The Relics of Structure Formation

Extra-Planar Gas and High-Velocity Clouds Around M31

Tobias Westmeier[1,2], Robert Braun[1], Christian Brüns[2], Jürgen Kerp[2], David A. Thilker[3]

[1] CSIRO *Australia Telescope National Facility, PO Box 76, Epping NSW 1710, Australia*
[2] *Universität Bonn, Argelander-Institut für Astronomie, Auf dem Hügel 71, 53121 Bonn, Germany*
[3] *Johns Hopkins University, Dep. of Physics & Astronomy, 3400 N. Charles Street, Baltimore, MD 21218, USA*

Introduction – HVCs and dark-matter halos

One of the currently most favoured cosmological models is the so-called **ΛCDM** model which predicts a **hierarchical** formation of gravitationally bound structures in the universe. A major problem of the ΛCDM scenario is that the number of low-mass dark-matter satellites predicted around the Milky Way is by more than one order of magnitude higher than the number of Milky Way satellite galaxies known to date. This discrepancy has been named the **"missing satellites"** problem.

A promising solution was suggested by Blitz et al. (1999) who proposed that the **high-velocity clouds** (HVCs) observed all over the sky in the 21-cm line of H I could be the gaseous counterparts of the "missing" dark-matter satellites. Unfortunately, the **distances** of most HVCs are only poorly constrained. This problem can be solved, however, by studying the HVC populations around **other galaxies** which would allow us to directly infer the radial distribution and mass spectrum of HVCs for comparison with ΛCDM simulations.

The first comprehensive search for HVCs around **M31**, the nearest large spiral galaxy, was carried out by Thilker et al. (2004) with the 100-m Green Bank Telescope. They discovered a population of about **20 HVCs** within 50 kpc projected distance from M31. We carried out a deep, complementary **H I blind survey** with the Effelsberg 100-m radio telescope to search for HVCs out to much larger projected distances from M31 in excess of 100 kpc. In addition, we carried out follow-up **interferometric** observations with the Westerbork Synthesis Radio Telescope (WSRT) to learn more about the internal structure and evolution of the HVCs around M31.

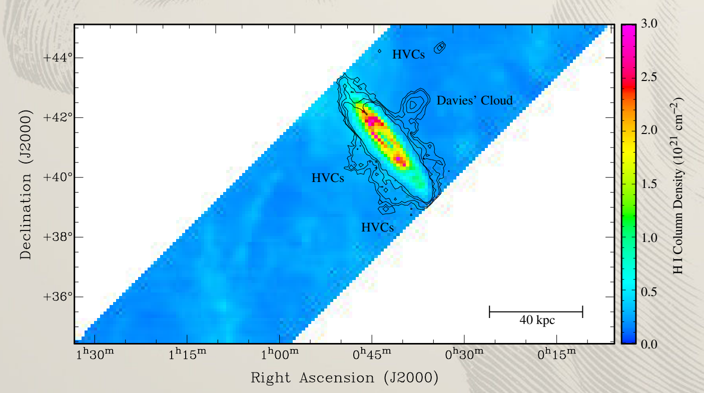


Fig. 1: *Total H I column density map of our Effelsberg survey of M31. The black contours of 2.5, 5, 15 and 30 × 10^{18} cm^{-2} show the column density in the LSR velocity range of −608 to −135 km s^{-1}. Several HVCs and regions of extra-planar gas can be seen within about 50 kpc projected distance from M31.*

Observations and data reduction

The observations for the H I blind survey were accomplished with the 100-m radio telescope at **Effelsberg**. The covered region in the sky has a trapezoidal shape with a size of about 15° × 5° (see Fig. 1). It reaches out to a maximum projected distance from the centre of M31 of about **140 kpc** in the south-eastern direction. In our follow-up observations with the **WSRT** (Fig. 2), nine pointings were centred on the most conspicuous HVCs found in the GBT survey of Thilker et al. (2004). The data reduction procedure is described in detail by Westmeier et al. (2005). The following table summarises the technical details of our observations.

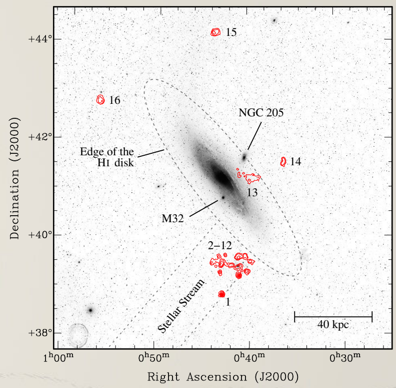
	H I blind survey	Follow-up observations
Telescope	Effelsberg	WSRT
Observing mode	H I spectroscopy	H I spectroscopy
Frequency	1420 MHz	1420 MHz
Field size	15° × 5°	36' primary beam FWHM
Beam width	9'	2'
Spatial resolution	2 kpc	0.45 kpc
3σ column density limit	2.2×10^{18} cm^{-2}	2.6×10^{18} cm^{-2}
3σ mass detection limit	$8 \times 10^4\ M_\odot$	$5 \times 10^3\ M_\odot$

Results – Parameters of the HVCs around M31

Our observations demonstrate that M31 is surrounded by a population of about **15 to 20 HVCs** (Fig. 1 and 2) with typical H I masses of a few times $\mathbf{10^5\ M_\odot}$ (Fig. 3) and diameters of the order of **1 kpc**. With these parameters the HVCs detected near M31 resemble the large HVC complexes observed around the Milky Way. Although our Effelsberg survey reaches out to projected distances in excess of 100 kpc, we do not detect any HVCs beyond a projected distance of about **50 kpc** from M31 (Fig. 3). In particular, we do not find an extended population of compact high-velocity clouds (CHVCs) around M31. If we assume that the Milky Way and M31 have a similar population of several hundred CHVCs, we can derive from our non-detection an upper limit for the distance of CHVCs from their corresponding host galaxy of about 60 kpc. Consequently, the small angular diameters of CHVCs are not due to their large distances from the Galaxy but simply reflect their intrinsically small sizes.

