

The Loop I Superbubble and the Local Interstellar Magnetic Field

Priscilla Chapman Frisch¹

Abstract

Recent data on the interstellar magnetic field in the low density nearby interstellar medium suggest a new perspective for understanding interstellar clouds within 40 pc. The directions of the local interstellar magnetic field found from measurements of optically polarized starlight and the very local field found from the Ribbon of energetic neutral atoms discovered by IBEX nearly agree. The geometrical relation between the local magnetic field, the positions and kinematics of local interstellar clouds, and the Loop I S1 superbubble, suggest that the Sun is located in the boundary of this evolved superbubble. The quasi-perpendicular angle between the bulk kinematics and magnetic field of the local ISM indicates that a complete picture of low density interstellar clouds needs to include information on the interstellar magnetic field.

1 Introduction

Over large spatial scales, the “ordered” versus “random” components of the interstellar magnetic field trace fundamentally different histories of the interstellar medium (ISM). The large-scale ordered interstellar magnetic field is traced through the interarm region of the galaxy with Faraday rotation measures (Rand & Kulkarni, 1989; Han, 2009) and polarized starlight (Mathewson & Ford, 1970), and is directed toward $\ell \sim 88^\circ$. Superimposed on that pattern are “random” distortions of the large-scale magnetic field, many caused by expanding superbubbles sweeping up the ISMF during stellar evolution in spiral arms and spurs (Vallee, 1993; Elmegreen, 1993).

The Sun is located away from the density maximum of the Orion spiral arm, also known as the Local Arm, or the Orion Spur, where active star formation is ongoing. The older clusters of the Scorpius-Centaurus Association (ScoOB2) are about 120 pc away (Elias et al., 2009). The Local Bubble region around the Sun, where average interstellar densities are very low, blends into the Loop I superbubble that is the result of stellar evolution in ScoOB2 over the past 15 Myrs (Fig. 1, Frisch, 1995; Maíz-Apellániz, 2001).

The Loop I superbubble is a local example of the “random” ISMF component. The spatial scale of Loop I, with a radius of $\sim 80^\circ$ and centered ~ 100 pc away (Heiles, 1998; Wolleben, 2007), is intermediary between the large-scale ordered ISMF component and the tiny-scale ISMF around the heliosphere. The Loop I ISMF is defined by synchrotron emission associated with the shell of the Loop I superbubble (Berkhuijsen, 1971; Wolleben, 2007). The most intense emission arises from a limb of Loop I called the North Polar Spur, which overlaps the spatial region between RA=16H and RA=20H. In this part of the sky, optical

