ABSORPTION LINE STUDIES IN THE HALO

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Abstract
Significant progress has been made over the last few years to explore the
gaseous halo of the Milky Way by way of absorption spectroscopy. I review
recent results on absorption line studies in the halo using various instruments,
such as the Far Ultraviolet Spectroscopic Explorer, the Space Telescope Imaging
Spectrograph, and others. The new studies imply that the infall of low-
metallicity gas, the interaction with the Magellanic Clouds, and the Galactic
Fountain are responsible for the phenomenon of the intermediate- and high-
velocity clouds in the halo. New measurements of highly-ionized gas in the
vicinity of the Milky Way indicate that these clouds are embedded in a corona
of hot gas that extends deep into the intergalactic space.

1. Introduction
Studying the gaseous halos of galaxies is important to understand the various complex processes that balance the exchange of gaseous matter and energy between individual galaxies and the intergalactic medium. Supernova explosions in spiral galaxies create large cavities filled with hot gas in the gaseous disk - such gas eventually breaks out of the the disk and flows into the halo where part of it can cool and condense before falling back onto the disk. This process - also called “Galactic Fountain” (Shapiro & Field 1976) - was for many years thought to be responsible for the phenomenon of the “High-Velocity Clouds” (HVCs) in our Galaxy. Also interaction and merging of galaxies will transport large amounts of interstellar material into the halos and immediate intergalactic environment of galaxies. Finally, left-over gas from the formation of galaxies and galaxy groups is expected to contribute to the circumgalactic medium around galaxies in the low-redshift Universe. To understand the intergalactic gaseous environment and the halos of galaxies it is therefore important to study each of these various components in detail.

With the availability of space-based spectroscopic instruments operating in the UV and FUV, such as the the Orbiting and Retrievable Far and Extreme
Ultraviolet Spectrometers (ORFEUS), the Space Telescope Imaging Spectrograph (STIS), and the Far Ultraviolet Spectroscopic Explorer (FUSE) it has become possible to explore the gaseous Milky Way halo and the very local intergalactic medium in absorption against distant extragalactic UV background sources like quasars (QSOs) and Active Galactic Nuclei (AGNs). The UV and FUV spectroscopic range is particularly interesting for studying the low-density, multiphase circumgalactic medium, because many atomic and molecular species and their ions have their electronic transitions in the region between 900 and 1800 Å (e.g., H$_2$, H I, D I, N I, O I, Si II, Fe II, C IV and O VI). Measurements of absorption lines from these species therefore allow us to analyze in detail the gas in the halo of the Milky Way in all of its phases (i.e., from molecular to highly-ionized).

2. Intermediate- and High-Velocity Clouds

The origin of the Intermediate- and High-Velocity Clouds (IVCs and HVCs, respectively) in the Milky Way halo has been controversial for a long time. These neutral gas clouds are observed in H I 21cm emission at radial velocities that deviate substantially from Galactic rotation models (e.g., Wakker & van Woerden 1997). However, unveiling the nature of the IVCs and HVCs is a difficult task. For most of the IVCs and HVCs it is impossible to directly derive distances. Therefore, the most valuable information about their origin comes from metal-abundance studies using FUV absorption spectroscopy. An extensive summary of many absorption line measurements of Galactic halo clouds is provided by Wakker (2001). Using high signal-to-noise UV and FUV absorption line data from STIS and FUSE it has become possible in the last few years to reliably determine metal abundances and physical conditions in several intermediate- and high-velocity clouds.

