Space Sci Rev (2009) 143: 323–331
DOI 10.1007/s11214-008-9422-4

Physical Properties of the Local Interstellar Medium

Seth Redfield

Received: 3 April 2008 / Accepted: 23 July 2008 / Published online: 12 September 2008

Abstract The observed properties of the local interstellar medium (LISM) have been facilitated by a growing ultraviolet and optical database of high spectral resolution observations of interstellar absorption toward nearby stars. Such observations provide insight into the physical properties (e.g., temperature, turbulent velocity, and depletion onto dust grains) of the population of warm clouds (e.g., 7000 K) that reside within the Local Bubble. In particular, I will focus on the dynamical properties of clouds within $\sim$15 pc of the Sun. This simple dynamical model addresses a wide range of issues, including, the location of the Sun as it pertains to the relationship between local interstellar clouds and the circumheliospheric interstellar medium (CHISM), the creation of small cold clouds inside the Local Bubble, and the association of interacting warm clouds and small-scale density fluctuations that cause interstellar scintillation. Local interstellar clouds that can be easily distinguished based on their dynamical properties also differentiate themselves by other physical properties. For example, the two nearest local clouds, the Local Interstellar Cloud (LIC) and the Galactic (G) Cloud, show distinct properties in temperature and depletion of iron and magnesium. The availability of large-scale observational surveys allows for studies of the global characteristics of our local interstellar environment, which will ultimately be necessary to address fundamental questions regarding the origins and evolution of the local interstellar medium.

Keywords Local interstellar medium · High resolution spectroscopy · Dynamics · Abundances

1 Introduction

The interstellar medium (ISM) in our local neighborhood (within $\sim$100 pc) is a diverse collection of material that informs us about general ISM phenomena that are occurring elsewhere in our galaxy and other galaxies, as well as, about the properties of our own solar system, namely the structure of the heliosphere. It is the momentum balance between the ever-changing circumheliospheric interstellar medium (CHISM) and the solar wind that defines

S. Redfield (✉)
Department of Astronomy, University of Texas, 1 University Station, C1400, Austin, TX 78712, USA
e-mail: sredfield@astro.as.utexas.edu

the location of the heliosphere, which today is located at approximately 100 AU. Therefore, if we are to study the general ISM or the heliosphere, it is important to understand the properties of the LISM. For thorough reviews of recent work on the local interstellar medium (LISM), see Redfield (2006), Frisch (1995, 2004), and Ferlet (1999).

Multiple phases of interstellar media have been identified within the LISM. Hot (i.e., a few $\times 10^5$ to 10^6 K) gas, that presumably pervades the Local Bubble cavity has been measured in soft X-rays (Snowden et al. 1998), O VI absorption lines (Oegerle et al. 2005), O VII and O VIII emission lines (Smith et al. 2005), extreme ultraviolet (EUV) emission lines (Hurwitz et al. 2005), and by the general lack of cold Na I gas (Lallement et al. 2003). Cold (i.e., $\sim$20 K) gas, though rare, has been detected well within the Local Bubble, using H I 21 cm and Na I absorption (Meyer et al. 2006; Heiles and Troland 2003), and CO emission (Magnani et al. 1996; Chol Minh et al. 2003). Warm (i.e., $\sim$7000 K) gas, is quite prevalent within the Local Bubble, and is actually the material that currently surrounds our solar system. This most local of interstellar material can be studied using Lyman-α backscatter measurements (Quémerais et al. 2000), *in situ* He I observations (Witte et al. 1996), and ultraviolet (UV) and optical absorption line spectroscopy (Redfield and Linsky 2002, 2004a; Welty et al. 1996; Crawford 2001; Frisch et al. 2002). Absorption line spectroscopy, and the resulting measurements of fundamental physical characteristics of the warm LISM, will be the focus of this particular paper.

Due to the relatively low column densities and short path lengths, measuring the properties of the LISM has been remarkably difficult. Ironically, from an observational perspective, it is much easier to detect the signature of more distant ISM structures with much higher column densities, than the nearest ISM clouds just beyond the solar system. In order to effectively measure the properties of LISM clouds, very sensitive atomic transitions are required in order to be sensitive to such low column densities. Only a few dozen such lines exist, and are predominately located in the ultraviolet (UV), see Fig. 2 in Redfield (2006). Although the LISM is more difficult to observe, it is actually much simpler to investigate physical characteristics once the observations have been made, because only a handful of absorbers are located along the line of sight, as opposed to possibly dozens of blended components along distant sight lines. For stars within 100 pc, on average, only 1.7 absorbers are observed along the line of sight in high resolution ($R \equiv \lambda/\Delta\lambda \sim 100{,}000$) UV spectra of multiple ions (Redfield and Linsky 2004a). Observations at even higher spectral resolution could possibly uncover additional absorption components Welty et al. (1996).

