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ORIGINAL ARTICLE

Solving the mysteries of the diffuse interstellar medium with high-resolution UV spectroscopy

Jeffrey L. Linsky

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Abstract Understanding the complex structure, dynamics, and ionization of gas in the nearby interstellar medium is required before one can realistically model interstellar gas in other galaxies. High-resolution ultraviolet spectra provide the essential data for such studies because the resonance lines of most important atoms, ions, and molecules are located in the ultraviolet, and high spectral resolution is needed to resolve line profiles and determine the velocity structure along a line of sight. I list ten important physical questions concerning interstellar gas that require a more sensitive spectrometer than STIS and the desired spectral resolution to answer these questions.

Keywords Ultraviolet: spectra · Ultraviolet: ISM · Techniques: spectroscopic

1 Why understanding the local ISM is critically important

Interstellar gas plays important roles in the chemical and dynamical evolution of galaxies, is the raw material for star formation, and chemically enriches galactic halos and the intergalactic medium (IGM) with its outflows. Understanding the physical processes occurring in the ISM of our Galaxy and other galaxies is complicated by the highly inhomogeneous nature of this gas, strong departures from ionization equilibrium, and complex structures. These physical processes provide severe challenges for theoreticians (Cox 2005). For observers of interstellar gas in the Milky Way, starburst galaxies, as well as low-z and distant galaxies, there is the further complication of very inhomogeneous gas properties along the line of sight.

Given the importance of this topic and the theoretical and observational challenges, it is prudent to study carefully the nearby interstellar gas where the lines of sight contain fewer structures and may be simpler. We must first understand the physical processes operating in our own back yard where we have the best data and highest angular resolution. Within 100–200 pc of the Sun, interstellar gas is embedded in the Local Bubble, a region of generally low-density gas carved out of the disk by the supernovae and hot star winds of young stars in the Scorpio-Centaurus Association (Berghöfer and Breitschwerdt 2002). The irregular shape of the Local Bubble edge is delineated by the rapidly increasing Na I absorption equivalent width (see Fig. 1), indicating surrounding cold material. Gas inside the Local Bubble is characterized by a wide range of temperatures, densities, and structures, providing prototypes for the variety of interstellar gas in galaxies. Here I describe ten important questions that data from a future high-resolution UV spectrograph could help answer.

2 Question #1: what is the structure of warm gas clouds?

The presence of warm gas inside the Local Bubble is revealed by absorption of resonance lines of H I, D I, N I, and O I, and many singly ionized species, including C II, Mg II, Al II, Si II, S II, and Ca II. Aside from Ca II, all of these species have resonance lines only in the ultraviolet. High-resolution spectroscopy with GHRS and STIS has provided the bulk of the existing data for the analysis of warm gas

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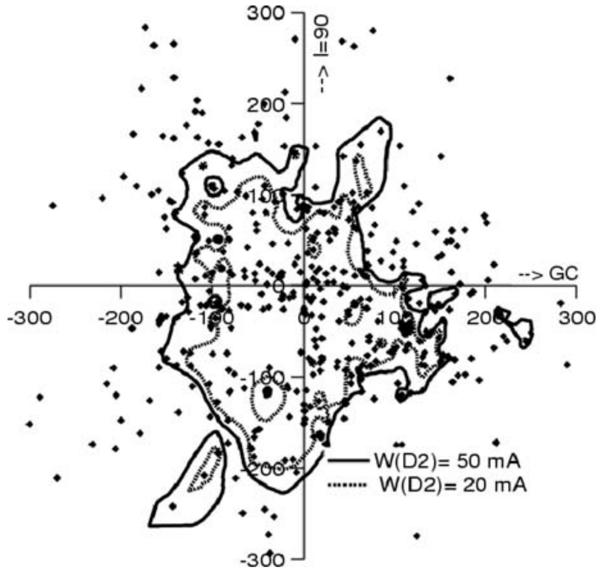


Fig. 1 Contours of the equivalent width of the Na I D2 line in a coordinate system with the Galactic Center to the right and the North Galactic Pole in the upward direction. Distances are in parsecs. The Na I *contours* indicate the onset of cold gas at the outer edge of the Local Bubble. *Dots* indicate the lines of sight with interstellar absorption measurements. Figure from Lallement et al. (2003)