¹University of Chicago, Dept. Astronomy and Astrophysics, Chicago, IL 60637

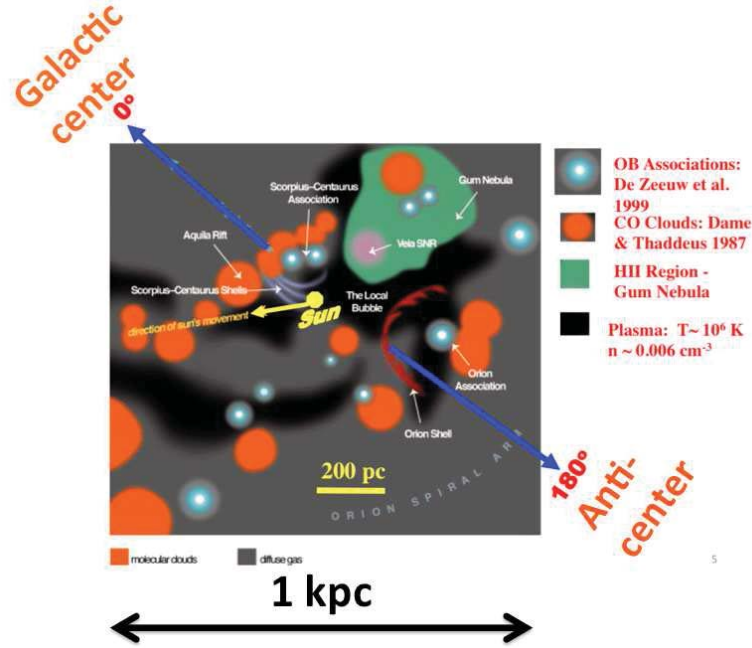


Figure 1: The distribution of molecular clouds (orange) traced by the CO 12 cm line is shown for regions within ~ 1 kpc of the Sun. Stellar associations (bright starry dots) form from these molecular clouds, generating superbubble shells that compress interstellar dust and gas during expansion (gray and red shell-like arcs). The solar motion through the local standard of rest (yellow arrow) has carried the Sun through the low density interior of the Local Bubble for the past several million years. (Figure from Frisch, 2000).

polarization data show that the ISMF extends from within 10 pc of the Sun, to out beyond 100 pc (Fig. 2; Bailey et al., 2010; Santos et al., 2011). Beyond ~ 100 pc, H^0 filaments in the North Polar Spur direction bound Loop I. The ratio of magnetic-to-thermal pressures in these filaments is ~ 67 (Heiles, 1989).

At the opposite end of the spatial domain, the heliosphere samples the very local interstellar magnetic field over spatial scales of $10^2 - 10^4$ AU, where the bow wave and heliotail are included (Zank et al., 2013). The ISMF is traced by a ‘Ribbon’ of energetic neutral atoms (ENAs) with energies of 0.2–6 keV (McComas et al., 2009; Schwadron et al., 2009). Although the detailed physical mechanism that generates the Ribbon is not yet well-understood (McComas et al., 2011, 2014), the Ribbon forms in directions perpendicular to the ISMF as it drapes over the heliosphere (e.g. Heerikhuisen et al., 2010; Heerikhuisen & Pogorelov, 2011; Heerikhuisen et al., 2014). The best diagnostic for the direction of the ISMF that shapes the heliosphere is the center of the extraordinarily circular Ribbon arc (Funsten et al., 2013). For the 2.73 keV ENAs, the IBEX Ribbon arc is centered at $\ell = 30.5^\circ \pm 2.6^\circ$, $b = 57.1^\circ \pm 1^\circ$. The uncertainties are from the variation of the ribbon center with energy. The ratio of magnetic-to-thermal pressures in the low density weakly ionized ISM around the heliosphere is ~ 1 (Frisch et al., 2011).

The low densities of nearby ISM within 10 pc, $\langle n \rangle \sim 0.1 \text{ cm}^{-3}$ and $N(H^0) < 10^{18.5} \text{ cm}^{-2}$ (Wood et al., 2005), corresponds to a minimal extinction by interstellar dust of $E(B-V) \leq$

0.001 mag (Frisch et al., 2012). Interstellar material with such low densities was originally characterized as “intercloud gas” (Rogerson et al., 1973), to differentiate it from the optically vivid dense ionized gas in star-formation regions such as Orion (Fig. 1), and the cold H^o gas that dominated the 21-cm sky. Nevertheless, dust in the nearby ISM polarizes starlight and these polarizations provide the local ISMF direction within 40 pc.

Eugene Parker once asked me “what is an interstellar cloud”. In the context of the very local ISM, a cloud is defined using the classical astronomical concept that a cloud is an entity if it has a velocity different from that of other gas in the same sightline. The result is that the dissection of interstellar gas into ‘clouds’ depends on the spectral resolution of the spectrometer. Welty has shown that the number of identified clouds increases nearly exponentially with the resolution of the spectrometer (Welty & Hobbs, 2001; Frisch, 2001). This tradition of identifying clouds by their velocity has been followed for the local ISM (e.g. Frisch et al., 2011), but the concept that clouds are individual entities is transcended by the inclusion of an interstellar magnetic field. We have found that the bulk flow of local interstellar gas past the Sun has a direction that is nearly perpendicular to the direction of the local ISMF determined from optical polarization data (Frisch et al., 2012, Section 2). This connection between cloud kinematics and magnetic field extends the concept of interstellar clouds beyond velocity components, so as to include large scale structural features in the ISMF such as the Loop I superbubble.

