climates.

1. Introduction

Our solar system is the best template for understanding the properties of extrasolar planetary systems. The interaction between the Sun and the constituents of its galactic environment regulates the properties of the interplanetary medium, including the influx of interstellar matter (ISM) and galactic cosmic rays (GCR) onto planetary atmospheres. In the case of the Earth, the evolution of advanced life occurred during the several million year time period when the Sun was immersed in the vacuum of the Local Bubble (Frisch and York 1986, Frisch 1993). Here we use our understanding of our heliosphere to investigate the astrospheres around extrasolar planetary systems.

The heliosphere, or solar wind bubble, is dominated by interstellar matter (a visualization of the heliosphere is shown in Fig. 1). Interstellar gas constitutes ~98% of the diffuse material in the heliosphere, and the solar wind and interstellar gas densities are equal near the orbit of Jupiter, beyond which the ISM density dominates. The solar wind and photoionization prevents nearly all ISM from reaching the Earth. Interstellar ions and the smallest interstellar dust grains(<0.1 µm) are deflected around the heliosphere. Neutral ISM, however, enters the heliosphere where it dominates the interplanetary environment throughout most of the heliosphere, except for the innermost regions where the solar wind dominates. Inner and outer planets experience radically different exposures to raw ISM over the lifetime of a planetary system. The exposure levels of the Earth to galactic cosmic rays and raw and processed ISM depends sensitively on heliospheric properties.

Longstanding theories suggest that interstellar material has the potential to modify the terrestrial climate. These theories have recently become less speculative because of the improved understanding of cosmic ray modulation in a time-varying heliosphere and

† This paper is based on the talk presented at the Space Telescope Science Institute May, 2002 Symposium on the “Astrophysics of Life”. See “Interstellar and Interplanetary Material”, linked to http://ntweb.stsci.edu/sd/astrophysicsoflife/index.htm.
the relation between cosmic rays fluxes and atmospheric electricity and tropospheric cloud cover (Section 3). Extrasolar planetary systems are surrounded by astrospheres formed by the interaction between stellar winds and interstellar material. In turn, these astrospheres modulate the entrance and transport of galactic cosmic rays, anomalous cosmic rays, neutral interstellar (IS) atoms, and IS dust into and within the planetary system. Planet habitability has been evaluated in terms of atmospheric chemistry and energy budget (see other papers in this volume). However by analogy with the solar system, an historically stable atmosphere may also be a predictor for stable planetary climates and thus the conditions which promote the development of advanced life. It is this relation between the galactic environment of a star, the stellar astrosphere, and the properties and prehistory of the interplanetary medium of planetary systems that are of the greatest interest.
2. Heliosphere and Interstellar Matter

The heliosphere is the region of space filled by the solar wind, which is the expanding solar corona. The solar wind corresponds to a solar mass loss rate of $\sim 10^{-14} \, M_{\text{Sun}} \, \text{year}^{-1}$. The solar wind density decreases with $R^{-2}$ as the solar wind expands, and the solar wind and interstellar medium pressures are equal at a plasma contact discontinuity known as the “heliopause” (e.g. Axford 1972, Holzer 1989). The basic properties of the heliosphere are shown in Fig. 2 (Zank et al. 1996). At the solar wind termination shock the solar wind becomes subsonic and the cool supersonic solar wind plasma is shock-heated to a hot ($T \sim 2 \times 10^6 \, \text{K}$) subsonic plasma. Interstellar neutrals cross the plasma regions with interaction mean free paths $\sim 100 \, \text{AU}$. If the relative Sun-cloud velocity (26 km s$^{-1}$) exceeds the fast magnetosonic speed of the surrounding interstellar cloud, a bow shock will form around the heliosphere.

Solar wind properties vary with the 22-year magnetic activity cycle of the Sun, with the solar magnetic polarity changing every 11 years during the period of maximum in solar activity. During solar minimum, high speed low density solar wind forms in coronal holes at the solar poles ($n(p^+) \sim 2.5 \, \text{cm}^{-3}$, velocity $V \sim 770 \, \text{km s}^{-1}$, McComas et al. 2001). During solar maximum conditions, high speed stream material expands to the equatorial regions and the 1 AU ecliptic solar wind properties are: density $n(p^+) \sim 4$–8 cm$^{-3}$, velocity $V \sim 350$–750 km s$^{-1}$, and magnetic field $B \sim 2 \, \text{nT}$ (or 20 $\mu$G). The activity cycle of the Sun is known to produce small modifications in the heliosphere over the 11-year solar cycle, with the termination shock moving outwards $\sim 10 \, \text{AU}$ in the upwind direction, and outwards by $\sim 40$ – 50 AU in the downstream direction during solar minimum.

The Sun is presently in a low density, warm, partially ionized interstellar cloud with $n_H \sim 0.24 \, \text{cm}^{-3}$, $n(e^-) \sim 0.1 \, \text{cm}^{-3}$, and $T \sim 6,500 \, \text{K}$ (Slavin and Frisch 2002). The upstream direction of the surrounding cloud, known as the Local Interstellar Cloud (LIC), is towards $l^{II}=-3.3^o$, $b^{II}=+15.9^o$ (in the rest frame of the Sun) and the relative Sun-LIC velocity is $26.4 \pm 0.5 \, \text{km s}^{-1}$ (Witte, private communication). The LIC upstream direction in the local standard of rest (LSR, after removing the solar apex motion) is $l=346^o$, $b=-1^o$ with a LIC velocity through the LSR of $-15 \, \text{km s}^{-1}$. The LIC is a member of a cluster of cloudlets flowing at $-17 \pm 5 \, \text{km s}^{-1}$ from the LSR upstream direction of $l^{II}=2^o$, $b^{II}=5^o$ (Frisch et al. 2002). The LSR upstream direction is sensitive to the assumed solar apex motion.

