Scientific presentation

Impact of feedback on the gas cycle in galaxies of the local Universe

The evolution of galaxies is regulated by the baryon cycle, which governs both star formation and the growth of the central black hole (Somerville & Davé, 2015). Feedback mechanisms can expel gas into the galactic halo, or even beyond, thereby altering the amount of cold gas available in the disk (Lilly et al. 2013, Veilleux et al. 2020). Circumgalactic gas, as well as gas flowing in from intergalactic filaments—initially hot—can subsequently cool and fall back onto the galaxy through a "galactic fountain" process, replenishing the reservoir required for star formation (Shapiro & Field, 1976, Bregman 1980). This framework underpins our understanding of the matter cycle, yet remains only weakly constrained observationally. It relies in particular on the existence of a hot, very low-density coronal gas component, detected in X-rays in a few galaxies (Anderson & Bregman, 2011), as well as on the presence of circumgalactic neutral gas revealed in absorption against quasars or stars (Werk et al. 2014, Lehner et al. 2013), consistent with this scenario (Tumlinson et al. 2017).

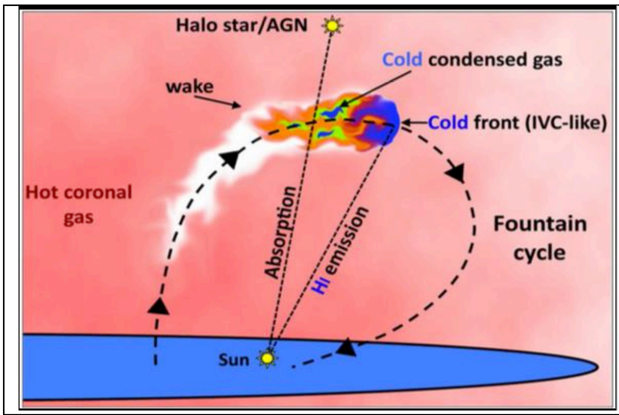
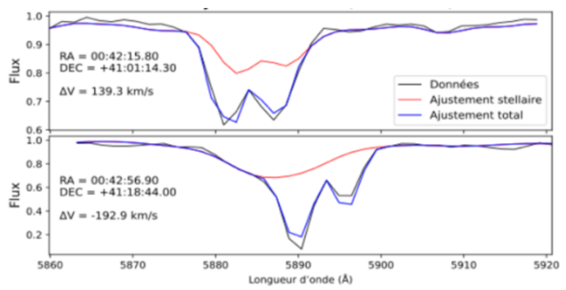


Diagram illustrating the fountain effect driven by stellar feedback (Fraternali 2016). Supernova-driven outflows interact with the hot corona, mixing with metal-rich disk gas and inducing condensation that returns to the disk. Sightlines through the wake show intermediate-temperature absorption, while sightlines toward the cold front reveal H I emission at IVC (Intermediate-Velocity Clouds)—and occasionally HVC (High-Velocity Clouds) — velocities (e.g. Putman et al. 2012)

This PhD project aims to explore these feedback mechanisms in nearby galaxies by simultaneously identifying the signatures of gas outflows and inflows. A multi-wavelength approach will make it possible to study both the kinematic signatures (in emission and absorption) and their connection to the dynamical environment (spiral arms, ring) and to star-forming regions. The work will begin with the Andromeda galaxy, for which an exceptional set of data is available (LGLBS, MMT/CfA, Astro UV sat, GALEX, SITELLE, IRAM, LOFAR).

1 HI cavities in the galactic discs. The new generation of H I data will make it possible to analyze the multiplicity of components along the lines of sight in nearby galaxies. In particular, the Local Group L-Band Survey (LGLBS) is an "Extra Large" survey based on the Karl G. Jansky Very Large Array that has observed Local Group galaxies in H I (Koch et al. 2025), and high-resolution data will soon be released (Pingel et al. 2026, in prep.). A first objective will be to revisit the "H I holes" identified in the 1990s (see also Bagetakos et al. 2011). In M31, Brinks and Bajaja (1986) detected 141 holes in the disk. These cavities, often larger than those observed in warmer phases (Hα), suggest a lack of local re-accretion. Gas outflows may also be detected in regions without H I cavities, particularly where star formation is active (e.g. McLeod et al. 2019, Egorov et al. 2021, 2023).