2 LISM Observational Database

The deployment of high spectral resolution UV instruments on space-based telescopes (e.g., the Goddard High Resolution Spectrograph (GHRS) and the Space Telescope Imaging Spectrograph (STIS) onboard the *Hubble Space Telescope* (*HST*)) has enabled the acquisition of high quality absorption spectra of the LISM. Because all observations of objects beyond are solar system necessarily traverse the LISM, a growing database of measurements have been accumulating, even though LISM absorption measurements did not typically motivate the observations. The current high resolution spectral database of LISM observations are summarized in Fig. 1. Observations using both *HST* high resolution spectrographs, GHRS and STIS, are shown as circles. Sight lines that also have far-ultraviolet (FUV) measurements from the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) are shown as triangles. High resolution optical observations of Ca II are indicated by squares. The current database of observations includes $\sim$160 stars within 100 pc, showing $\sim$270 LISM absorption components, where $\sim$60% of the observations were taken for purposes other than to study the

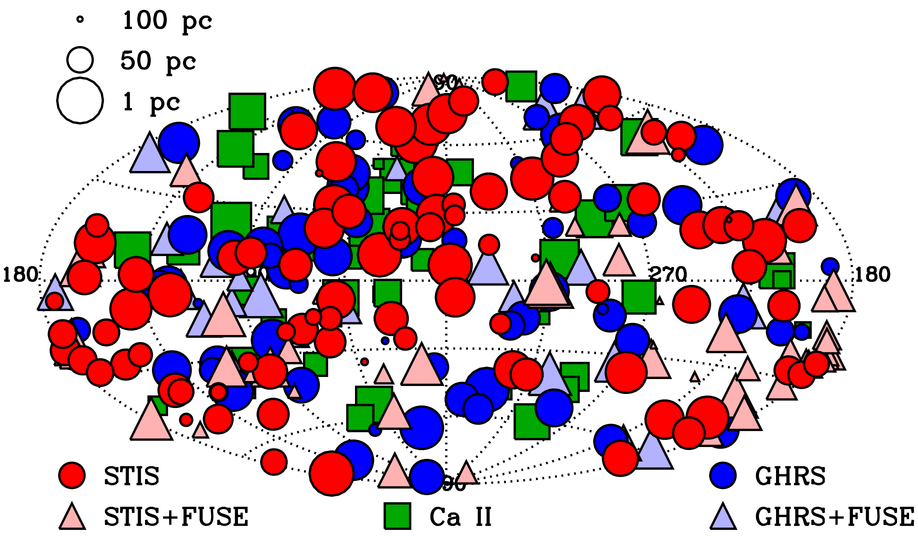


Fig. 1 Distribution of current LISM observational database. More than 270 individual velocity components are detected toward ∼160 stars within 100 pc. The high resolution UV spectrographs on *HST* have provided a rich database with which to study the LISM

LISM. Clearly, a substantial database of LISM observations have quickly accumulated, and provide an excellent opportunity to study the physical properties of our local interstellar environment.