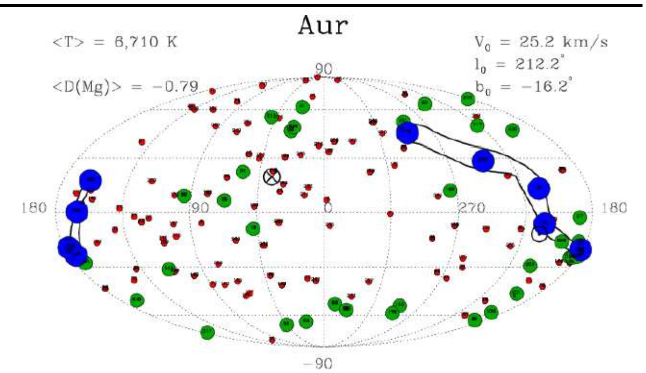


Fig. 2 *Large blue dots* indicate lines of sight with interstellar absorption radial velocities consistent with the Aur cloud velocity vector. Components of the velocity vector are given in the *upper right* of the figure. *Smaller dots* indicate lines of sight with inconsistent velocities. The *solid line* is a rough outline of the Aur cloud boundaries. Figure from Redfield and Linsky (2008)

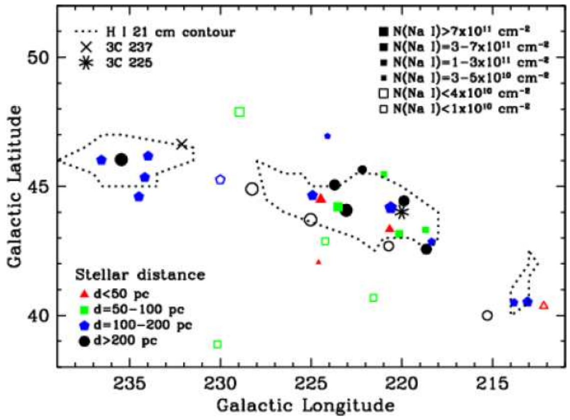
inside the Local Bubble, but optical observations of Ca II absorption and FUSE studies of Ar I and the higher Lyman series lines of H I are also useful. All lines of sight toward even the nearest stars show interstellar absorption at one or more radial velocities.

Redfield and Linsky (2008) presented a model of the nearby warm gas based on 270 radial-velocity measurements toward 157 stars located within 100 pc of the Sun. They find that these data can be fit by 15 velocity vectors consistent with the interstellar gas radial velocities toward groups of stars in different parts of the sky. They call each parcel of gas a "cloud". The nearest star with an interstellar radial velocity consistent with the cloud velocity vector sets an outer limit to the cloud distance. In many cases the cloud temperature and turbulence are determined from the measured line widths of ions with different masses. All of the clouds in their sample have temperatures in the range of 4,000–10,000 K and lie within 15 pc of the Sun. Figure 2 shows the filamentary shape of one nearby warm cloud. The rejuvenation of STIS and ongoing optical observations using the Ca II line will add to the existing database, but a high-resolution UV spectrometer, preferably with a resolution of $3\ \mathrm{km\,s^{-1}}$, is needed to measure the physical properties of warm gas further out in the Local Bubble and beyond. One can then address the following questions:

- Are thin filamentary structures like the Aur cloud (Fig. 2) typical of warm clouds?
- How realistic is the assumption that the warm clouds have rigid gas flows?
- Are these clouds uniformly filled with gas or do they contain holes (e.g., like swiss cheese)?
- Are the outer edges of clouds sharp or soft?
- What are the roles played by magnetic fields and cloud-cloud interactions?

3 Question #2: how do cold gas clouds survive in an unfriendly environment?

In their 21 cm survey of the Galaxy, Heiles and Troland (2003) identified a large region of cold gas in the constellation Leo (Fig. 3) with an H I spin temperature of ∼25 K. Meyer et al. (2006) observed Na I absorption toward a number of stars in this region including one at a distance of only 41 pc. Since the widths of the Na I absorption lines correspond to a temperature of about 20 K and the Na I and H I radial velocities are consistent, the cold gas cloud must exist inside the Local Bubble, perhaps much closer to the Sun than 41 pc. How can this cold gas coexist with the warm and hot gas in the Local Bubble and the photoionizing radiation from hot stars like ϵ CMa? McKee and Ostriker (1977) predicted that this could occur in their pressure equilibrium models of the ISM if the cold cloud is surrounded by warm clouds that shield the cold gas from external UV and X-ray heating and ionization. To test this model, we need to determine the three-dimensional geometry of warm clouds located near the line of sight to the cold cloud. This requires UV absorption measurements for a much denser sampling of stars, in particular nearby faint M stars that could lie in front of the warm clouds. A more sensitive high-resolution spectrograph than STIS is needed to test this model.



