AU Scale Structures in Extra-planar Gas

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Abstract.
Recent spectroscopic observations of intermediate- and high-velocity clouds (IVCs and HVCs) in the Milky Way halo have unveiled the presence of diffuse interstellar molecular hydrogen (H$_2$) several kpc away from the Galactic disk. Most of this H$_2$ gas appears to reside in relatively small (∼0.1 pc), dense ($n_H \approx 30$ cm$^{-3}$) gaseous filaments that probably are part of the cold neutral medium (CNM) in IVCs and HVCs. Also much smaller structures at AU scale and very high densities ($n_H \approx 800$ cm$^{-3}$) have been observed, suggesting the presence of tiny-scale atomic structures (TSAS) in the Milky Way’s extra-planar gas. It is not yet understood how such objects can form and exist in the Milky Way halo, but the high detection rate of H$_2$ absorption in IVCs implies that the CNM represents a gas phase that is characteristic for neutral clouds in the lower halo.

1. Introduction

Significant progress has been made over the last few years to understand the distribution and origin of extra-planar gas in the halo of the Milky Way. Studies of the metal content of intermediate- and high-velocity clouds - neutral gas clouds embedded in the hot halo with radial velocities different from those expected from galactic rotation - have shown that various different processes contribute to the neutral gas flow in the halo. Intermediate-velocity clouds (IVCs) appear to located closer to the disk at $z$-heights < 3 kpc, typically. They have metal abundances similar to those found in the disk of the Milky Way (Richter et al. 2001a, 2001b) and probably represent gas that is circulating from the Milky Way disk into the halo and back, for instance as part of a Galactic Fountain (Shapiro & Field 1976). In contrast, most of the high-velocity clouds (HVCs) appear to have metallicities lower than in the Milky Way disk (Wakker et al. 1999; Lu et al. 1998; Richter et al. 2001b) and thus are probably extragalactic in origin. These measurements demonstrate that the Milky Way is still in a formation process, accreting gas and stars from satellite galaxies and the intergalactic medium, and expelling gaseous material into the halo as a result of star formation in the disk.

Next to the distribution and origin of the gas in the Milky Way halo, its physical properties are of great interest as well. The Galactic halo gas is an extreme multi-phase medium with temperatures ranging from 50 to several million degrees Kelvin. Although the large HVC complexes like Complex C and the Magellanic Stream span several kpc in the halo, small-scale structure in this gas is present down to scales of several AU (e.g., Meyer & Lauroesch 1999). With-
out being influenced by local star formation, the the Milky Way’s extra-planar
gas represents an excellent laboratory to study physical processes in the diffuse
interstellar and intergalactic medium.

2. $\text{H}_2$ as diagnostics for small-scale structure in the halo

Molecular hydrogen is an excellent diagnostic tool to investigate physical conditions
in the interstellar and intergalactic medium (ISM and IGM, respectively). A large number of $\text{H}_2$ absorption lines from the Lyman and Werner band are available in the far-ultraviolet (FUV) in the range between 900 and 1200 Å. The Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer (ORFEUS) was the first instrument that allowed us to study $\text{H}_2$ absorption in IVCs and HVCs, but these ORFEUS observations (due to the low sensitivity) were limited to only a few stellar background sources in the halo and the Magellanic Clouds (Richter et al. 1999; Gringel et al. 2000; Bluhm et al. 2001). With the availability of the Far Ultraviolet Spectroscopic Explorer (FUSE) in 1999 (e.g., Moos et al. 2000) it has become possible to systematically study the distribution and abundance of diffuse $\text{H}_2$ in the halo along a large number of sight lines towards stars in the halo and the Magellanic Clouds, and towards quasars (e.g., Richter et al. 2001; Sembach et al. 2001; Richter et al. 2003c).