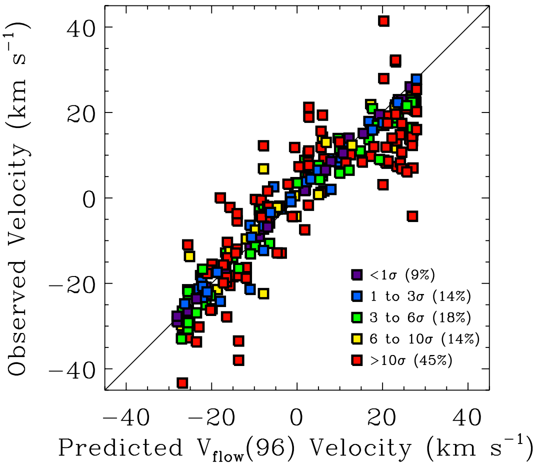
The scientific value of multiple observations over many sight lines is immediately clear from Fig. 1, in that a dense sampling of observations provides a detailed mapping of both large- and small-scale structures in the LISM. Scientific value is also dramatically increased by another multiplicity: observations of multiple absorption ions. A single ion observed along a single sight line provides two fundamental physical measurements of the absorbing material, its radial velocity and column density. The line width, or Doppler width, is also measured, but alone, provides little insight into any property of the absorption gas. If multiple ions are observed, even along just a single sight line, a large number of physical properties become accessible, including temperature and turbulence (Redfield and Linsky 2004b), electron density (Redfield and Falcon 2008), depletion (Linsky et al. 2006), volume density (Redfield and Linsky 2000), and ionization fraction (Jenkins et al. 2000). If ultimately, multiple ions are observed along multiple sight lines, fundamental issues, such as the origin and evolution of the LISM and the interaction of the different phases of material in the LISM, can be addressed by studying the global morphology (Redfield and Linsky 2008), global dynamics (Frisch et al. 2002), and small-scale structure (Redfield and Linsky 2001).

3 Physical Properties of Individual Structures in the LISM

3.1 Dynamics

One of the most fundamental measurements of LISM absorption is the radial velocity of the absorbing medium along the line of sight. Due to the proximity of LISM clouds, a single

Fig. 2 Comparison of observed LISM radial velocities and the $V_{\rm flow}(96)$ global LISM velocity vector derived from Frisch et al. (2002). All LISM absorption velocities can be *roughly* described by a single velocity vector, although there is clear evidence for dynamical variations from this global flow. In particular, a deceleration is detected at the leading edge of the LISM cloud complex (Redfield and Linsky 2001), and the majority of measurements deviate $>3\sigma$ from that predicted from the global flow vector



structure can extend over much of the sky. The Local Interstellar Cloud (LIC) and Galactic (G) Cloud each occupy large areas of the sky, 45% and 20%, respectively (Redfield and Linsky 2008). Because multiple radial velocity measurements of the same collection of gas can be made along various directions, a three-dimensional velocity vector can be fit to characterize the bulk flow of the LISM cloud. Frisch et al. (2002) presented a global model of the entire LISM which led to a single velocity vector, $V_{\rm flow}(96)$, based on 96 velocity components. The collection of sight lines extend to distance of 132 pc, although the majority (62%) are within 30 pc. Figure 2 shows the observed radial velocity for all 270 velocity components (limited to sight lines within 100 pc) shown in Fig. 1 compared to that predicted by the $V_{\rm flow}(96)$ velocity vector. Although both samples utilize sight lines out to $\sim$100 pc, the absorbing material is likely located within $\sim$30 pc, as indicated by the lack of an increase of absorbing components for sight lines extending from 30–100 pc (Redfield and Linsky 2004a). Figure 2 demonstrates that as a whole, the entire LISM can be roughly characterized by a single velocity vector, indicating a common history or common dynamical driver for all LISM clouds. However, highly significant deviations from this velocity vector are also clear. First, the leading edge of the LISM, where the greatest positive velocities are measured, show considerable deceleration, as if the gas is colliding with other material and being compressed and slowed down. This deceleration was identified by Redfield and Linsky (2001) using a sample of LISM observations toward stars in the Hyades, which fortuitously is located very closely to the downwind direction of the LISM flow. Second, the vast majority of measurements (77%) are $>3\sigma$ from the general flow velocity, and almost half (45%) are $>10\sigma$.

Redfield and Linsky (2008) developed a large-scale empirical dynamical model of 15 LISM clouds within 15 pc. This work builds on previous research on LISM dynamics by several groups (e.g., Crutcher 1982; Lallement et al. 1986; Bzowski 1988; Lallement and Bertin 1992; Frisch et al. 2002). Crutcher (1982) calculated the average LISM velocity flow from 7 Ti II observations of nearby stars, Lallement and Bertin (1992) identified two independent velocity vectors for the LIC and G Cloud based on 16 optical and UV observations, and Frisch et al. (2002) measured a LISM average velocity vector from 96 velocity components toward 60 stars, as well as identified vectors for several individual clouds. The Redfield and Linsky (2008) dynamical model is based on 270 velocity components toward $\sim$160 stars. Velocity vectors for 15 independent cloud structures are determined. All velocity vectors are roughly parallel in flow direction, but vary in velocity magnitude from 0–60 km s^{-1} relative to the motion of the Sun.