2 Atomic gas in absorption. A complementary approach will rely on detecting cold gas in absorption (Na D) in front of stars. Unlike gas seen in emission, this gas must lie directly along the line of sight, making it easier to distinguish between accretion and outflow. The archival data collected from the MMT Observatory are available through the CfA Optical/Infrared Science Archive[1] website. 13,000 stellar spectra available in the field of M31 will enable a statistical study of the gas distribution. This will make it possible to assess the filling factor across different regions, analyze the kinematics to determine whether the gas is accreting or being expelled, and compare these signatures with H I data to identify the analogs of high-velocity clouds in an external galaxy.



Examples of Na I D detections along the lines of sight toward two stars, based on spectra from Li et al. (2018). The stellar component has been fitted using the Nburst software, and the neutral gas shows a mean velocity that is clearly offset from that of the stars. ΔV is the difference between the velocity of the stellar populations and the velocity of the gas detected in absorption.

3 Ionised and molecular gas in emission. A multiphase study will place these structures within their galactic environment: internal dynamics, interactions, and ambient density. Our LOFAR observation at 140 MHz enables to study the radio continuum at low frequency with a high frequency with a unprecedented sensitivity (and resolution <5 arcsec, in prep.), will be compared with the new VLA continuum map from the LGLBS survey (1.4 GHz at 2 arcsec, in prep.). These data dominated by synchrotron emission will provide information on supernova remnants and the acceleration of electrons by the magnetic field. Optical ionized gas is available from SITELLE/CFHT, an Imaging Fourier Transform Spectrometer for the study of emission lines, installed on the Canada–France–Hawaii Telescope, with which we have obtained several data cubes of M31, as well as from various studies which identified isolated HII regions (e.g. Azimlu et al. 2011). In parallel, UV data are available from GALEX, a NASA UV satellite that obtained two FUV and NUV images of M31. (Thilker et al. 2005; Kang et al. 2009; Bianchi et al. 2012), and Astro-UVIT sat (Leahy et al. 2020, 2021; contact with S. Barway) surveys. Hα emission and UV maps will trace the spatial and temporal evolution of star-forming regions and will be compared with the distribution of molecular gas (CO(1-0) mapped entirely mapped at IRAM[2]-30m survey, Nieten et al. 2006) to identify potential offsets between the different phases of the gas cycle.

4. Numerical simulations to test feedback mechanisms. Once the mechanisms have been identified in M31, a comparison with RAMSES[3] hydrodynamical simulations (Teyssier 2000) will make it possible to assess whether the observed signatures are consistent with supernova explosions, with processes intrinsic to the galaxy itself (collisional ring, spiral arms, bar), or with a combination of these effects. This methodology can then be extended to other nearby galaxies, in particular the dwarf galaxies of the LGLBS or those from the PHANGS (Physics at High Angular Resolution in Nearby GalaxieS) program, for which a large amount of data is available (phangs.org, Leroy et al. 2021, Santoro et al. 2022).

[1] https://oirsa.cfa.harvard.edu/
[2] Institute for Millimetric Radio Astronomy,
[3] https://ramses.cnrs.fr/

Research plan and timeline

Year 1 — Data exploration, Pipeline Development, First Maps of Gas Flows

Main Objectives

Build expertise with the multi-wavelength datasets (H I, Na D, UV, IR, CO, Hα, radio).
Develop automated tools for detecting H I cavities and extracting Na D absorption components.
Produce the first maps of gas flows in M31.

