Understanding Physical Processes in the Diffuse Interstellar Medium Using High-Resolution UV Spectroscopy

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Abstract

High-resolution UV spectroscopy with the GHRS and STIS instruments on HST and FUSE has provided valuable new information and identified new questions concerning the structure and physical properties of diffuse gas in the ISM. Future high-resolution UV instruments with greater sensitivity are needed to answer such important questions as: (1) What physical processes occur at the interface between hot and warm gas? (2) Why is the ISM structured? (3) How is the interstellar gas ionized? (4) Is the ISM in equilibrium or disequilibrium? The nearby ISM is an astrophysical laboratory providing useful prototypes for interstellar gas in the more distant universe but with far less confused lines of sight.

1 The Local Region of the ISM is an Astrophysical Laboratory

Why study interstellar gas in our region of the Galaxy? The prime reason is that the physical processes, dynamics, ionization processes, morphological structures, and departures from equilibrium provide many (but not all) prototypes for what is occuring elsewhere in the Galaxy and in other galaxies. If we ever want to understand galactic chemical evolution, we must first understand what is occuring in the gas and dust phases of the ISM, which provide the transition between the loss of chemically-enriched matter from stars and the formation of the next generation of stars.

A second reason is that short lines of sight are much simpler to interpret than long lines of sight. Over short distances, the gas properties may show little variation along the line of sight to a star with only one or a small number of identifiable velocity components.

A third reason is that the background stars that provide the light against which nearby interstellar absorption is measured need not be luminous in the ultraviolet. Thus one can avoid using luminous OB stars with their wind-blown hot bubbles and also the hotter white dwarfs and subdwarfs that may be surrounded by large Stromgren spheres. This means that the absorption is primarily interstellar rather than circumstellar.

Given simple uncontaminated lines of sight, we can use the local ISM as an astrophysical laboratory to answer some critical questions. Here are a few.

2 BIG QUESTION #1: Interface Physics

A major unanswered question is whether absorption by O VI is smoothly distributed in the hot component of interstellar gas, or is mostly from interface regions where cold or warm gas meets hot gas. In their study of O VI absorption toward OB stars located in the Galactic plane more than 1 kpc from the Sun, Bowen et al. (ApJS 176, 59 (2008)) conclude that the O VI absorption is clumpy, mostly from many small clouds but also from a few sparsely distributed large clouds.

In their study of O VI absorption toward 39 white dwarfs located at 37–230 pc from the Sun, Savage and Lehner (ApJS 162, 134 (2006)) concluded that the O VI absorbing gas is located in conductive interfaces between warm and hot gas. A major piece of evidence is that radial velocities of the O VI and warm C II gas are often in agreement. Since they could not determine where along the line of sight the O VI absorption occurs, they could not identify the interfaces.

Figure 1 may provide the answer. Redfield & Linsky (in preparation) are comparing the absorption profiles of high and low ionization lines toward cool stars and white dwarfs located inside of the Local Bubble. Figure 1 shows profiles for the line of sight to G191-B2B (69 pc) using data from STIS and FUSE. Shown from bottom to top are profiles of ions with increasing ionization along the line of sight. The vertical lines from left to right are the radial velocities of the Hyades and LIC clouds of nearby warm interstellar gas and the stellar photospheric velocity. The velocity scale for the C III line is uncertain.

Strong absorption in the C IV line and weaker absorption in Si IV have radial velocities consistent with that of the warm ($T \approx 5,000$ K) gas in the nearby Hyades cloud. This absorption could occur at an interface between the Hyades cloud and surrounding hotter gas rather than in circumstellar gas near the white dwarf. We are investigating many other lines of sight to determine whether the O VI absorption can provide information on the interface physics.

What physical processes are occuring at interfaces? Are we observing conduction, evaporation of the warm gas, or condensation of the hotter gas? What roles do magnetic fields play? What are the timescales?

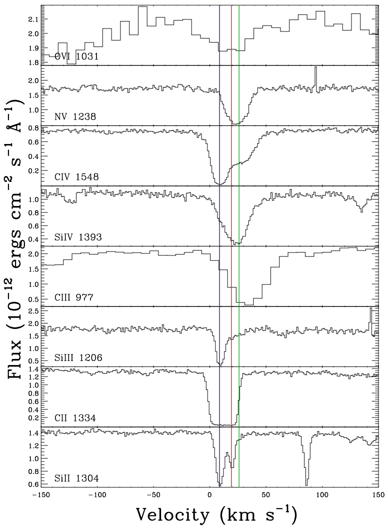

FIGURE 1: From Redfield & Linsky (in preparation).