The present-day Galactic environment of the Sun yields a highly asymmetrical heliosphere that is much larger than the planetary system. A range of multifluid, Boltzmann-kinetic, and MHD models of the heliosphere has been developed (see Zank, 1999, for a review). In the upstream direction, the solar wind termination shock (where the solar wind becomes subsonic) is at about 75–90 AU. The heliopause is located near 140 AU and represents the contact discontinuity between the solar wind and interstellar plasma component. The Sun is moving supersonically with respect to the LIC (sound speed is $\sim 10 \, \text{km s}^{-1}$), however a weak interstellar magnetic field ($\sim 3 \, \mu$G, fast mode velocity $\sim 23 \, \text{km s}^{-1}$) may yield a barely supersonic heliosphere ($M \sim 1$) with a bow shock. Several heliosphere models place a weak bow shock at $\sim 250 \, \text{AU}$ in the upstream direction (see Zank 1999). For comparison, the planet Pluto is at 39 AU, and the Voyager 1 and Voyager 2 spacecraft are at 84 AU and 65 AU, respectively. In the downstream direction, the termination shock is elongated by a factor of $\sim 2$ compared to the upstream direction.

† These quoted values use a solar apex motion derived from Hipparcos data (Dehnen Binney 1998). The basic solar apex motion yields the LIC LSR upstream direction $l^{II} \sim 326^o$, $b^{II} \sim +4^o$ (Frisch 1995).
Figure 2. This figure displays the neutral hydrogen density (bottom panel) and plasma temperature (top panel) of the heliosphere immersed in the LIC, which has properties \( T \sim 6,500 \) K, \( n(H^0) \sim 0.24 \) cm\(^{-3}\), \( n(H^+) \sim 0.1 \) cm\(^{-3}\), and an unknown but probably weak magnetic field. The hydrogen wall is formed by charge exchange coupling between weakly decelerated and deflected interstellar protons, and interstellar \( H^0 \).

The north ecliptic pole points towards the galactic coordinates \( l=96^\circ, b=+30^\circ \), so the ecliptic plane is inclined by \( \sim 60^\circ \) with respect to the plane of the galaxy. A pronounced asymmetry between the northern and southern ecliptic is predicted for the heliosphere because of this tilt and the LIC upstream direction (e.g. Linde et al. 1998), combined with the likelihood that the localized interstellar magnetic field is in the galactic plane (Frisch 1990).

Interstellar plasma piles up against the compressed solar wind in the outer heliosphere, and charge-coupling between interstellar \( H^0 \) and interstellar \( H^+ \) produces a low column density \( (N(H^0) \sim 3 \times 10^{14} \) cm\(^{-2}\)), decelerated \( (\delta V \sim 8 \) km \( s^{-1}\)), heated \( (\sim 29,000 \) K) \( H^0 \) component that is visible as a redshifted shoulder in the Ly\( \alpha \) absorption profile towards \( \alpha \) Cen (Linsky Wood 1996, Gayley et al. 1997, the “hydrogen wall”). Similar pileups of interstellar \( H^0 \) have been detected against the astrospheres around several nearby cool stars (Section 3).

The charged component of the ISM is deflected by the tightly wound solar wind magnetic field in the heliosheath region. The smallest interstellar dust grains\(<0.1 \) \( \mu \)m) are also deflected around the heliopause (Frisch et al. 1999). Neutral ISM, however, enters the
heliosphere where it dominates the interplanetary environment throughout most of the heliosphere, with the exception of the innermost regions where the solar wind dominates.

The Voyager 1 and Voyager 2 spacecraft are sending back data from the frontiers of the outer heliosphere, and future spacecraft may penetrate interstellar space (e.g., the Interstellar Probe mission, Liewer and Mewaldt 2000) and provide the first in situ measurements of the galactic environment of the Sun. These spacecraft, and others (e.g. Ulysses, Galileo, Cassini) have provided a wealth of data which clearly demonstrate that the ISM dominates the interplanetary environment throughout most of the solar system and heliosphere.

3. Historical Variations of the Heliosphere

The Galactic environment of the Sun and stars vary with the motions of the stars and interstellar clouds through space. The Sun itself has been immersed in the vacuum of the Local Bubble \((n(H^{0})<0.0005 \text{ cm}^{-3}, n(H^{+})~0.005 \text{ cm}^{-3}, \text{and } T\sim10^6 \text{ K})\) during the millions of years over which \textit{homo sapiens} developed and civilization emerged (Frisch and York 1986, Frisch 1993). The Sun has recently (2,000 – 105 years ago) entered an outflow of diffuse ISM from the Sco-Cen Association (Frisch 1994, Frisch et al. 2002), and is now surrounded by a warm low density partially ionized cloud. The Sun may encounter other possibly denser cloudlets in the flow, with one possibility being the “Aql-Oph” cloudlet that is within 5 pc of the Sun near the solar apex direction. A study of nearby ISM shows 96 interstellar absorption components are seen towards 60 nearby stars sampling ISM within 30 pc (Frisch et al. 2002). Since the nearest stars show \(~1\) interstellar absorption component per 1.4-1.6 pc, relative Sun-cloud velocities of 0-32 km s\(^{-1}\) suggest variations in the galactic environment of the Sun on timescales \(<50,000\) years.

