A&A 442, L49–L52 (2005)
DOI: 10.1051/0004-6361:200500182

Astronomy & Astrophysics

Low-column density gas clumps in the halo of the Milky Way⋆

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Received 17 August 2005 / Accepted 11 September 2005

ABSTRACT

We report on the detection of low-column density neutral hydrogen clumps in the halo of the Milky Way. Using high-resolution (*FWHM* ∼ 7 km s^{-1}) optical spectra obtained with the VLT/UVES spectrograph we detect narrow interstellar absorption by Ca II and Na I at high radial velocities near $v_{\rm LSR} \approx -150$ km s^{-1} toward the quasar PKS 1448−232 ($l = 335.4, b = +31.7$). Follow-up H I 21 cm observations with the VLA unveil the presence of a complex of small neutral hydrogen clumps with H I column densities $<8 \times 10^{18}$ cm^{-2}. The measured H I line widths imply that the gas is relatively cold with temperatures $T \leq 900$ K. Although the line of sight towards PKS 1448−232 does not pass immediately through a known large high-velocity cloud (HVC), the sky position and the measured radial velocities suggest that these clumps are associated with HVC cloud complex L. An inspection of other UVES quasar spectra shows that weak, narrow Ca II absorption at high velocities is a common phenomenon, even in directions where high-velocity H I 21 cm emission is not detected. This suggests that the Milky Way halo contains a large number of high-velocity neutral gas clumps with low H I column densities. If such clumps are typical for halos of spiral galaxies, they should contribute significantly to the population of strong Mg II absorbers and Lyman-Limit Systems (LLS) seen in the circumgalactic environment of other galaxies.

Key words. Galaxy: halo – galaxies: halos – ISM: structure – quasars: absorption lines

1. Introduction

During the last decades, absorption and emission line measurements have demonstrated that the Milky Way is surrounded by a complex, multi-phase gaseous halo. Embedded in a corona of million-degree gas, neutral and ionized gas clouds move with high radial velocities (>40 km s^{-1}) through the Milky Way halo, giving rise to the population of intermediate- and high-velocity clouds (IVCs and HVCs, respectively; Wakker 2004). The origin of these clouds (Galactic or extragalactic) was uncertain for many years. However, recent abundance measurements have shown that the Galaxy is accreting gas from satellite galaxies and from intergalactic space, but at the same time is circulating gas from the disk into the halo by way of a galactic fountain (see Bregman 2004 for a review). While most of the recent HVC measurements have focussed on the distribution and properties of the large IVC and HVC complexes (e.g., Wakker et al. 1999; Richter et al. 2001), compact high-velocity clouds (CHVCs; e.g., Braun & Burton 1999; Westmeier et al. 2005), and highly-ionized HVCs (e.g., Sembach et al. 2003), relatively little attention has been paid so far to the abundance and distribution of neutral gaseous structures in the halo that have H I column densities below the detection limit of the large 21 cm HVC surveys (∼10^{19} cm^{-2}). Using more sensitive Arecibo 21 cm data, Hoffman et al. (2004) have found a population of "mini-HVCs" with low H I column densities (a few 10^{18} cm^{-2}, typically) and small angular diameters (≤35′). Towards the Large Magellanic Cloud, Richter et al. (2003) have detected FUV absorption by molecular hydrogen and various weakly ionized metals in a dense gas filament in the halo that has a total H I column density of ∼10^{18} cm^{-2} and a thickness of only ∼40 AU.

In this paper we discuss low-column density, small-scale structures in the halo that have been detected in Ca II and Na I absorption toward the quasar (QSO) PKS 1448−232 and other extragalactic background sources. Studying the frequency and distribution of these low-column density absorbers is important to better understand the connection between the different gas phases in the Milky Way halo, and to link the column density distribution of neutral gas in the halo to the properties of absorption line systems in the circumgalactic environment of other galaxies.

