Galactic Environments of the Sun and Cool Stars

Priscilla C. Frisch

University of Chicago, Dept. Astronomy and Astrophysics, 5640 S. Ellis Ave., Chicago, IL 60637

Abstract The importance of understanding the current and historical galactic environments of cool stars is discussed. The penetration of interstellar gas into a stellar astrosphere is a function of the interaction of the star with the interstellar cloud surrounding the star, and this factor needs to be understood if an efficient search for life-bearing planets is to be made. For the Sun, both current and historical galactic conditions are such that if a solar wind were present, it would have excluded most inflowing interstellar matter from the inner regions of the heliosphere for the past few million years. Variations in heliosphere size over the recent historical path of the Sun are estimated, along with estimates of astrosphere sizes for selected nearby stars. Considering only possible effects due to encounters with interstellar clouds, stable planetary climates are more likely for inner than outer planets.

0.1 Introduction

The Sun moves through space at a velocity of about 17 pc per million years. This motion, combined with interstellar cloud motions driven by stellar evolution, yield a constantly changing galactic environment for the Sun and solar system. This environment affects the interplanetary environments of both outer and inner planets in the solar system, including Sun–Earth coupling mechanisms. By analogy, the interactions between other cool stars and the galactic environment of that star needs to be understood as part of the process of identifying planets conducive to “higher” life forms.

The interstellar cloud surrounding the Sun at this time (known as the “local interstellar cloud”, LIC), is warm, low density, and partially ionized: $T \approx 7,000$ K, $n$(H$^+$)$\approx 0.2$ cm$^{-3}$, and $n$(e$^-$)$\approx 0.1$ cm$^{-3}$. The standard assumption for diffuse interstellar clouds is that $n$(p$^+$)$=n$(e$^-$). On the scale of typical cloud densities, the LIC is rather tenuous, and notably lower density than the 1 au solar wind density (see Fig. [I]). This accounts for the ability of the solar wind today to exclude most interstellar material from 1 au.

\footnote{To be published in Planetary Systems – The Long View, eds. L. M. Celnikier and J. Tran Than Van, Editions Frontieres, 1998}
In this paper the basis for understanding the relation between the properties of stellar wind envelopes around cool star systems and the physical properties of the surrounding interstellar clouds are examined. The author believes that the historical galactic environment of a star would have a direct impact on the stability of planetary atmospheres, and therefore on the distribution of intelligent life forms. This conclusion rests partly on the observation that the solar system has been in a region of space virtually devoid of interstellar matter over the past several million years [12], [11].

Additional reviews on interstellar matter (ISM) within the solar system can be found in the book *The Heliosphere in the Local Interstellar Medium* [29]. For more information on the properties of local ISM (LISM) see [3]. For more information on nearby G-star space motions and environments, and the use of astrospheres as a test for interstellar pressure, see [11].

### 0.2 Penetration of ISM into Heliosphere

Heliosphere studies offer an opportunity to study the impact of interstellar material on the interplanetary medium. Based on spacecraft data, we know that neutral interstellar hydrogen flowing through the heliopause region is the source of several particle populations observed in both the inner and outer heliosphere, including energetic ions captured...
in the terrestrial magnetosphere. Also, interstellar dust is observed within the solar system. Since the heliosphere is the only system where we are currently able to evaluate the interplanetary environment in terms of the properties of the surrounding interstellar cloud, data on these populations are now briefly summarized. Heliosphere dimensions change as a phase of the solar cycle; therefore both the interaction of interstellar hydrogen with the solar system, and the distribution of the daughter pickup ion and anomalous cosmic ray populations, are solar-cycle dependent. Hence for external cool stars, where stellar winds may not mimic the solar wind, the distribution of ISM and interaction products within the astrosphere may differ from those in the heliosphere.

Neutral interstellar hydrogen interacts weakly in the heliopause region, with, for example, ~20% of the incident particles lost through charge exchange with interstellar protons in the heliosphere nose region. However, most of the incident interstellar H penetrates to the inner solar system, 2–5 au from the Sun. Hydrogen ionization rates evaluated at 1 au yield 85% ionization by charge-exchange with solar wind protons, and 15% ionization by photoionization, depending somewhat on the phase of the solar cycle. Helium destruction is dominated by photoionization. Observations of the resonance fluorescence of solar radiation is observed in the Lyα radiation of H and the 584 Å line of He. The main fluorescence for H originates from a region 3–5 au from the Sun, while most of the He fluorescence arises from the inner <0.5 au.