3 BIG QUESTION #2: Why structure

The ISM is not homogeneous but is rather structured on many scales. Why? Filamentary structures are typical (e.g., optical images of "wisps" in the Pleiades). Cold gas clouds are observed with structures as small as 20 AU (0.0001 pc) (Lauroesch et al. ApJ 543, L43 (2000)). Redfield & Linsky (ApJ 673, 283 (2008)) identified 15 velocity vectors of warm gas "clouds" located within 15 pc of the Sun. Some are filamentary and some are irregular in shape.

Are these structures real, or are they artifacts of the way that we identify clouds (e.g., by assuming that they are rigid structures with a common velocity vector)? If they are real, is their shape determined by magnetic fields, thermal or other instabilities, or are we observing a dynamic phenomenon driven by ram pressure from supernova explosions?

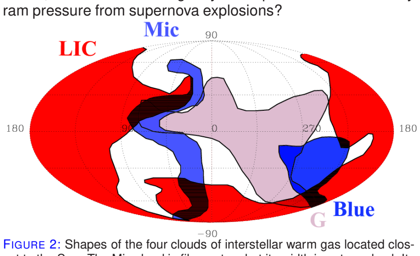

FIGURE 2: Shapes of the four clouds of interstellar warm gas located closest to the Sun. The Mic cloud is filamentary but its width is not resolved. Its shape may be determined by the collision of the LIC and G clouds. From Redfield & Linsky (2008).

4 BIG QUESTION #3: Causes of Ionization

Figure 1 shows a wide range of ionization along a sightline only 69 pc long with ionization energies 8.1 eV (Si° to Si^{+}) to 113.9 eV (O^{+4} to O^{+5}). Possible ionization processes include collisional ionization equilibrium (thermal), photoionization, and recombination from a shock. Highly-ionized species require very hard nearby radiation sources. Difficult to measure electron densities are critically important in determining whether a plasma is thermal or, if not, the recombination time scale. Whether or not radiation from thermal interfaces between warm and hot gas is an important source of photoionization in the Local Bubble is not yet known. Even the existence of hot (i.e., 10^6 K) gas in the Local Bubble has been challenged by several authors on the basis that much or nearly all of the soft X-ray background is charge-exchange emission produced inside of the heliosphere and O VI absorption may be produced in a recombining plasma.

5 BIG QUESTION #4: Equilibrium or Disequilibrium

Field et al. (ApJ 155, L149 (1969)), McKee & Ostriker (ApJ 218, 148 (1977)) and subsequent authors developed theoretical models of the ISM that assume steady-state thermal and pressure equilibrium. These models describe a multiphase ISM consisting of cold, warm, and hot components. The hydrodynamic and MHD simulations of de Avillez & Breitschwerdt (A+A 436, 585 (2005)) describe a highly dynamic ISM driven by supernova explosions in which all temperatures are present and mixing of hot and warm gas is important. Figure 3 shows that a very wide range of parameters is present at any one time. Is this nonsteady state pressure disequilibrium ISM realistic?

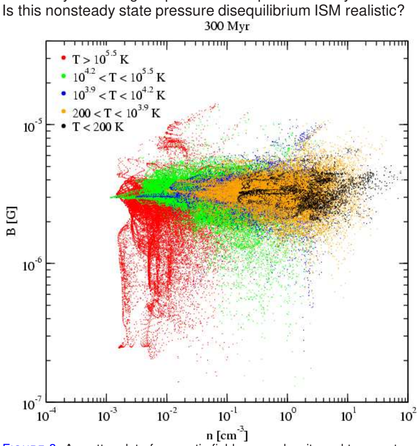

FIGURE 3: A scatter plot of magnetic field versus density and temperature in the de Avillez & Breitschwerdt (2005) MHD simulation.

6 Needed after HST and JWST

Resolution: 2 km/s for brighter sources and 5 km/s for fainter sources.

Sensitivity: 10 times corresponding STIS modes.

Velocity accuracy: 1.5 km/s (absolute), 1 km/s (relative over full wavelength interval)

Wavelength range: 912–3000 Å (highly desirable) perhaps in two instruments.

Scattered light suppression: Better than STIS.

Other modes: Coronography and long slit spectroscopy are desirable.