Dynamical Masses of Local Group Galaxies
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Circumgalactic gas flows in the Local Group

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Abstract. I discuss circumgalactic gas flows in the extended Milky Way halo in the context of the on-going formation and evolution of the Local Group. UV absorption-line measurements, in combination with H I 21 cm observations, provide detailed information on the chemical composition, dust content, physical conditions, and large-scale kinematics of the so-called high-velocity clouds, which are believed to trace neutral and ionized gas in the gaseous halos of the Milky Way, M31, and in the intragroup medium of the Local Group. Recent results in this field and ideas for future observational studies are being presented.

Keywords. Local Group, Milky Way, high-velocity clouds, CGM, UV absorption spectroscopy

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1. Introduction

A considerable fraction of the gaseous material in spiral galaxies is situated outside the disk in an extended halo that reaches out to the virial radius and even beyond. We refer to this extraplanar gas component as the circumgalactic medium (CGM). The CGM connects to the large-scale cosmological envrionments in which galaxies reside (groups, clusters, filaments).

Also the Milky Way (MW) and M31 are surrounded by extended gaseous envelopes that originate in their CGM and in the intragroup medium of the Local Group (LG; see Richter et al. 2017, hereafter R17; Putman et al. 2012; Lehner et al. 2020). Studies that aim at characterizing the nature of the diffuse gas around Milky Way and M31 and its connection to the on-going assembly of the Local Group are very important for our general understanding of circumgalactic gas in the local Universe and its role in the hierarchical structure formation. This is because the gaseous outskirts of the Milky Way and M31 can be studied in great detail (in contrast to more distant galaxies) owing to the large amounts of emission and absorption-line data that are available from various instruments.

The Milky Way's CGM ususally is characterized by the so-called high-velocity clouds (HVCs), extraplanar gaseous structures that are observed at high radial velocities ($v_{\rm LSR} > 100\ {\rm km\,s^{-1}}$) in H I 21 cm radio emission or in line-absorption against extragalactic background sources, such as QSOs. The so-called intermediate-velocity clouds (IVCs) represent extraplanar clouds at lower radial velocities in the range $v_{\rm LSR} = 50 - 100\ {\rm km\,s^{-1}}$). IVCs are typically related to gas in the disk-halo interface at low vertical distances from the disk ($z \leq 2$ kpc; see Wakker 2001).

Substantial progress has been made over the last two decades in characterizing the role of the HVCs and IVCs in the on-going evolution of the Milky Way and the Local Group. By combining UV absorption-line data from HST/COS, HST/STIS, and FUSE with 21 cm observations, various research groups were able to put tight contraints on the chemical composition of the HVCs and IVCs, the physical conditions in the gas, and

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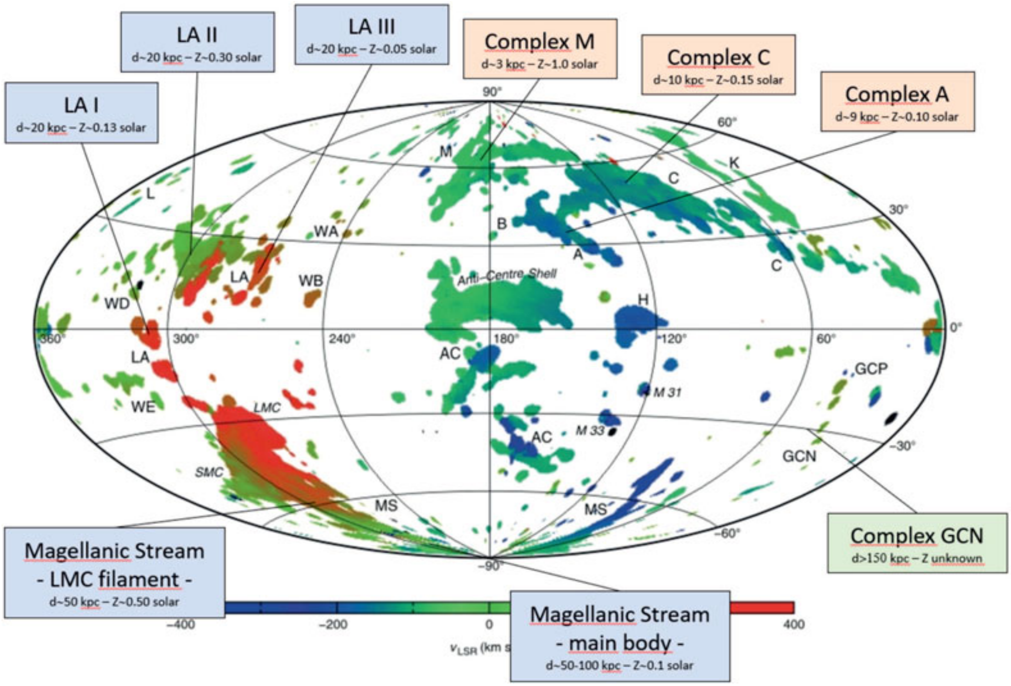