2. Observations and data handling

The optical spectral data for the quasar PKS 1448−232 ($l = 335.4$, $b = +31.7$, $z_{\rm em} = 2.2$) were obtained in June 2001

⋆ Based on observations carried out at the European Southern Observatory (ESO), La Silla, under prog. ID No. 166.A-0106 with the UVES spectrograph at the ESO Very Large Telescope, Paranal, Chile.

with the *Ultraviolet and Visual Echelle Spectrograph* (UVES) at the ESO Very Large Telescope as part of the UVES Large Programme *The Evolution of the Intergalactic Medium* (PI: J. Bergeron). The data provide a spectral resolution of $R \sim 42\,000$, corresponding to 6.6 $\mathrm{km\,s^{-1}}$ *FWHM*. The raw data were reduced using the UVES pipeline implemented in the ESO-MIDAS software package. The pipeline reduction includes flat-fielding, bias- and sky-subtraction, and a relative wavelength calibration. The signal-to-noise (S/N) per resolution element is ~110 in the region of the Ca II absorption near 3950 Å, and ~190 near the Na I lines (~5895 Å). The spectra were analyzed using the FITLYMAN program in MIDAS (Fontana & Ballester 1995), which delivers velocity centroids[1], column densities and Doppler parameters (b values) from Voigt-profile fitting.

The follow-up H I 21 cm observations (two coverages of 6 h each) were carried out in June 2004 with the Very Large Array (VLA) in the DnC configuration, which is especially well suited for sources with a declination of $\delta < -15°$. We chose 1331+305 (3C 286) as flux and bandpass calibrator and 1526−138 as gain calibrator. For each of the two polarisations the correlator provided a bandwidth of 1.56 MHz with 256 spectral channels, resulting in a channel separation of 1.3 $\mathrm{km\,s^{-1}}$. After flagging the data affected by radio frequency interference, we carried out the standard bandpass, flux and gain calibration with AIPS. To further improve the gain calibration, we self-calibrated on the continuum sources in an iterative procedure. We then deconvolved the data cube using the CLEAN algorithm (originally developped by Högbom 1974). To increase the signal-to-noise ratio, a Gaussian uv taper with a radius of 1 kλ at the 30% level was applied. In addition, we smoothed the velocity resolution to 5.1 $\mathrm{km\,s^{-1}}$. The resulting synthesised beam has a *FWHM* of about 2′. The rms in the final data cube is 1.4 mJy/beam towards the centre of the field, corresponding to a brightness temperature rms of 60 mK.

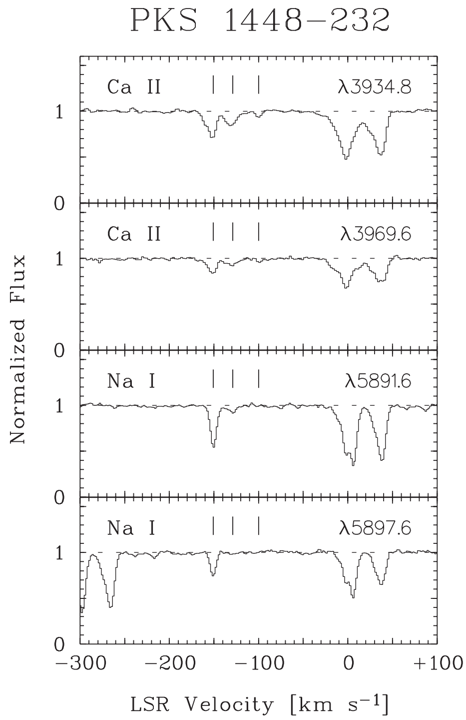

Fig. 1. Ca II and Na I absorption profiles in the UVES spectrum of PKS 1448−232. Three high-velocity absorption components related to gas in the Galactic halo are seen at −101, −130 and −152 $\mathrm{km\,s^{-1}}$ (indicated with the long dashes).

Table 1. Summary of UVES Ca II and Na I measurements toward PKS 1448−232.

