FUSE FUV Absorption Line Measurements of the Magellanic Clouds and their Environment

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Abstract

We review recent FUV absorption line measurements of interstellar gas in the Magellanic Clouds and their environment, based on data obtained with the *Far Ultraviolet Spectroscopic Explorer* (FUSE). FUSE spectra provide important information about abundances and physical conditions in the ISM of the Clouds, including absorption lines from molecular hydrogen, weakly ionized species, and O VI.

1 Introduction

The launch of FUSE in June 1999 (Moos et al. 2000) has provided a major new instrument for obtaining medium resolution (FWHM$\sim$ 25 km s^{-1}) absorption spectra in the far ultraviolet (FUV) regime from 905 to 1187 Å. Many spectral diagnostic lines exist in this wavelength regime to sample a wide range of physical conditions found in the diffuse and translucent interstellar medium. The Lyman and Werner bands of molecular hydrogen (H_2) provide important information about molecular gas along the sight-line. The Lyman series of neutral hydrogen and deuterium and a large number of transitions of low-ionized species can be used to study abundances in the neutral and diffuse ionized gas. Highly ionized species, in particular O VI, trace the hottest components of the ISM, including halos of galaxies, shells and superbubbles. Thus, absorption spectroscopy in the FUV range is a powerful technique for the study of the multi-phase structure of gas in the Milky Way, in other galaxies, and in the intergalactic medium (IGM).

During the seventies, FUV absorption spectroscopy with the *Copernicus* satellite (1972-1981) was used to examine the local interstellar medium (for a review see Spitzer & Jenkins 1975), but was limited in sensitivity to nearby bright stars as background sources. Later satellites, such as the *International Ultraviolet Explorer* (IUE) and the *Hubble Space Telescope* (HST), did not cover the wavelengths below 1150 Å. The *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer* (ORFEUS), launched in 1996 for a 14-day *Space Shuttle* mission, obtained a limited number of intermediate resolution FUV spectra toward extragalactic background sources. With the FUSE satellite, the number of extragalactic sight-line spectra in the FUV range is growing rapidly. First FUSE results (e.g., Oegerle et al. 2000, Savage et al. 2000; Sembach et al. 2000; Shull et al. 2000; Snow et al. 2000) suggest that FUSE will make important contributions to the studies of the ISM and IGM. Because of its high sensitivity and its moderate resolution FUSE is able to obtain spectra toward fainter (and thus also more distant) background sources; it so gives acces to regions in space which could not be studied before in the FUV range.

FUSE consists of four coaligned prime focus telescopes and Rowland type spectrographs in combination with microchannel plate detectors. Two of the telescope channels have Al:LiF coatings, working in the wavelength range from 1000 to 1187 Å. The two other channels use SiC coatings and are senstive from 905 to 1105 Å. A more detailed description of the instrument is presented in

"Dwarf Galaxies and their Environment"; Bad Honnef, Germany, 23-27 January 2001; Eds. K.S. de Boer, R.-J.Dettmar, U. Klein; Shaker Verlag

Moos et al. (2000). The spectral resolution for the standard aperture is $\lambda/\Delta\lambda \approx 12,000$, equivalent to 25 km s^{-1}.

2 FUSE Measurements of the Magellanic System

2.1 The Magellanic Clouds

The two Magellanic Clouds are nearby ($\sim$ 60 kpc) satellite galaxies of the Milky Way and provide a large number of bright stars suitable as background sources for FUV absorption spectroscopy. The Large Magellanic Cloud (LMC) has a metallicity of [Fe/H]=-0.3 dex and a gas-to-dust ratio of $N(\mathrm{H\,I})/E(B-V) = 2.0 \times 10^{22}$ cm^{-2}; the Small Magellanic Cloud is even more metal-deficient ([Fe/H]=-0.65 dex; see Westerlund 1997) and its gas-to-dust ratio is with $N(\mathrm{H\,I})/E(B-V) = 4.0\times10^{22}$ cm^{-2} twice as high as that of the LMC. The Magellanic Clouds show regions of active star formation (e.g., 30 Doradus) and tidal interaction with the Milky Way. Together with their lower metal and dust content, they offer an ideal hunting-ground for studies on interstellar matter in environments very different from that of the Galaxy. Therefore, an important fraction of the FUSE observation campaign is dedicated to observations of the Magellanic Clouds in 1) either individual sight-line analyses or 2) survey-type (several sight-lines combined) projects covering smaller fields or the entire Magellanic system. Over 50 sight-lines toward LMC and SMC stars have been observed with FUSE so far, and this number will grow over the near future. An example for a typical FUSE spectrum of a LMC star is shown in Fig. 1. Representative for other studies, we here briefly present two FUSE survey-type projects, dealing with the distribution of both the very hot and the very cool gas phase in the Magellanic Clouds.