The galactic environment of an astrosphere has a striking effect on the resulting astrosphere. This is illustrated in Fig. 5 for the heliosphere, which shows the heliosphere properties several million years ago when the heliosphere was embedded in the Local Bubble (left), and at some time in the future when it might be embedded in a cloud with density \(n(H^0)=15 \text{ cm}^{-3}\) (but otherwise like the LIC). During the time the Sun was embedded in the fully ionized Local Bubble Plasma, described by \(T=10^6 \text{ K}, n(p^+)=0.005 \text{ cm}^{-3}\), there were no interstellar neutrals in the heliosphere, and hence very few pickup ions or anomalous cosmic rays (very small quantities of each may have been present from a poorly understood inner source that may be related to either interplanetary dust or outgassing from planetary atmospheres). An increase to \(n=10 \text{ cm}^{-3}\) for the cloud around the Sun would contract the heliopause to radius of \(\sim14 \text{ AU}\), increase the density of neutrals at 1 AU to 2 cm\(^{-3}\), and create a Rayleigh-Taylor unstable heliopause from variable mass loading of solar wind by pickup ions (Zank & Frisch 1999). Models with higher densities (e.g. \(n=15 \text{ cm}^{-3}, T=3,000 \text{ K}\)) show that planets beyond \(\sim15 \text{ AU}\) (Uranus, Neptune, Pluto) will be outside of the heliosphere for moderate density diffuse clouds, and thus exposed to raw ISM. The Sun is predicted to encounter about a dozen giant molecular clouds, with much higher densities \((>10^3 \text{ cm}^{-3})\) over its lifetime (Talbot & Newman 1977), but encounters with diffuse clouds \((n \sim10 \text{ cm}^{-3})\) will occur more frequently.

4. Interstellar and Interplanetary Matter

Components of the interstellar medium which enter the heliosphere from deep space include neutral gas atoms, larger interstellar dust grains, and galactic cosmic rays. The products created by the interactions of the ISM and solar wind create an ISM-dominated
Figure 3. Heliosphere predicted for a Sun immersed in the hot Local Bubble (left) and immersed in a $n_H = 15 \text{ cm}^{-3}$ diffuse cold cloud (right). Figure from Müller et al. (2002).

heliosphere. Fig. 4 shows an overview of the heliosphere, with the products of the interaction between the ISM and solar wind identified.

4.1. High Energy Galactic Cosmic Rays in the Heliosphere

Galactic cosmic rays with energies less than $\sim 100 \text{ GeV/nucleon}$ are modulated by the increasingly nonuniform structure of magnetic fields embedded in the outward flowing solar wind during solar maximum (Fig. 5). The result of this modulation is a well known anticorrelation between the solar activity cycle and the cosmic ray flux at the Earth's surface. The anti-correlation is illustrated in Fig. 5, which shows neutron monitor counts, from secondary particles produced by cosmic ray interactions at the top of the atmosphere, versus the sunspot number. This anticorrelation reflects variations in the heliospheric modulation of the galactic cosmic ray flux as a function of the solar wind magnetic activity. Anomalous cosmic rays (see below), formed by accelerated pickup ions, experience modulation in the heliosphere similar to GCRs. Most cosmic ray modulation occurs in the outer part of the heliosphere, so that evidence of CR interactions on meteorites or planetary surfaces should contain fossil evidence on the heliosphere radius. The heliosphere varies with the solar cycle, as does cosmic ray modulation. Disorder in the solar wind magnetic field at sunspot maximum corresponds to an increase in cosmic ray modulation, although the heliosphere is smaller than at solar minimum. GCRs are capable of changing the flow pattern of the solar wind and the surrounding local ISM provided the particles’ coupling to the plasma is sufficiently strong. The interstellar cosmic-ray spectra and the diffusion coefficients and cosmic-ray pressure gradients within the heliosphere are now becoming better understood (e.g. Ip & Axford 1985).

4.2. Raw ISM in the Heliosphere: $H^\circ$, $He^\circ$

Neutral interstellar H and He atoms enter and penetrate the solar system, and are ionized by charge exchange with the solar wind or photoionization. A weak interplanetary glow from the fluorescence of solar Lyα radiation off of interstellar $H^\circ$, and solar 584 Å radiation off of interstellar $He^\circ$, led to the discovery of interstellar matter in the solar system.
Figure 4. Overview of the heliosphere, with termination shock, heliopause, bow shock, and outer and inner heliosheath (HS). Some sample plasma \((\text{H}^+)\), pickup ion (PU Ion), and solar wind plasma \((v_{\text{HS}})\) trajectories are shown, as well as trajectories of neutral hydrogen \((\text{H})\) coming from the interstellar medium \((\text{H}_{\text{ISM}})\) and experiencing charge exchange \((\ast)\), and galactic cosmic rays (GCR). The solar and interstellar magnetic fields \((B)\) are sketched (based on a plot by J. R. Jokipii).