$v_{\rm LSR}$ [$\mathrm{km\,s^{-1}}$]	log $N_{\rm Ca\,II}$ [N in cm^{-2}]	$b_{\rm Ca\,II}$ [$\mathrm{km\,s^{-1}}$]	log $N_{\rm Na\,I}$ [N in cm^{-2}]	$b_{\rm Na\,I}$ [$\mathrm{km\,s^{-1}}$]
−101	11.00 ± 0.04	4.0 ± 1.2	≤10.84	...
−130	11.62 ± 0.03	8.3 ± 2.7	10.96 ± 0.10	5.1 ± 2.1
−152	11.83 ± 0.03	6.6 ± 2.3	11.77 ± 0.04	2.2 ± 1.3

3. Results

Figure 1 shows the absorption profiles of Ca II λ3934.8, Ca II λ3969.6, Na I λ5891.6, and Na I λ5897.6 from the UVES spectrum of PKS 1448−232 plotted on an LSR velocity scale. Next to the absorption components near zero velocity that refer to gas in the local Galactic disk, high-velocity Ca II and Na I absorption from gas in the halo is visible in the range −100 to −150 $\mathrm{km\,s^{-1}}$. For the high-velocity gas, three individual velocity components at −101, −130 and −152 $\mathrm{km\,s^{-1}}$ can be identified. Logarithmic Ca II and Na I column densities for these components range between ~10.8 and ~11.8. Measured column densities and b values are summarized in Table 1.

No high-velocity H I 21 cm emission at this position is seen in the H I data of the Leiden/Argentine/Bonn (LAB) survey (Kalberla et al. 2005; Hartmann & Burton 1997), but our follow-up high-resolution VLA observations unveil the presence of several high-velocity H I clumps at low H I column densities (Fig. 2)[2]. Four of these clumps are labeled with the letters A, B, C, and D (Fig. 2). These clumps have typical peak-brightness temperatures of $T_{\rm B} \sim 0.3$–0.4 K, corresponding to H I column densities of ~4–8 × 10^{18} cm^{-2}. Measurements of these features are summarized in Table 2. As indicated, the sight line towards PKS 1448−232 passes the outer envelope of clump A. The mean LSR velocity of the H I emission is approximately −150 $\mathrm{km\,s^{-1}}$, thus similar to what is found for the strongest component of the Ca II and Na I absorption. No significant H I emission is seen at velocities ≥−140 $\mathrm{km\,s^{-1}}$, implying that the H I column densities of the Ca II absorption components at −101 and −130 $\mathrm{km\,s^{-1}}$ fall below the detection limit of the 21 cm observations. Velocity sub-structure is present in clumps A, B, and D, while the profile of C is consistent with a single Gaussian component. From the velocity width of the H I emission in clump C we obtain an upper limit for the kinetic gas temperature of $T_{\rm kin} \leq 900$ K. However, in view of

[1] Radial velocities cited in this paper refer to the Local Standard of Rest (LSR).

[2] Note that follow-up Effelsberg H I 21 cm observations confirm the presence of these H I structures.

Table 2. Summary of VLA H I measurements.

Clump	α (J2000) [h:m:s]	δ (J2000) [d:m:s]	$v_{\rm LSR}$ [km s^{-1}]	*FWHM* [a] [km s^{-1}]	N(H I) [b] [cm^{-2}]	$T_{\rm B}$ [K]	$T_{\rm kin}^{\rm max}$ [K]
A	14:51:12	−23:27:45	−147	13.7 ± 0.7	7.1×10^{18}	0.34	4200
B	14:51:25	−23:28:00	−151	11.3 ± 0.6	7.5×10^{18}	0.34	2900
C	14:51:23	−23:34:00	−153	6.2 ± 1.0	4.0×10^{18}	0.32	900
D	14:51:18	−23:36:30	−155	11.0 ± 2.0	7.4×10^{18}	0.38	2700

[a] *FWHM* is derived from a Gauss fit.
[b] Typical 1σ error from the fit is $\sim 1.0 \times 10^{18}$ cm^{-2}.

