Absorption Line Search through Three Local Group Dwarf Galaxy Halos

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Abstract

Dwarf galaxies are missing nearly all of their baryons and metals from the stellar disk, which are presumed to be in a bound halo or expelled beyond the virial radius. The virial temperature for galaxies with $M_\text{halo} \sim 10^7-10^9 M_\odot$ is similar to the collisional ionization equilibrium temperature for the C IV ion. We search for UV absorption from C IV in six sightlines toward three dwarf galaxies in the anti-M31 direction and at the periphery of the Local Group ($D \approx 1.3 \text{ Mpc}$; Sextans A, Sextans B, and NGC 3109). The C IV doublet is detected in only one of six sightlines, toward Sextans A, with $\log N(\text{C IV}) = 13.06 \pm 0.08$. This is consistent with our gaseous halo models, where the halo gas mass is determined by the cooling rate, feedback, and the star formation rate; the inclusion of photoionization is an essential ingredient. This model can also reproduce the higher detection rate of O VI absorption in other dwarf samples (beyond the Local Group), with C IV only detectable within $\sim 0.5 R_{\text{vir}}$.

Unified Astronomy Thesaurus concepts: Dwarf galaxies (416); Circumgalactic medium (1879); Local Group (929)

1. Introduction

Several lines of study have revealed that galaxies have lost most of their baryons and most of their metals. The “missing baryons” problem involves finding that the mass of the stars and cold disk gas is only about one quarter of the cosmic baryon mass expected for the dynamical mass of a galaxy (McGaugh et al. 2010). The fraction of baryons declines toward lower-mass galaxies, where dwarfs may only account for 5% of their baryons. Closely related is the “missing metals” problem, where about 70%–80% of the metals formed by galaxies are present in the stars and cold disk gas (Peeples et al. 2014).

A likely solution is that the baryons and metals exist as a gaseous halo surrounding the galaxy, possibly extending beyond the virial radius. This requires strong feedback due to supernovae and active galactic nuclei (AGNs), which is predicted to have a profound effect on the gaseous halo (e.g., Oppenheimer 2018; Davies et al. 2020). Many searches focus on the more massive galaxies ($M_\text{halo} > 10^{11} M_\odot$), which should have more extended halos, and there have been a number of successes (e.g., Stocke et al. 2013; Werk et al. 2014). In massive galaxies, the ultraviolet (UV) absorption lines occur at temperatures below virial, so the gas that they trace is not the volume-filling component.

High-ionization UV lines can trace the volume-filling medium in lower-mass galaxies, the targets of this program. The C IV ion can produce strong UV absorption lines, and is typically found in gas at $6 \times 10^4$ K in collisional ionization equilibrium, which corresponds to the virial temperature for a $M_\text{halo} \sim 10^9 M_\odot$ system. Such systems correspond to dwarf galaxies that are less massive than the Small Magellanic Cloud, but more massive than the very faint dwarf galaxies in the Local Group. It might be possible to detect such hot halos or winds around dwarf galaxies using ions like C IV or Si IV. In this study, we search for evidence of these absorption lines around three dwarf galaxies in the Local Group: NGC 3109, Sextans A, and Sextans B (Figure 1 and Table 1). These galaxies were chosen because they are far from the Milky Way and M31 ($D = 1.33 \text{ Mpc}$), and they are in the anti-M31 direction. In this direction, the velocity difference between the Sun and these galaxies is 300–400 km s$^{-1}$, largely due to the infall of the Milky Way toward M31. This provides enough velocity separation such that one can hope to identify absorption as being due to the dwarf halos.

1.1. The NGC 3109 Association of Dwarfs

NGC 3109 is the most massive of the galaxies in this “group,” with $M_\text{halo} + M(\text{H I}) = 6.7 \times 10^8 M_\odot$, or about $10^{-2}$ of the equivalent Milky Way value, although with the important difference that the H I mass is significantly larger than the stellar mass (Carignan et al. 2013), as $M_\text{halo} \approx 8 \times 10^7 M_\odot$. It is classified as a Magellanic-type spiral that is close to being edge-on, and with a rotation curve that is flattening by 8.25 kpc (the last data point in Carignan et al. 2013), with an implied dynamical mass of at least $8.6 \times 10^8 M_\odot$.