One of the most remarkable structures resolved in our follow-up observations with the WSRT is the **complex** of **12 HVCs** near the south-eastern edge of the disk of M31 (Fig. 2). The individual clouds in this complex are arranged in multiple interesting filaments. A comparison with the distribution of RGB stars in M31 reveals that the HVC complex spatially and kinematically overlaps with the giant **stellar stream** (Ibata et al. 2001), suggesting a **tidal origin** of the gas in connection with the stream. Another HVC close to NGC 205 could also have been formed by tidal or ram-pressure forces during a close encounter between NGC 205 and M31. The remaining three HVCs studied with the WSRT are completely isolated from any known satellite galaxy or stellar structure of M31. They are the most promising candidates for the primordial **dark-matter satellites** predicted by CDM structure formation scenarios.

Fig. 2: *H I column density contour lines (red) from our WSRT observations of several HVCs near M31 overlaid on an optical image from the Digitised Sky Survey. The contour levels are 0.2, 1, 3 and 8 × 10^{19} cm^{-2}. One of the most remarkable structures detected with the WSRT is the complex of HVCs near the south-eastern edge of the disk of M31 which overlaps in position and velocity with the giant stellar stream.*



Discussion – Comparison with ΛCDM models

Numerical **ΛCDM** structure formation **simulations** by Kravtsov et al. (2004) predict between **2** and **5** dark-matter satellites with total gas masses of $\mathbf{M_{gas} > 10^6\ M_\odot}$ within a distance of **50 kpc** from M31. This is less than the 15–20 HVCs detected in our Effelsberg survey. However, as indicated by our WSRT observations and suggested by Kravtsov et al. (2004), only a few of the HVCs found near M31 could be primordial dark-matter satellites, whereas others were most likely created during the tidal distortion of satellite galaxies of M31. On the other hand, the simulations of Kravtsov et al. (2004) predict many more dark-matter satellites (about **50–100** with $\mathbf{M_{gas} > 10^6\ M_\odot}$) at distances **beyond 50 kpc** from M31 (also see Fig. 3) which have not been detected in our Effelsberg H I survey. Obviously, the direct identification of HVCs with dark-matter satellites fails, and the simulations still predict too many gaseous dark-matter halos.

To solve this problem we can look at the internal structure of the individual halos in more detail. Sternberg et al. (2002) carried out **hydrostatic simulations** of spherical, dark-matter-dominated HVCs at a distance of 150 kpc from the Milky Way and compared their results with the CHVCs observed on the sky. The basic parameters of their model clouds, such as H I mass, H I peak column density or diameter, are in excellent agreement with the parameters of the HVCs detected near M31 with the WSRT. In their model, Sternberg et al. (2002) had to introduce an external pressure of $\mathbf{P / k \gtrsim 50\ K\ cm^{-3}}$. This pressure, exerted by the hot, ionised **corona** of the Galaxy, is required to stabilise the clouds in addition to their own gravitational potential. Without this constraint the clouds would become so diffuse that their gas would no longer be sufficiently shielded against the extragalactic radiation field. Hence, HVCs beyond 50 kpc from M31 could be mainly **ionised** and undetectable in the 21-cm line emission of neutral hydrogen.

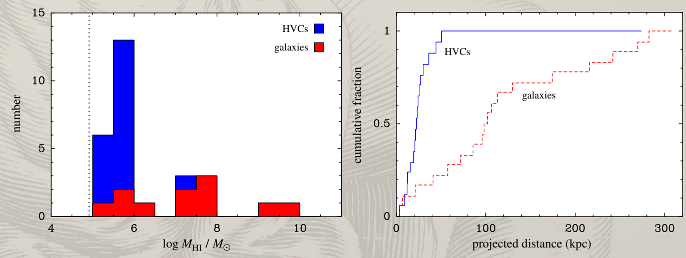


Fig. 3: *H I mass histogram (left) and cumulative projected distances (right) of the HVCs found in our Effelsberg survey in comparison with the satellite galaxies of M31. The HVCs are accumulating at the lower end of the galaxy mass function. For many M31 satellite galaxies, however, H I mass measurements are not available. On the other hand, the cumulative projected radial distribution of the M31 satellite galaxies is much more extended than that of the HVCs ($d_{proj} \lesssim 50$ kpc), although only those galaxies within 300 kpc of M31 (which is approximately the virial radius) have been considered for the plot.*

Summary & conclusions

- M31 is surrounded by a population of **15–20 HVCs** with $M_{HI} \gtrsim 10^5\ M_\odot$ and $D \simeq 1$ kpc.
- HVCs are **circumgalactic** clouds with distances of $d \lesssim 50$ kpc.
- Several HVCs around M31 are most likely of **tidal** origin in connection with the stellar stream and NGC 205, whereas others could be primordial **dark-matter** satellites.
- The number and distribution of HVCs around M31 is consistent with **ΛCDM** structure formation simulations (Kravtsov et al. 2004) if additional **pressure** stabilisation is assumed (Sternberg et al. 2002).
- Beyond a distance of 50 kpc from M31 the pressure of the circumgalactic corona might drop below the critical value of $\mathbf{P / k \simeq 50\ K\ cm^{-3}}$ which is required to keep the gas in HVCs neutral.
- Therefore, many more mainly **ionised** or **pure** dark-matter satellites could exist at larger distances from M31 which cannot be detected in H I.

References

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