3.2 Solar Location Relative to LISM Clouds

Interplanetary *in situ* measurements of warm gas streaming into our solar system indicates that we are currently surrounded by warm gas that is similar to the LISM material we observe via absorption line spectroscopy (Möbius et al. 2004). Early estimates of the velocity vector of the LIC, based on approximately a dozen lines of sight, were within the errors of the *in situ* measurements, so it was claimed that the solar system was surrounded by the LIC. However, LIC material is not observed in all directions, which therefore indicates that if we are indeed surrounded by the LIC, that it extends only a very short distance in some directions. Indeed, based on the motion of the Sun toward the G Cloud, and the roughly antiparallel relative motion of the LIC, we might expect to travel outside the boundaries of the LIC, toward the G Cloud, in $\leq$7000 years (Redfield and Linsky 2000).

The new velocity vectors for the LIC and G clouds by Redfield and Linsky (2008) now include 79 and 21 lines of sight, respectively. This substantial improvement has led to a refinement of the velocity vectors. Now the *in situ* measurements in velocity, direction, and temperature, fall intermediate to the LIC and G Cloud values. The discrepancy in velocity is $\sim 3\sigma$ for both the LIC and G Cloud. This argues that the Sun may actually be located in the transition zone between the LIC and G Cloud.

3.3 Turbulence and Depletion

Physical characteristics of specific LISM clouds, other than their dynamical properties, such as, abundances, depletion onto dust grains, temperature, and turbulence, can also be analyzed in a global sense. Redfield and Linsky (2008) found that cloud-averaged measurements of the depletion of iron and magnesium are correlated with cloud-averaged turbulent velocity measurements. The linear correlation coefficients are 0.69 and 0.73, respectively, with $\sim$1.2–1.7% likelihoods that the distributions could have been drawn from an uncorrelated parent sample. This correlation may arise if turbulent shocks can destroy dust grains and return ions to the gas phase and thus decrease the magnitude of the depletion. Weak shock grain destruction has also been invoked to explain depleted deuterium (Linsky et al. 2006). It is important to keep in mind that the absorption line measurements of both abundance and turbulent velocity are line-of-sight-averages, and extreme environments, such as where dust destruction may be occurring, would be difficult to identify.

3.4 Inter-cloud Variation of Physical Properties

Figure 3 indicates the distribution of physical measurements made for LISM absorbers. Physical properties of the LIC and G Cloud, the two nearest LISM clouds which have the most independent measurements, are also shown. The LIC and G Cloud appear to have distinct properties, in terms of, temperature and depletion of iron and magnesium. The LIC is significantly warmer, with an average temperature of 7500 $\pm$ 1300 K, while the average temperature of G Cloud gas is 5500 $\pm$ 400 K. The LIC is also significantly more depleted in both magnesium and iron, with average depletions of –0.97 $\pm$ 0.23 and –1.12 $\pm$ 0.10, respectively, while the G Cloud depletions are –0.36 $\pm$ 0.35 and –0.54 $\pm$ 0.11. Note that the depletions do not take into account partial ionization of hydrogen, which is likely important although unknown for almost all sight lines, or neutral or doubly ionized magnesium and