2.1.1 A Survey of Interstellar Molecular Hydrogen in the Magellanic Clouds (Tumlinson et al., in prep.)

In this project, Tumlinson et al. (in prep.) study the abundance of diffuse molecular hydrogen (H_2) in both SMC and LMC. Over 50 lines of sight are examined to derive column densities, molecular fractions and excitation temperatures in the Magellanic Clouds. As a preliminary result, they find evidence for a reduced molecular fraction in the Clouds, implying reduced H_2 formation and/or enhanced UV photo dissociation due to the lower dust content and the higer UV radiation field (see Richter 2000).

2.1.2 A Survey of Interstellar O VI in the Magellanic Clouds (Howk et al., in prep.)

O VI absorption in the Magellanic Clouds toward several of LMC stars is analyzed by Howk et al. (in prep.) in order to study the distribution and kinematics of hot gas in the Large Magellanic Cloud and its halo. The velocity distribution of O VI absorption provides important information about O VI in shells and bubbles and the data will extend previous investigtions of the hot corona of the LMC, as seen in other species (C IV, Si IV & N V; see e.g. de Boer & Savage 1980).

2.2 Intermediate & High-Velocity Gas in the Vicinity of the Magellanic Clouds

The Milky Way halo is full of neutral gas clouds with different abundances (e.g., Richter et al. 1999, Wakker et al. 1999; Richter et al., in prep.). These intermediate- and high-velocity clouds cannot be explained by a single origin, but are caused my multiple mechanisms, such as Galactic Fountains (e.g., Houck & Bregman 1990), tidal interaction between the Magellanic Clouds (and other satellite galaxies) and the Milky Way (e.g., Lu et al. 1998), and the infall of metal-poor gas clouds from intergalactic space onto the Milky Way (e.g., Wakker et al. 1999). Therefore it is important to quantify the properties of IVCs and HVCs to the greatest extent possible. A summary of all measurements of intermediate- and high-velocity gas so far is given by Wakker (2001).

In the direction of the Magellanic Clouds intermediate- and high-velocity clouds are also present and their abundances (most important for learning about their origin) can be precisely studied with FUSE absorption line data. Two studies, representative for other FUSE investigations, are presented in the following. They deal with the investigation of molecular hydrogen in the Leading Arm of the Magellanic Stream and abundances in intermediate- and high-velocity gas directly in front of the LMC.

2.2.1 FUSE Observations of Molecular Hydrogen in the Leading Arm of the Magellanic Stream (Sembach et al., 2001)

The analysis of the FUSE spectrum of the Seyfert 1 galaxy NGC 3783 (Sembach et al. 2001) reveals the presence of moderate H_2 absorption in the high-velocity cloud HVC 287.5+22.5+240, thought to be part of the Leading Arm of the Magellanic Stream. This is the second detection of molecular hydrogen in high-velocity halo gas. The total H_2 column density is log $N = 16.80 \pm 0.10$ and the fraction of hydrogen in molecular form is $f = 1.6 \times 10^{-3}$. Together with the abundances found by Lu et al. (1998), it seems likely that this cloud, together with the entire Magellanic Stream, has been pulled out of the Magellanic System during a close encounter with the Milky Way. Probably, the H_2 found in HVC 287.5+22.5+240 has not formed within the HVC. More likely, it has formed within the Magellanic Clouds and survived the tidal stripping.

2.2.2 The Nature of Intermediate- and High-Velocity Gas in Front of the LMC (Richter et al., in prep.)

A FUSE data set of four sight-lines toward the LMC stars Sk -67 101, Sk -67 104, Sk -68 80 and Sk-68 82 is used by Richter et al. (in prep.) to investigate abundances and small-scale structure in the intermediate- and high-velocity clouds in front of the LMC, extending previous studies with ORFEUS by Richter et al. (1999) and Bluhm et al. (2001). Preliminary results are the confirmed presence of H_2 in both components and nearly solar abundances in both IVC and HVC. Both clouds exhibit a large ionization fraction of > 70 percent. The data suggest that this HVC can be regarded as a high-velocity extension of common IVCs, being part of a Galactic fountain.