2 ISMF Direction from Locally Polarized Starlight

For the purpose of understanding the propagation of galactic cosmic rays (GCRs) with energies ≤ 10 TeV into the heliosphere vicinity, the relation between the Loop I magnetic field and the ISMF traced by the IBEX Ribbon needs to be understood. The only known way to obtain the nearby ISMF direction over scales of ≤ 50 pc is by extracting this information from measurements of starlight that is polarized in the local ISM (Tinbergen, 1982; Piirola, 1977; Frisch, 2010; Bailey et al., 2010; Frisch et al., 2010, 2012, 2014). Linear polarization of starlight occurs when starlight traverses an optically asymmetric interstellar medium created by charged dust grains that are aligned with respect to the ISMF (e.g., Lazarian, 2007; Hoang & Lazarian, 2014). Loop I is measured in both polarized synchrotron emission, where polarization is perpendicular to the ISMF direction, and starlight polarization, where polarization is parallel to the ISMF direction. Comparisons between the Loop I synchrotron emission (Berkhuijsen, 1971; Wolleben, 2007) and polarized starlight (Mathewson & Ford, 1970; Santos et al., 2011) show that the polarization vectors are parallel to the ISMF.

We have assembled a database of new and existing measurements of the polarizations of nearby stars with the goal of extracting the direction of the local ISMF from these data (Frisch et al., 2014, 2012, hereafter Paper III). Our method for obtaining the ISMF direction exploits the fact that the sine of the polarization position angle will be zero when the polarization vector is perfectly aligned with the direction of the ISMF, and uses that property to determine the ISMF direction that provides the best fit to the ensemble of polarization data. The stars that are included in the fit are selected based on three criteria:

(1) Stars must be within 40 pc of the Sun. Beyond that, in some directions such as the RA=16H–20H interval containing the North Polar Spur, more distant stars are sampling polarizations caused by dust in dense filaments that are not related to the low density local ISM. (2) Stars are restricted to those that are within 90° of the heliosphere nose, which is located at $\ell=5.3^\circ$, $b=+12.0^\circ$ (McComas et al., 2012). This restriction is partly historical because this is the spatial region where Tinbergen (1982) first discovered a nearby patch of polarizing dust. However regions more than 90° from the heliosphere nose tend to be in the anti-center hemisphere of the galaxy where less ISM is found close to the Sun (Figs. 1, 3). (3) A fully aligned dust population with no foreground depolarization will give polarization position angles that are parallel to the direction of the ISMF. Fig. 2 shows that polarizations become significantly stronger for stars beyond about 50 pc, so that grains aligned with the ISMF are unlikely to be local.

Plots of polarization versus star distance show an upper envelope that gives the relation $P(\%)=9 \cdot E(B-V)$ for reddened stars (Serkowski, 1968). For the low color excesses of nearby stars we expect polarizations of $P(\%) \sim 0.01\%$ or less. Special techniques are required to extract the ISMF direction from weak polarization data. Because of the low polarizations expected from the ISM within 40 pc, many stars have polarization strengths that are less than twice the mean measurement error. We therefore developed a statistical method for combining weighted polarizations so that the best-fitting ISMF direction could be derived from the polarization position angles of all of the data, including measurements where the detection is statistically insignificant (Frisch et al., 2012, 2014). The technique makes use of the statistical properties of polarization data, where the Stokes parameters Q and U are normally distributed but the polarization, $P = (Q^2 + U^2)^{0.5}$ is always positive (Naghizadeh-Khouei & Clarke, 1993). The directional analysis is based entirely on polarization position angles, with the polarizations themselves entering only through the statistical properties of the weighting function.