in 1971 (Thomas & Krassa 1971, Bertaux & Blamont 1971, Weller & Meier 1974). \(\text{H}^o\) is ionized at \(\sim 4\) AU by charge exchange with the solar wind and photoionization, while \(\text{He}^o\) penetrates to \(\sim 0.4\) AU before becoming photoionized. The flux of \(\text{He}^o\) atoms has been measured directly by Ulysses, yielding values \(n(\text{He}^o) = 0.014 \pm 0.002\) \(\text{cm}^{-3}\), temperature \(6,500\) K, and velocity of \(26.4\) \(\text{km s}^{-1}\) and and upstream direction \(l_{II} = 3.3\)^{\circ}, \(b_{II} = +15.9\)^{\circ} (Witte et al. 1996 and private communication). The first spectral observations of interstellar \(\text{H}^o\) in the solar system observed a projected velocity \(-24.1 \pm 2.6\) \(\text{km s}^{-1}\) during solar minimum towards the direction \(l_{II} = 16.8\)^{\circ}, \(b_{II} = +12.3\)^{\circ} (Adams & Frisch 1977). Correcting this velocity towards the \(\text{He}^o\) upstream direction gives a cloud velocity \(24.8 \pm 2.6\) \(\text{km s}^{-1}\), in agreement with the \(\text{He}^o\) velocity (since during solar minimum radiation pressure and gravity are approximately equal). The LSR upstream direction of the LIC is \(l_{II} \sim 346\)^{\circ}, \(b_{II} \sim -1\)^{\circ}.

Interstellar \(\text{H}^o\) and \(\text{He}^o\) behave differently in the heliosphere. About 20%–40% of the
Figure 5. Solar cycle modulation of >3 GeV galactic cosmic rays: Sunspot number versus modulated galactic cosmic ray intensity. This figure is also available at http://ulysses.uchicago.edu/NeutronMonitor/neutron_mon.html along with related data.

$H^o$ is lost in the outer heliosheath through charge-exchange with interstellar $H^+$, and once in the solar system the $H^o$ trajectory is governed by the relative strengths of the solar Ly$\alpha$ radiation pressure force and gravity. Interstellar He$^o$ passes through the heliosheath unaltered, and the trajectory in the heliosphere is governed by gravity so that interstellar He is gravitationally focused downstream of the Sun. The Earth passes through the He focusing cone about December 1 of each year. The He$^o$ cone density is enhanced at 1 AU by a factor of \( \sim 250 \) over the value at infinity, but the peak density of the focusing cone is inside 1 AU (Michels et al. 2002).

4.3. Raw ISM in the Heliosphere: Dust

Interstellar dust grains (ISDG) with radii $>0.2 \, \mu m$ enter the heliosphere and have been detected by instruments on board Ulysses, Galileo, and Cassini (e.g. Baguhl et al. 1996, Frisch et al. 1999, Landgraf 2000). The mass flux distribution of these grains is shown in Fig. 7. Smaller grains ($< 0.1 \, \mu m$) are deflected in the heliosheath region and do not enter the heliosphere.

Large ISDGs (radii $>0.35 \, \mu m$) are focused downstream of the Sun, in a prominent gravitational focusing cone which is more extensive than the He focusing cone, extending over 10 AU in the downstream direction (Landgraf 2000). Large ISDGs constitute \( \sim 30\% \) of the interplanetary grain flux with masses $> 10^{13}$ gr (or radius $> 0.2 \, \mu m$) at 1 AU (Gruen & Landgraf 2000).

ISDGs in the size range comparable to classical dust particles (0.1-0.2 $\mu m$, charge $\sim$1 eV) show a distribution in the heliosphere which varies with time because of Lorentz coupling to a solar wind magnetic field which changes in polarity every 11-year solar cycle. These positively charged grains alternately are focused and defocused towards the
Figure 6. An example of the modulated cosmic ray spectrum at different locations in the heliosphere. The dashed line shows the modulated proton spectrum in the heliosheath ($\theta = 0^\circ$) at 110 AU, the dash-dotted line is for the supersonic solar wind at 10 AU, and the dotted line is for the heliotail ($\theta = 180^\circ$) at 650 AU. The unmodulated interstellar spectrum is shown as a solid line. Experimental data from BESS (squares) and IMP8 (circles) are shown for comparison. Figure from Florinski et al. (2002). (At $10^{2}$ MeV, from top to bottom the lines are: solid, dotted, dashed, dot-dashed.)

ecliptic plane. The 1996 solar minimum corresponded to a defocusing phase (Landgraf 2000).

The gas-to-dust mass ratio ($R_{gd}$) in the LIC is $R_{gd}=125^{+18}_{-14}$, based on comparisons between interstellar dust in the solar system and the properties for the gas in the LIC, or $R_{gd}=158$ based on missing mass arguments (Frisch & Slavin, 2002).

Radar measurements of micrometeorites show sources from outside the solar system. Interstellar micrometeorites with masses $\sim 10^{-7}$ g are detected by radar observations of the atmospheric trajectories and velocities (Baggaley 2000, Landgraf et al. 2000). A discrete source is seen at the location of $\beta$ Pic (determined after solar motion is removed). These observations from the southern hemisphere also show an enhanced flux from the southern ecliptic. In the northern hemisphere, Doppler radar measurements of micrometeorites provide evidence for a radiant direction towards the Local Bubble (Meisel et al. 2002).