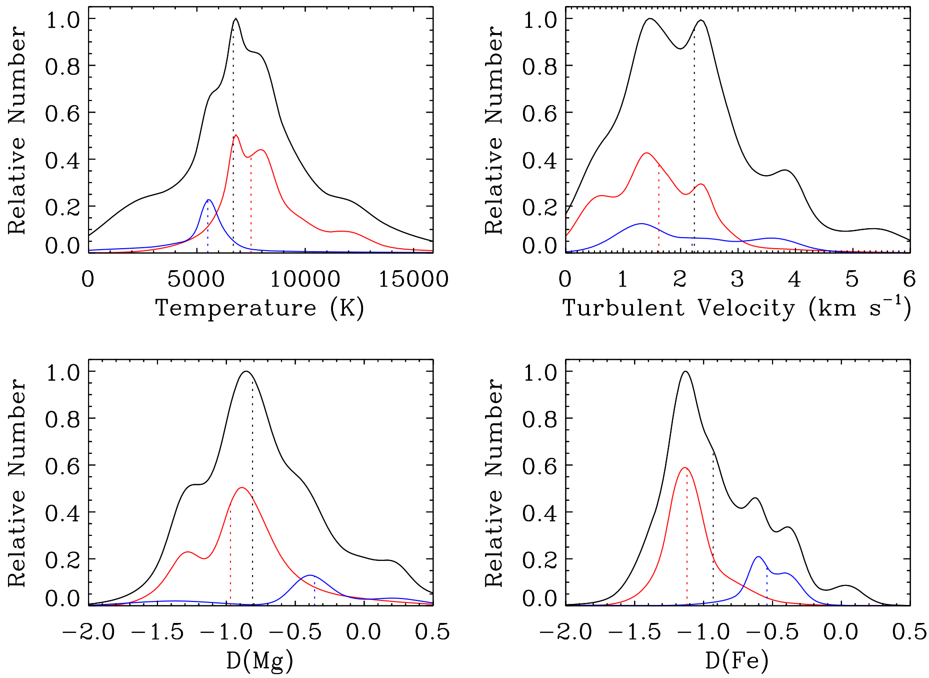


Fig. 3 Distribution of full LISM (black), LIC (red), and G Cloud (blue) samples. The distributions are created using Gaussian profiles for each measurement consistent with their particular errors. For temperature and depletion, the LIC and G Cloud are significantly different

iron, which are likely much less important since they are not expected to become a dominant ionization stage of either element (e.g., Slavin and Frisch 2002; Lehner et al. 2003). Redfield and Linsky (2008) searched for a gradient in properties as a function of flow direction, and did not find any for temperature. Although differences are not dramatic, Fig. 3 argues that the individual cloud structures, such as the LIC and G Cloud, have distinct properties, with modest internal variation.

3.5 Dynamical Cloud Interactions

Although the flow directions of LISM clouds are similar, they are not necessarily identical, and the flow velocity of adjacent clouds can very by 10's of km s^{-1}. For these reasons, neighboring clouds with different velocity vectors could produce regions of dynamical disturbance where the clouds are interacting. Indeed, the dynamical studies of LISM clouds relate to two recent discoveries of structures in our cosmic neighborhood: (1) the existence of a cold (e.g., ∼20 K) cloud, well inside the Local Bubble, <40 pc away (Meyer et al. 2006), and (2) distance measurements to turbulent electron density fields that cause interstellar scintillation of high redshift radio sources, which place these screens at ∼10 pc (Rickett et al. 2002; Bignall et al. 2006).

Cold Clouds The Local Bubble has typically been assumed to be a region devoid of any cold neutral gas. Lallement et al. (2003) took advantage of this fact to define the Local Bubble boundaries using Na I absorption line observations of nearby stars. Stars within ∼100 pc typically show no Na I absorption, indicating that no cold gas exists locally, whereas more distant stars, beyond the Local Bubble boundary, show very strong Na I absorption lines, as the sight lines traverse the nearby star-forming clouds, such as, Taurus, Ophiuchus, and Chamaeleon. The rapid onset of Na I absorption is used to define the shape of the Local Bubble. However, a few small cold clouds have been identified well within the Local Bubble (e.g., Meyer et al. 2006; Lallement et al. 2003). The origins and evolution of these objects is unknown, though the dynamical properties of nearby warm LISM clouds may provide an answer. In simulations of turbulent interstellar clouds, collisions of warm gas clouds can produce small sheetlike clouds of cold gas (Vázquez-Semadeni et al. 2006; Audit and Hennebelle 2005). The three-dimensional velocity vectors of warm LISM clouds can be used to search for compressive flows between neighboring clouds that may create local cold clouds. In the direction of the cold Leo cloud studied by Meyer et al. (2006), differential velocities in the radial direction reach magnitudes of $\sim$15 km s^{-1} (Redfield and Linsky 2008), which may act to produce the small, sheetlike cold cloud that has been observed in 21 cm H I absorption (Heiles and Troland 2003). Using the dynamical properties of the LISM clouds, we can identify regions that are conducive to cold cloud creation, and search for further evidence of small cold clouds within the Local Bubble.