To perform the data analysis, a merit function was developed to describe the goodness-of-fit of the data to the ISMF direction. Minimization of the merit function, corresponding to

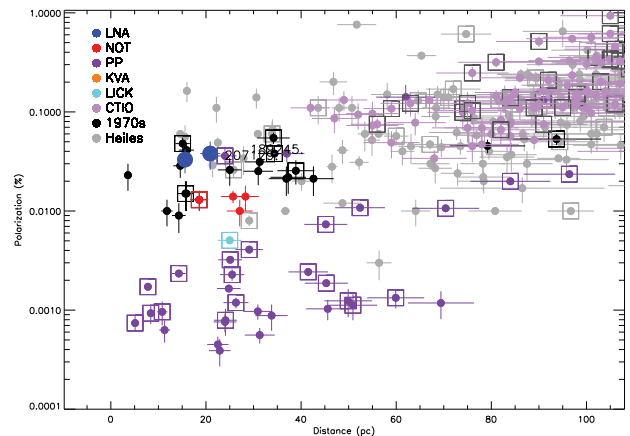


Figure 2: Strength of starlight polarizations due to the intervening ISM, for the spatial region on the sky corresponding to RA=16H–20H where polarization was found to increase with distance. The dark purple symbols represent polarizations collected in the red band where the grain extinction is less efficient. This figure is from Frisch et al. (2012), where additional details can be found.

minimization of the sines of the polarization position angles, then produces the best fitting ISMF direction to the data sample. We have found the direction of the local ISMF in a series of successive studies based on variations of the fitting algorithm (Frisch et al., 2010, Paper III). Each study is based on a larger dataset than the earlier studies, and used the same constraints on the scope of the data set. Using only polarization measurements with $P/dP \geq 2.0$, where P , dP are the polarization strength and mean error, an ISMF direction toward $\ell = 37^\circ \pm 15^\circ$, $b = 22^\circ \pm 15^\circ$ was found (Paper III). When the data were statistically weighted according to the Naghizadeh-Khouei & Clarke (1993) prescription above, an ISMF direction toward $\ell = 47^\circ \pm 20^\circ$, $b = 25^\circ \pm 20^\circ$ was found (Paper III). The values of the merit functions for these fits are plotted in Fig. 4. The ISMF direction based on these polarizations of nearby stars nearly agrees with the ISMF direction obtained from the IBEX Ribbon. The difference in direction is $34^\circ \pm 28^\circ$. One explanation is that the ISMF affecting the heliosphere and the ISMF that controls the polarizations of nearby stars are drawn from the same nearby magnetic field.

A third paper, in preparation, refines the data sample based on the behavior of the individual polarization position angles, and obtains ISMF direction that is consistent with the previous studies and more closely agrees with the IBEX Ribbon direction (Frisch et al., 2014).

3 Local Interstellar Magnetic Field and Gas

Very young superbubble shells are semi-spherical, but the ISMF introduces a fundamental asymmetry into superbubble expansion (e.g. Ferriere et al., 1991). The small pitch angles of plasma particles that expand parallel to the ISMF will distort the spherical shape, when the ram pressure of the expanding material becomes comparable to the total pressure of the upstream ISM. The initial expansion phase of the Loop I superbubble, corresponding to times of the earliest stellar evolution in ScoOB2 about 15 Myrs ago (de Geus, 1992), would have

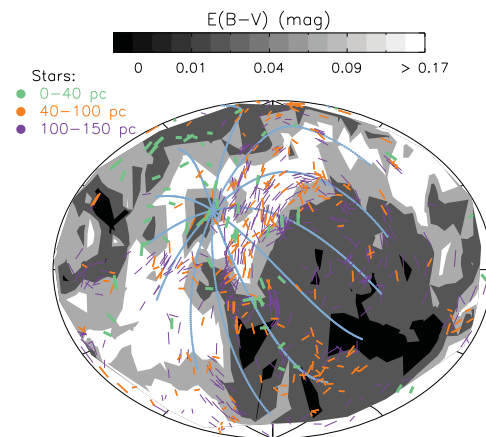


Figure 3: The color excess $E(B-V)$ associated with the nearside of Loop I, 50–100 pc, is displayed in a reverse color scale with white regions representing the largest extinctions. Polarization vectors are color-coded by star distance. The gray-blue lines indicate field lines for the best-fitting ISMF (Fig. 4). The Loop I ISMF, traced by the purple vectors, extends to within 40 pc in directions where the polarization direction does not vary with distance. Color excesses are based the Hipparcos catalog (Perryman, 1997) and are spatially smoothed over $\sim \pm 13^\circ$ intervals for overlapping distances. $E(B-V)=0.01$ corresponds to $\log(N(H))=19.76 \text{ cm}^{-2}$. Figure from Paper III.