Once ionized, interstellar hydrogen is bound to the outward moving solar wind by the Lorentz force, becoming pickup ions. Heavier elements such as He, C, O, N, Ne are also observed, and references therein. As a measure of the importance of pickup ions on solar wind dynamics, the partial pressures of the pickup protons and solar wind protons are equal at about 6 au, with the pickup proton partial pressure surpassing the solar wind partial pressure by orders of magnitude external to that location.

In the region of the termination shock of the solar wind (where the solar wind goes from being supersonic to subsonic), the pickup ions are accelerated to MeV energies, and they become the anomalous cosmic ray component.

Heavy N, O, C, Ar, Ne, He ions from the anomalous cosmic ray populations become trapped in the terrestrial magnetosphere, leaking out over a period of about two weeks. Interstellar dust grains with a mean mass of 3.10^{-13} g, corresponding to a mean radius of 0.31 µm for density 2.5 gr cm^{-3} have been observed by the Ulysses and Galileo satellites within the orbit of Jupiter. Smaller charged grains are excluded at the heliopause and by the solar wind, but the larger grains penetrate more freely.

### 0.3 Solar and Cloud Motions

The discussions in this paper are based on solar and stellar motions, referred to the Local Standard of Rest (LSR) velocity frame. The Sun is assumed to have a velocity of 16.5 km s^{-1} through the LSR, directed towards galactic coordinates l=53° and b=+25°. Because the orbit of the Sun is inclined with respect to the galactic plane, the Sun oscillates through the plane with a period of ~66 million years, an amplitude of ~80 pc.\footnote{The LSR is the velocity frame of reference in which the velocities of nearby stars average to zero.}
and the last galactic plane crossing $\sim$21 Mys ago\(^4\). The amplitude of oscillation about the galactic plane is not large enough to carry the Sun out of the H\(^\circ\) disk of the plane.

Five million years ago the Sun was located at a distance of $\approx$83 pc from the current position of the Sun, and $\approx$35 pc below the galactic plane. The Sun is emerging from a region of space that is deficient in interstellar matter,\(^{12}\),\(^{11}\). This is seen in Fig. 3. X-ray data indicate that the nearest portions of this region are deficient in H\(^\circ\), and evidently filled with hot plasma with $T \sim 10^6$ K, $n(e^-) \sim 0.005$ cm\(^{-3}\)\(^3\). For millions of years, this hot plasma has constituted the galactic environment of the Sun.

The bulk motions of the interstellar clouds surrounding the Sun are approximately perpendicular to the solar motion in the LSR, so that in effect this cloud system is sweeping down on the solar system,\(^{14}\). Based on HST observations towards Sirius, there is a second interstellar cloud, in addition to the LIC cloud, towards this nearby star, at $d=2.7$ pc\(^{22}\). This second cloud (which is blue-shifted relative to the LIC, hence the term “blue-shifted”) has $n(e^-)=0.46$ cm\(^{-3}\), $T=3600$ K, and a relative velocity with respect to the Sun of 10 km s\(^{-1}\)\(^{18}\). This blue-shifted cloud is a somewhat denser diffuse cloud than the LIC. Since this cloud is seen in front of two stars at the positions $(l,b)=(227^\circ, -9^\circ)$ and $(240^\circ, -11^\circ)$, compared to the anti-apex direction of $(233^\circ, -25^\circ)$, the Sun is likely to have encountered this cloud sometime within the past $\sim 250,000$ years.

This cloud provides the second historical environment of the Sun that will be considered.

### 0.4 Heliospheres and Astrospheres

The fundamental variable governing the penetration of interstellar matter into the region of space occupied by a stellar wind is the size of the heliosphere/astrosphere\(^4\). In this section, a simple effort is made to predict the response of the heliosphere to different types of interstellar clouds. This discussion also applies to the sizes of astrospheres formed around cool stars with stellar winds of similar properties to those of the solar wind. These predictions are made based on the discussions of Holzer (1989) for the heliopause radius as a function of the equilibrium between the ram pressure of the solar and interstellar winds. This equation yields a simplified approximation to the detailed predictions of two and three-dimensional kinetic, multi-fluid, and magneto-hydrodynamic models of the heliosphere\(^{32}\),\(^{12}\),\(^{24}\). The pickup ion and anomalous cosmic ray pressures are not included in this equation. However this approximation does give us a basis for understanding how different cloud types might affect the properties of our heliosphere relative to each other.