The H I gas is more extended than the stellar disk, which is typical of a field spiral, and it has ongoing star formation at a rate of $\sim 5 \times 10^{-3} M_\odot \text{yr}^{-1}$.

The dwarf irregular galaxies Sextans A and Sextans B are similar, in that they have the same luminosity, stellar mass ($M_\text{halo} \approx 4 \times 10^7 M_\odot$), and dynamical mass ($1 \times 10^7 M_\odot$; Bellazzini et al. 2014). In Sextans A, the H I gas is less extended than the asymmetric stellar light distribution, and has $M(\text{H I}) = 6.2 \times 10^7 M_\odot$, which is slightly larger than the stellar mass. In Sextans B, the H I and stellar light are nearly identical in size and shape, where $M(\text{H I}) = 4.1 \times 10^7 M_\odot$, about equal to the stellar mass. Star formation is active in both systems, with similar rates during the past Gyr of $\sim 2 \times 10^{-3} M_\odot \text{yr}^{-1}$ (Weisz et al. 2011). NGC 3109, Sextans A, and Sextans B are at nearly the same distance and the same part of the sky, which might be coincidental, but Tully et al. (2006) showed that many, if not most, of the dwarfs in the Local Group lie in associations, and sometimes in well-defined planes (Libeskind et al. 2015). The association containing NGC 3109, Sextans A, and Sextans B has at least two other confirmed and five other possible nearby members (Tully et al. 2006; Bellazzini et al. 2013). These galaxies are separated by distances (250–500 kpc) that are large compared to their virial radii (40–80 kpc; Figure 1), so we can view them as each being primary galaxies.
Table 1: Target Dwarf Galaxies and Background AGNs

| Dwarf     | Glong deg. (1) | Glat deg. (2) | D (Mpc) (3) | v (km s\(^{-1}\)) (4) | M\(_e\) (mag) (5) | AGN Name  | Glong deg. (6) | Glat deg. (7) | z (9) | FUV (mag) (10) | Offset kpc (12) |
|-----------|----------------|---------------|-------------|------------------------|-------------------|------------|---------------|---------------|------|----------------|------------------|
| NGC 3109  | 262.1029       | 23.0706       | 1.33        | 403                    | −16.3             | CTS M00.02 | 261.23032    | 24.85116      | 0.154| 18.20          | 44               |
| Sextans A | 246.1482       | 39.8755       | 1.32        | 324                    | −15.6             | ESO 499-G 041 | 260.41529    | 25.84116      | 0.012| 18.05          | 73               |
| Sextans B | 233.2001       | 43.7838       | 1.36        | 301                    | −15.6             | IRXS J1015-2748 | 265.65866    | 23.59321      | 0.011| 18.03          | 75               |

Note. Columns: (1) dwarf galaxy; (2) and (3) Galactic coordinates of the galaxy; (4) distance to the galaxy; (5) projected heliospheric velocity; (6) absolute K-band magnitude; (7) background AGN; (8) and (9) Galactic coordinates of the AGN; (10) redshift of the AGN; (11) far-UV magnitude of the AGN; (12) projected distance between the AGN and the galaxy.

Figure 1. The locations of the three dwarfs in this program in Galactic coordinates, with their virial radii (solid flattened circles), the five AGN sightlines (black points), and the projected separation between galaxies (dashed lines).

This group of galaxies may have passed closer to the center of the Local Group in the past, but without a strong interaction with an ambient medium, as ram pressure stripping has not made these galaxies HI-poor (Putman et al. 2021). The orbital period is comparable to the age of the universe, although the dynamical models are not in perfect agreement with the velocities and positions of these dwarfs (Banik & Zhao 2017; Peebles 2017). This may be due to the gravitational influence of the Virgo Cluster (Banik & Zhao 2017), as these galaxies are nearly in the Hubble flow. Regardless of these details, these galaxies have spent more than a Gyr in a relatively poor environment, not near any massive galaxy. A Galactic wind or hot halo could have established itself in this period of relative isolation.

2. Data Reduction and Results

In this study, there are six QSO sightlines around the three dwarf galaxies (NGC 3109, Sextans A, and Sextans B) within the Local Group. These observations are obtained by two Hubble Space Telescope (HST) programs (13347 and 11524), which are summarized in Table 2.