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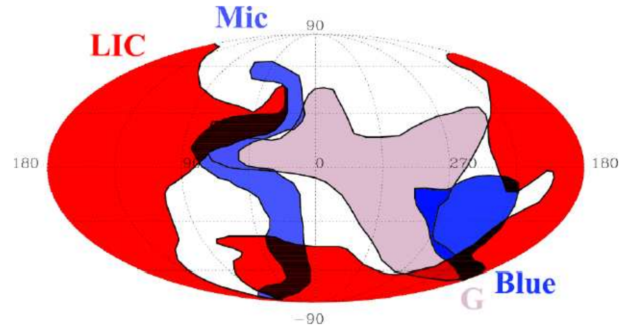

Fig. 4 Location in Galactic coordinates of four of the 15 warm interstellar clouds identified by Redfield and Linsky (2008). The quasar with the largest intrahour radio flux variability produced by interstellar scintillation is located at galactic coordinates $l = 66.2°$, $b = +22.5°$ where the LIC, G, and Mic clouds may interact with each other producing turbulence

4 Question #3: what happens when interstellar clouds interact?

The velocity vectors for the 15 nearby clouds indicate relative cloud motions that can exceed the sound speed (about 8 $\mathrm{km\,s^{-1}}$). In this dynamic environment, colliding clouds can generate turbulence and heat. Figure 4 shows the location in Galactic coordinates of four nearby clouds. According to Redfield and Linsky (2008), the Sun is located in a transition zone between the Local Interstellar Cloud (LIC) and the G cloud. The shape of the Microscopium (Mic) cloud indicates that it may be formed by a collision between the LIC and G clouds, and the high temperature (10,000 K) of the Mic cloud is consistent with compression produced by a collision. The lines of sight to quasars with the largest intraday variability at radio wavelengths pass though locations where the warm clouds appear to interact (Linsky et al. 2008). This suggests that the turbulent scattering screens responsible for the radio scintillation could result from cloud-cloud interactions (Linsky et al. 2008). A powerful high-resolution UV spectrometer is needed to further this program.

5 Question #4: why is there severe pressure disequilibrium in the ISM?

Theoretical models of the ISM which assume thermal and gas pressure equilibrium (Wolfire et al. 2003; Cox 2005) predict a nonlinear relation between thermal gas pressure and density. Figure 5 shows this relation for the local-heating rate and 10 times this rate. In such models, warm gas clouds (densities below 1 $\mathrm{cm^{-3}}$) and cold gas clouds (densities above 10 $\mathrm{cm^{-3}}$) can coexist in gas pressure equilibrium with an unstable regime at intermediate densities. Jenkins and Tripp (2001) found that typical warm gas cloud

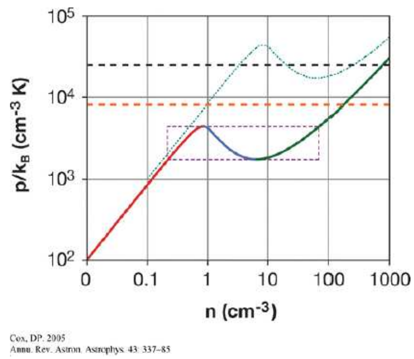

Fig. 5 Theoretical relation of thermal pressure with gas density for the local heating rate (*solid line*) and 10 times that rate (*dotted line*). The top dashed line is the total midplane pressure and the *dashed line* below is the estimated magnetic pressure. Figure from Cox (2005)

pressures are 2240 $\mathrm{cm^{-3}}$ K which is in the stable regime and that about 15% of interstellar gas has thermal pressures greater than 5,000 and a very small amount of gas has thermal pressures above 100,000 $\mathrm{cm^{-3}}$ K with very small size scales (0.01 pc). These results are based on their study of C I fine structure excitation using the very narrow slit mode of STIS (resolution 1.5 $\mathrm{km^{-1}s}$).

A major problem with these theoretical models is that the thermal gas pressure is generally only a small component of the total pressure. As shown in Fig. 5, the total pressure in the midplane of the Galaxy due to the weight of the overlying material is about 22,000 $\mathrm{cm^{-3}}$ K, ten times the mean thermal pressure. The total pressure must be balanced by the sum of the magnetic, cosmic ray, ram, and thermal pressure terms, the first three of which are likely larger than the mean thermal pressure. Although difficult to measure, the three nonthermal pressure terms must be included in more realistic future models which are needed to explain the wide range of observed thermal pressures. Fortunately, ram pressures can be measured by high-resolution UV spectroscopy. The warm cloud vectors presented by Redfield and Linsky

