FUSE’s Five Years of Progress on the Interstellar Medium

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Abstract. I review the five years of progress by FUSE on current topics in the interstellar medium. FUSE's sensitivity and unique access to the far ultraviolet allow investigators to solve problems in all phases of the interstellar medium. I describe FUSE’s contributions in four major areas: 1) the Local Interstellar Medium (LISM), 2) the hot phase (O VI), 3) the cold phase (H$_2$), and 4) interstellar gas abundances. I devote particular attention to the common themes of ISM phase interactions and changes with metallicity. As a whole, these results show that FUSE is the most powerful machine ever to address problems of the ISM, and that FUSE points vividly to the future of ISM studies in the Galaxy, Local Group, and beyond.

1. Introduction

This contribution reviews the fundamental advances FUSE has made in our understanding of the interstellar medium (ISM). To get a broad picture of recent progress, I surveyed all publications based on FUSE data appearing in the refereed literature between 1999 and 2004. I do not distinguish results from FUSE PI Team observations and GO investigations, but the PI-dominated schedule of the first three observing cycles is clearly apparent. A review of the more than one hundred ISM-related GO programs proves the great potential that awaits us in the future. The present volume also contains many excellent contributions too new to make my July 2004 cutoff. Related ISM topics are addressed in other contributions on deuterium (Pettini, Hébrard, Linsky, Draine), high-velocity clouds (HVCs), including O VI (Sembach, Collins, Fox), O VI in the Galactic disk (Bowen) and the Magellanic Clouds (Howk), dust (Clayton), and supernova remnants (SNRs; Sankrit).

As a whole, these studies show that in terms of topical scope (the number of diverse topics addressed) and astrophysical range (6 decades of distance, 8 decades of column density, and 3 decades of metallicity), FUSE is the most powerful instrument that has ever addressed problems of the ISM. The first point follows from FUSE’s wavelength coverage and efficient multiplexing, and the second from its unprecedented sensitivity. These themes recur throughout our review of specific results, and will be revisited in § 8 to motivate future work.

In the following sections I discuss FUSE’s specific contributions to four areas of ISM research. First, in § 2 I sketch out our basic understanding of interstellar processes to help assess the basic character of FUSE’s contributions. In § 3 I review FUSE results on the structure and ionization of the Local Interstellar Medium (LISM). Section 4 discusses FUSE work on the hot phase of the ISM, as
traced by O VI. Section 5 turns to the studies of H\textsubscript{2} in the Galaxy and Magellanic Clouds. Section 6 briefly summarizes other results on the Magellanic Clouds. In § 7 I discuss the wide range of \textit{FUSE} interstellar abundance studies and their astrophysical implications. Finally, the concluding section (§ 8) revisits the themes introduced in § 2 and considers how \textit{FUSE}'s legacy will inspire the conception and design of future FUV instruments.

2. \textbf{FUSE and the Cartoon ISM}

Figure 1 shows a simplified cartoon of interstellar “ecology” that will help us understand the unique contributions of \textit{FUSE}. Starting from the cold, dense molecular clouds where stars are born, we proceed to the “blister” regions where young hot stars emit the winds and strong UV radiation that heat and disrupt their immediate environments. On Myr timescales, hot stars end their lives as supernovae and inject energy and mass into the ambient medium. Where hot-star formation occurs in coeval clusters, multiple supernovae can evacuate large superbubbles filled with hot ionized medium (HIM), some of which may escape from the Galactic disk into the halo in a “Galactic fountain”. This hot gas eventually cools, recombines, returns to the disk, and mixes with other phases to form the cold and warm neutral media (CNM and WNM). These classical diffuse clouds, traced by H I and H\textsubscript{2}, eventually cool below 100 K and coalesce to form new molecular clouds. The entire process is thereafter repeated.

The relative levels of detail in our understanding of the stages track closely our capability to detect and study their emission and/or absorption. Because nearby examples are spatially resolved and emit at optical wavelengths, young star-forming regions are probably the best-understood objects in the diagram. By contrast, the hotter (HIM) gas, which emits in X-rays and absorbs in the UV, and the diffuse WNM and CNM, which emit in H I and absorb in H I, H\textsubscript{2}, and the low ions, are not as well understood.

\textit{FUSE}'s fundamental contributions to ISM studies add both sophistication and dimension to this simple picture. \textit{FUSE} provides details where we currently have only the speculative “evolution” arrows on the diagram. In particular, \textit{FUSE}'s unique access to the O VI λλ1032,1038 doublet has enabled study of the highly-ionized boundary regions where the hot and cold phases interact. \textit{FUSE}'s access to the hundreds of Lyman and Werner ro-vibrational lines of H\textsubscript{2} and extensive abundance studies have added a metallicity dimension to this diagram. Using \textit{FUSE} we have shown that H\textsubscript{2} responds to the metallicity and ambient radiation field in its environment, so we are learning how interstellar processes change their character in chemically primitive galaxies. \textit{FUSE}'s sensitivity and efficient multiplexing have placed most of its substantive conclusions on statistically sound footing.