Interstellar Radio Scintillation Some high redshift, compact quasars show variability on timescales of hours at radio (3–8 GHz) frequencies (e.g., Quirrenbach et al. 1992). The characteristic timescale of variability itself varies precisely over the course of a year. This behavior has been attributed to interstellar scintillation, caused by small-scale density fluctuations in the galactic ISM. Recent observations have placed the location of the scintillation screen very nearby, on the order of $\sim$10 pc (Dennett-Thorpe and de Bruyn 2003; Macquart and de Bruyn 2006). Observations of scintillation toward nearby pulsars also show evidence for a local source (Putney and Stinebring 2006). Since the scintillation screens and the warm LISM clouds share the same volume, the question arises, whether these two phenomena are physically related. Linsky et al. (2008) used the dynamical properties of both structures in order to argue that indeed the two structures are physically associated. The yearly variation of the characteristic timescale of scintillation provides an estimate of the transverse flow of the scintillation screen, while the velocity vectors of the warm LISM clouds allows for the calculation of the transverse flow of the warm gas. For three independent scintillating sight lines, the warm LISM clouds located along the line of sight provide much better fits to the transverse flow of the scintillating screen than the Local Standard of Rest, indicating a physical relationship between the warm LISM clouds and the scintillation source (Linsky et al. 2008). Interactions at the boundaries of neighboring clouds could produce small-scale density fluctuations, and thereby facilitate scintillation. Additional distance measurements of warm LISM clouds and scintillating screens are needed in order to further confirm the relationship between these two phenomena.

4 Conclusions and Future Work

The dynamical properties of the warm LISM clouds provide tremendous insight into the morphological and physical structure of our most immediate interstellar environment, as well as possible explanations for associated phenomena, such as the creation of small cold clouds and density fluctuations that cause interstellar scintillation. This work was made possible by a large-scale survey of interstellar absorption toward nearby stars (UV observations of $\sim$160 stars). Such a dense sampling was required to deconvolve the subtle velocity difference of LISM clouds and to provide distance constraints on the absorbing medium. Future studies will be enabled by even larger surveys. One such survey, the Ca II LISM Optical Survey of our Environment (CLOSE), will provide absorption measurements toward ∼400 nearby stars (Redfield et al. 2006). The observations utilize the two highest resolution spectrographs in the world, the Coúde Spectrograph (maximum resolving power: $R \equiv \lambda/\Delta\lambda \sim$500,000) on the 2.7 m Harlan J. Smith Telescope at McDonald Observatory in the northern hemisphere, and the Ultra High Resolution Facility (UHRF; maximum resolving power: $R \sim$1,000,000) on the 3.9 m Anglo-Australian Telescope at the Anglo-Australian Observatory in the southern hemisphere. Although the Ca II line is not as sensitive as many lines in the UV, access to ultra high resolution ground-based spectrographs allows for a large-scale dedicated survey of individual warm LISM absorbers. With the anticipated repair of the only high resolution UV spectrograph in space, STIS on *HST*, the UV LISM database will hopefully continue to grow. Such high spectral resolution observations will continue to provide a rich database in order to probe the detailed physical conditions of our most local interstellar environment.

Acknowledgements I would like to thank my collaborators on various projects that were mentioned in passing in this review, they include Jeff Linsky, Barney Rickett, Brad Gibson, Chris Thom, Annie Hughes, Naomi McClure-Griffiths, and Povilas Palunas. I thank the organizers of this ISSI workshop for inviting me to participate. The reviewer of this manuscript provided many careful and helpful comments, which were much appreciated. I acknowledge support provided by NASA through Hubble Fellowship grant HST-HF-01190.01 awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555.