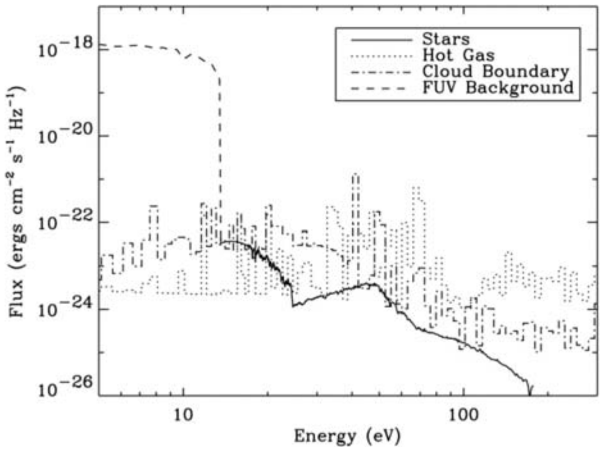

Fig. 6 Compilation of UV and EUV radiation field within 5 pc of the Sun from Slavin and Frisch (2002)

(2008) provide a start toward measuring the ram pressures, but additional observations are needed to determine a more comprehensive picture of the various pressure terms.

6 Question #5: ionization rates in the ISM?

We have just seen that the UV radiation field plays a major role in determing the relation between gas pressure and density in interstellar models. The UV radiation both heats and ionizes the gas, but the spectral energy distribution of the radiation must be known to determine the ionization of the various gas components. Figure 6 shows a compilation of the UV and EUV radiation field near the Sun from Slavin and Frisch (2002), including the radiation from stars (mostly ϵ CMa and hot white dwarfs), assumed emission from evaporative boundaries of warm clouds, hot gas in the Local Bubble, and the FUV background. Unfortunately the latter three terms are uncertain. While it is generally assumed that the warm clouds embedded in a hot medium have evaporative boundaries, the presence of O VI and C IV absorption or emission at the cloud boundaries has not yet been detected.

7 Question #6: how do starbursts alter the surrounding ISM?

The powerful winds and photoionizing radiation of young massive stars and the occasional supernova explosion when a massive star reaches the end of its short life play important roles in starburst galaxies. These outflows compress the surrounding gas clouds to trigger star formation, and they clear out the surrounding gas and dust, effectively ending the starburst event. One important unanswered question is the nature of the gas flows generated by these events. The Local

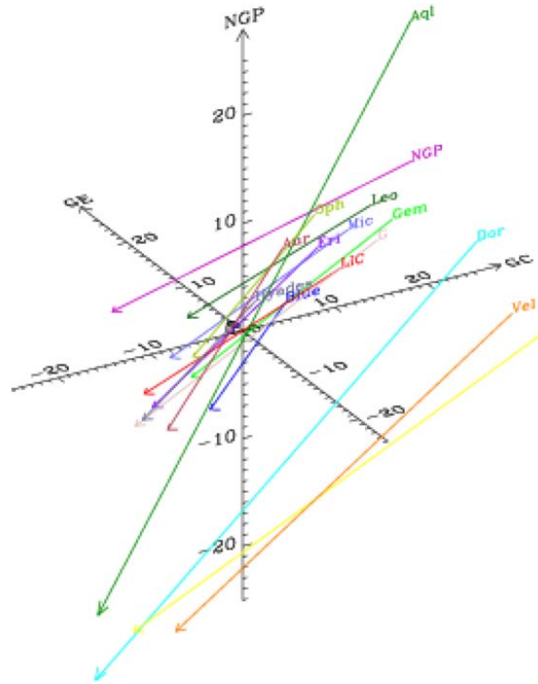

Fig. 7 Velocity vectors for the 15 warm interstellar clouds identified by Redfield and Linsky (2008). The axes are toward the Galactic Center (GC, $l = b = 0°$), Galactic East (GE, $l = 90°$, $b = 0°$), and the North Galactic Pole (NGP, $b = 90°$)

Bubble was formed by the winds and explosions of massive stars in the Scorpio-Centaurus Association several million years ago. While formation of the Sco-Cen Association could be considered only a ministarburst event and the violent activity has largely subsided, the present day gas flows provide an interesting dynamic picture. Figure 7 shows the flow vectors of the 15 nearby warm clouds. While the center of the Sco-Cen Association is located close to the Galactic Center direction, the individual flow vectors are not all from this direction and are not of the same magnitude. This complex flow pattern indicates that internal shocks, heating, and grain destruction in the gas surrounding starbursts are inevitable. Since many of the vectors for individual clouds are based on only a few lines of sight, many more radial velocities are needed to infer the dynamics and energetics of the Local Bubble and by extrapolation starburst events.