The $\text{H}_2$ abundance in the diffuse ISM is balanced by the formation of molecules on the surface of dust grains and the $\text{H}_2$ destruction by the dissociating UV radiation. The volume densities of $\text{H}_2$ and $\text{H}_1$, $n(\text{H}_1)$ and $n(\text{H}_2)$, are linked to the total hydrogen volume density, $n_\text{H}$, the $\text{H}_2$ grain formation rate, $R$, and the photoabsorption rate, $\beta_0$, in a formation-dissociation equilibrium (Spitzer 1978; Richter et al. 2003):

$$\frac{n(\text{H}_1)}{n(\text{H}_2)} = \phi \frac{N(\text{H}_1)}{N(\text{H}_2)} = \frac{\langle k \rangle \beta_0}{R n_\text{H}}.$$  \hspace{1cm} (1)

In this equation, $\langle k \rangle \approx 0.11$ is the probability that the molecule is dissociated after photoabsorption, $N(\text{H}_1)$ and $N(\text{H}_2)$ are the measured $\text{H}_1$ and $\text{H}_2$ column densities, and $\phi \leq 1$ is a scaling factor that accounts for the possibility that only a fraction of the $\text{H}_1$ is physically related to the $\text{H}_2$ gas. For known photoabsorption and grain formation rates and $\phi$ one can use equation (1) to estimate gas volume densities from measured $\text{H}_1$ and $\text{H}_2$ column densities. The size of an $\text{H}_2$ absorbing structure, $D$, then can easily be calculated from $N(\text{H}_1)$ and $N_\text{H}$ via $D = \phi N(\text{H}_1) n_\text{H}^{-1}$.

Also the rotational excitation of the $\text{H}_2$ molecules can be used to investigate physical properties of the ISM and IGM. The lowest rotational energy states of $\text{H}_2$ (rotational levels $J = 0$ and 1) are usually excited by collisions, so that the column density ratio $N(1)/N(0)$ serves as a measure for the kinetic temperature of the gas. If one plots the column densities $N(1)$ and $N(2)$ (divided by the quantum-mechanical statistical weight, $g_J$) against the excitation energy, $E_J$, one can derive the temperature $T_{01}$ by fitting a Boltzmann distribution to the data points. Also higher rotational states (e.g., $J = 3, 4$ and 5) normally are excited, but for these states other excitation mechanisms such as UV photon pumping and $\text{H}_2$ formation pumping are often dominating.
3. Detections of H$_2$ absorption in IVCs and HVCs

A number of positive detections of H$_2$ absorption with FUSE and ORFEUS have been reported for both IVCs and HVCs, as listed in Table 1. The first detection of H$_2$ in a Galactic halo cloud was presented by Richter et al. (1999) in the high-velocity gas in front of the Large Magellanic Cloud. Since then, H$_2$ absorption in halo gas has been found in several intermediate- and high-velocity clouds, such as the IV Arch, LLIV Arch, IV Spur, Complex gp, Draco cloud, LMC-IVC, LMC-HVC, and the Magellanic Stream (see Table 1 for details). In all cases, the observed column densities are low (log $N$(H$_2$) ≤ 17), implying that the H$_2$ resides in a predominantly neutral gas phase. As expected, H$_2$ absorption preferentially occurs in halo clouds that have a high metal and dust abundance (see, e.g., Richter et al. 1999) As an example, we show in Fig. 1 the FUSE spectrum of the quasar PG 1351+640 in the range between 1076.5 and 1079.5 Å, where a number of H$_2$ lines from various rotational states are present. Halo H$_2$ absorption at negative intermediate velocities from gas in the IV Arch (core IV 19) is clearly visible in the various H$_2$ lines shown. The two-component H$_2$ absorption pattern (Milky Way disk absorption near zero velocities, IVC H$_2$ absorption near −50 km s$^{-1}$) can be well approximated by a two-component Gaussian fit (solid line).

