Internship Information

Categories

Cosmology, Early Universe, Origin and Evolution of the Large Structures of the Universe and Galaxies

Internship topic

Balance and feedback of star formation in spiral galaxy disks

Multi-wavelength study of neutral hydrogen holes in the M31 disk

Context and problem:

Spiral galaxies evolve in a dynamic equilibrium between the accretion of primary gas, provided by the filaments of the cosmic lattice, and the energy feedback processes resulting from star formation (supernova explosions, stellar winds). This balance regulates the efficiency of star formation and determines the long-term evolution of the galactic disk. However, the coupled mechanisms that maintain this quasi-stationary state – modulation of external accretion by hot halo gas and internal regulation by heating and turbulence – remain poorly constrained. The measurement of star formation rate (SFR) and cold gas distribution in galaxies relies on the use of indirect observational tracers, each of which is sensitive to distinct physical phases and time scales. A comprehensive understanding of galaxy evolution therefore requires a critical combination of these different indicators.

The Andromeda galaxy (M31), the nearest major spiral galaxy (at 780 kpc), offers a unique laboratory to study the small-scale mechanisms that regulate the evolution of galaxies. Its history, marked by a collision with M32 (Block et al. 2006), led to the formation of a star formation ring at ~10 kpc. This environment is the site of an intense stellar feedback, materialized by the presence of more than 140 "holes" and shells in the atomic gas distribution (HI), discovered by Brinks & Bajaja (1986). These structures are interpreted as the result of the cumulative impact of stellar winds and supernovae, playing a presumed central role in the **baryon cycle** by ejecting gas from the disk to potentially re-accrete it via a **galactic "fountain" effect**. However, direct observational evidence for this cycle remains scarce and fragmentary.

1. Tracers of the Recent Star Formation

The history of star formation can be broken down by probing different stellar populations using complementary tracers:

- **Tracers of recent massive stars (~10 Myr).** The combination of **Hα** emission (from ionized gas) and infrared emission **at 24 µm** (from heated dust) is used to estimate the instantaneous star formation rate. These tracers are sensitive to ionizing radiation from short-lived massive OB-type stars, as well as to dust emission that corrects absorption in dense regions. It thus captures episodes of star formation that have taken place over the **last 10 million years**, even partially obscured.

- **A tracer of extended young populations (~100 Myr).** Emission in **the far ultraviolet (FUV)** comes mainly from the photospheric emission of young stars of OB types but also A. As A-type stars have a longer lifetime, this tracer integrates star formation on a longer timescale, on the order of **100 million years**. It thus offers a more "smooth" view of recent activity.

2. Raw Material Tracers: Neutral and Molecular Gas

The surface density of the gas, a precursor to star formation, is also plotted indirectly:

- **The atomic phase (HI):** This is mainly traced by the emission of the line at 21 cm of neutral hydrogen. This gas diffuses and forms the reservoir from which the molecular gas is formed.

- **Molecular phase (H_2):** Molecular hydrogen, which is difficult to observe directly, is generally quantified via the emission of **carbon monoxide (CO)** in radio, used as a tracer of the column density of H_2 under the assumption of a constant conversion factor (X_CO).

Problem and objectives of the internship:

While the feedback scenario is theoretically well established, the dynamic processes that govern it – gas removal, heating, phase transition and re-accretion – are still poorly constrained from an observational point of view. The main objective of this internship is to **understand the multi-phase impact of stellar feedback** by characterizing HI holes in M31.

To do this, the intern will be required to:

1. **Characterizing the HI hole population:** Re-analyzing the historical catalogue of Brinks & Bajaja (1986) using modern HI data from Koch et al. (2025) (see also Chemin et al. 2009) to derive precise physical properties (sizes, required energy masses, dynamic ages).
2. **Establishing a causal link with young stellar populations:** Systematically correlate hole position and morphology with recent star formation maps (Hα, 24μm/Spitzer, FUV/GALEX tracers) and HII region catalogs (Azimlu et al. 2011) to identify responsible feedback sources.
3. **Probe the impact on the molecular phase:** Investigate the gaseous environment of the holes by comparing them with the distribution of cold molecular gas (CO data from Nieten et al. 2006). The goal is to determine whether feedback dissociates H_2, compresses it to form H_2, or has no detectable effect.
4. **Look for observational signatures of the fountain effect:** Try to identify, by combining all these diagnostics, indirect evidence of the gas-ejection-relapse cycle, such as the presence of falling gas or cooling signatures around the holes.