8 Question #7: how much alien material is there in the local ISM?

According to the hierarchical model of galaxy formation, spiral galaxies like the Milky Way grow by accreting satellite and dwarf galaxies that venture too close (Abadi et al. 2003). One way of testing this model is to look for "alien" stars with unusual space motions and abundances representative of dwarf galaxies. The Arcturus moving group likely originated from debris of a disrupted satellite galaxy since its stars move about 100 km s^{-1} more slowly about the Galactic center than the local standard of rest, the abundances of the α elements (Mg–Ti) are unusual, and the Fe abundances are about 1/10 solar (Navarro et al. 2004). Some of the Arcturus Moving Group stars are indeed very close including Arcturus itself (11.2 pc) and HD 199288 (21.6 pc).

Additional evidence for alien material in our Galaxy may be in the lines of sight with D/H gas ratios very close to the primordial ratio (about 27 parts per million). Linsky et al. (2006) identified five lines of sight with D/H gas ratios $\geq$ 23 ppm which is difficult to explain by galactic chemical evolution models without the addition and incomplete mixing of captured near-primordial gas from the IGM or dwarf galaxies (Romano et al. 2006; Steigman et al. 2007). Alternatively, possible systematic errors in the hydrogen column density determinations could result in high gas D/H ratios. Most of the existing measurements of D/H are based on FUSE spectra of the higher Lyman series lines. A future mission that will obtain FUV spectra with higher spectral resolution and signal/noise is needed to obtain more accurate D/H measurements and thereby test the alien gas hypothesis and search for systematic errors.

9 Other ISM science questions requiring UV/FUV spectroscopy

- How hot is the Local Bubble gas and why is it hot? (Need spectroscopic diagnostics to separate thermal emission from charge-exchange processes in the heliosphere.)
- What are the important physical processes at cloud interfaces? (Thermal conduction, evaporation, MHD interactions, etc.)
- What are the causes and scales of turbulence in the ISM? (Kolmogorov turbulent spectrum on all scales?, how produced?, how maintained?)

10 Instrumental requirements for a future UV spectroscopy mission

Table 1 summarizes the instrumental goals needed to address each of the 10 science questions. I would hope that a future UV spectroscopic mission would be able to meet most of these goals.

11 Other considerations for a future high-resolution UV spectroscopy mission

- High S/N spectra require detectors with low fixed pattern noise and low background.
- An accurate wavelength scale requires an onboard spectral line lamp and excellent thermal stability.
- Many observing programs require the full 912–3000 Å spectral range, but this could be achieved with separate spectral bands on the same spacecraft.
- Small and large apertures are needed for different observing programs.
- Large amounts of observing time are required to complete major programs with many sightlines and targets.
- With increasing spectral resolution, more programs become feasible. Three km/s resolution is highly desirable. This requires excellent stable optics.
- High Earth orbit (HEO) or a more distant orbit is desirable. Observing with a somewhat smaller aperture telescope in HEO is more efficient and likely less expensive compared to a larger aperture telescope in low Earth orbit where Earth occultations decrease observing time and observatory operations are more complex.

Table 1 Requirements for a future UV mission

Science objectives	R[a]	S/N	λ[b]
Cloud structures	3	50	UV, FUV
Cold gas clouds	1	50	UV, FUV
Cloud interactions	3	30	UV, FUV
Pressure disequilibrium	1	50	UV, FUV
Ionization processes	3	30	UV, FUV
Effects of starbursts	3	30	UV, FUV
Alien matter	3	30	UV, FUV
How hot is the LB?	10	30	UV, FUV
Cloud interfaces	3	30	UV, FUV
Turbulence	1	50	UV

[a]Desired spectral resolution (km s^{-1})

[b]The wavelength range for the UV is 1175–3200 Å and for the FUV is 912–1175 Å

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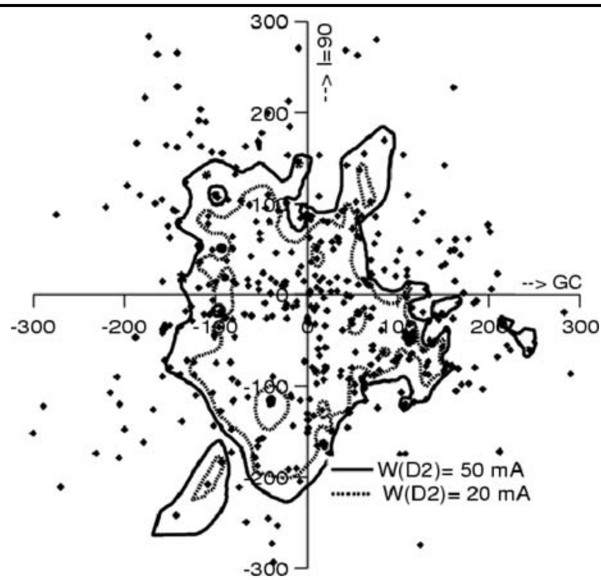