3 Concluding Remarks

FUSE absorption line data allow to study the ISM in the Magellanic Clouds and their environment in great detail. FUSE will observe additional Magellanic Cloud stars over the next years and will create a large FUV data archive, available to the public through the MAST archive (`http://archive.stsci.edu/fuse`). Detailed information about the FUSE project is available at `http://fuse.pha.jhu.edu`.

References

Bluhm, H., de Boer, K.S., Marggraf, O., Richter, P. 2001 A&A 367, 299

de Boer, K.S., Savage, B.D. 1980, ApJ, 238, 86

Houck, J.C., Bregman, J.N. 1990, ApJ, 352, 506

Lu, L., Sargent, W.L.W., Savage, B.D., Wakker, B.P., Sembach, K.R., Oosterloo, T.A. 1998, AJ, 115, 162

Moos, H.W., et al. 2000, ApJ, 538, L1

Oegerle, W.R., et al. 2000, ApJ, 538, L23

Richter, P. 2000, A&A, 359, 1111

Richter P., de Boer K.S., Widmann H., Kappelmann N., Gringel W., Grewing M., & Barnstedt J. 1999, Nature 402, 386

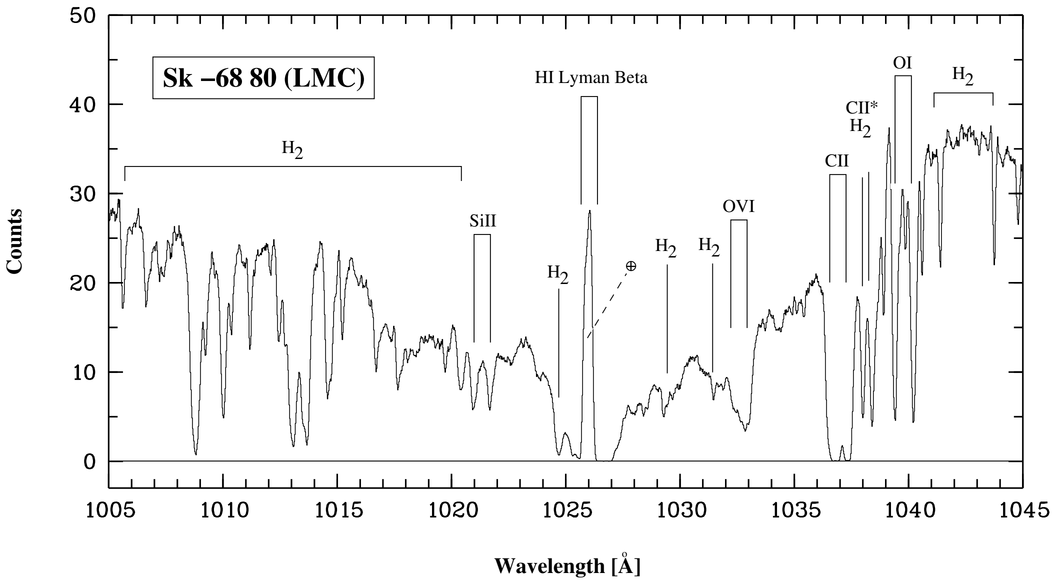

Figure 1: Excerpt of the FUSE spectrum of the LMC star Sk-68 80 (LiF 1a channel) in the wavelength region between 1005 and 1045 Å. Absorption lines from several atomic species and molecular hydrogen are present; they are labeled above the spectrum. The atomic species show absorption from local Galactic gas near +10 km s^{-1} and from LMC gas near +250 km s^{-1} (LSR), as indicated by the splitted tick marks. Molecular hydrogen absorption is seen only in the Galactic component. Geocoronal emission by H I Lyman β is marked with an earth-symbol.

Richter, P., Savage, B.D., Wakker, B.P., Sembach, K.R., Kalberla, P.M.W. 2001, ApJ, 549, 281
Savage, B.D., et al. 2000, ApJ, 538, L27
Sembach, K.R., et al. 2000, ApJ, 538, L31
Shull, J.M., et al. 2000, ApJ, 538, L73
Snow T.P., et al. 2000, ApJ, 538, L65
Spitzer L. & Jenkins E.B. 1975, ARA&A, 13, 133
Wakker B.P., et al. 1999, Nature, 402, 388
Wakker B.P. 2001, ApJS, in press
Westerlund B., 1997, The Magellanic Clouds, Cambridge University Press, Cambridge