For one of the most prominent HVCs, Complex C, several studies using FUSE and STIS data imply metallicities varying between 0.1 and 0.3 solar along different lines of sight (Wakker et al. 1999; Richter et al. 2001a; Collins et al. 2003; Tripp et al. 2003). Complex C also exhibits a notable underabundance of nitrogen. Probably, this HVC therefore represents a metal-deficient intergalactic gas cloud that is falling onto the Milky Way, and that recently has started to mix with outflowing (metal-rich) Galactic Fountain gas. An example for absorption of neutral oxygen in Complex C is presented in Fig. 1. Another prominent HVC complex for which accurate abundances have been measured is the Magellanic Stream. It has abundances close to those of the Small Magellanic Cloud (SMC) and thus likely represents material stripped out of the SMC during a close encounter with the Milky Way (Lu et al. 1998; Sembach et al. 2001). In contrast to the HVCs, absorption line studies of several IVCs show that these clouds tend to have higher abundances, close to those found in
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Figure 1. Interstellar absorption of neutral oxygen (O\textsc{i}) and highly-ionized oxygen (O\textsc{vi}) in the direction of the quasar PG 1259+593 (\(l = 120.6, b = +58.1, z_{\text{em}} = 0.478\)). The O\textsc{i} absorption shows two Galactic halo components at \(-128\text{ km s}^{-1}\) (high-velocity cloud Complex C) and at \(-55\text{ km s}^{-1}\) (intermediate-velocity cloud IV Arch), while local ISM absorption is seen at \(-5\text{ km s}^{-1}\). These three main velocity components are marked with dotted lines. Also the O\textsc{vi} absorption extends to high negative velocities, possibly arising in the interface regions between the neutral HVC gas (as sampled by O\textsc{i}) and a surrounding hot medium - the Galactic Corona (see also Fox et al. 2003).

The recent absorption line measurements of IVCs and HVCs clearly show that various different processes are responsible for the phenomenon of high-velocity neutral gas clouds in the halo of the Milky Way - they cannot have a single origin.

3. The Galactic Corona

It was Lyman Spitzer (1956) who proposed the existence of a hot gaseous corona around the Milky Way that would confine the cooler and denser IVCs...
and HVCs with its thermal pressure (see also Spitzer 1990; McKee 1993). Absorption line spectroscopy in the UV and FUV is well suited to study hot gas in the vicinity of the Milky Way, as this range contains a number of lines from highly-ionized species, such as $\text{C}^{\text{IV}}$, $\text{N}^{\text{V}}$, and $\text{O}^{\text{VI}}$. These lines sample gas in the temperature range between $1 \times 10^5$ and $5 \times 10^5$ K. Studying $\text{O}^{\text{VI}}$ absorption in the halo is particularly interesting, as $\text{O}^{\text{VI}}$ has the highest ionization potential of the three ions listed above.

The first absorption-line studies of the Galactic Corona were based on observations of $\text{Si}^{\text{IV}}$, $\text{C}^{\text{IV}}$, and $\text{N}^{\text{V}}$ obtained with the *International Ultraviolet Explorer* (IUE; Savage & de Boer 1979) and the *Hubble Space Telescope* (HST; Savage, Sembach, & Lu 1997). Using data from the *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometers* (ORFEUS), Widmann et al. (1998) presented the first systematic study of $\text{O}^{\text{VI}}$ absorption in the halo. With the availability of a large number of FUSE absorption spectra from extragalactic background sources our knowledge about the $\sim 10^5$ K gas component in the halo (as traced by $\text{O}^{\text{VI}}$ absorption) has further improved during the last few years. Wakker et al. (2003), Savage et al. (2003), and Sembach et al. (2003) present a large survey of $\text{O}^{\text{VI}}$ absorption along 102 lines of sight through the Milky Way halo. They find strong $\text{O}^{\text{VI}}$ absorption in a radial-velocity range from approximately $-100$ to $+100$ km s$^{-1}$ with logarithmic $\text{O}^{\text{VI}}$ column densities ranging from $13.85$ to $14.78$ (Savage et al. 2003). At these radial velocities, the $\text{O}^{\text{VI}}$ absorbing gas should be located in the thick disk and/or halo of the Milky Way. The distribution of the $\text{O}^{\text{VI}}$ absorbing gas in the thick disk and halo is not uniform, but appears to be quite irregular and patchy. A simple model assuming a symmetrical plane-parallel patchy layer of $\text{O}^{\text{VI}}$ absorbing material provides a rough estimate for the exponential $\text{O}^{\text{VI}}$ scale height in the halo. Savage et al. (2003) find $h_{\text{O}^{\text{VI}}} \sim 2.3$ kpc with an $\sim 0.25$ dex excess of $\text{O}^{\text{VI}}$ in the northern Galactic polar region. The correlation of $\text{O}^{\text{VI}}$ with other ISM tracers such as soft X-ray emission, H$\alpha$, and H$\text{I}$ 21cm is rather poor (Savage et al. 2003). Mixing of warm and hot gas and radiative cooling of outflowing hot gas from supernova explosions in the disk could explain the irregular distribution of $\text{O}^{\text{VI}}$ absorbing gas in the halo of the Milky Way.