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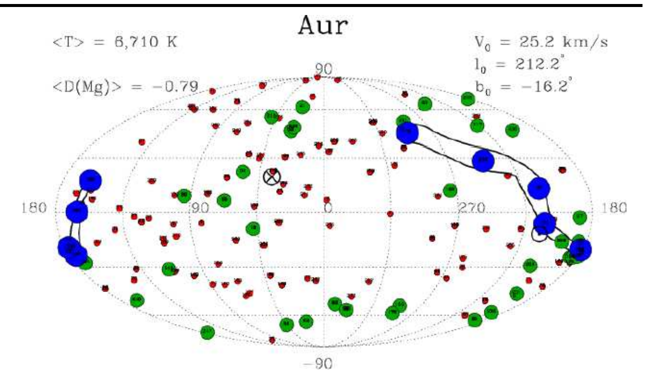

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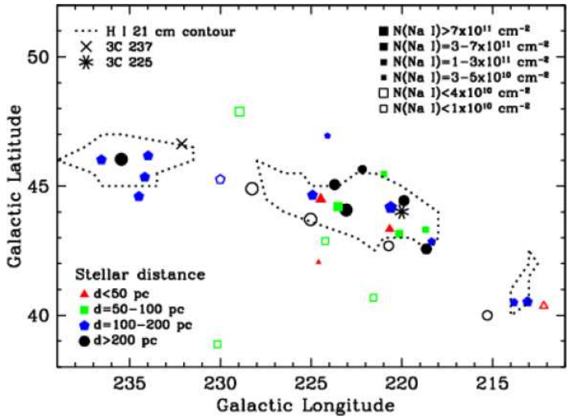

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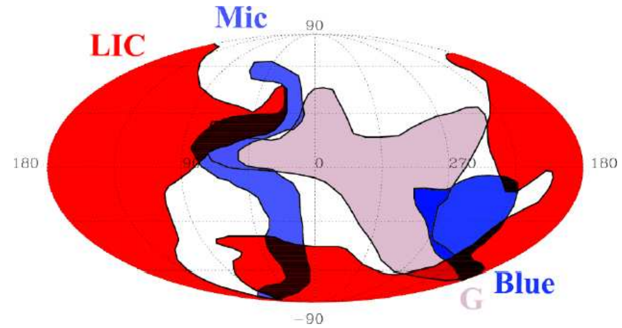

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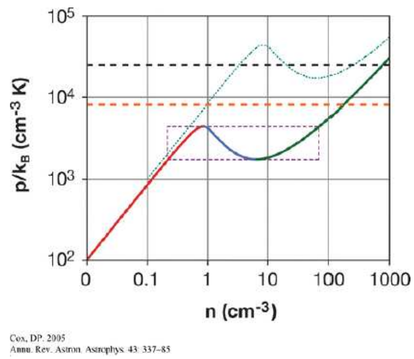

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The velocity vectors for the 15 nearby clouds indicate relative cloud motions that can exceed the sound speed (about 8 $\mathrm{km\,s^{-1}}$). In this dynamic environment, colliding clouds can generate turbulence and heat. Figure 4 shows the location in Galactic coordinates of four nearby clouds. According to Redfield and Linsky (2008), the Sun is located in a transition zone between the Local Interstellar Cloud (LIC) and the G cloud. The shape of the Microscopium (Mic) cloud indicates that it may be formed by a collision between the LIC and G clouds, and the high temperature (10,000 K) of the Mic cloud is consistent with compression produced by a collision. The lines of sight to quasars with the largest intraday variability at radio wavelengths pass though locations where the warm clouds appear to interact (Linsky et al. 2008). This suggests that the turbulent scattering screens responsible for the radio scintillation could result from cloud-cloud interactions (Linsky et al. 2008). A powerful high-resolution UV spectrometer is needed to further this program.

5 Question #4: why is there severe pressure disequilibrium in the ISM?

Theoretical models of the ISM which assume thermal and gas pressure equilibrium (Wolfire et al. 2003; Cox 2005) predict a nonlinear relation between thermal gas pressure and density. Figure 5 shows this relation for the local-heating rate and 10 times this rate. In such models, warm gas clouds (densities below 1 $\mathrm{cm^{-3}}$) and cold gas clouds (densities above 10 $\mathrm{cm^{-3}}$) can coexist in gas pressure equilibrium with an unstable regime at intermediate densities. Jenkins and Tripp (2001) found that typical warm gas cloud pressures are 2240 $\mathrm{cm^{-3}}$ K which is in the stable regime and that about 15% of interstellar gas has thermal pressures greater than 5,000 and a very small amount of gas has thermal pressures above 100,000 $\mathrm{cm^{-3}}$ K with very small size scales (0.01 pc). These results are based on their study of C I fine structure excitation using the very narrow slit mode of STIS (resolution 1.5 $\mathrm{km^{-1}\,s}$).