The data reduction follows Wakker et al. (2015) and Qu et al. (2019), and we briefly summarize the reduction steps here. First, we coadd the gross counts obtained from individual exposures, which are corrected for the background and the fixed pattern noise. Then, the net count rates are calculated from the gross counts by dividing the coadded effective exposure times. The coadded noise is the Poisson noise derived from the total counts, which is found to be better matched with the measured noise of the coadded spectrum than the coadded noise (Wakker et al. 2015). The final coadded spectrum is in the heliospheric frame. The signal-to-noise ratios of the coadded spectra are also summarized in Table 2.

There is a known instrumental shift issue for the wavelength solution calculated from CALCOS for the COS spectrum (Wakker et al. 2015). Here, we perform a wavelength calibration for the coadded spectra, which employs the H I 21 cm lines as references for the UV absorption lines. The H I 21 cm emission lines are extracted from the Leiden/Argentine/Bonn Survey of Galactic H I, with an effective beam size of 0.1' around the QSO sightlines (Kalberla et al. 2005). The Galactic absorption lines of low-ionization-state ions (e.g., Si II and C II) are assumed to have the same velocity line centroid as the HI 21 cm lines, and a set of velocity shifts are obtained over the entire spectrum. Then, we fit polynomial functions to the obtained velocity shifts simultaneously for the four spectrum segments in both G130M and G160M. In most cases, we only use a constant or linear functions to correct the wavelength, and only segment B of G130M and PG 1001+054 uses a second-order polynomial. The coadded spectrum is binned by three pixels for fitting and line identification, yielding bin widths of Δ\(\lambda\) = 0.02991 Å and 0.03669 Å for G130M and G160M, respectively.

Most lines are nondetections. The equivalent widths (EWs) and uncertainties are calculated over a typical width of 60 km s\(^{-1}\), which is about three times the typical \(b\) values (20 km s\(^{-1}\)) measured for the cool–warm circumgalactic medium. The only detection is C IV for Sextans A toward PG 1011-040 at heliocentric \(v = 294\) km s\(^{-1}\) (Figure 2) and −30 km s\(^{-1}\) from the systemic velocity of Sextans A. We fit the Voigt profile for this C IV detection, obtaining a column density of \(\log N = 13.04\) ± 0.08 and \(b = 9.9\) ± 5.3 km s\(^{-1}\). The 2σ upper limits of the column densities are calculated from the EW uncertainties by assuming \(b = 20\) km s\(^{-1}\) for other nondetections (Table 3).

In this sightline of PG 1011-040, there is also a possible Si III \(\lambda = 1260.5\) Å feature at \(v_{\text{helio}} = 280\) km s\(^{-1}\), which is different in velocity from the 294 km s\(^{-1}\) C IV system by 3σ. We do not consider it as an absorption feature associated with Sextans A for two reasons. First, Si III only has one transition at 1206.5 Å, second, if this were a true absorption feature, its velocity would be too low with respect to the expected systemic velocity of Sextans A. In addition, the signal-to-noise ratio of this feature in the coadded spectrum is lower than the other features, making it less likely to be a real detection.
The HST/COS spectra for the strongest lines from common ions along the sightline of PG 1011-040 around Sextans A, showing the sum of all of the model components (red), the data (black), and the observation uncertainties (cyan). Individual absorption components are marked above the continua. The unmarked features are from the contamination of other lines (e.g., the red-most line in the CII panel at the top left). One finds a weak C IV doublet at 294 km s$^{-1}$ (marked by a long magenta bar), 30 km s$^{-1}$ from the systemic velocity of Sextans A (324 km s$^{-1}$ marked by long cyan bars).