4.4. Solar Wind-ISM Interactions Products: Pickup Ions and Anomalous Cosmic Rays

Interstellar atoms with first ionization potentials $\geq 13.6$ eV enter and penetrate the solar system, and are ionized by charge exchange with the solar wind. The resulting ions are coupled to the solar wind by the Lorentz force, where they are observed as a population of pickup ions (PUI, Gloeckler and Geiss 2002). PUIs of H, He, N, O, and Ne provide a direct sample of ionization levels in the LIC (Slavin & Frisch 2002). PUIs are accelerated to cosmic ray energies in the region of the termination shock of the solar wind, forming an anomalous population of cosmic rays (Garcia-Munoz et al. 1973, McDonald et al. 1974, Fisk et al. 1974). Anomalous cosmic rays, which are “anomalous” because of composition
and energy, typically have lower energies than galactic cosmic rays. The anomalous cosmic ray H, He, N, O, Ne, and Ar populations have an interstellar origin, and thus provide an additional tracer of the neutral species in the LIC (Cummings and Stone 2002). Anomalous cosmic rays with energies >1 MeV/nucleon and an interstellar origin are also found trapped in the radiation belts of the Earth’s magnetosphere (e.g. Adams & Tylka 1993, Mazur et al. 2000).

5. Astrospheres and Extrasolar Planetary System

An astrosphere is the stellar wind bubble around a cool star. Cool stars with stellar winds will have astrospheres regulated by the physical properties of the interstellar cloud surrounding each star (Frisch 1993), and stellar mass loss properties can be inferred from $H^\alpha$ Ly$\alpha$ absorption formed in the hydrogen wall region in the compressed heliosheath gas (Wood et al. 2002). The nearest star $\alpha$ Cen AB (1.3 pc) has a mass loss rate $\sim$ 2 times greater than the solar value (Wood et al. 2001). The pileup of interstellar $H^\alpha$ in the nose region of astrospheres surrounding nearby cool stars (e.g. $\alpha$ Cen, $\epsilon$ Eri, 61 CygA, 36 OphAB, 40 Eri A, Gayley et al. 1997, Wood et al. 2002), indicates that other cool stars have astrospheres which can be modeled using methodology developed for the heliosphere.

The astrosphere configuration for extrasolar planetary systems will vary with the individual properties of each system. The Sun moves through the local standard of rest with a velocity of $V$$\sim$13 km s$^{-1}$, but many cool stars have larger velocities. Typical diffuse interstellar clouds move through space with velocities 0–20 km s$^{-1}$ (or more), and the dynamical ram pressure ($\sim V^2$) may vary by factors of $\sim 10^3$, and cause variations in the astrosphere radius of factors of $>30$. The result is that inner and outer planets of extrasolar planetary systems will be exposed to different amounts of raw interstellar matter over the lifetime of the planetary system. Frisch (1993) estimated astrosphere

![Figure 7](image-url)

**Figure 7.** Mass flux of interstellar dust grains observed within the solar system by the Ulysses, Galileo and Cassini spacecraft (Baguhl et al. 1996, Landgraf et al. 2000). The AMOR radar data points are of extrasolar micro-meteorites, and the point source corresponds to a direction towards $\beta$ Pic (Baggaley 2000).
Figure 8. Locations of \( \sim 40 \) extrasolar planetary systems in galactic longitude and latitude. The plotted numbers are the star distance. The regions marked “High N(H)” show the upstream direction of the cluster of local interstellar clouds, towards which stars within \( \sim 30 \) pc are likely to be embedded in a diffuse interstellar cloud. The direction towards “Low N(H)” shows the direction towards the interior of the Local Bubble or the north pole of Gould’s Belt, towards which stars beyond \( \sim 5 \) pc are more likely to be embedded in the hot gas of the Local Bubble or high-latitude very low density ISM. The N(H) regions are based on Genova et al. (1990).

Radii and historical galactic environments of \( \sim 70 \) G-stars within 35 pc of the Sun from the basic Axford-Holzer equation using the correct stellar dynamics, a solar-like stellar wind, and a realistic guess for the cloud properties. However, this primitive approach can now be improved upon with sophisticated multifluid astrosphere models (e.g. Zank 1999), improved data from the Hipparcos catalog, and improved understanding of the nearby ISM.

Astrosphere models, based on self-consistent algorithms for the coupling of interstellar and secondary neutrals and ions through charge exchange, predict observable signatures of the interaction of stellar winds and the ISM. The interaction products contain several distinct populations which trace both ISM kinematics and the underlying donor plasma population. Comparisons between predictions of global astrospheric models and Ly\( \alpha \) absorption lines towards nearby cool stars demonstrate that external cool stars have astrospheres with detectable hydrogen walls.

The modulation of GCRs and ACRs in the heliosphere indicates that the cosmic ray fluxes in an atmosphere will depend on the characteristics of the stellar wind interaction with the surrounding interstellar cloud. Stellar activity cycles give information on the mass loss from external cool stars. Activity cycles are observed towards many G-stars, although true solar analogues are not obvious (e.g. Baliunas & Soon 1995, Henry et al. 2000).

The galactic positions and distances of \( \sim 40 \) nearby planetary systems are shown in Fig. 8. The same figure illustrates the asymmetric distribution of interstellar matter within
∼35 pc of the Sun, with most of the material located in the upstream direction towards the galactic center (labeled “High N(H)”) and very little ISM in the downstream direction (towards the interior of the Local Bubble, “Low N(H)”) or near the North Pole (“Low N(H)”). Stars beyond ∼5 pc towards low-N(H) directions are likely to be embedded in the Local Bubble, while stars within ∼40 pc in the high-N(H) directions are likely to be in diffuse clouds (which may have densities of up to several particles cm\(^{-3}\)). By analogy with the Sun, the galactic environments of extrasolar planetary systems will change with time.