A major problem with these theoretical models is that the thermal gas pressure is generally only a small component of the total pressure. As shown in Fig. 5, the total pressure in the midplane of the Galaxy due to the weight of the overlying material is about 22,000 $\mathrm{cm^{-3}}$ K, ten times the mean thermal pressure. The total pressure must be balanced by the sum of the magnetic, cosmic ray, ram, and thermal pressure terms, the first three of which are likely larger than the mean thermal pressure. Although difficult to measure, the three nonthermal pressure terms must be included in more realistic future models which are needed to explain the wide range of observed thermal pressures. Fortunately, ram pressures can be measured by high-resolution UV spectroscopy. The warm cloud vectors presented by Redfield and Linsky

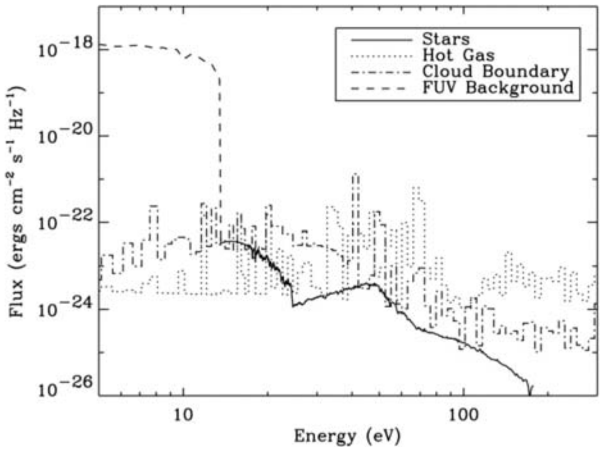

Fig. 6 Compilation of UV and EUV radiation field within 5 pc of the Sun from Slavin and Frisch (2002)

(2008) provide a start toward measuring the ram pressures, but additional observations are needed to determine a more comprehensive picture of the various pressure terms.

6 Question #5: ionization rates in the ISM?

We have just seen that the UV radiation field plays a major role in determing the relation between gas pressure and density in interstellar models. The UV radiation both heats and ionizes the gas, but the spectral energy distribution of the radiation must be known to determine the ionization of the various gas components. Figure 6 shows a compilation of the UV and EUV radiation field near the Sun from Slavin and Frisch (2002), including the radiation from stars (mostly ϵ CMa and hot white dwarfs), assumed emission from evaporative boundaries of warm clouds, hot gas in the Local Bubble, and the FUV background. Unfortunately the latter three terms are uncertain. While it is generally assumed that the warm clouds embedded in a hot medium have evaporative boundaries, the presence of O VI and C IV absorption or emission at the cloud boundaries has not yet been detected.

7 Question #6: how do starbursts alter the surrounding ISM?

The powerful winds and photoionizing radiation of young massive stars and the occasional supernova explosion when a massive star reaches the end of its short life play important roles in starburst galaxies. These outflows compress the surrounding gas clouds to trigger star formation, and they clear out the surrounding gas and dust, effectively ending the starburst event. One important unanswered question is the nature of the gas flows generated by these events. The Local

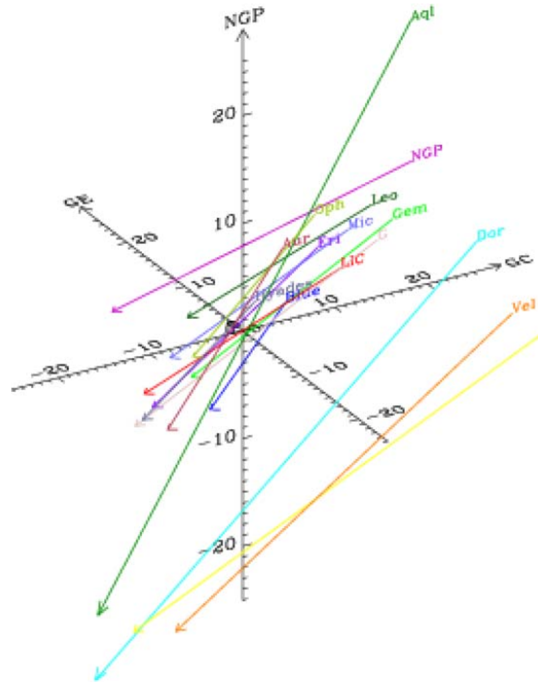

Fig. 7 Velocity vectors for the 15 warm interstellar clouds identified by Redfield and Linsky (2008). The axes are toward the Galactic Center (GC, $l = b = 0°$), Galactic East (GE, $l = 90°$, $b = 0°$), and the North Galactic Pole (NGP, $b = 90°$)