Table 2
Observations of the HST/COS UV Spectra

| Target | Dwarf | R.A. | Decl. | Exp$^a$ | S/N$^a$ | PI program | obs. ID. | Date |
|--------|-------|------|-------|---------|---------|------------|---------|------|
|        |       | h m s| d m s |         |         |            |         |      |
| CTS M00.02 | NGC3109 | 10 05 32.7 | $-24 17 16$ | 5.5 7.8 | 8.0 5.8 | Bregman 13347 | LCCV030 | 2014 Apr 13 |
| 1RXS J1015-2748 | NGC3109 | 10 15 59.2 | $-27 48 29$ | 5.6 7.9 | 7.2 5.3 | Bregman 13347 | LCCV050 | 2014 Nov 23 |
| ESO 499-G 041 | NGC3109 | 10 05 55.4 | $-23 03 25$ | 5.5 7.1 | 6.1 4.7 | Bregman 13347 | LCCV040 | 2014 Jun 05 |
| MRK1253 | SextansA | 10 19 32.9 | $-03 20 14$ | 3.2 3.8 | 10.2 8.2 | Bregman 13347 | LCCV010 | 2014 Jun 08 |
| PG 1011-040 | SextansA | 10 14 20.7 | $-04 18 40$ | 5.3 4.7 | 27.7 15.7 | Green 11524 | LB4Q040 | 2010 Mar 26 |
| PG 1001+054 | SextansB | 10 04 20.1 | $+05 13 00$ | 3.2 3.8 | 15.1 8.1 | Bregman 13347 | LCCV020 | 2014 Jun 18 |

Notes. Columns: (1) AGN name; (2) dwarf galaxy; (3) and (4) equatorial coordinates of the AGN; (5) exposure time; (6) signal-to-noise ratio; (7) principal investigator and HST program; (8) observation ID; (9) observation date.

$^a$ G130M and G160M.

Table 3
Column Measurements of Ions

| Galaxy | AGN | $\rho$ | C II | C IV | O I | Si II | Si III | Si IV |
|--------|-----|--------|------|------|-----|-------|--------|-------|
| NGC 3109 | CTS M00.02 | 44 | 13.6 | 13.3 | ...$^a$ | 12.7 | 12.7 | 12.6 |
| ESO 499-G 041 | 73 | 13.6 | 13.5 | ...$^a$ | 12.6 | 12.7 | 13.0 |
| 1RXS J1015-2748 | 75 | 13.6 | 13.3 | 14.4 | 12.5 | 12.5 | 13.0 |
| Sextans A | MRK1254 | 64 | ...$^a$ | 13.2 | ...$^a$ | 12.2 | 12.4 | 12.8 |
| PG 1011-040 | 21 | $^{*}$ | 13.04 ± 0.08 | 13.4 | 11.8 | 11.9 | 12.3 |
| Sextans B | PG 1001+054 | 28 | ...$^a$ | 13.1 | 13.8 | 12.2 | 12.1 | 12.6 |

Notes. Columns: (1) dwarf galaxy; (2) AGN; (3) impact parameter in kpc; (4)–(9) log of the column densities of ions, where the column is in units of cm$^{-2}$.

$^a$ Affected by geocoronal emission or Galactic absorption.
in the HST/COS coverage, and no other ions show absorption features at a similar velocity. Thus, it may be contamination from intervening absorption systems beyond the Local Group. Second, this feature is 44 km s\(^{-1}\) away from the bulk velocity from Sextans A, which is beyond the rotation velocity of the galaxy (\(\approx 30\ km\ s\^{-1}\); Namumba et al. 2018).

### 3. Discussion and Conclusions

Our only detection is in the sightline closest to Sextans A, where the separation is 55′′ or 21 kpc, well within the virial radius, \(\approx 44\ kpc\) (Figure 1). This can be compared to the outermost radius at which the H\(\text{I}\) emission is detected in LITTLE THINGS (the Very Large Array; VLA) and by the Square Kilometre Array pathfinder KAT-7 (Hunter et al. 2012; Namumba et al. 2018). The two observations yield the same radial profile and have a limiting 3\(\sigma\) H\(\text{I}\) column density for the VLA observation of \(2 \times 10^{18}\ \text{cm}^{-2}\) and a value of \(5.8 \times 10^{18}\ \text{cm}^{-2}\) for the KAT-7 observation. The H\(\text{I}\) is detected to a radius of 3.5 kpc (9′), which is six times smaller than the sightline–galaxy separation. This indicates that the absorption is more likely due to the gaseous halo around Sextans A than an extension of the disk.