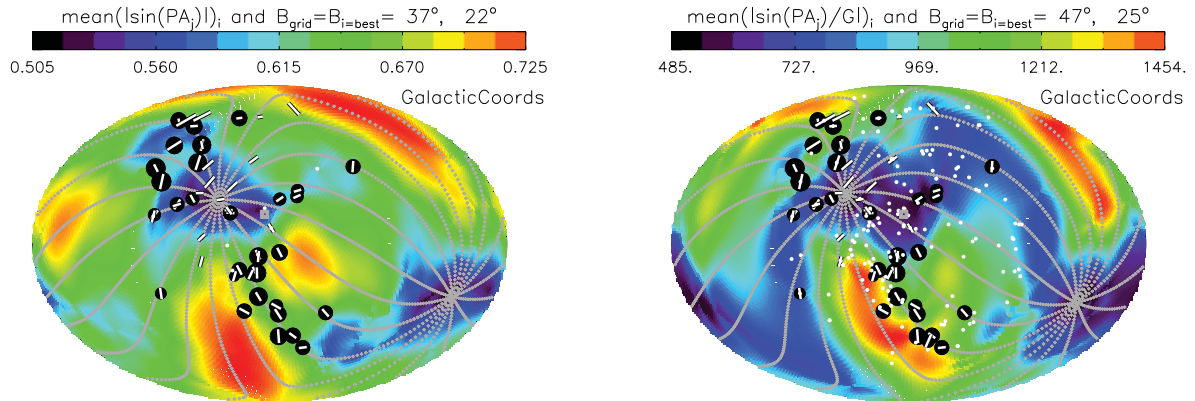


Figure 4: The value of the polarization position angle merit function evaluated over a regular grid of possible interstellar field directions is plotted, based on unweighted (left) and weighted (right) fits to the data (see Frisch et al., 2012, for more details). The symbol size is coded to increase with polarization strength, and the dots (right) represent stars where observed polarizations are not statistically significant. The gray dotted grid shows the best-fit ISMF listed in the figure title. The secondary weaker minimum centered near the heliosphere nose in the right figure (plot center) is dominated by the randomly distributed position angles contributed by low significance data points. The best-fitting ISMF is directed towards the North Polar Spur and represents the ISMF within 40 pc. The figures are centered on the galactic center with longitude increasing to the left.

expanded into an asymmetric medium resulting from the ordered ISMF field, an ISM density gradient in the galactic plane due to our location near an interarm region, and the vertical density gradient away from the galactic plane. This original star formation epoch created the Upper Centaurus subgroup of ScoOB2, and initiated hierarchical star formation that created the predecessor of the Loop I superbubble (de Geus, 1992; Crawford, 1991; Frisch, 1995; Maíz-Apellániz, 2001). The expanding superbubble would have broken out of the denser ISM beyond 100 pc where the Aquila Rift and other molecular clouds are located (Fig. 1) and expanded into the low density ISM in the Local Bubble around the heliosphere. The current geometry of the Loop I superbubble is consistent with the theoretical evolutionary models of expanding superbubbles based on fluid dynamics (Frisch, 1995). The polarization versus distance relation in Fig. 2 suggests that the local ISMF detached from the more distant ISMF of Loop I at distances of $\sim 45 - 50$ pc in the RA=16H–20H region (Fig. 2).

Wolleben (2007) has modeled the polarized radio continuum of Loop I in terms of two superbubbles, rather than a single shell. His model of the S1 shell is consistent with both the flow of ISM past the Sun and with the best-fitting ISMF direction obtained from the polarization data. The complex high-latitude structure of the ISMF associated with Loop I (Berdyugin et al., 2014), and the high-latitude H⁰ 21-cm filaments, support the existence of two sep-

arate magnetic field structures within several hundred parsecs. The S1 shell of Wolleben is centered at $\ell = 346^\circ \pm 5^\circ$, $b = 3^\circ \pm 5^\circ$, a distance of 78 ± 10 pc away from the Sun, with a rim thickness of 19 ± 20 pc. These geometrical properties of the S1 shell were obtained from the polarized intensity expected for a spherical superbubble shell with the ISMF compressed in the rim of the shell.