4. H$_2$ and the cold-neutral medium in the halo

With FUSE, we have systematically studied the properties of the H$_2$ gas in IVCs towards a large number (56) of mostly extragalactic background sources (Richter et al. 2003). The sample includes 61 IVC components with H$_1$ column densities ≥ 10$^{19}$ cm$^{-2}$ and radial velocities 25 $\leq |v_{\text{LSR}}|$ ≤ 100 km s$^{-1}$. In FUSE spectra with good signal-to-noise ratios (S/N $> 8$ per resolution element) we found 14 clear detections of H$_2$ in IVC gas with H$_2$ column densities between

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Figure 1. FUSE spectrum of the quasar PG 1351+640 in the range between 1076.5 and 1079.5 Å. Next to local disk absorption near zero velocities, H$_2$ absorption near −50 km s$^{-1}$ related to gas of the Intermediate-Velocity Arch in the halo is clearly visible in the various H$_2$ lines shown. A two-component Gaussian fit (solid line) is overlaid.
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Table 1. Detections of H\(_2\) absorption in Galactic IVCs and HVCs

| Target       | \(l\) (deg) | \(b\) (deg) | Cloud Name                  | \(v_{\text{LSR}}\) [km s\(^{-1}\)] | \(\log N(\text{H}_2)\) | \(\log f^a\) | Ref.\(^b\) |
|--------------|-------------|-------------|-----------------------------|---------------------------------|----------------------|----------|-----------|
| Intermediate-Velocity Clouds | | | | | | | |
| Mrk 509      | 36.0        | −29.9       | Complex gp                 | +60                             | 14.9±0.5             | −4.3     | 1         |
| Mrk 876      | 98.3        | +40.4       | Draco                       | −30                             | 15.6±0.2             | −4.0     | 1         |
| Mrk 59       | 111.5       | +82.1       | IV Arch                     | −44                             | 14.7±0.2             | −4.3     | 1         |
| PG 1351+640  | 111.9       | +52.0       | IV Arch (IV 16)             | −47                             | 16.4±0.1             | −3.3     | 1         |
| HD 121800    | 113.0       | +49.8       | IV Arch                     | −70                             | 14.3±0.6             | −5.3     | 1         |
| PG 1259+593  | 120.6       | +58.1       | IV Arch                     | −54                             | 14.1±0.2             | −5.1     | 2         |
| PG 0804+761  | 138.3       | +31.0       | LLIV Arch                   | −55                             | 14.7±0.3             | −4.5     | 3         |
| PG 0832+675  | 147.8       | +35.1       | LLIV Arch                   | −50                             | 15.8±0.3             | −3.9     | 1         |
| NGC 4151     | 155.1       | +75.1       | IV Arch (IV 26)             | −29                             | 15.4±0.1             | −4.5     | 1         |
| NGC 3310     | 156.6       | +54.1       | IV Arch                     | −47                             | 15.0±0.8             | −4.5     | 1         |
| HD 93521     | 183.1       | +62.2       | IV Arch                     | −62                             | 14.6±0.4             | −4.7     | 4         |
| HD 100340    | 223.4       | +68.2       | IV Spur                     | −42                             | 15.3±0.3             | −4.3     | 1         |
| HD 100340    | 258.9       | +61.2       | IV Spur                     | −29                             | 16.0±0.8             | −3.7     | 1         |
| Sk-68 82     | 279.3       | −32.8       | IVC toward LMC              | +55                             | present\(^b\)       | \(\ldots\) | 5, 6, 7   |
| Sk-60 80     | 279.3       | −32.8       | IVC toward LMC              | +50                             | 14.6±0.5             | −1.2     | 6         |
| 3C 273       | 290.0       | +64.4       | ...                         | +25                             | 15.7±0.2             | −3.4     | 1         |
| High-Velocity Clouds | | | | | | | |
| Sk-68 82     | 279.3       | −32.8       | HVC toward LMC              | +120                            | present\(^b\)       | \(\ldots\) | 5, 6, 7   |
| NGC 3783     | 287.5       | +23.0       | Lead. Arm. of the MS        | +240                            | 16.8±0.1             | −2.9     | 8         |
| Fairall 9    | 295.1       | −57.8       | Magellanic Stream           | +190                            | 16.4\(^b\) \(±0.3\) | −3.3     | 2         |

\(^a\) \(f = 2N(\text{H}_2)/[N(\text{H}1)+2N(\text{H}_2)]\)

