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# Constructing Physically Realistic Models of Interstellar Gas in Galaxies: Start with Understanding the Physics of the Local ISM

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**Abstract.** High resolution spectra in the ultraviolet and optical regions from HST, FUSE, and ground-based telescopes are providing important information on the structure and physical properties of the local region of the Galactic disk. This ongoing study is critically important because a detailed understanding of our local region of space provides essential guidance for understanding the ISM elsewhere in the Galaxy, in other galaxies, and even the IGM. I describe some of the important questions that must be answered and the observational capabilities that are needed in future space telescopes to address these issues.

## 1. Why Understanding the Local ISM is Critically Important

The low density and dilute radiation fields in the interstellar medium (ISM) require that atoms and ions have significant populations only in their ground states. Atomic physics requires us to study the gas components in the ISM at the wavelengths where their resonance lines are located, which for most species is in the ultraviolet and shorter wavelengths. To study the ionization, chemical abundance, and dynamics of interstellar gas requires measurement of the line shapes and Doppler shifts of narrow resonance absorption lines along the lines of sight to stars or extragalactic sources. Thus the study of interstellar gas requires ultraviolet spectroscopy with the highest spectral resolution of STIS, where $R = \lambda/\Delta\lambda \approx 100,000$ (3 km s$^{-1}$) and for some studies even higher resolution.

Before describing in more detail the important scientific questions of interstellar science that should be addressed in future space missions and the observational capabilities needed to address them, I would like to ask two questions:

**Question No. 1**: Is it possible to construct a physically realistic model of interstellar gas in a starburst galaxy or a low metal abundance galaxy without first understanding the essential physical processes occuring in the galaxy?

**Question No. 2**: Can one understand the physical processes operating in any galaxy without first understanding the physical processes occuring in the ISM close to home – the local region of the Galactic disk?

I believe that the answer to both questions is a resounding NO. So, let us take a closer look at the ISM in the solar neighborhood.

## 2. Some Important Unanswered Questions Concerning the Local ISM

### 2.1. What is the structure of the Local ISM?

There are several identified components of the ISM in the Galactic plane within about 200 pc of the Sun:

**Local Bubble**: This consists of mostly hot ($\log T = 6.0$–$6.1$), very low density gas extending 50–200 pc in different directions. A rough outline of its shape is determined from the observed "wall" of NaI absorption (Sfeir et al. 1999). The origin of the hot gas is likely from the winds of massive stars and supernove in the Sco-Cen Association. The gas flow is from $l = 12.6°$, $b = +11.7°$ at 28.2 km s$^{-1}$ (Frisch 2001).

**Local Interstellar Cloud**: This is a warm ($T \approx 7,000$ K) partially ionized cloud with dimensions about 4.7 x 6.8 pc (Redfield & Linsky 2000). The Sun is located just inside the LIC and will leave in $< 7000$ years. In most directions the measured velocities are consistent with the projected flow of one vector, which is consistent with the flow of neutral interstellar gas inside the heliosphere. However, in the downwind direction the flow is 3 km s$^{-1}$ too slow, and in the upwind direction (usually called the G cloud), the flow is 3 km s$^{-1}$ too fast. Does this mean that the LIC is not behaving as a rigid body but is instead compressed by outside forces?

**Other warm clouds**: At least 10 other warm clouds located near the LIC have been identified tentatively from GHRS or STIS spectra. They have a range of temperatures and metal depletions. The G cloud (in the upflow direction) and the Hyades Cloud (in the downflow direction) may be in contact with the LIC.

**Cold gas**: Significant column densities of Na I define the outer edge of the Local Bubble (e.g., Sfeir et al. 1999), indicating the presence of cold gas at this location. Small clouds of cold gas are also present in the local ISM as seen, for example, toward several binary stars, but there has been no systematic survey that could identify these clouds.

Although ultraviolet and optical spectroscopy has revealed some information on the physical properties and structure of the gas in the local ISM, there remain important unanswered questions:

- Is it realistic to talk in terms of discrete clouds with sharp boundaries in which metal depletions, temperature, and density are homogeneous, or should one talk in terms of "clouds" in which all quantities vary spatially?
- Is the LIC surrounded by other warm clouds or by hot Local Bubble gas? Does this make a big difference?