Figure 1. Properties of 21 cm HVCs in the Milky Way halo, as compiled from various studies (see R17 and references therein). The figure shows the 21 cm map of HVCs, with their radial velocities colour-coded, and further indicates position, metallicity, and distance for the most prominent HVCs.

even the distances to these clouds (see R17 and references therein). The Milky Way's CGM is metal-enriched, but typically has sub-solar abundances in the range 0.01 to 1.0 solar (e.g., Wakker et al. 1999; Richter et al. 2001a; Fox et al. 2013). The presence of low and high metal ions in the gas reflects an extreme multi-phase nature of the CGM in the temperature range $T = 10^2$ to 10^7 K. Recent studies further imply that the bulk of the baryons in the Milky Way CGM reside in warm-hot, predominantly ionized gas phase that is detected in UV and X-ray absorption lines of intermediate and high ions against extragalactic background point sources (see R17). The main properties of the Milky Way's HVC population are summarized in Fig. 1.

2. Spatial distribution of 21 cm HVCs in the Milky Way halo

The HVC population of the Milky Way, as seen in neutral gas in H I 21 cm emission, has a total sky covering fraction of ~ 35 percent (for neutral gas column densities $N(\text{H I}) \geq 7 \times 10^{17}$ cm^{-2}; Wakker 2004 and references therein). This is substantially smaller than the covering fraction of HVCs seen in UV absorption (see Sect. 4.1). The most prominent Milky Way CGM feature is the Magellanic Stream (MS), an enormous stream of neutral and ionized gas in the southern hemisphere extending over more than 200 degrees (Nidever et al. 2010; see Fig. 1). The spatial extension of the MS into the northern sky is called Leading Arm (LA), a conglomerate of scattered clouds (labeled LA I, LA II, etc.) observed in 21 cm data and in UV absorption (e.g., Fox et al. 2018; R17; see also Fig. 1). The MS (including the LA) probably spans several 100 kpc in linear size and has an estimated distance in the range between 20 and 100 kpc (e.g., D'Onghia & Fox 2016). The stream is a result of the interaction between the Magellanic Clouds

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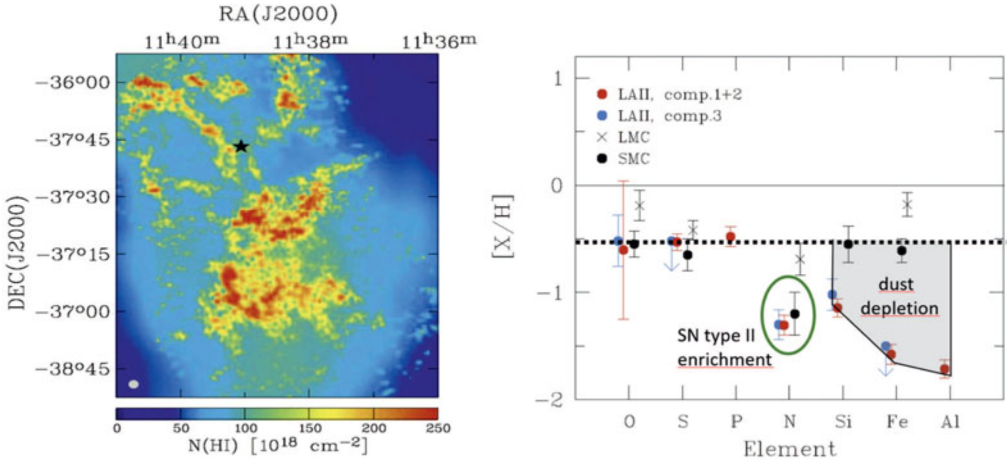