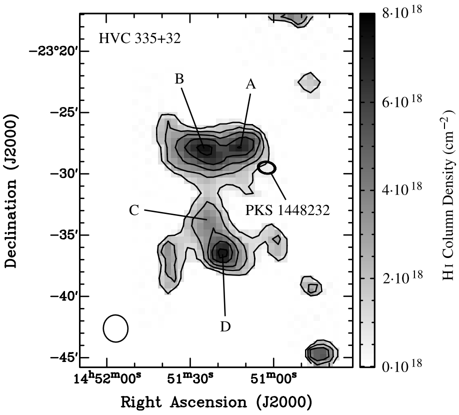

Fig. 2. VLA 21 cm column-density map of high-velocity H I gas in the direction of the quasar PKS 1448−232 (velocity range: −130 to −170 km s^{-1}). Several small H I clumps with low H I column densities (<10^{19} cm^{-2}) are detected. The line of sight towards PKS 1448−232 passes the outer envelope of clump A. The beam size is indicated in the lower left corner. The contours refer to H I column densities of 1, 2.5, 4, 5.5 and 7×10^{18} cm^{-2}.

the relatively large Na I/Ca II ratio and the possible presence of non-thermal gas motions, the actual gas temperature could be much lower than that.

Although the column densities for both Ca II and Na I are measured with high accuracy, unknown ionization conditions and dust depletion effects as well as the limited beam size of the H I measurements makes it impossible to reliably measure the metal abundance in the gas (see also Wakker 2001). Given the sky position of the clumps and the observed velocity range, it is likely that the gas is associated with HVC complex L, which is only a few degrees away (Wakker et al. 2004). If so, our Ca II and Na I measurements represent the first secure detection of this HVC in absorption. Weiner et al. (2001) and Putman et al. (2003) have observed strong Hα emission from complex L with typical fluxes of several hundred mR. According to their models of the Galactic ionizing flux, this places complex L in the lower Galactic halo with a distance of ∼8−22 kpc and a z height of ∼4−12 kpc above the Galactic center region. From the typical angular size of the H I clumps (∼3′) and a typical H I column density of N(H I) $= 5 \times 10^{18}$ cm^{-2} we can infer an estimate of the gas density as a function of distance via n(H I)/cm^{-3} $= 1.85\,(d/{\rm kpc})^{-1}$ (note that for this estimate we assume spherical symmetry, which may not be a good approximation for the true shape of the cloud). For d = 4−12 kpc we obtain n(H I) ≈ 0.1−0.2 cm^{-3}. This, together with $T_{\rm kin} \leq 900$ K from the H I line widths, implies that the thermal pressure is $P/k = nT \leq 180$ cm^{-3} K. This pressure is relatively low but is consistent with values predicted for high-velocity galactic fountain gas at $z \sim 10$ kpc with solar abundances and moderate dust destruction (Wolfire et al. 1995; their Fig. 1).

4. Other high-velocity Ca II absorbers

The fact that we have identified a low-column density H I structure in Ca II and Na I absorption along a random line of sight through the halo raises suspicion that such objects have a significant sky covering fraction and thus may be ubiquitous in the Milky Way halo. To test this idea, we have done a preliminary inspection of other QSO sight lines through the halo, based on high-resolution, high S/N data from the above mentioned UVES Large Programme. All QSOs in this sample have Galactic latitudes $|b| > 30$. In eight out of 13 suitable QSO sightlines[3] we find high-velocity Ca II absorbers with $|v_{\rm LSR}| = 50$−200 km s^{-1}; many of these absorbers have no HVC counterparts in the H I 21 cm data of the LAB survey (Kalberla et al. 2005; Hartmann & Burton 1997). Two examples for high-velocity Ca II absorption are shown in Fig. 3. Many of these sightlines have severe blending problems with high-redshift Ly α forest lines and intervening metal-line absorbers, so that a significant fraction of the high-velocity Ca II features in these data even may remain unnoticed. However, the number of detected HVC Ca II lines implies that the covering fraction of these low-column density gas clumps is large, indeed. All of the detected HVC Ca II lines are narrow (some with multiple velocity components), suggesting the presence of dense filamentary or clump-like gaseous structures but not large, extended diffuse clouds. Associated high-velocity Na I absorption is seen only along two sightlines (PKS 1448−232 and Q 0109−3518). Given the coordinates and the observed radial velocities, many of these low-column density absorbers most likely are associated with large, extended HVC complexes such as the Magellanic Stream. A more detailed analysis of these Ca II absorbers and their H I 21 cm counterparts will be presented in a future paper.