\[
\frac{P_{SW}}{R_A^2} = \frac{\alpha B^2}{8\pi} + 2\beta n_e kT + \gamma n_e m_H u^2 + \delta \beta n_H kT + \delta \gamma n_H m_H u^2 + \epsilon P_{CR} \tag{1}
\]

The variables $P_{SW}$ and $R_A$ are the solar wind ram pressure at 1 au and the heliopause radius (in units au), respectively. The solar wind parameters used here are a density of 7.63 particles cm\(^{-3}\) and a velocity of 440 km s\(^{-1}\), based on 14-year average values determined from the Voyager spacecraft\(^{30}\), giving a ram pressure of $P_{SW}=2.5 \times 10^{-8}$ dynes cm\(^{-2}\). $B^2$ is the strength of the interstellar magnetic field; $n_e$ is the interstellar...
electron density; \( n_H \) is the density of interstellar H\(^o\); T is the temperature (K); \( m_H \) is the mass of the hydrogen atom; k is the Boltzman constant; u is the relative velocity of the Sun and the surrounding interstellar cloud; and \( P_{CR} \) is the pressure of cosmic rays. The factors of \( \alpha \), \( \beta \), \( \gamma \), \( \delta \), and \( \epsilon \) are, respectively, assumed to be 2.5, 1.1, 0.2, 0.23 (Holzer 1989). The constant \( \alpha \) represents the amplification of the interstellar magnetic field by interaction with the heliosphere; the constants \( \beta \) and \( \gamma \) relate to the flow of interstellar matter around the heliosphere; \( \delta \) and \( \epsilon \) are the fractions of interstellar H\(^o\) and galactic cosmic rays excluded from the heliosphere, respectively. The distance of the heliopause from the Sun will vary according to the properties of the cloud surrounding the solar system.

The distribution of interstellar matter within the heliosphere depends on the dimensions of the heliosphere; therefore the expected heliopause distance is calculated for encounters with a sample of different types of interstellar clouds (Table 4). The main value of these estimates is comparative, in that they illustrate the response of the heliosphere to encounters with clouds of different properties. True two-dimensional and three-dimensional heliosphere models now exist that provide more accurate estimates of heliosphere dimensions (see the references above). The salient properties of these results
are that all types of interstellar cloud types considered, except for the diffuse LIC, ‘blue-shifted’ cloud, and hot plasma, give heliopause dimensions significantly smaller than found today. This result derives partly from the assumption that most of the clouds are at rest in the LSR, so that the relative Sun-cloud velocity is 17 km s$^{-1}$. The high-velocity shock front, likewise, yields a smaller heliosphere, but the effect would be transient since such a shock front would pass over the heliosphere in less than one year.

The two historical solar environments identified in Section 0.3 are a hot plasma and a slightly denser diffuse cloud. In the hot plasma case (column 4, Table 1) the heliosphere would be slightly larger (25%) than today. A diffuse cloud blue-shifted with respect to the LIC has been observed by the Hubble Space Telescope towards Sirius and ε CMa, [22], [13]. Assuming that $n(e^-)\approx n(H^0)$, the heliosphere would have been approximately the same size as today, since the larger densities are offset by the lower temperature and relative velocity (column 2, Table 1). The other clouds considered in the table were assumed to be at rest in the LSR, so that the larger densities effectively compressed the heliosphere to much smaller dimensions than today.

The solar wind flux used in Table 1 is based on a 14 year average value. During periods such as the Maunder minimum, when sunspots virtually disappeared, solar wind properties were different, [6], indicating that the size of external cool star astrospheres will be expected to fluctuate with starspot activity.