6. Connections between Astrospheres and Planetary Climates

Building on the knowledge that the Sun is receding from the constellation of Orion, an area of active star formation and giant molecular clouds, Shapley (1921) speculated that the ice ages on Earth resulted from a solar encounter with the molecular clouds in Orion. Since this earliest speculation, there have been a number of attempts to link cosmic phenomena and the terrestrial climate. The investigated phenomena include (but are not limited to) studies of encounters with molecular clouds that may be in spiral arms (Thaddeus 1986, Scoville & Sanders 1986, Innanen et al. 1978, Begelman & Rees 1976, McCrea 1975, Talbot & Newman 1977), changes in atmosphere chemistry due either to energetic particles from supernova or the accretion of ISM (Brakenridge 1981, McKay & Thomas 1978, Butler et al. 1978, Fahr 1968), nearby supernova (Sonett et al. 1987, Sonett 1997), or variations in the global electrical circuit or tropospheric cloud cover from cosmic ray flux variations in the atmosphere (Roble 1991, Rycroft et al. 2000, Tinsley 2000, Marsh & Svensmark 2000).

Marsh and Svensmark (2000) presented plausible evidence that a correlation is present between cosmic ray fluxes and low altitude (<3.2 km) cloud cover, which they attribute to cloud condensation around ionized aerosol particles. They also argue that low optically thick clouds cool the climate. The correlation was observed for low altitude clouds over the 1980–1995 interval, and the correlation is dominated by a cosmic ray flux minimum corresponding to the ∼1991 solar maximum, using Huancayo neutron counts (cutoff rigidity 13 GeV) as the cosmic ray monitor. This correlation, apparently related to water nucleation on ionized aerosols, provides a possible mechanism for an astrosphere-climate connection which can be quantitatively evaluated.

The evolution of advanced life has occurred while the Sun was immersed in the vacuum of the Local Bubble, and the anomalous cosmic ray population inside the heliosphere would have nearly vanished and the enlarged heliosphere would have yielded an effective cosmic ray modulation (Mueller et al. 2002). Such a galactic environment may have promoted stability in the terrestrial climate.

7. Conclusions

The evolution of advanced life has occurred during a time when the Sun was immersed in the vacuum of the Local Bubble, so that the enlarged heliosphere would have yielded effective modulation of galactic cosmic rays. In contrast, an encounter with a modest density diffuse cloud (n(HI) ∼10 cm\(^{-3}\)) is possible within 10\(^4\) - 10\(^5\) years, and would destabilize the heliosphere and modify cosmic ray fluxes impinging on the Earth. The modulation of both galactic and anomalous cosmic rays by solar wind magnetic fields, and the emerging link between cosmic ray fluxes and climate forcing, suggests that a stable heliosphere, and by analogy stable astrospheres, are significant factors in maintaining climatic stability as is necessary for sustainable civilization.
The Galactic environment of a star determines interplanetary medium properties, including the distribution of cosmic rays in the astrosphere. How does this affect the “Astrophysics of Life”, which is the topic of this conference? Over the past century many suggestions have been made regarding Galactic effects on Earth’s climate. Recent work has demonstrated that the global electrical circuit is moderated by the cosmic ray flux (Roble 1991), and that, for instance, cloud cover in the lower troposphere (<3.2 km) correlates with cosmic ray flux (Marsh & Svensmark 2002). The fact which is clear, however, is that at the present time the solar wind shields the Earth from most ISM products. Relatively low fluxes of energetic particles, including galactic cosmic rays (>1 GeV/nucleon) and anomalous cosmic rays (<0.5 GeV/nucleon), are able to penetrate to the Earth however.

Simulations which describe the interaction between interstellar clouds and stellar winds will provide valuable information on the properties of the astrospheres of extrasolar planetary systems, as well as a basis for evaluating the interplanetary environment. Understanding the historical properties of astrospheres around extrasolar planetary systems will provide a basis for evaluating the climatic stability on possible Earth-like extrasolar planets. The differences in exposure to raw ISM for inner and outer planets over the planet lifetimes may be significant.

acknowledgments PCF would like to thank NASA for research support through grants NAG5-8163, NAG5-1105, and NAG5-6405 to the University of Chicago. GPZ and HRM acknowledge the partial support of an NSF-DOE grant ATM-0296114 and NASA grant NAG5-11621. CL thanks and acknowledges NSF grant ATM 99-12341 for providing support for the cosmic ray research.