- Why is there a large range of depletions in the local ISM?

### 2.2. Are we resolving the microstructure of molecular clouds?

This is an important question because cold clouds are regions of star formation. We do not know how many small cold clouds are present in the local ISM.

- In a high resolution (0.3–1.2 km/s) survey of interstellar CaII absorption (formed in warm and cold gas), Welty et al. (1996) concluded that they had identified only about 40% of the velocity components that are likely present. Very narrow velocity components indicate cold gas.
- Thus most velocity features for heavy elements are unresolved even by STIS, and one cannot accurately measure the gas temperature or nonthermal velocity components without higher resolution spectra. Line saturation is also difficult to determine with the resolution of STIS.
- Are the nonthermal motions subsonic or supersonic? Can they support the gas against collapse?
- The smallest observed structures are subparsec in size:
  - Lauroesch et al. (1998) used the GHRS to observe both components of the $\mu$ Cru binary system. They found large differences between the absorption profiles in the lines of sight to the two stars for neutral species (NaI, ClI, MgI) but no significant differences in the profiles of first ions (CrII and ZnII). They infered that the extra absorber toward one of the stars is likely a cold interstellar gas cloud with a size of 10–6600 AU (the binary separation) and $n_{HI} < 250$ cm$^{-3}$.
  - Lauroesch et al. (2000) found changes in the NaI absorption toward HD 32040 over a 4.25 year observing run. Since the star's proper motion was 15–21 AU during this time period, the scale size for the cold interstellar gas must be comparable and $n_{HI} = 20$–$200$ cm$^{-3}$.
  - Redfield & Linsky (2001) identified a warm interstellar cloud towards stars in the Hyades Association and extending over a large portion of the sky. This Hyades Cloud could be the "blue cloud" seen toward Sirius (2.6 pc) and thus lie just outside of the LIC. The smallest dimension in the Hyades cloud is $\leq 0.6$ pc, but could be much smaller.

Are these small structure sizes controlled by magnetic fields, shocks, thermal instabilities, or something else? Is the LIC filled or does it contain large holes with very low density like Swiss cheese?

### 2.3. What is the ionization of the Local ISM, and what is responsible for the ionization?

**Some fundamental questions:**

- Are the ionization states of H, He, and metals in steady-state equilibrium with the incident radiation fields, or are they out of equilibrium following catastrophic events (e.g., supernovae)?

- What are the major sources of ionization: early-type stars, white dwarfs, diffuse UV background, shocks, cloud interfaces, or something else?

**Some recent progress:**

- Lyu & Bruhweiler (1996) computed time-dependent ionization models of the local ISM to explain the observed high ionization of He. They assumed that a supernova (like SN 1987A) in Sco-Cen Association produced a blast wave that completely ionized H and He, and the gas is now recombining. Their best fit to the observed H and He ionization is for a supernova event occuring 1–3.6 million years ago. Their result does not change significantly when the EUV radiation field from $\epsilon$ CMa and other hot stars and white dwarfs and the EUV background are included or ignored.

- Jenkins et al. (2000) studied ArI 1048 Å absorption toward four nearby white dwarfs observed by FUSE. The observed low N(ArI)/N(HI) ratios favor steady-state photoionization models, because the photoionization cross section of ArI is larger than HI, but the recombination coefficients are nearly the same. Thus photoionization will make argon more ionized than hydrogen, yielding a lower N(ArI)/N(HI) ratio than would be predicted for a recombining plasma.

- Slavin and Frisch (2002) computed photoionization models for the local ISM (within $\sim 5$ pc of the Sun) including radiation fields from hot stars (e.g., $\epsilon$ CMa and white dwarfs), the uncertain EUV radiation from the hot gas responsible for the soft X-ray background, and a possible evaporative boundary between hot gas in the Local Bubble and warm clouds. Some of their models can explain the observed ionization fractions, column densities, heating, and cooling in the LIC.

- The recent Wood et al. (2002) empirical study of the first three ionization stages of carbon, nitrogen, and silicon in the LIC toward Capella using STIS and FUSE spectra finds good agreement with the predictions of the Slavin and Frisch (2002) steady-state photoionization model 17.

**How to proceed:**

- Cloud geometries are needed because clouds absorb the incident EUV radiation field. We need high resolution ultraviolet spectra to separate individual velocity components along a line of sight.