4. **Local Group Gas**

$\text{O}^{\text{VI}}$ absorption towards extragalactic background sources is seen not only at radial velocities $|v_r| \leq 100$ km s$^{-1}$, but also at higher velocities (Wakker et al. 2003; Sembach et al. 2003). Studying high-velocity $\text{O}^{\text{VI}}$ is of crucial interest to understand the immediate intergalactic environment of the Milky Way and the various processes that determine the distribution of hot gas in the Local Group.
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From their survey of high-velocity O\textsc{vi} absorption Sembach et al. (2003) find that probably more than 60 percent of the sky at high velocities is covered by ionized hydrogen (associated with the O\textsc{vi} absorbing gas) above a column density level of log $N$(H$^+$) = 18, assuming a metallicity of the gas of 0.2 solar. Some of the high-velocity O\textsc{vi} detected with FUSE appears to be associated with known high-velocity H\textsc{i} 21cm structures (e.g., the High-Velocity Clouds Complex A, Complex C, the Magellanic Stream, and the Outer Arm). Other high-velocity O\textsc{vi} features, however, have no counterparts in neutral gas. The high radial velocities for most of these O\textsc{vi} absorbers are incompatible with those expected for Galactic halo gas (even if the halo gas motion is decoupled from the underlying rotating disk). A transformation from the LSR into the GSR and LGSR velocity reference frames reduces the dispersion about the mean of the high-velocity O\textsc{vi} centroids (Sembach et al. 2003). This can be interpreted as evidence, that some of the O\textsc{vi} high-velocity absorbers are intergalactic clouds in the Local Group rather than clouds directly associated with the Milky Way. The presence of local intergalactic O\textsc{vi} absorbing gas is in line with theoretical predictions that there should be a large reservoir of hot gas left over from the formation of the Local Group (e.g., Cen & Ostriker 1999). However, further FUV absorption line measurements and additional X-ray observations will be required to test this interesting idea.

It is unlikely that the high-velocity O\textsc{vi} is produced by photoionization. Probably, the gas is collisionaly ionized at temperatures of several $10^5$ K. The O\textsc{vi} then may be produced in the turbulent interface regions between very hot ($T > 10^6$ K) gas in an extended Galactic Corona and the cooler gas clouds that are moving through this hot medium (see Sembach et al. 2003). Evidence for the existence of such interfaces also comes from the comparison of absorption from neutral species like O\textsc{i} with absorption from highly-ionized species like O\textsc{vi} (Fox et al. 2003; see also Fig. 1).

5. Summary

Absorption line studies towards extragalactic background sources represent an important tool to study the halo of the Milky Way and its immediate intergalactic environment. Recent studies based on data from FUSE, STIS and other instruments unveil a complex interplay between a number of different processes that determine the distribution of cool, warm, and hot gas around the Galaxy. These processes include Galactic-Fountain type flows, interaction of the Milky Way with the Magellanic Clouds and other satellite galaxies, and possibly infalling Local Group gas. The measurements demonstrate that the formation of the Milky Way has not been completed yet.
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6. Discussion

Kuntz: Complex M was the first HVC complex to be detected in absorption, and thus its distance is known to be less than ~ 4 kpc. What limits on O vi can be placed in this direction?

Richter: The information on O vi Complex M is relatively sparse. The FUSE spectrum of TON 1187 - the only Complex M sight line included in the FUSE
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O\textsc{vi} survey - shows no evidence for O\textsc{vi} absorption associated with Complex M.

Hurwitz: Do there exist any FUSE observations of adjacent sight line that can be used establish an unambiguous lower limit to the distance of O\textsc{vi} absorbing gas?

Richter: O\textsc{vi} exists also in the disk of the Milky Way and therefore can be observed also toward nearby stars. The difficulty for us is to separate O\textsc{vi} absorption that occurs in the Milky Way disk from absorption that is produced in the halo or disk/halo interface, as O\textsc{vi} absorption is broad and the velocity information is not unambiguous.

Konz: You mentioned that there is no correlation between H\textsc{i} emission and O\textsc{vi} absorption. Did you check for an anticorrelation?

Richter: Yes, we checked that. There is neither a correlation nor an anticorrelation between O\textsc{vi} and H\textsc{i} seen in the data.