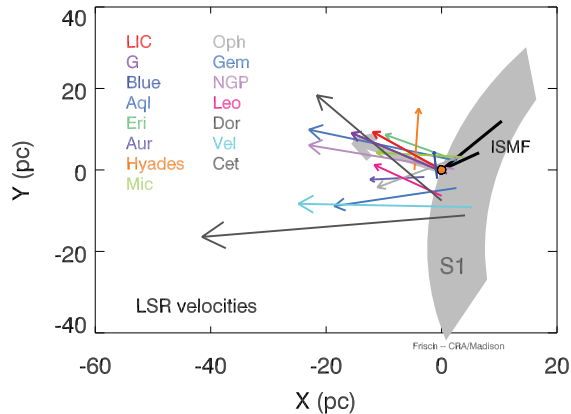


Figure 5: Velocities of interstellar clouds near the Sun are shown relative to the Loop I superbubble shell as defined by the S1 shell derived in Wolleben (2007). The velocities of the fifteen clouds derived in Redfield & Linsky (2008) are plotted in the local standard of rest, using velocities from Frisch & Schwadron (2013). The direction of the local interstellar magnetic field is the upper black line, while the IBEX ISMF direction is the lower black line. The bulk motion of the local ISM through the LSR is shown by the large thick gray arrow (Frisch et al., 2011). The local ISM flow is nearly perpendicular to the S1 shell. All quantities are projected onto the galactic plane and the Sun is located at the orange dot.

ISMF to the polarization data is $76^\circ \pm 28^\circ$. The angle between the ISMF at the heliosphere given by the center of the ENA Ribbon, and the CLIC bulk motion, is $76.5^\circ \pm 2.8^\circ$. Both of these angles suggest that the local ISMF is nearly perpendicular to the bulk motion of the CLIC past the Sun. The uncertainties on the CLIC flow direction are not included for either of these estimates. Much closer, the ISMF traced by the IBEX Ribbon is perpendicular to the LSR velocity vector of the Local Interstellar Cloud that surrounds the heliosphere (Schwadron et al., 2014).

The properties of the very local ISM are fully consistent with a scenario where the local clouds are part of the rim of the S1 shell (Frisch, 2010; Frisch et al., 2010, Paper III). The cluster of local interstellar clouds (CLIC) flows past the Sun with a local standard of rest (LSR) velocity of 16.8 ± 4.6 km s⁻¹, and away from the up-wind direction $\ell = 335^\circ$, $b = -5^\circ$. The up-wind direction of the CLIC flow is within $13.6^\circ \pm 7.1^\circ$ of the center of the S1 shell. Fig. 5 shows the shell projected onto the galactic plane, together with the LSR bulk flow of the CLIC past the Sun (large gray arrow) and the LSR velocities of the fifteen interstellar clouds within several parsecs that have been identified by Redfield and Linsky (Redfield & Linsky, 2008; Frisch et al., 2011).

The other feature of the S1 shell that supports the association of local ISM with the S1 shell is the ISMF directions obtained from both the polarization data and IBEX Ribbon center. The angle between the CLIC bulk flow and the best-fitting

4 Continuity of ISMF over hundreds of parsecs

Salvati (2010) has derived the direction and polarity of the ISMF from four pulsars in the third galactic quadrant. Using the Faraday rotation and dispersion measure data for these pulsars, Salvati found that the ISMF direction is directed toward $\ell = 5^\circ$, $b = 42^\circ$, with a strength of $3.3 \mu\text{G}$. This direction corresponds to ecliptic coordinates of $\lambda = 232^\circ$, $\beta = 18^\circ$, so that the ISMF would be directed upwards through the plane of the ecliptic. The ISMF direction from the pulsar data differs by 22° from the ENA Ribbon ISMF direction. Although the four pulsars are not optimally located for tracing the local ISMF since they are at distances of 160–290 pc, the agreement between the ISMF field directions found from the IBEX ENA Ribbon and pulsars suggests the presence of a nearby large scale coherent ISMF.