3. The Nature of the Local Interstellar Medium

The Solar System resides in the Local Interstellar Cloud (LIC), one of the Local Interstellar Medium Clouds (LISM), all embedded within the Local Bubble (LB). The LB is filled with hot diffuse gas and which apparently extends into the low Galactic halo (Figure 2). In a twist to the truism that higher sensitivity
pushes outward, *FUSE* has opened new windows into the LISM by observing faint white dwarfs (WDs) at < 100 pc from the Sun, generally closer than the bright O-stars accessible to *Copernicus*. Using measurements of Ar I, N I/II/III, and O I toward these new targets, [Jenkins et al. (2000)] inferred that the LISM clouds are steadily photoionized by EUV from OB stars and hot gas rather than “overionized” from an earlier period of strong heating by SNe. The [Lehner et al. (2002)] survey of 31 WDs (squares in Figure 2) confirmed this result, found little H$_2$ in the LISM, and measured the local C II cooling rate.

In studies of the hot phase of the local ISM, [Shelton et al. (2001), Dixon et al. (2001), and Welsh et al. (2002)] detected O VI emission along 6 high-latitude sightlines (marked by arrows in Figure 2). Using a “shadowing” technique that observed an optically thick cloud just beyond the LB boundary, [Shelton (2003)] placed a strict upper limit on O VI emission from the LB itself. This limit implies that LB and LISM interfaces are rare, small, and/or produce little O VI. The inferred cloud sizes of $\sim 10$ pc at $T = 300,000$ K suggest conductive interfaces or mixing layers between hot and cold gas.

These results have been confirmed by the larger O VI absorption survey by Oegerle et al. (2004, in preparation), who found weak or absent O VI absorption toward the local WD sample. This surprising result suggests that patchy O VI occurs only where conductive interfaces between the hot LB gas and cool LISM clouds are not quenched by magnetic fields.
Figure 2. The Local Bubble contains a hot, X-ray emitting plasma of uncertain extent (X-ray contour in grey; Snowden et al. 1998). The neutral boundary to the Local Cavity is marked with the heavy black contour (Lallement et al. 2003) figure from Welsh, Sallmen, & Lallement 2004). The grey squares mark the WD sample observed by FUSE (Oegerle et al. 2004, in prep). The grey arrows trace the complete sightlines observed in O VI emission.

*FUSE* has resolved the debate over the source of ionization in favor of photoionization models rather than incomplete recovery from a past highly ionized condition, as had been proposed. *FUSE* has also thoroughly characterized the distribution of O VI-bearing hot gas in the LISM, implying that the interfaces between the hot LB gas and the nearby neutral ISM are more complicated than previously believed. The theme of ISM phase interaction continues into the next section, where I review O VI results from the more distant ISM.

4. O VI and Phase Interactions

*FUSE*’s access to the O VI $\lambda\lambda 1032,1038$ doublet provides us with our clearest window into the hot phase of the interstellar medium. In an attempt to explain how neutral ISM clouds could remain stable at high Galactic latitudes, Spitzer (1956) first predicted the existence of hot interstellar gas extending to several kpc above the Galactic plane. *Copernicus* first confirmed this prediction with short
Galactic disk sightlines, but with its high sensitivity and efficient multiplexing, FUSE has vindicated Spitzer’s idea in spectacular fashion. However, by studying more than 10 times as many complete sightlines through the disk and halo, FUSE has revealed that the distribution and character of the O VI is somewhat more complicated than Spitzer foresaw.

Surveys by Wakker et al. (2003), Savage et al. (2003), Sembach et al. (2003), and Zsargó et al. (2003) found four key features of the O VI, listed here with their physical implications.¹ The O VI is:

*Ubiquitous:* O VI is detected in 100 of 102 complete sightlines through the Galactic thick disk and halo, so it traces a common phenomenon in the ISM.

*Short-lived:* Because O VI reaches its peak ionization fraction at 300,000 K, where solar-metallicity gas cools in \( \leq 10^7 \) yr, the O VI must trace short-lived, non-equilibrium processes.

*Variable:* The strong 2–4 \( \times \) variations in \( N(O\ VI) \) of over 10 pc – 1 kpc (Howk et al. 2002) imply that the O VI arises in small structures rather than a stably stratified, stable hot layer.