#### 3.1. Comparison to Other Dwarf Surveys

There are four studies of dwarf galaxies beyond the Local Group that can be used for comparison. They differ somewhat in their selection criteria and redshift space, and for \(M_\text{vir}\), similar to our galaxies are either at \(z < 0.02\) (Stocke et al. 2013; Bordoloi et al. 2014; Burchett et al. 2016) or \(z \approx 0.2\) (Johnson et al. 2017). The \(\text{C}\text{IV}\) absorption detection rates are similar between these surveys, and for \(7.5 < \log M_\text{vir} < 9\) the detection rate is three in 37 galaxies, summed over the four surveys. For the detected systems, the impact parameter is \(<0.5R_\text{vir}\), and a similar result is found for more massive dwarfs, \(9 < \log M_\text{vir} < 10\) (Burchett et al. 2016).

We acknowledge the differences between the samples, but find that the results of these surveys are consistent with the absorption results in this work, where one of six sightlines has a \(\text{C}\text{IV}\) detection, and that sightline is the closest to the galaxy (Sextans A). The probability of having one detection in six sightlines is about 50%, assuming a Poisson probability of three thirty-sevenths per sightline, so our detection rate is in agreement with the surveys.

It is worth noting that the absorption line detection rate is larger for H\(\text{I}\) and O\(\text{VI}\) (ions that we cannot observe in our sample). Johnson et al. (2017) find that H\(\text{I}\) is detected in nearly every galaxy (17/18) and that O\(\text{VI}\) is detected in one-third of the galaxies (6/18). We return to this result for O\(\text{VI}\) when discussing absorption models for dwarf galaxies (below).

One can also consider some of the observations toward other dwarfs in the Local Group. One of the problems with such studies, including ours, is that Galactic gas comes in various forms (e.g., high-velocity cloud, intermediate-velocity cloud, and Magellanic Stream), which cover a range of velocities (Richter et al. 2017). This can lead to a confusion problem that one tries to resolve by using velocity separation from the known gaseous features in the halo.

The dwarfs IC 1613 and WLM are in the same part of the sky as the Magellanic Stream, and within 30°–40° of M33 and M31. In WLM, Zheng et al. (2019) find absorption components that include CIV at velocities of \(-150\) and \(-220\ km\ s^{-1}\). These velocities can be compared to the systemic velocities of WLM (\(-132\ km\ s^{-1}\)) and the Magellanic Stream, where the mean velocity is \(<-190\ km\ s^{-1}\). They tentatively assign the \(-150\ km\ s^{-1}\) system to the halo of WLM.

The dwarf IC 1613 has four sightlines toward hot stars in the dwarf and six more from AGN sightlines (Zheng et al. 2020). This is more massive than WML, having \(M_\text{vir} \approx 1 \times 10^9 M_\odot\), \(M(\text{H I}) = 0.65 \times 10^8 M_\odot\), and \(R_\text{vir} \approx 4 \times 10^8 H_0\), at a velocity shift of \(-232\ km\ s^{-1}\). Zheng et al. (2020) identify absorption, typically within 100 km s\(^{-1}\) of the systemic velocity of IC 1613, for all ten sightlines. This 100% success rate makes IC 1613 quite unusual relative to other dwarfs. They discuss whether some of these features might be associated with the Magellanic Stream, but conclude that IC 1613 is the most likely absorption line host.

We also consider the contamination from unassociated Galactic gas for Sextans A. From a survey of 270 sightlines, Richter et al. (2017) show that sightlines in this general direction (200° < \(l < 300°\), 30° < \(b < 60°\)) have absorption at velocities of 100–200 km s\(^{-1}\), which we find in our sightlines as well. However, it is impossible to be certain that a small amount of halo gas, unrelated to Sextans A, is responsible for the absorption at 294 km s\(^{-1}\).