Figure 2. Precision measurements of metal abundances in the Leading Arm (cloud LA II) adopted from Richter et al. (2018). The left panel shows the H I 21 cm map of the LA with the position of NGC 3783, the background source used in this study, indicated by the black star. The right panel shows the abundances of various elements in the LA in the direction of NGC 3783.

and the Milky Way, but many details on *how* the MS was generated and what the exact origin of the individual components is, are still lacking. Various MS formation scenarios, motivated by observations as well as simulations (e.g., Lucchini et al. 2021; Hammer et al. 2015) were also discussed in the context of this IAU conference.

All other HVCs, for which direct distance information from the so-called bracketing method is available, are located within 20 kpc. The prominent HVC Complexes A & C have distances $d \approx 10$ kpc, the Cohen Stream and Complex GCP are at $d = 5 - 15$ kpc, and the HVC towards the LMC has $d \approx 9$ kpc (see R17 and references therein). Combining the 21 cm emission in Milky Way HVCs and in M31 halo clouds, Richter (2012) concludes that the H I covering fraction in HVCs around Milky Way-type galaxies declines exponentially with galactocentric distance. From deep 21 cm observations of the M31 halo, Westmeier et al. 2007 further conclude that the so-called compact high-velocity clouds (CHVCs), isolated high-velocity 21 cm gas clumps in the Milky Way halo with very small angular sizes, are located at $d < 50$ kpc, disproving a previous scenario in which CHVCs are regarded as gas-filled dark matter halos residing in the Local Group (e.g., Blitz et al. 1999).

3. Abundance measurements and origin of individual HVCs

3.1. *General trends*

Most of the IVCs have near-solar metallicities, supporting the idea that these clouds reflect the return flow of a Galactic Fountain (e.g., Richter et al. 2001b). In contrast, the metal abundance in many HVCs is substantially lower (by a factor $5 - 10$, typically). For Complex C, the metallicity has been constrained to ~ 0.15 solar (Wakker et al. 1999; Richter et al. 2001a). The metallicity of the main body of the Magellanic Stream has been constrained to 0.1 solar (Fox et al. 2010), but the MS also contains a filament that is somewhat more metal rich (0.3 solar; Richter et al. 2013). Complex A also has metallicity of only ~ 0.1 solar Wakker (2004). These low metal abundances support the scenario in which HVCs represent gas infalling from a pre-enriched intergalactic medium (or intragroup gas; Bouma et al. 2021). These low-metallicity halo clouds, on the other hand, could also trace material removed from satellite dwarf galaxies as they are being

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accreted by the Milky Way. Another possible scenario is that low-metallicity HVCs trace gas that has been part of the Milky Way a long time ago, then was ejected at relatively low metallicity by outflows/winds, and now is raining back towards the disk ("intergalactic fountain"). Even lower metallicities, down to ~ 0.01 solar, are probably seen in some CHVCs (Ashley et al., in prep.), pointing to an extragalactic origin for these clouds.

3.2. *The Leading Arm as a case study*

Next to the overall metal abundance (usually derived from O/H or S/H), abundance *ratios* of certain elements provide important information on the origin of HVCs and the various MS components. We recently have presented a detailed abundance study of elements such as O, S, P, N, Si, Fe, Al in the Leading Arm of the MS in the cloud LA II (Richter et al. 2018; see Fig. 2). We find that LA II has an α abundance and N/α ratio that mimics that of the current-day SMC, possibly indicating that the gas recently was removed from the SMC and pushed deep into the Milky Way halo. In this scenario, the age of LA II would be at most a few hundred Myr. On the other hand, if we consider only the chemical abundance pattern as age indicator, LA II could be older if the gas originates in the LMC, reflecting the LMC abundance pattern as it was 1-2 Gyr ago.