\(^b\) H\(_2\) is detected, but the H\(_2\) column density is highly uncertain

\(^c\) References: 1) Richter et al. 2003; 2) Richter et al. 2001c; 3) Richter et al. 2001a; 4) Gringel et al. 2000; 5) Bluhm et al. 2001; 6) Richter, Sembach & Howk 2003; 7) Richter et al. 1999; 8) Sembach et al. 2001

10\(^{14}\) and 10\(^{17}\) cm\(^{-2}\) (see also Table 1). In lower S/N data, H\(_2\) absorption in IVC gas was tentatively detected in additional 17 cases. The molecular hydrogen fraction in these clouds, \(f = 2N(\text{H}_2)/[N(\text{H}1)+2N(\text{H}_2)]\), varies between 10\(^{-6}\) and 10\(^{-3}\). This suggests that the H\(_2\) lives in a relatively dense, mostly neutral gas phase that probably is linked to the cold neutral medium (CNM) in these clouds. We now can use equation (1) to determine the hydrogen volume density and the thickness of the absorbing structure. The H\(_2\) photoabsorption rate in the halo, \(\beta_0\), depends on the mean ultraviolet radiation field at a height \(z\) above the Galactic plane. The models of Wolfire et al. (1995) predict that that the radiation field at \(\sim 1\) kpc above the disk is approximately 50 percent of that within the disk, suggesting that the photoabsorption rate in the halo is \(\sim 2.5 \times 10^{-10}\) s\(^{-1}\) (see Richter et al. 2003). If we now assume that the H\(_2\) grain formation rate in IVCs, \(R\), is roughly similar to that within the disk, and further set \(\phi = 0.5\), the H\(_2\) and H\(_1\) column densities measured for our IVC sample imply mean H\(_1\) volume densities of \(n_\text{H} \approx 30\) cm\(^{-3}\) and linear diameters of the H\(_2\) absorbing structures of \(D \approx 0.1\) pc. Moreover, if one considers the rotational excitation of the halo H\(_2\) gas that can be measured for some of the IVC sight lines, one finds for the kinetic temperature of this gas a conservative upper limit of \(T_{\text{kin}} \leq 300\) K. Given the relatively high detection rate of H\(_2\) in these clouds, the measurements indicate that the CNM phase in IVCs is ubiquitous.
Figure 2. Selection of H$_2$ absorption profiles towards the LMC star Sk$-68.80$ (Richter, Sembach, & Howk 2003). H$_2$ halo absorption is detected at intermediate velocities near +50 km s$^{-1}$ and possibly also at high velocities near +120 km s$^{-1}$ (dashed lines).

Most likely, the CNM filaments are embedded in a more tenuous gas phase that corresponds to the warm neutral medium (WNM).

5. H$_2$ and AU-scale atomic structures in the halo

A particularly interesting region to study small-scale structure in the Milky Way halo is the intermediate- and high-velocity gas in direction of the Large Magellanic Cloud (LMC). In this gas complex, H$_2$ absorption in intermediate- and high-velocity halo gas was detected for the first time based on data obtained with the ORFEUS instrument (Richter et al. 1999). We recently have reanalyzed the H$_2$ content of the IVC towards the LMC using high S/N FUSE data of LMC background stars (Richter, Sembach, & Howk 2003). Towards the bright LMC star Sk$-68.80$ H$_2$ absorption at intermediate velocities near +50 km s$^{-1}$ (LSR) is particularly well defined. Weak H$_2$ absorption in the HVC near +120 km s$^{-1}$ is detected, too. Also other sight lines towards LMC stars possibly exhibit H$_2$ absorption at intermediate and high velocities, but their spectra often are difficult to analyze because of blending problems and irregular stellar background continua. Towards Sk$-68.80$ we have detected H$_2$ absorption in the +50 km s$^{-1}$
Figure 3. Rotational excitation of the IVC H$_2$ gas towards Sk $-68.80$. The two rotational ground states ($J = 0, 1$) can be fitted to an equivalent Boltzmann temperature of $T = 51 \pm 11$ K, providing a measure for the kinetic temperature of the H$_2$ absorbing gas.