*Poorly correlated:* The poor correlation of \( N(O\ VI) \) with H I (CNM), Hα (WIM), and soft X-rays (HIM) suggests that the transition temperature gas traced by O VI lies outside these phases.

Conductive interfaces, turbulent mixing layers, radiative cooling zones, supernova remnants, and a Galactic fountain flow all meet the basic criteria. Eight sightlines with HST data on C IV, N V, and O VI \( (T = 1, 2, 3 \times 10^5 \) K) favor a cooling Galactic fountain model with \( \dot{M} \sim 1.4 \) M\(_\odot\) yr\(^{-1}\) from either side of the disk, but all these non-equilibrium transition zones probably contribute at some level (Indebetouw & Shull 2004a,b). In the future we need spectral resolution \( R \sim 100,000 \) to count individual interfaces, more sightlines with supporting data on C IV and N V (a perfect project for the Cosmic Origins Spectrograph), and new theory to help isolate the different ionization mechanisms. Thanks to its unique waveband and efficient multiplexing, FUSE has made a major advance in the understanding of how the hot and cool phases of the ISM interact.

### 5. H\(_2\) and the Low-Metallicity ISM

Although H\(_2\) was shown by *Copernicus* to be widespread in the Galactic disk, FUSE has found diffuse H\(_2\) virtually everywhere it has looked, including:

*The Galactic disk and halo,* where it forms a baseline for comparison to other environments (Shull et al. 2004, in preparation; Gillmon contribution);

*Galactic intermediate velocity clouds,* where it links them closely to the Galactic disk (Richter et al. 2003);

*The Monoceros Loop SNR,* where it may have reformed behind the remnant’s shock front (Welsh, Rachford, & Tumlinson 2002);

*High-velocity clouds,* where H\(_2\) formed *in situ* shows that HVCs can have significant dust (Richter et al. 2001a);

*The Small and Large Magellanic Clouds,* where it reflects low metallicity and robust star formation (Bluhm & de Boer 2001; Tumlinson et al. 2002);

¹Disk and LMC/SMC O VI results are discussed in the papers by Bowen and Howk, respectively.
The Magellanic Stream and Bridge, showing that it can survive tidal stripping from dwarf galaxies (Sembach et al. 2001; Lehner 2002); and

The Local Group spiral galaxy M33, where it indicates how to analyze composite spectra of many sources (Bluhm et al. 2003).

Thanks to these surprising results we are now learning how to use H$_2$ as a sensitive indicator of local physical conditions, such as temperature, density, metallicity, and radiation field. Two such studies are reviewed here, while a large number of contributed talks and posters in this volume present additional H$_2$ and CO results.

Richter et al. (2003) detected H$_2$ in 14 of 61 H I IVCs ($|v_{LSR}| = 30 - 90$ km s$^{-1}$). Because H$_2$ dissociation by FUV radiation occurs in less than $10^3$ yr where there is no competing molecule formation on the surfaces of dust grains, the widespread H$_2$ in the IVCs must have formed in situ. Kinematically the IVCs appear to be Galactic fountain gas returning to the disk in the form of small ($\sim 0.1$ pc), dense ($n_H \sim 30$ cm$^{-3}$) clouds. That FUSE has identified both the beginning and end of the Galactic fountain using essentially the same set of sightlines illustrates FUSE’s multiplexing power.

In a survey of 70 LMC/SMC sightlines, Tumlinson et al. (2002) found evidence of elevated FUV radiation fields and reduced H$_2$ grain formation rates in the LMC and SMC. Figure 3 shows the Magellanic Cloud data and models for Galactic conditions in panel A and 10 – 100× Galactic radiation field and 1/3 – 1/10 Galactic grain formation rate in panel D. These data confirm that H$_2$ formation-destruction balance shifts with metallicity and starburst activity, as predicted by theoretical models (Browning, Tumlinson, & Shull 2003). Molecular hydrogen is therefore providing critical insights into how interstellar processes change with metallicity, and may also allow us to diagnose physical conditions and stellar populations where they are not resolved, or even detected (such as in damped Ly$\alpha$ systems).