Bubble was formed by the winds and explosions of massive stars in the Scorpio-Centaurus Association several million years ago. While formation of the Sco-Cen Association could be considered only a ministarburst event and the violent activity has largely subsided, the present day gas flows provide an interesting dynamic picture. Figure 7 shows the flow vectors of the 15 nearby warm clouds. While the center of the Sco-Cen Association is located close to the Galactic Center direction, the individual flow vectors are not all from this direction and are not of the same magnitude. This complex flow pattern indicates that internal shocks, heating, and grain destruction in the gas surrounding starbursts are inevitable. Since many of the vectors for individual clouds are based on only a few lines of sight, many more radial velocities are needed to infer the dynamics and energetics of the Local Bubble and by extrapolation starburst events.

8 Question #7: how much alien material is there in the local ISM?

According to the hierarchical model of galaxy formation, spiral galaxies like the Milky Way grow by accreting satellite and dwarf galaxies that venture too close (Abadi et al. 2003). One way of testing this model is to look for "alien" stars with unusual space motions and abundances representative of dwarf galaxies. The Arcturus moving group likely originated from debris of a disrupted satellite galaxy since its stars move about 100 km s^{-1} more slowly about the Galactic center than the local standard of rest, the abundances of the α elements (Mg–Ti) are unusual, and the Fe abundances are about 1/10 solar (Navarro et al. 2004). Some of the Arcturus Moving Group stars are indeed very close including Arcturus itself (11.2 pc) and HD 199288 (21.6 pc).

Additional evidence for alien material in our Galaxy may be in the lines of sight with D/H gas ratios very close to the primordial ratio (about 27 parts per million). Linsky et al. (2006) identified five lines of sight with D/H gas ratios ≥ 23 ppm which is difficult to explain by galactic chemical evolution models without the addition and incomplete mixing of captured near-primordial gas from the IGM or dwarf galaxies (Romano et al. 2006; Steigman et al. 2007). Alternatively, possible systematic errors in the hydrogen column density determinations could result in high gas D/H ratios. Most of the existing measurements of D/H are based on FUSE spectra of the higher Lyman series lines. A future mission that will obtain FUV spectra with higher spectral resolution and signal/noise is needed to obtain more accurate D/H measurements and thereby test the alien gas hypothesis and search for systematic errors.

9 Other ISM science questions requiring UV/FUV spectroscopy

- How hot is the Local Bubble gas and why is it hot? (Need spectroscopic diagnostics to separate thermal emission from charge-exchange processes in the heliosphere.)
- What are the important physical processes at cloud interfaces? (Thermal conduction, evaporation, MHD interactions, etc.)
- What are the causes and scales of turbulence in the ISM? (Kolmogorov turbulent spectrum on all scales?, how produced?, how maintained?)

10 Instrumental requirements for a future UV spectroscopy mission

Table 1 summarizes the instrumental goals needed to address each of the 10 science questions. I would hope that a future UV spectroscopic mission would be able to meet most of these goals.

11 Other considerations for a future high-resolution UV spectroscopy mission

- High S/N spectra require detectors with low fixed pattern noise and low background.

Table 1 Requirements for a future UV mission

Science objectives	R[a]	S/N	λ[b]
Cloud structures	3	50	UV, FUV
Cold gas clouds	1	50	UV, FUV
Cloud interactions	3	30	UV, FUV
Pressure disequilibrium	1	50	UV, FUV
Ionization processes	3	30	UV, FUV
Effects of starbursts	3	30	UV, FUV
Alien matter	3	30	UV, FUV
How hot is the LB?	10	30	UV, FUV
Cloud interfaces	3	30	UV, FUV
Turbulence	1	50	UV

[a]Desired spectral resolution (km s^{-1})

[b]The wavelength range for the UV is 1175–3200 Å and for the FUV is 912–1175 Å

- An accurate wavelength scale requires an onboard spectral line lamp and excellent thermal stability.
- Many observing programs require the full 912–3000 Å spectral range, but this could be achieved with separate spectral bands on the same spacecraft.
- Small and large apertures are needed for different observing programs.
- Large amounts of observing time are required to complete major programs with many sightlines and targets.
- With increasing spectral resolution, more programs become feasible. Three km/s resolution is highly desirable. This requires excellent stable optics.
- High Earth orbit (HEO) or a more distant orbit is desirable. Observing with a somewhat smaller aperture telescope in HEO is more efficient and likely less expensive compared to a larger aperture telescope in low Earth orbit where Earth occultations decrease observing time and observatory operations are more complex.

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