REFERENCES

Adams, J. H. & Tylka, A. J. 1993 Anomalous Cosmic Rays and the Local Interstellar Medium. In AIP Conf. Proc. 278: Back to the Galaxy, pp. 186–+.
Adams, T. F. & Frisch, P. C. 1977 High-resolution observations of the Lyman alpha sky background. ApJ 212, 300–308.
Axford, W. I. 1972 The interaction of the solar wind with the interstellar medium. In Solar Wind (ed. C. P. Sonnet, P. J. Coleman Jr. & J. M. Wilcox), pp. 609-660. NASA Spec. Publ., SP-308.
Baggaley, W. J. 2000 Advanced Meteor Orbit Radar observations of interstellar meteoroids. J. Geophys. Res. 105, 10353–10362.
Baguhl, M., Grun, E. & Landgraf, M. 1996 In Situ Measurements of Interstellar Dust with the ULYSSES and Galileo Spaceprobes. Space Science Reviews 78, 165–172.
Baliunas, S. & Soon, W. 1995 Are Variations in the Length of the Activity Cycle Related to Changes in Brightness in Solar-Type Stars? ApJ 450, 896–+.
Begelman, M. C. & Rees, M. J. 1976 Can cosmic clouds cause climatic catastrophes. Nature 261, 298–+.
Bertaux, J. L. & Blamont, J. E. 1971 Evidence for a source of an extraterrestrial hydrogen Lyman-alpha emission. A&A 11, 200.
Brakenridge, G. R. 1981 Terrestrial paleoenvironmental effects of a late quaternary-age supernova. Icarus 46, 81–93.
Butler, D. M., Newman, M. J. & Talbot, R. J. 1978 Interstellar cloud material - Contribution to planetary atmospheres. Science 201, 522–525.
Cummings, A. C., Stone, E. C. & Steenberg, C. D. 2002 Composition of Anomalous Cosmic Rays and Other Heliospheric Ions. ApJ submitted.
Dehnen, W. & Binney, J. J. 1998 Local stellar kinematics from Hipparcos data. MNRAS 298, 387–394.
Fahr, H. J. 1968 On the Influence of Neutral Interstellar Matter on the Upper Atmosphere. Ap&SS 2, 474–+. 
Fisk, L. A., Kozlovsky, B. & Ramaty, R. 1974 An interpretation of the observed oxygen and nitrogen enhancements in low energy cosmic rays. ApJ 190, L35–L38.

Florinski, V., Zank, G. P. & Pogorelov, N. V. 2002 Galactic cosmic ray transport in the global heliosphere submitted.

Frisch, P. & York, D. G. 1986 Interstellar clouds near the Sun. In The Galaxy and the Solar System, pp. 83–100. University of Arizona Press.

Frisch, P. C. 1990 Characteristics of the local interstellar medium. In Physics of the Outer Heliosphere, pp. 19–22.

Frisch, P. C. 1993 G-star astropauses - A test for interstellar pressure. ApJ 407, 198–206.

Frisch, P. C. 1994 Morphology and ionization of the interstellar cloud surrounding the solar system. Science 265, 1423.

Frisch, P. C. 1995 Characteristics of nearby interstellar matter. Space Sci. Rev. 72, 499–592.

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. & Zank, G. P. 1999 Dust in the Local Interstellar Wind. ApJ 525, 492–516.

Frisch, P. C., Grodnicki, L. & Welty, D. E. 2002 The Velocity Distribution of the Nearest Interstellar Gas. ApJ 574, 834–846.

Frisch, P. C. & Slavin, J. D. 2002 Chemical Composition and Gas-to-Dust Mass Ratio of the Nearest Interstellar Matter. ApJ p. in preparation.

Garcia-Munoz, M., Mason, G. M. & Simpson, J. A. 1973 A New Test for Solar Modulation Theory: the 1972 May-July Low-Energy Galactic Cosmic-Ray Proton and Helium Spectra. ApJL 182, L81–+.

Gayley, K. G., Zank, G. P., Pauls, H. L., Frisch, P. C. & Welty, D. E. 1997 One- versus two-shock heliosphere: Constraining models with Goddard High Resolution Spectrograph Ly-alpha spectra toward alpha Centauri. ApJ 487, 259–270.

Genova, R., Beckman, J. E., Molaro, P. & Vladilo, G. 1990 Mg II observed in the local interstellar medium - The local cloud. ApJ 355, 150–158.

Gloeckler, G. & Geiss, G. 2002 Derivation Of Local Interstellar Medium Parameters From Pickup Ion Observations. In American Geophysical Union, Spring Meeting 2002, abstract #SH31B-01, pp. B1–+.

Gruen, E. & Landgraf, M. 2000 Collisonal consequences of big interstellar grains. J. Geophys. Res. 105, 10291–10298.

Henry, G. W., Baliunas, S. L., Donahue, R. A., Fekel, F. C. & Soon, W. 2000 Photometric and Ca II H and K Spectroscopic Variations in Nearby Sun-like Stars with Planets. III. ApJ 531, 415–437.

Holzer, T. E. 1989 Interaction between the solar wind and the interstellar medium. ARA&A 27, 199–234.

Innanen, K. A., Patrick, A. T. & Duley, W. W. 1978 The interaction of the spiral density wave and the sun's galactic orbit. Ap&SS 57, 511–515.

Ip, W.-H. & Axford, W. I. 1985 Estimates of galactic cosmic ray spectra at low energies. A&A 149, 7–10.

Landgraf, M. 2000 Modeling the motion and distribution of interstellar dust inside the heliosphere. J. Geophys. Res. 105, 10303–10316.

Landgraf, M., Baggaley, W. J., Grün, E., Krüger, H. & Linkert, G. 2000 Aspects of the mass distribution of interstellar dust grains in the solar system from in situ measurements. J. Geophys. Res. 105, 10343–10352.

Liewer, P. C., Mewaldt, R. A., Ayon, J. A. & Wallace, R. A. 2000 NASA's Interstellar Probe mission pp. 911–1000.

Linde, T. J., Gombosi, T. I., Roe, P. L., Powell, K. G. & DeZeeuw, D. L. 1998 Heliosphere in the magnetized local interstellar medium: Results of a three-dimensional MHD simulation 103 (A2), 1889–1904.

Linsky, J. L. & Wood, B. E. 1996 The alpha Centauri line of sight: D/H ratio, physical properties of local interstellar gas, and measurement of heated hydrogen (the 'hydrogen wall') near the heliopause. ApJ 463, 254–270.