6. Magellanic ISM

FUSE investigators have done fundamental work on the LMC and SMC ISM, providing a critical link between the Milky Way and high-redshift galaxies on the cosmic metallicity ladder. Some examples of FUSE LMC/SMC work are the dust extinction curve study by Hutchings & Giasson (2001), the Lehner (2002) study of abundances, ionization, and molecules in the Magellanic Bridge, and the extremely thorough sightline analysis of the SMC star Sk 108 by Mallouris (2003). In studies of Magellanic CO, Bluhm & de Boer (2001) and Andrè et al. (2004) find CO/H$_2$ ratios that match the Galaxy, despite low $Z$. A broad view of the LMC and SMC interstellar medium is provided by the Danforth et al. (2002) atlas, which is a vital starting point for the analysis of LMC/SMC data or for the planning of new FUSE observations. Thus FUSE is beginning to make good on the long-standing promise of using the Magellanic Clouds as a template for understanding damped Ly$\alpha$ systems and primordial galaxies.
7. **FUSE Abundances Unlock Interstellar Secrets**

In accord with our theme of adding a metallicity dimension to the interstellar ecology diagram, FUSE has obtained interstellar abundances over 6 decades of distance and 3 decades of metallicity (Figure 4). FUSE can measure abundances directly for elements with dominant ions in the FUV and assist studies of many other elements by accurately determining $N$(H I) and $N$(H$_2$). As seen below, in almost every case abundances measured or assisted by FUSE reveal key insights into the operation of physical processes at low metallicity or high density. Some examples are:

1. Wood et al. (2002) measured roughly solar CNO but $10 \times$ depleted Si, Mg, Fe, Al, which indicates significant dust on FUSE's shortest sightline.

2. Knauth et al. (2003) found strong variations in the interstellar N I abundance in the Galactic disk. A deficit of N I at high N(H) suggests a “missing N problem” or poor understanding of N chemistry in dense clouds.

3. Snow, Rachford, & Figoski (2002) found that Fe depletions in “translucent cloud” sightlines do not increase beyond $A_V \sim 1$. This finding supports
Figure 4. Interstellar abundances in diverse environments. FUSE has measured details abundances from the 14 pc Capella sightline to the metal-poor ISM of I Zw 18 at 10 Mpc. The boxed numerals correspond to the summary points in § 7.

the conclusion from their high-extinction H$_2$ survey (Rachford et al. 2002) that true translucent clouds, if they exist, have not yet been found.

4. Richter et al. (2001a,c) measured near-solar abundances for non-refractory elements (S, O) in IVCs, suggesting that this extra-planar gas originates in the Galactic disk.

5. Mallouris (2003) found undepleted Ar, O, S, and Si, but depleted Fe toward Sk 108 in the SMC, which suggests unusual grain composition or lower dust-to-metal ratios at 40% solar metallicity.

6. Aloisi et al. (2003) used abundances in the blue compact dwarf galaxy I Zw 18 to diagnose its star formation history. They found abundances consistent with ancient star formation $> 1$ Gyr in the past (see her contribution).

In addition to abundances obtained directly from FUSE data, FUSE contributes $N$(H I) and/or $N$(H$_2$) to measurements of $N$(H). This subtle capability of FUSE is especially important for dense interstellar environments where the H$_2$ fraction is large. These studies have measured abundances for Kr in the
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Galactic disk (Cartledge, Meyer, & Lauroesch 2003), refined O/H in the Galactic (André et al. 2003), and extensively probed elements from C to Ge toward reddened disk stars (Sonnentrucker et al. 2002, 2003).

The abundance studies of distant objects (LMC, SMC, I Zw 18) illustrate all our major themes - the changes of interstellar processes with metallicity, the push to new environments, and the future potential of new instruments.

8. Discussion, Conclusions, and the Future

My literature review of FUSE results led me to four conclusions about the present state and future prospects of interstellar medium studies:

1. FUSE has shifted our focus from characterizing the basic properties of the ISM phases to detailed studies of their interactions in transition zones. I hope that our poor understanding of these regions and the high-quality database from FUSE will motivate theorists to address this problem.

2. Thanks to FUSE, we are moving beyond simple characterizations of H$_2$ in the Galactic disk and learning how to use H$_2$ as a sensitive indicator of local physical conditions in low-metallicity ISM.

3. To interstellar astrophysics, FUSE will be remembered as the mission that extended ISM studies to external galaxies, showing us a tantalizing glimpse of what awaits FUSE and its successors.

4. Extending the detailed LMC/SMC studies by FUSE throughout the Local Group and beyond should be the primary goal of an FUV successor mission. The desired sensitivity will also open new Galactic windows.

In the final analysis, we see that FUSE has made fundamental contributions to our understanding of the ISM, in ways that no other instrument can claim. These achievements derive directly from FUSE’s high sensitivity and unique waveband. Thus FUSE demonstrates the extraordinary potential of a successor with higher sensitivity and resolution to make another qualitative leap in our understanding. Indeed, FUSE shows that any future mission focussed on ISM and star formation studies should cover the FUV to get access to the important tracers discussed here. FUSE has also provided an excellent science case by leading us out of the narrow confines of the Galactic disk into diverse interstellar environments. This is how FUSE will be remembered to interstellar astronomers of the future.

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