Tasks

1.1. Data acquisition and literature review

- Familiarization with LGLBS (H I, continuum), MMT/CfA spectral archives (Na D), Astro UV, GALEX, SITELLE, IRAM (CO) and LOFAR (cont.) datasets.
- Setup of the analysis environment (Python, Astropy, SpectralCube, YT, Nbursts and ppxf spectral fitting tools).
- Comprehensive review of H I holes, galactic fountains, High Velocity Clouds (HVC), and feedback processes in M31.

1.2. H I cavity detection pipeline

- Development of an automated detection algorithm (inspired by Brinks & Bajaja 1986, Rosolowsky & Leroy 2006; Shaji et al. 2025).
- Application to new high-resolution VLA data (Koch et al. 2025; Pingel et al. 2026, in prep).
- First updated catalogue of H I cavities in M31.

1.3. Na D absorption analysis

- Extraction and stellar-continuum fitting of CfA archival spectra.
- Identification of cold gas components along stellar sightlines.
- First Na D absorption map of the inner disk of M31.

End-of-Year Deliverables

• Operational H I cavity detection pipeline.	• First H I cavity catalogue for M31.
• Internal presentation and Year-1 report.	• First Na D absorption map.

Year 2 — Kinematic Analysis, Multiphase Comparison, Hydrodynamical Simulations

Main Objectives

- Characterize inflows and outflows using H I and Na D kinematics.
- Connect gas flows to the galactic environment (spiral arms, ring, star-forming regions).
- Begin systematic comparison with RAMSES simulations.

Tasks

2.1. Kinematic decomposition of H I and Na D

- Multi-component line-of-sight decomposition (following methods applied to M33).
- Identification of accreting vs. outflowing gas.
- Systematic comparison between H I emission and Na D absorption across thousands of sightlines.

2.2. Multiphase and multi-wavelength analysis

- Cross-comparison with CO(1–0), UV/IR star-formation tracers, radio continuum (VLA, LOFAR) and SITELLE Hα maps.
- Study of spatial offsets between cold, warm, and ionized phases.

- Quantification of the link between star formation, supernovae, and gas morphology.

2.3. RAMSES simulations

- Familiarization with RAMSES (Fortran 90, MPI) and analysis tools (YT).
- Exploration of feedback scenarios: supernova-driven outflows, galactic fountains, internal dynamics.
- First direct comparison between simulated and observed gas structures.

End-of-Year Deliverables

• Kinematic maps of inflows and outflows in M31 • First observation–simulation comparison. • Presentation at an international conference.	• Identification of HVC in an external galaxy. • Draft of a first scientific article.

Year 3 — Physical Interpretation, Extension to Other Galaxies, Thesis Writing

Main Objectives

- Derive the physical origin of the detected gas flows.
- Apply the methodology to other nearby galaxies (LGLBS dwarfs, PHANGS spirals).
- Finalize publications and complete the thesis manuscript.

Tasks

3.1. Physical interpretation with simulations

- Detailed comparison between observations and RAMSES predictions.
- Constraints on the efficiency of galactic fountains and local re-accretion.
- Assessment of the impact of feedback on the cold-gas reservoir.

3.2. Extension to a broader galaxy sample

- Application of the H I cavity pipeline to LGLBS dwarf galaxies.
- Extension of Na D or equivalent absorption analyses to other galaxies with spectral data available (e.g. PHANGS galaxies).
- Comparative study of gas-cycle efficiency across environments.

3.3. Synthesis and thesis writing

- Integration of observational and simulation results.
- Writing of thesis chapters and preparation of 1–2 additional publications.
- Preparation and defense of the PhD dissertation.

End-of-Year Deliverables

• Final interpretation of gas flows in M31. • Final publications submitted.	• Generalized methodology for nearby galaxies. • Completed thesis manuscript & defense.

Year	Focus	Key Outputs
1	Data mastery, pipeline development, first maps	H I cavity catalogue, Na D map, Year-1 report
2	Kinematics, multiphase analysis, simulations	Inflow/outflow maps, HVC identification, first article
3	Physical interpretation, extension, thesis	Comparative study, publications, thesis manuscript