Marsh, N. D. & Svensmark, H. 2000 Low Cloud Properties Influenced by Cosmic Rays. Physical Review Letters 85, 5004–5007.
Mazur, J. E., Mason, G. M., Blake, J. B., Klecker, B., Leske, R. A., Looper, M. D. & Mewaldt, R. A. 2000 Anomalous cosmic ray argon and other rare elements at 1-4 MeV/nucleon trapped within the Earth’s magnetosphere. J. Geophys. Res. 105, 21015–21024.

McComas, D. J., Baraclough, B. L., Funsten, H. O., Gosling, J. T., Santiago-Muñoz, E., Skoug, R. M., Goldstein, B. E., Neugebauer, M., Riley, P. & Balogh, A. 2000 Solar wind observations over Ulysses’ first full polar orbit. J. Geophys. Res. 105, 10419–10434.

McCrea, W. H. 1975 Ice ages and the Galaxy. Nature 255, 607–609.

McDonald, F. B., Teegarden, B. J., Trainor, J. H. & Webber, W. R. 1974 The Anomalous Abundance of Cosmic-Ray Nitrogen and Oxygen Nuclei at Low Energies. ApJL 187, L105–+.

McKay, C. P. & 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. & Mathews, J. D. 2002 Extrasolar Micrometeors Radiating from the Vicinity of the Local Interstellar Bubble. ApJ 567, 323–341.

Michels, J. G., Raymond, J. C., Bertaux, J. L., Quèmerais, E., Lallement, R., Ko, Y.-K., Spadaro, D., Gardner, L. D., Giordano, S., O’Neal, R., Finischi, S., Kohl, J. L., Benca, C., Ciavarella, A., Romoli, M. & Judge, D. 2002 The Helium Focusing Cone of the Local Interstellar Medium Close to the Sun. ApJ 568, 385–395.

Mueller, H. R., Zank, G. P. & Frisch, P. C. 2002 Heliospheric response to different possible interstellar environments in preparation.

Roble, R. G. 1991 On modeling component processes in the earth’s global electric circuit. Journal of Atmospheric and Terrestrial Physics 53, 831–847.

Rycroft, M. J., Israelsson, S. & Price, C. 2000 The global atmospheric electric circuit, solar activity and climate change. Journal of Atmospheric and Terrestrial Physics 62, 1563–1576.

Scoville, N. Z. & Sanders, D. B. 1986 Observational constraints on the interaction of giant molecular clouds with the solar system. The Galaxy and the Solar System pp. 69–82.

Shapley, H. 1921 Note on a possible factor in changes of geological climate. J. Geology 29.

Slavin, J. D. & Frisch, P. C. 2002 The Ionization of Nearby Interstellar Gas. ApJ 565, 364–379.

Sonett, C. P., McHargue, L. & Damon, P. E. 1997 Is Geminga the Source of the Pleistocene Beryllium-10 Spikes? In 25th Intl. Cosmic Ray Conf., Durban, , vol. preprint.

Sonett, C. P., Morfill, G. E. & Jokipii, J. R. 1987 Interstellar Shock Waves and 10/BE from Ice Cores. Nature 330, 458–+.

Talbot, R. J. & Newman, M. J. 1977 Encounters between stars and dense interstellar clouds. ApJS 34, 295–308.

Thaddeus, P. 1986 Molecular clouds and periodic events in the geologic past. The Galaxy and the Solar System pp. 61–68.

Thomas, G. E. & Krassa, R. F. 1971 OGO 5 measurements of the Lyman alpha sky background. A&A 11, 218–233.

Tinsley, B. A. 2000 Influence of Solar Wind on the Global Electric Circuit, and Inferred Effects on Cloud Microphysics, Temperature, and Dynamics in the Troposphere. Space Science Reviews 94, 231–258.

Weller, C. S. & Meier, R. R. 1974 Observations of helium in the interplanetary/interstellar wind - the solar-wake effect. ApJ 193, 471–476.

Witte, M., Banaszkiewicz, M. & Rosenbauer, H. 1996 Recent results on the parameters of the interstellar helium from the ULYSSES/GAS experiment. Space Sci. Rev. 78, 289–296.

Wood, B., Linsky, J., Müller, H. & Zank, G. 2001 Observational Estimates for the Mass-Loss Rates of alpha; Centauri and Proxima Centauri Using Hubble Space Telescope Ly-alpha; Spectra. ApJL 547, L49–L52.

Wood, B., Müller, H., Zank, G. & Linsky, J. 2002 Measured Mass-Loss Rates of Solar-Like Stars as a Function of Age and Activity. ApJL 574, 412–425.

Wood, B. E., Müller, H. & Zank, G. P. 2000 Hydrogen Ly-alpha; Absorption Predictions by Boltzmann Models of the Heliosphere. ApJ 542, 493–503.
ZANK, G. P. 1999 Interaction of the solar wind with the local interstellar medium: a theoretical perspective. Space Science Reviews 89, 413–688.

ZANK, G. P. & FRISCH, P. C. 1999 Consequences of a change in the Galactic environment of the Sun. ApJ 518, 965–973.

ZANK, G. P., PAULS, H. L., WILLIAMS, L. L. & HALL, D. T. 1996 Interaction of the solar wind with the local interstellar medium: A multifluid approach 101 (A10), 21639–21655.
This figure "fig1.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208556v3
This figure "fig2.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208556v3
This figure "fig3a.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208556v3
This figure "fig3b.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208556v3
This figure "fig4.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208556v3
This figure "fig5.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0208556v3