Table 1: Heliopause Radius versus Cloud Type

| Variable | Diffuse LIC | Diffuse Blue | Shock Front | Hot Plasma | $10^2$ | $10^3$ | $10^4$ | $10^5$ | H II |
|----------|-------------|--------------|-------------|------------|--------|--------|--------|--------|-----|
| Cloud No.| 1           | 2            | 3           | 4          | 5      | 6      | 7      | 8      | 9   |
| $u$ (km s$^{-1}$) | 26       | 10           | 100         | 17         | 17    | 17     | 17     | 17     | 17   |
| $n_H$ (cm$^{-3}$) | 0.2      | 0.46         | 0.8         | 0.0003     | 10$^2$ | 10$^3$ | 10$^4$ | 10$^5$ | 0    |
| $n_e$ (cm$^{-3}$) | 0.1      | 0.46         | 0.4         | 0.005      | 0.01  | 0.1    | 1      | 10     | 10   |
| $T^0$ | 7,000       | 3,600        | $10^5$      | $10^6$     | 100   | 50     | 20     | 20     | 10,000 |
| $B$ ($\mu$G) | 2         | 2            | 6           | 0          | 5     | 5      | 5      | 5      | 0    |
| $R_A$ (au) | 106       | 118          | 15          | 134        | 16    | 5      | 2      | 0.5    | 18   |

0.5 Historical Environments of Nearby Cool Stars Traversing Low Density Regions for the Past 5 Myrs

A sensible search for external planets with stable climates must be based on an understanding of the galactic environment of that star. Past studies of the historical environments of nearby stars include a search for star-cloud encounters as a basis for under-
standing the formation and equilibrium of dusty circumstellar disks around A-stars, [31], [25], and a study of single nearby cool stars with historical space trajectories through regions of space with low average spatial densities so that the star is unlikely to have encountered significant interstellar clouds over the past 5 Myrs [16]. Main sequence stars spend typically 3% of their lifetimes inside of interstellar clouds [25]. A list of a subset of G-stars with historical galactic environments in low density regions of space is given in Table 0.5, along with an estimate of the astropause radius for each star based on the space velocity of the star given in [10]. Column 1 gives the HD number of the star; columns 2–4 give the galactic coordinates and distance; V gives the velocity of the star through the LSR. The Cloud No. column refers to the cloud numbers in Table 4, and the last column gives the astropause radius predicted assuming the cloud is at rest in the LSR with a cloud type from column 6. The listed stars were selected as stars which are not likely to have encountered interstellar clouds over the past several million years. The cloud type assumed for the surrounding interstellar cloud is also listed in the table, where the cloud type is based on an informed guess as to the properties of the interstellar cloud surrounding each star. The number listed in column 6 gives the number of the cloud type from Table 4.

| Star HD | l Deg. | b Deg. | r pc | V km s⁻¹ | Cloud No. | Rₐ AU |
|---------|--------|--------|------|--------|-----------|-------|
| 1461    | 101    | −69    | 19   | 23     | 1         | 66    |
| 12235   | 155    | −55    | 27   | 33     | 1         | 48    |
| 13421   | 155    | −49    | 30   | 39     | 1         | 41    |
| 14412   | 214    | −70    | 12   | 34     | 1         | 47    |
| 14802   | 209    | −69    | 12   | 7      | 1         | 137   |
| 38529   | 205    | −13    | 34   | 22     | 4         | 69    |
| 48938   | 237    | −13    | 17   | 35     | 4         | 46    |
| 50692   | 191    | 13     | 19   | 25     | 4         | 62    |
| 84737   | 173    | 50     | 13   | 26     | 4         | 60    |
| 96700   | 278    | 28     | 20   | 29     | 1         | 54    |
| 102438  | 288    | 30     | 16   | 11     | 1         | 112   |
| 126053  | 348    | 55     | 17   | 38     | 1         | 42    |
| 147513  | 342    | 7      | 15   | 23     | 2         | 66    |
| 175225  | 83     | 21     | 24   | 25     | 1         | 62    |
| 186760  | 91     | 16     | 21   | 15     | 1         | 92    |
| 199960  | 45     | −31    | 28   | 12     | 2         | 107   |
| 217014  | 91     | −35    | 18   | 27     | 1         | 58    |
0.6 Closing Comments

Based on observations of interstellar matter within our solar system, we can say with confidence that the interplanetary environments of external planetary systems are a function of the interaction of each star with the interstellar cloud surrounding that star. Factors that regulate this interaction will be the stellar wind flow, and the cloud density, temperature, and velocity relative to the star. In turn, the interplanetary environment will affect the planetary atmospheres and climate. A discussion of climate variations due to encounters with interstellar clouds is outside of the scope of this review. But it is worth noting that the climates of outer planets will be more sensitive to perturbations by interstellar gas than will be the climates of inner planets. For instance, in the solar system today the densities of the solar wind and incident interstellar gas are equal at the orbit of Jupiter. Therefore, considering only the interstellar cloud encounter aspect, stable planetary climates are more likely for inner than outer planets. These factors need to be considered if a sensible search for extraterrestrial life is to be conducted.
Bibliography