#### 3.2. Comparison to Gaseous Halo Models

One can try to estimate whether a gaseous halo around a dwarf galaxy would have enough column density in metals to be detectable. The upper limit in the column is \(N_{\text{CIV}} = n_{\text{CIV}} R_{\text{200}}\), where \(n_{\text{CIV}} = 200\) times the critical baryon density of the universe at \(z = 0\). For our dwarfs, this yields \(N_{\text{CIV}} = 5-10 \times 10^{18} \text{cm}^{-2}\), and for gas at 0.1 Solar metallicity, and an ionization fraction of 0.2 (near the peak), the \(\text{C}\text{IV}\) column density would be \(N(\text{C IV})_{200} = 3-5 \times 10^{13} \text{cm}^{-2}\), which is somewhat larger than our upper limits for \(\text{C IV}\) of 1.3–2 \times 10^{13} \text{cm}^{-2}\, or the single \(\text{C}\text{IV}\) detection of 1.48 \pm 0.30 \times 10^{13} \text{cm}^{-2}\. However, agreement would occur with a somewhat lower \(\text{C IV}\) ionization fraction, which motivates the need for more realistic models.

A more accurate and realistic estimate is possible by considering the processes likely to occur in the halos of galaxies. These include radiative cooling, feedback, and photoionization from the ambient metagalactic radiation field. These processes were considered for a range of galaxy masses in Qu & Bregman (2018a) and Qu & Bregman (2018b), which consider several models, including those with collisional ionization equilibrium.
and photoionization equilibrium. The most realistic model is where photoionization (Haardt & Madau 2012) is included in the ionic distribution and where the net cooling rate of the gaseous halo equals the star formation rate in the galaxy. For star formation, we use a mean value for a galaxy of mass $M_*$ and photoionization equilibrium. The most realistic model is defined in Qu & Bregman (2018a). Here, we extend the masses of the halos to values lower than those previously published, along with the column densities for both OVI and CIV.

In the TCIE model (collisional ionization equilibrium in multitemperature gas), the OVI column density turns sharply downward for $\log M_*/M_* < 11.4$, as the virial temperature falls below the peak OVI ionization fraction. However, in the TPIE model, that downturn at lower $M_*$ does not occur because photoionization raises the fractional ionization (Figure 3). The result is that the CIV column density is raised by a factor of 2 for $7.5 < \log M_*/M_* < 10.5$ ($z < 0.2$), and rarely rises above a column density of $10^{13}$ cm$^{-2}$. This is similar for the OVI ion, although the column density is larger by a factor of 3 to 6. There is scatter in these column densities, as galaxies differ in their star formation rates and halo masses. In general, the model suggests that the typical N(CIV) column density lies below the HST/COS detection limit in these surveys, while N(O VI) is close to the detection threshold.

We also calculated the EWs of CIV $\lambda 1548$ as a function of radius (Figure 4). There is a decline in the EW with radius, typically by a factor of 3 from 0.1–0.5$R_{\text{vir}}$, and by another factor of 2 to 5 from 0.5–1.0$R_{\text{vir}}$, depending on mass and redshift (Figure 4). This helps to explain why absorption detections are rarely found beyond $\approx 0.5 R_{\text{vir}}$, although more detectable absorption lines were expected for the dwarfs with $\log M_*/M_* > 9$.

To summarize, the TPIE models produce predictions for the column densities of CIV and O VI that reproduce some of the features found in studies of the absorption of dwarfs beyond the Local Group. This suggests that dwarf galaxies contain extended gaseous halos, provided they are not in environments where their halos have been stripped by the ambient hot medium of a more massive galaxy.

Figure 4. Left panel: the EW of C IV $\lambda 1548$ (in Å) vs. the fractional virial radius for galaxies with two stellar masses and at two redshifts. The two distributions by stellar mass (at fixed redshift) are similar, with sharp declines beyond $\approx 0.8 R_{\text{vir}}$ at $z = 0$ and $\approx 1.2 R_{\text{vir}}$ at $z = 0.2$. The difference is mainly due to the increased star formation rate at higher redshift. Right panel: the EW of CIV $\lambda 1548$ (in Å) vs. the projected radius in kpc for the three $z = 0$ galaxies in this study, which have $\log M_*/M_* = 7.6$–8.6. The only detection is for Sextans A ($\log M_*/M_* = 7.6$) at the smallest radius; the downward triangles are upper limits. The results for Johnson et al. (2017) are in the range $\log M_*/M_* = 7.7$–9.2 and at $z \approx 0.2$. The model seems to be consistent with the data for $\log M_*/M_* \approx 8$, but might overpredict the columns for $\log M_*/M_* \approx 9$.

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