Interestingly, there is a substantial metallicity/age spread within the LA (Fox et al. 2018). The lowest metallicity ($\sim 0.04 - 0.06$ solar) is measured in LA III, followed by LA I, which has ~ 0.12 solar abundance, similar to that in the main body of the MS (Fox et al. 2010). The metallicity in LA II (~ 0.3 solar), as presented in Richter et al. (2018), is substantially higher (~ 0.3 solar) than for LA I and LA III, but lower than the LMC filament of the MS (Richter et al. 2018). This metallicity spread may hint at an episodic removal of gas from the SMC, with LA III being the oldest part stripped from the SMC together with the main body of the MS 1-2 Gyr ago, followed by the later removal of LA I and LA II due to more recent encounters of SMC and LMC (Fox et al. 2018). Another possible scenario is, that the LA (or parts of it) does *not at all* originates in the Magellanic Clouds, but instead represents gas stripped from *other* MW satellites, coincidentally being located in the region, where a leading arm would be expected. As it was discussed during this IAU conference, it would be extremely interesting to further investigate the latter scenario by combining MS formation simulations with new observations.

4. A UV absorption-line survey of HVCs in the Milky Way halo

4.1. *UV absorption characteristics*

In R17, we have presented the so-far largest survey of UV absorption the Milky Way's HVC population and in the LG using archival HST/COS data of 270 extragalactic background sources. The great advantage of such a survey in the UV is that it is sensitive to the various different gas phases (from cold/warm neutral to warm ionized gas) that are present in the CGM, and not only to the neutral gas phase (as for H I 21 cm-selected clouds). The aim of that survey was to characterize the absorption properties of the Milky Way's CGM and intragroup gas in the LG based on proper statistics, to explore the overall physical conditions and the distribution of the different CGM gas phases, and to estimate the total gas mass in HVCs and the Milky Way's gas-accretion rate.

The overall sky-covering fraction of high-velocity UV absorption is 77 percent for the most sensitive ion in the survey, Si III. This value is several times higher than the covering fraction of 21 cm neutral hydrogen (see above), demonstrating that the Milky Way's CGM is multi-phase and predominantly ionized. The equivalent-width ratios of low and intermediate metal ions (e.g., Si II, Si III, C II, C IV) are inhomogeneously distributed on large and small angular scales. This implies a complex spatial distribution of multi-phase gas that surrounds the neutral 21 cm HVCs. From our survey we estimate that the total

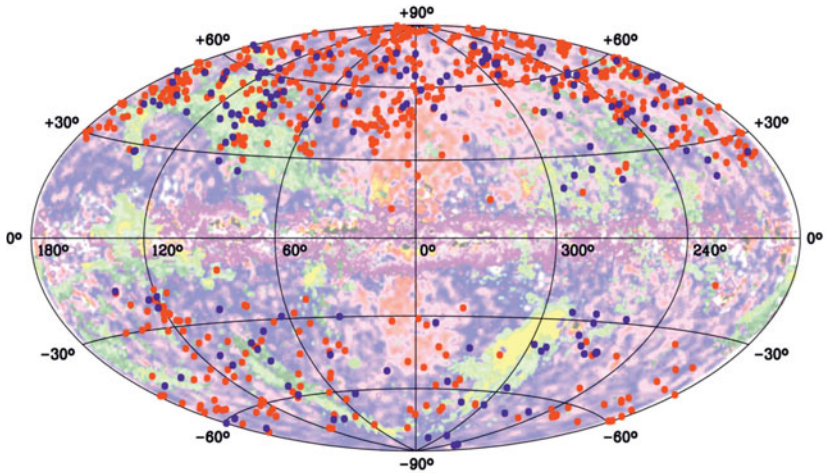

Figure 3. Sky coverage of QSO sightlines to study the Milky Way CGM and gas in the Local Group overlaid on a CGM heat map. The blue dots indicate the positions of the QSOs used in R17, the red dots show the positions of additional QSO sightlines for which archival UV data are available.

mass and accretion rate of neutral and warm ionized gas in the Milky Way CGM is $M_{\rm HVC} > 3 \times 10^9\, M_\odot$ and $\mathrm{d}M_{\rm HVC}/\mathrm{d}t > 6 M_\odot\,\mathrm{yr}^{-1}$, where the MS contributes with more than 90 percent to this mass/mass-flow.