[1] Adams, T. F., and Frisch, P. C. 1977, Ap. J., 212, 300

[2] Ajello, J. M., Pryor, W. R., Barth, C. A., Hord, C. W., Stewart, A. IK. F., Simmons, K. E., and Hall, D. T. 1994, Astr. Ap., 289, 283

[3] Baguhl, M., Grun, E., and Landgraf, M. 1996, Sp. Sci. Rev., 78, 165

[4] Bash, F. 1986, in R. Smoluchowski, J. N. Bahcall, and M. Matthews (eds) ‘Interstellar Clouds Near the Sun’, The Galaxy and the Solar System, U. Arizona Press, Tucson

[5] Baranov, V., and Malama, Y. G. 1996, Sp. Sci. Rev., 78, 305

[6] Cliver, E., Bounar, K., Boriskoff, V. 1997, Proceedings of Solar Physics Conference, Sunspot New Mexico, Sept. 1997, P. A. S. P.

[7] Cox, D. P., and Reynolds, R. J. 1987, An. Rev. Astr. Ap., 25, 303

[8] A. C., and Stone, E. C., 1996, Sp. Sci. Rev., 78, 117

[9] Cummings, J. R., Cummings, A. C., Mewaldt, R. A., Selesnick, R. S., Stone, E. C., and Von Rosenvinge, T. T. 1993, Geo. R. L. 20, 2003

[10] Frisch, P.C. 1998, Sp. Sci. Rev., in press

[11] Frisch, P. C., preprint

[12] Frisch, P. C., and York, D. G. 1986, in R. Smoluchowski, J. N. Bahcall, and M. Matthews (eds) ‘Interstellar Clouds Near the Sun’, The Galaxy and the Solar System, U. Arizona Press, Tucson, 83

[13] Frisch, P. C. 1995, Sp. Sci. Rev., 72, 499

[14] Frisch, P.C. 1996, Sp. Sci. Rev., 78, 213

[15] Frisch, P. C. 1996, Sp. Sci. Rev., 78, 335

[16] Frisch, P. C. 1993, Ap. J., 407, 198

[17] Gloeckler, G. 1996, Sp. Sci. Rev., 78, 335

[18] Gryn, C., and Dupin, O. 1995, Science with the Hubble Space Telescope – II, P. Benvenuti, u F. D. Macchetto, and E. J. Schreier, Paris, France
[19] Holzer, T. 1989, A. R. A. A., 27, 199
[20] Izmodenov, V., Malama, Y. G., Lallement, R. 1998, Astr. Ap., 317, 193
[21] Kausch, T., and Fahr, H. 1997, Astr. and Ap., 325, 828
[22] Lallement, R., Bertin, P., Ferlet,R., Vidal-Madjar, A., Bertaux, J. L. 1994, Astr. Ap. 286, 898
[23] Lallement, R., Bertaux, J. -L., Chassefiere, E., and Sandel, B. R. 1991, Astr. Ap. 252, 385
[24] Linde, T. J., Gombosi, T. I., Roe, P. L., Powell, K. G., DeZeeuw, D. L. 1998, J. G. R., 103, 1889
[25] Lissauer, J. J., Griffith, C. A. 1989, Ap. J., 340, 468L
[26] Quemerais, E., Bertaux, J.-L., Sandel, B. R., and Lallement, R. 1994, Astr. Ap., 290, 941
[27] Rucinski, D., Cummings, A. C., Gloeckler, G., Lazarus, A. J., Mobius, E., and Witte, M. 1996, Sp. Sci. Rev., 78, 73
[28] Tylka, A., Boberg, P. R., Adams, J. H., Jr. 1996, Ad. Sp. R., 17, 47
[29] Von Steiger,R., Lallement, R., and Lee, M. A. 1996, The Heliosphere in the Local Interstellar Medium, Kluwer: Dordrecht
[30] Whang, Y. C., Burlaga, L. F., and Ness, N. F. 1996, Sp. Sci. Rev., 78, 393
[31] Whitmire, D. P., Matese, J. J., Whitman, P. G. 1992, Ap. J., 388, 190
[32] Zank, G., and Pauls, H. L. 1996, Sp. Sci. Rev., 78, 95