Together, the ISMF directions obtained from the polarization data, the ENA Ribbon ISMF data, and the pulsar data are consistent with the existence of an ISMF that is relatively non-turbulent over 150 pc or more, stretching from a pole near $\ell \sim 45^\circ$, $b \sim 25^\circ$ in the North Polar Spur direction, through the heliosphere location, and into the third galactic quadrant. The spatial variations in the ISMF direction over this interval are consistent with a mild curvature of the field of roughly $\sim 0.2^\circ$ per parsec. The connectivity between this large scale ISMF and the ISMF that shapes the heliosphere affects the flux of galactic cosmic rays into the heliosphere (Schwadron et al., 2014).

Acknowledgements This work has been supported by the Interstellar Boundary Explorer mission as a part of NASA’s Explorer Program. This paper is part of the proceedings of the Cosmic Ray Anisotropy workshop held September 2013 in Madison Wisconsin.

References

- Bailey, J., Lucas, P. W., & Hough, J. H. 2010, MNRAS, 405: 2570.
- Berdyugin, A., Piirola, V., & Teerikorpi, P. 2014, A&A, 561: A24
- Berkhuijsen, E. M. 1971, A&A, 14: 359
- Crawford, I. A. 1991, A&A, 247: 183
- Dame, T. M., Ungerechts, H., Cohen, R. S., de Geus, E. J., Grenier, I. A., May, J., Murphy, D. C., Nyman, L. A., & Thaddeus, P. 1987, ApJ, 322: 706
- de Geus, E. J. 1992, A&A, 262: 258
- de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, AJ, 117: 354
- Elias, F., Alfaro, E. J., & Cabrera-Caño, J. 2009, MNRAS, 397: 2
- Elmegreen, B. G. 1993, in Protostars and Planets III, 97

- Ferriere, K. M., Mac Low, M., & Zweibel, E. G. 1991, *ApJ*, 375: 239
- Frisch, P. C. 1995, *Space Sci. Rev.*, 72: 499
- Frisch, P. C. 2000, *American Scientist*, 88: 52
- Frisch, P. C. 2001, *Century of Space Science*, Eds: J. Bleeker, J. Geiss and M. C. E. Huber, Kluwer Academic Publishers”, p. 647
- 2010, *ApJ*, 714: 1679
- Frisch, P. C., Andersson, B., Berdyugin, A., Funsten, H. O., Magalhaes, M., McComas, D. J., Piirola, V., Schwadron, N. A., Slavin, J. D., & Wiktorowicz, S. J. 2010, *ApJ*, 724: 1473
- Frisch, P. C., Andersson, B.-G., Berdyugin, A., Piirola, V., DeMajistre, R., Funsten, H. O., Magalhaes, A. M., Seriacopi, D. B., McComas, D. J., Schwadron, N. A., Slavin, J. D., & Wiktorowicz, S. J. 2012, *ApJ*, 760: 106.
- 2014, in preparation.
- Frisch, P. C., Redfield, S., & Slavin, J. 2011, *ARA&A*, 49: 237
- Frisch, P. C., & Schwadron, N. A. 2013, eprint = ArXiv e-prints/astro-ph:1205.4017
- Funsten, H. O., DeMajistre, R., Frisch, P. C., Heerikhuijsen, J., Higdon, D. M., Janzen, P., Larsen, B., Livadiotis, G., McComas, D. J., Möbius, E., Reese, C., Reisenfeld, D. B., Schwadron, N. A., & Zirnstein, E. J. 2013, *ApJ*, 776: 30
- Han, J. 2009, *IAU Symposium, Magnetic Structure of our Galaxy*, 259:455
- Heerikhuisen, J., & Pogorelov, N. V. 2011, *ApJ*, 738: 29
- Heerikhuisen, J., Pogorelov, N. V., Zank, G. P., Crew, G. B., Frisch, P. C., Funsten, H. O., Janzen, P. H., McComas, D. J., Reisenfeld, D. B., & Schwadron, N. A. 2010, *ApJ*, 708: L126
- Heerikhuisen, J., Zirnstein, E. J., Funsten, H. O., Pogorelov, N. V., & Zank, G. P. 2014, *ApJ*, 784: 73
- Heiles, C. 1989, *ApJ*, 336: 808
- 1998, *ApJ*, 498: 689
- Hoang, T., & Lazarian, A. 2014, *MNRAS*, 438: 680
- Lazarian, A. 2007, *J. Quant. Spec. Radiat. Transf.*, 106, 225
- Maíz-Apellániz, J. 2001, *ApJ*, 560: L83