References

E. Audit, P. Hennebelle, Astrophys. J. **433**, 1–13 (2005)
H.E. Bignall, J.-P. Macquart, D.L. Jauncey, J.E.J. Lovell, A.K. Tzioumis, L. Kedziora-Chudczer, Astrophys. J. **652**, 1050–1058 (2006)
M. Bzowski, Acta Astron. **38**, 443–453 (1988)
Y.C.Y. Chol Minh et al., New Astron. **8**, 795–803 (2003)
I.A. Crawford, Mon. Not. R. Astron. Soc. **327**, 841–848 (2001)
R.M. Crutcher, Astrophys. J. **254**, 82–87 (1982)
J. Dennett-Thorpe, A.G. de Bruyn, Astron. Astrophys. **404**, 113–132 (2003)
R. Ferlet, Astron. Astrophys. Rev. **9**, 153–169 (1999)
P.C. Frisch, Space Sci. Rev. **72**, 499–592 (1995)
P.C. Frisch, Adv. Space Res. **34**, 20–26 (2004)
P.C. Frisch, L. Grodnicki, D.E. Welty, Astrophys. J. **574**, 834–846 (2002)
C. Heiles, T.H. Troland, Astrophys. J. Suppl. Ser. **145**, 329–354 (2003)
M. Hurwitz, T.P. Sasseen, M.M. Sirk, Astrophys. J. **623**, 911–916 (2005)
E.B. Jenkins et al., Astrophys. J. Lett. **538**, L81–L85 (2000)
R. Lallement, P. Bertin, Astron. Astrophys. **266**, 479–485 (1992)
R. Lallement, A. Vidal-Madjar, R. Ferlet, Astron. Astrophys. **168**, 225–236 (1986)
R. Lallement, B.Y. Welsh, J.L. Vergely, F. Crifo, D. Sfeir, Astron. Astrophys. **411**, 447–464 (2003)
N. Lehner, E.B. Jenkins, C. Gry, H.W. Moos, P. Chayer, S. Lacour, Astrophys. J. **595**, 858–879 (2003)
J.L. Linsky et al., Astrophys. J. **647**, 1106–1124 (2006)
J.L. Linsky, B.J. Rickett, S. Redfield, Astrophys. J. **675**, 413–419 (2008)
J.-P. Macquart, A.G. de Bruyn, Astron. Astrophys. **446**, 185–200 (2006)
L. Magnani, D. Hartmann, B.G. Speck, Astrophys. J. Suppl. Ser. **106**, 447 (1996)
D.M. Meyer, J.T. Lauroesch, C. Heiles, J.E.G. Peek, K. Engelhorn, Astrophys. J. **650**, L67–L70 (2006)
E. Möbius et al., Astron. Astrophys. **426**, 897–907 (2004)
W. Oegerle, E. Jenkins, R. Shelton, D. Bowen, P. Chayer, Astrophys. J. **622**, 377–389 (2005)
M.L. Putney, D.R. Stinebring, Chin. J. Astron. Astrophys. Suppl. **6**, 233–236 (2006)
E. Quémerais, J.-L. Bertaux, R. Lallement, M. Berthé, E. Kyrölä, W. Schmidt, Adv. Space Res. **26**, 815–818 (2000)

A. Quirrenbach, A. Witzel, T.P. Kirchbaum, C.A. Hummel, R. Wegner, C.J. Schalinski, M. Ott, A. Alberdi, M. Rioja, Astron. Astrophys. **258**, 279–284 (1992)
S. Redfield, in *ASP Conf. Ser. 352, New Horizons in Astronomy, Frank N. Bash Symposium 2005*, ed. by S.J. Kannappan, S. Redfield, J.E. Kessler-Silacci, M. Landriau, N. Drory (ASP, San Francisco, 2006), p. 79
S. Redfield, R.E. Falcon, Astrophys. J. **683**, 207 (2008)
S. Redfield, J.L. Linsky, Astrophys. J. **534**, 825–837 (2000)
S. Redfield, J.L. Linsky, Astrophys. J. **551**, 413–428 (2001)
S. Redfield, J.L. Linsky, Astrophys. J. Suppl. Ser. **139**, 439–465 (2002)
S. Redfield, J.L. Linsky, Astrophys. J. **602**, 776–802 (2004a)
S. Redfield, J.L. Linsky, Astrophys. J. **613**, 1004–1022 (2004b)
S. Redfield, J.L. Linsky, Astrophys. J. **673**, 283–314 (2008)
S. Redfield, B. Gibson, C. Thom, A. Hughes, N. McClure-Griffiths, P. Palunas, Anglo-Aust. Obs. Epp. Newslett. **110**, 9 (2006)
B.J. Rickett, L. Kedziora-Chudczer, D.L. Jauncey, Astrophys. J. **581**, 103–126 (2002)
J.D. Slavin, P.C. Frisch, Astrophys. J. **565**, 364–379 (2002)
R.K. Smith, R.J. Edgar, P.P. Plucinsky, B.J. Wargelin, P.E. Freeman, B.A. Biller, Astrophys. J. **623**, 225–234 (2005)
S.L. Snowden, R. Egger, D.P. Finkbeiner, M.J. Freyberg, P.P. Plucinsky, Astrophys. J. **493**, 715 (1998)
E. Vázquez-Semadeni, D. Ryu, T. Passot, R.F. González, A. Gazol, Astrophys. J. **643**, 245–259 (2006)
D.E. Welty, D.C. Morton, L.M. Hobbs, Astrophys. J. Suppl. Ser. **106**, 533 (1996)
M. Witte, M. Banaszkiewicz, H. Rosenbauer, Space Sci. Rev. **78**, 289–296 (1996)