IVC gas in 30 lines from rotational states $J = 0$ to 4. Some examples for the H$_2$ absorption profiles are shown in Fig. 2. The total H$_2$ column density in the IVC is $\log N$(H$_2$) = 16.6$\pm$0.5 together with a very low $b$ value of $1.5_{-0.2}^{+0.8}$ km s$^{-1}$. The low $b$ value implies that the H$_2$ absorbing gas resides in a very confined region with a low velocity dispersion.

The presence of H$_2$ in this cloud is surprising, given the fact that the measured O I column density implies a rather low neutral hydrogen column density of $N$(H I) $\sim 10^{18}$ cm$^{-2}$. This value is consistent with the upper limit of $\sim 2 \times 10^{18}$ cm$^{-2}$ from Parkes 21cm emission observations, although beam smearing effects may apply. Despite the fact that the H I column density is low, the fraction of hydrogen in molecular form, $f$, is as high as $\sim 0.07$. Such a relatively high molecular fraction at this low total gas column density is unusual considering previous measurements of H$_2$ absorption in the Milky Way disk (e.g., Savage et al. 1977). If the H$_2$ gas stays in a formation-dissociation equilibrium (equation (1)) and if H$_2$ self-shielding applies, the measured values for $N$(H I) and $N$(H$_2$) suggest that the molecular gas resides in a small, dense gaseous filament at a volume density of $n_H \approx 800$ cm$^{-3}$ and a linear diameter of only $6.2 \times 10^{14}$ cm or $\sim 41$ AU. Possibly, this filament corresponds to a tiny-scale atomic structure (TSAS; Heiles 1997). Such AU scale gaseous structures have been found in the
Milky Way disk using H I 21cm absorption line measurements (e.g., Faison et al. 1998). The analysis of the H$_2$ rotational excitation for $J = 0$ and 1 yields a kinetic gas temperature of only $T = 51 \pm 11$ K (see Fig. 3). This temperature is lower than what is found on average in local H$_2$ gas in the disk ($\sim 80$ K; Savage et al. 1977). The thermal pressure in this cloud then can be derived from our estimates of $n_H$ and $T$ and comes out to be $\sim 5 \times 10^4$ cm$^{-3}$ K, about 13 times higher than the standard thermal pressure in the CNM in the disk. It is not yet clear how TSAS with such overpressures can form and survive in the otherwise very diffuse Galactic halo gas, and more data is required to investigate the physical properties of these objects in more detail. Unfortunately, the line of sight towards Sk $-$68 80 so far remains the only one that shows an H$_2$ absorbing structure in the the halo with such extreme properties. The lack of further H$_2$ detections of TSAS in the halo is not surprising, however. In view of their extremely small size, such structures should have a very low area filling factor. Thus, the chance to find a TSAS in front of a UV background source is very low.

6. Conclusions

Our study of diffuse molecular hydrogen absorption in Galactic IVCs and HVCs has unveiled the presence of sub-pc/AU scale gaseous structures in the Milky Way’s extra-planar ISM. Most of the H$_2$ absorption in the IVCs in the lower Galactic halo appears to be associated with the cold neutral medium (CNM) at temperatures of $T \leq 300$ K, volume densities of $n_H \approx 30$ cm$^{-3}$, and linear diameters of $D \approx 0.1$ pc. The CNM in IVCs has a relatively large area filling factor and thus must represent a gas phase that is characteristic for the denser, neutral regions in the halo. The detection of H$_2$ absorption in an IVC towards the LMC star Sk $-$68 80 has shown that even smaller filaments at AU scale and with very high densities (almost $10^5$ cm$^{-3}$) exist in the halo, possibly representing tiny-scale atomic structures (TSAS). This finding implies that the Milky Way’s extra-planar gas consists of extreme small-scale structure. Many aspects that concern the physical nature of these filaments (e.g., formation processes, thermal pressures, dust content, etc.) are not well understood yet, and more data is required to explore these intriguing objects in more detail.

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