- Mathewson, D. S., & Ford, V. L. 1970, *MmRAS*, 74: 139
- McComas, D. J., Alexashov, D., Bzowski, M., Fahr, H., Heerikhuisen, J., Izmodenov, V., Lee, M. A., Möbius, E., Pogorelov, N., Schwadron, N. A., & Zank, G. P. 2012, *Science*, 336: 1291
- McComas, D. J., Allegrini, F., Bochslers, P., Bzowski, M., Christian, E. R., Crew, G. B., DeMajistre, R., Fahr, H., Fichtner, H., Frisch, P. C., Funsten, H. O., Fuselier, S. A., Gloeckler, G., Gruntman, M., Heerikhuisen, J., Izmodenov, V., Janzen, P., Knappenberger, P., Krimigis, S., Kucharek, H., Lee, M., Livadiotis, G., Livi, S., MacDowall, R. J., Mitchell, D., Möbius, E., Moore, T., Pogorelov, N. V., Reisenfeld, D., Roelof, E., Saul, L., Schwadron, N. A., Valek, P. W., Vanderspek, R., Wurz, P., & Zank, G. P. 2009, *Science*, 326: 959
- McComas, D. J., Funsten, H. O., Fuselier, S. A., Lewis, W. S., Möbius, E., & Schwadron, N. A. 2011, *Geophys. Res. Lett.*: 381, L18101
- McComas, D. J., Lewis, W. S., & Schwadron, N. A. 2014, *Reviews of Geophysics*
- Naghizadeh-Khouei, J., & Clarke, D. 1993, *A&A*, 274: 968
- Perryman, M. A. C. 1997, *A&A*, 323: L49
- Pirola, V. 1977, *A&AS*, 30: 213
- Rand, R. J., & Kulkarni, S. R. 1989, *ApJ*, 343: 760
- Redfield, S., & Linsky, J. L. 2008, *ApJ*, 673: 283
- Rogerson, J. B., York, D. G., Drake, J. F., Jenkins, E. B., Morton, D. C., & Spitzer, L. 1973, *ApJ*, 181: L110
- Salvati, M. 2010, *A&A*, 513: A28
- Santos, F. P., Corradi, W., & Reis, W. 2011, *ApJ*, 728: 104
- Schwadron, N. A., Adams, F. C., Christian, E. R., Desiati, P., Frisch, P., Funsten, H. O., Jokipii, J. R., McComas, D. J., Moebius, E., & Zank, G. P. 2014, *Science*, 343: 988
- Schwadron, N. A., Bzowski, M., Crew, G. B., Gruntman, M., Fahr, H., Fichtner, H., Frisch, P. C., Funsten, H. O., Fuselier, S., Heerikhuisen, J., Izmodenov, V., Kucharek, H., Lee, M., Livadiotis, G., McComas, D. J., Moebius, E., Moore, T., Mukherjee, J., Pogorelov, N. V., Prested, C., Reisenfeld, D., Roelof, E., & Zank, G. P. 2009, *Science*, 326: 966
- Serkowski, K. 1968, *ApJ*, 154: 115
- Tinbergen, J. 1982, *A&A*, 105: 53

Vallee, J. P. 1993, Ap&SS, 207: 109

Welty, D. E., & Hobbs, L. M. 2001, ApJS, 133: 345

Wolleben, M. 2007, ApJ, 664: 349.

Wood, B., Redfield, S., Linsky, J., Müller, H.-R., & Zank, G. 2005, ApJS, 159: 118

Zank, G. P., Heerikhuisen, J., Wood, B. E., Pogorelov, N. V., Zirnstein, E., & McComas, D. J. 2013, ApJ, 763: 20