- What is the magnetic field at the the cloud/Local Bubble boundary? This is an important question because magnetic fields can suppress thermal conduction at the interface and thus lower the EUV photoionizing radiation.

- Why is helium more highly ionized than hydrogen along some lines of sight? We need to measure accurately the diffuse background at $E > 24.6$ eV which photoionizes neutral helium. The Cosmic Hot Interstellar Plasma Spectrometer (CHIPS) should measure this quantity.

- Significant deviations from steady-state ionization equilibrium are possible because the recombination time for hydrogen is short in the LIC. The case for steady-state ionization equilibrium is not yet proven.

- Why are there large differences in metal depletions over short distances? For example, the depletion of magnesium is 4.4 times smaller in the G cloud toward $\alpha$ Cen than in the LIC.

- We need to test and refine the photoionization models by comparison with accurate measured column densities for a wide range of targets observed with very high resolution ($\sim$ 1 km/s) in the UV and FUV.

### 2.4. Do we really understand Galactic Chemical Evolution?

One of the pilars of astrophysics is the standard model of galactic chemical evolution. It is generally assumed that the initial chemical abundances in a newly formed galaxy are the primordial abundances from Big Bang nucleosynthesis, and that as stars evolve they destroy deuterium and create metals that are dispersed in the ISM by stellar winds and explosions. New generations of stars form out of this metal enriched and deuterium depleted gas and the process continues. It is important to test the predictions of this model to see whether something important is missing. In particular, what are the relevant temporal and spatial scales for mixing of the chemical elements in a galaxy? What roles do turbulence, magnetic fields, starbursts, supernovae, etc. play in establishing these mixing scales? Is our Galaxy well mixed?

**Recent results from FUSE concerning D and O**: The analysis of FUSE spectra of seven nearby hot stars published in seven papers in the May 2002 issue of the *Astrophysical Journal Supplements Series* and summarized by Moos et al. (2002) provide new information on the abundances of deuterium and oxygen in the local ISM and challenge the standard model for galactic chemical evolution.

- These new results show that D/H $= (1.52 \pm 0.08) \times 10^{-5}$ for five sightlines within the local Bubble (out to $\sim$ 100 pc), consistent with previous HST results towards cool stars (Linsky 1998). Beyond the Local Bubble, the Copernicus and IMAPS data show large variations in the D/H ratio in the range $(0.5\text{–}2.18) \times 10^{-5}$. Why is there such a large range? The most recent value for the lines of sight toward four quasars is D/H $= (3.0 \pm 0.4) \times 10^{-5}$ (O'Meara et al. 2001). This may not be the primordial value of D/H, but it likely refers to gas with low metal abundances and thus only minimal change from the primordial value. Why does the decrease of D/H in the Galactic disk appear to cover the large range between 1.4 and 6?

- Analyses of the FUSE spectra also determine that D/O $= (3.76 \pm 0.20) \times 10^{-2}$ in the Local Bubble but may vary at larger distances.

- Using STIS spectra, Meyer (2001) found that O/H $= (3.43 \pm 0.15) \times 10^{-4}$ and is nearly constant in the Galactic disk out to 5 kpc from the Sun.

- These results indicate large D/H variations but no significant O/H variations beyond the Local Bubble in the disk 100–500 pc from the Sun.

- There is also some evidence that O/H may be correlated (not anticorrelated) with D/H, contrary to the prediction of the standard model for galactic chemical evolution. Additional observations are needed to confirm and quantify or refute this apparent correlation, but the data in hand provide a challenge to our understanding of galactic chemical evolution. My hunch is that a realistic model for the geometrical scale and rate of mixing of gas in the ISM must be added to the theory.

**What do we need?**

- We clearly need accurate measurements of D/H and D/O over a much larger region of the Galaxy. FUV spectroscopy with resolution $< 3$ km s$^{-1}$ is needed instead of the 15–20 km s$^{-1}$ resolution of FUSE.
- UV spectroscopy with resolution $\sim 1$ km s$^{-1}$ is needed to characterize the physical properties of the gas in which D/H and D/O are measured for the same lines of sight.
- We also need a better theoretical understanding of the sources and sinks of important elements and the mechanisms controlling mixing in the Galaxy.