[3] Including the PKS 1448−232 sightline.

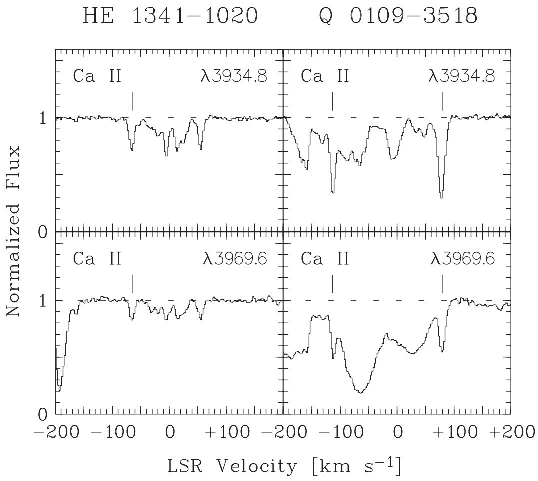

Fig. 3. High-velocity Ca II absorption (indicated by the long dashes) in the direction of the QSOs HE 1341−1020 (l = 323.5, b = +50.2) and Q 0109−3518 (l = 275.5, b = −81.0). The absorption near −70 km s^{-1} toward HE 1341−1020 apparently is not related to any known large HVC/IVC complex. The two absorption components near −110 and +80 km s^{-1} toward Q 0109−3518 most likely are associated with the Magellanic Stream. H I emission at $v_{\rm LSR}$ = −100 to −180 km s^{-1} is seen in the LAB survey in the immediate environment of this sightline.

5. Discussion

Our study suggests that the Milky Way halo contains a population of low-column density neutral gas clumps (see also Hoffman et al. 2004) that give rise to weak high-velocity Ca II absorption. Due to the low H I column densities, many of these clumps may lie below the detection limit of current 21 cm surveys of H I clouds in the halo. Many of the high-velocity Ca II absorbers probably are associated with known HVCs, implying that both Galactic and extragalactic gas contributes to the population of these systems. Although it remains unclear to what extent such clouds contribute to the total mass flow of the neutral gas in the halo, they appear to have a considerable area filling factor (given the high Ca II detection rate). If low-column density H I clumps are typical for the halos of spiral galaxies, they should produce H I Lyman-Limit absorption and Mg II absorption along almost all lines of sight that pass through the circumgalactic gas of other galaxies. In fact, with typical H I column densities $\leq 10^{19}$ cm^{-2} and a complex velocity component structure, the properties of the Ca II structures in the Milky Way halo resemble those of strong Mg II absorbers that are nearly always found within an impact parameter of $\sim 35\,h^{-1}$ kpc of a luminous galaxy (e.g., Ding et al. 2005; Bergeron & Boissé 1991). These strong Mg II systems are believed to sample both disk and halo gas in galaxies. The Ca II systems presented in this paper possibly represent the Galactic counterparts of halo Mg II systems with Mg II equivalent widths $W_{2796} < 1$ Å. At H I column densities $\leq 10^{19}$ cm^{-2} the neutral gas fraction probably is only a few percent or less (Corbelli & Bandiera 2002), so that one would expect that low-column density H I clumps in the halo have substantial ionized gaseous envelopes. Therefore it seems likely that the detected Ca II high-velocity features also are related to the population of highly-ionized HVCs in the halo seen in C IV and O VI absorption (e.g., Sembach et al. 2003).

Summarizing, the observations presented in this paper suggest that the weak high-velocity Ca II absorbers may provide an important link between absorption line systems observed in the circumgalactic environment of other galaxies and the neutral and highly-ionized high-velocity gas in the halo of the Milky Way.

Acknowledgements. P.R. acknowledges financial support by the German *Deutsche Forschungsgemeinschaft*, DFG, through Emmy-Noether grant Ri 1124/3-1. T.W. is supported by the DFG through grant KE 757/4-1. We thank K.S. de Boer, J. Bergeron & B.P. Wakker for helpful comments.

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