4.2. *Relation between HVCs and other LG galaxies*

As part of the UV absorption survey, we have also systematically investigated sightlines that pass the outskirts of Local Group galaxies located outside the MW's virial radius to search for absorption signatures that might be related to the CGM of these galaxies. Along seven sightlines, high-velocity absorption from gas in the extended M31 halo is present in the LSR velocity range between -300 and -150 km s^{-1}, in line with the more recent AMIGA survey of the M31 CGM presented by Lehner et al. (2020). Interestingly, no CGM absorption is found at impact parameters $\rho \leq 2R_{\rm vir}$ and at velocities close to the systemic velocities of the galaxies NGC 3109, Antlia, Sextans A, Aquarius (one sightline per galaxy, respectively), and Leo I (12 sightlines). Absorption *is* found along a sightline that passes IC 1613 at $\sim 1.5R_{\rm vir}$ near the systemic velocity of IC 1613, but this absorption most likely is associated with gas from the MS. Therefore, only for M31 and the Milky Way the COS data provide evidence for the presence of an extended CGM, while for the LG dwarfs/satellite population outside the Milky Way halo there is no compelling hint for the existence of a circumgalactic gas component from UV observations. This apparent lack of CGM gas in LG dwarfs deserves more attention in future LG absorption-line surveys and in simulations that study gas stripping/gas removal processes in group environments.

4.3. *Local Group gas flows*

Another interesting aspect of our UV survey is the possible detection of a velocity signature of intragroup gas that is moving towards the LG barycenter at a speed that is lower than that of the LG member galaxies. High-velocity absorbers in two distinct regions in the northern sky (northern ionized region, NIR) and in the southern sky (SIR), that are roughly aligned with the LG's major axis, show a particularly high degree of ionization, in line with the idea that they could be located at large distances beyond the virial radius of the MW. In R17, we demonstrate that the NIR and SIR form a dipole on the sky with opposite signs for the observed absorption velocities. In view of the observed high radial velocities and the high absolute Galactic latitudes of these antipodal regions, the observed dipole pattern cannot be produced by the rotation of the Galactic disk. Galaxies outside the virial radius of the Milky Way form a similar dipole-velocity pattern on the sky, which reflects the general flow of galaxies towards the barycenter of the cosmological filament that forms the LG. The Milky Way, being part of that flow, leaves behind LG gas that moves at smaller speeds towards the LG barycenter (leading to red-shifted absorbers in the anti-barycenter direction), while it is moving towards gas that falls in from the other side of the LG barycenter (leading to blue-shifted absorbers in the barycenter direction).

This scenario is supported by constrained cosmological simulations of the LG and its gaseous environment from the CLUES project (Nuza et al. 2014) and, more recently, from the HESTIA project (Biaus et al. 2022).

5. Summary and outlook

As we have discussed here, UV absorption-line measurements of the Milky Way CGM and high-velocity absorbers possibly related to gas in the Local Group provide a detailed insight into the on-going assembly of the Local Group and the evolution of its member galaxies. Since the R17 survey, several hundred *additional* QSO sightlines have been observed with HST/COS (see Fig. 3), providing a rich data basis for another, more detailed all-sky UV survey of large-scale gas flows in the Local Group - a project, that we are currently working on.

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Discussion

Jianling Wang: Excellent talk! From the metallicity of the LA it is very likely that the LA has a different origin than the Magellanic Clouds. You have shown distances of the LA in your talk. I am curious: how do you get these distances? And what are their errors?

Philipp Richter: The cited distance of $d = 20$ kpc for the LA is based on the studies by Casetti-Dinescu et al. (2014) and Zhang et al. (2017), who claimed that there is a young stellar population in the LA. There are also some more recent indirect measurements using H α fluxes. All these results are, however, afflicted with systematic uncertainties, so there is also a substantial uncertainty in this distance estimate.