## 3. Observational Requirements for a Future Mission

I believe that we will need the following observing capabilities to address these fundamental issues in a systematic way. This table includes science objectives that I have had time to discuss here.

| Science Objective | Resolution (km/s) | S/N | Spectral Range |
|---|---|---|---|
| 2.1 LISM Structure | 1 | 100 | UV, FUV |
| 2.2 LISM Microstructure | 0.3 | 100 | UV, Opt |
| 2.3 LISM Components | 1 | 50 | UV, FUV, X |
| 2.4 Interfaces | 1 | 100 | UV, FUV |
| 2.5 Ionization | 3 | 100 | UV, FUV, EUV |
| 2.6 Starburst galaxies | 3 | 50 | UV, FUV |
| 2.7 Grains | 1 | 100 | UV, Opt, IR |
| 2.8 Distant ISM | 3 | 50 | UV, FUV |
| 2.9 Pressure Disequilibrium | 3 | 300 | UV, FUV |
| 2.10 Chemical Evolution | 1 | 100 | UV, FUV |
| 2.11 Imaging Spectroscopy | 10 | 50 | UV, FUV |

UV Spectral Range: 1170–3000 Å.
FUV Spectral Range: 910–1170 Å.

**Other capabilities needed in future space missions:**

- Suppression of fixed pattern noise is essential for achieving high S/N.
- An onboard wavelength calibration lamp and thermal stability of the spectrograph are essential for an accurate velocity scale.

- Doppler compensation is essential for a satellite in low Earth orbit.
- Simultaneous observations in all spectral bands are not required.
- Synergy is required. Observations in the UV and FUV complement each other beautifully. A FUV + UV data set is far more valuable than either a FUV or UV data set alone. HST TACs please take notice.
- Sufficient observing time is essential to sample the required number of sightlines is essential.
- Simultaneous observations of several nearby targets (e.g., in a cluster) would be beautiful.

## 4. Let's Think out of the Box: Compare a Full Size Multiple-instrument Behemoth to a Series of Half-size Single Instrument Satellites

### Motivation

**Scientific capabilities**: To accomplish the important scientific objectives in the 2010–2020 time frame, new UV/optical instruments in space must have many capabilities (e.g., wide-field imaging, low resolution faint object spectroscopy, high resolution spectroscopy, coronography, high UV/optical and FUV throughput, imaging spectroscopy, etc.)

**Efficiency**: High throughput can be achieved by limiting the types of supported observations and optimizing the telescope/instrument system for just these limited observations. COS will have a factor of 20–30 higher throughput over STIS at 20,000 resolution, effectively increasing Hubble's aperture from 2.4 m to 10–14 m.

**Limiting magnitude**: Detector background is often proportional to the pixel size of a resolution element. In this regime, longer integrations can compensate for smaller aperture.

**Observing time**: Time sharing of the focal plane means each instrument has a low duty cycle. Four focal plane instruments decrease the telescope aperture by a factor of 2 compared to full time use of each instrument.

**Cost**: Satellite costs are often proportional to weight plus complexity. If all else is equal, doubling the aperture raises the cost by roughly a factor of 4–8. Multiple focal plane instruments increase complexity and cost for construction, testing, and operations. High cost satellites take forever to build and are eventually descoped.

**A modest proposal that deserves serious thought and study**:

- Design and build a series of satellites each with half the aperture of the behemoth (say 4 m each instead of 8 m). Constellation-X is an example of a multisatellite program.

- Each satellite will have only one focal plane instrument with limited observing modes that are optimally matched to its telescope optics (f-number, coating, field of view, mirror quality, scattered light suppression, etc.). Make no compromises.
- Each spacecraft will be as identical as possible so that they can be mass produced to reduce cost. Produce a few spares to be used to replace satellites as needed.
- Launch one satellite in the program every year or two and do not design for on-orbit replacement.
- A program of many satellites greatly reduces program risk because failure of a critical component can only end the life of one satellite not the whole program. Less perceived risk means lower costs. The program is designed to live with individual failures.
- If the scaling law is approximently correct, then roughly 4–8 half-size satellites can be built and operated for the cost of one behemoth. This program should produce far more data of similar quality to the behemoth. Even 4 half-size satellites will be more scientifically productive than a behemoth at much lower cost and fewer delays.

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