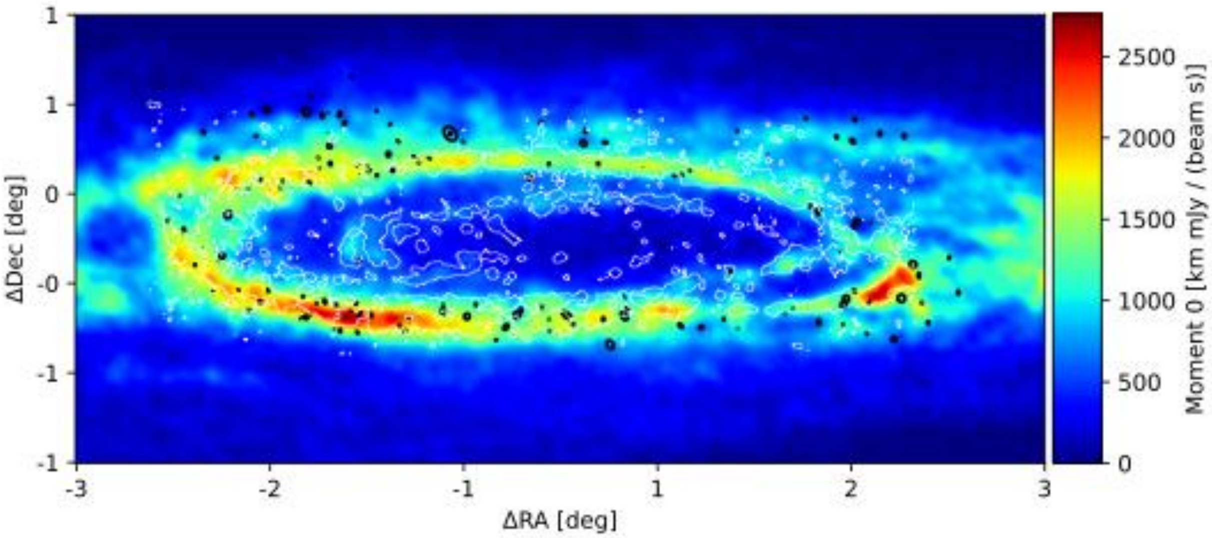

Figure: Distribution of neutral hydrogen HI from the galaxy M31 (Chemin et al. 2009). The white outlines correspond to molecular gas (Neininger et al. 2006). The small black ellipses correspond to the HI holes identified by Brinks & Bajaja (1986).

The interstellar medium of M31, marked by hundreds of "holes" in HI gas, is thought to be a direct manifestation of stellar feedback. However, the quantitative link between young stellar populations, the explosion of supernovae, and the creation of these structures remains poorly constrained. This internship aims to answer fundamental questions: **Under what conditions does star formation generate an observable HI hole? Why do some active regions lack them?** By understanding these mechanisms, we can quantify the actual effectiveness of feedback in regulating the gas cycle.

Methodology:

To address this issue, the internship will focus on three main areas:

1. **Establish a quantitative causal link between star formation and HI holes.**
   - The intern will test and quantify the historical hypothesis of Brinks & Bajaja (1986): **Are holes (D < 300 pc) systematically and exclusively associated with regions of recent star formation** (traces Hα, 24µm, HII regions)?
   - **Method:** Comparative mapping and statistical analysis of co-locations to derive probabilities of association.
2. **Understanding the absence of holes: constraints on the effectiveness of feedback.**
   - An equally crucial question will be to study **the regions of star formation where no holes are detected**. The intern will seek to determine if this absence is related to the age of the stellar populations, the density of the ambient gas, the morphology of the disk, or a different stage in the feedback cycle.
   - **Method:** Comparative analysis of the properties (SFR density, metallicity, gas pressure) between the "with holes" and "without holes" regions.
3. **Constrain time sequence and energy efficiency.**
   - By correlating the properties of the holes (size, dynamic energy, estimated age) with the intensity and age of the triggering star formation episode, the trainee will try to **reconstruct the causal sequence linking ionization, stellar winds and supernova explosion to the creation of cavities**.

This observational work on M31 will be enriched by a **comparative approach on a galactic scale**. The intern will compare his/her results with studies conducted in other galaxy disks (e.g. work by Bagetakos et al. 2011, Boomsma et al. 2008, Shaji et al. 2025). Finally, a critical comparison with the predictions of **cosmological numerical simulations** (e.g., Bahé et al. 2016) will allow to assess the extent to which the theoretical models faithfully reproduce the diversity and properties of the observed feedback structures.

Data:

This observational project will be based on the analysis and correlation of high-quality multi-wavelength datasets:

- **Atomic gas:** HI maps by Chemin et al. (2009).
- **Molecular gas:** CO maps by Nieten et al. (2006).
- **Star formation:** Hα, 24μm (Spitzer), FUV (GALEX) images and HII region catalogues.

The work will consist of a processing and quantitative analysis of these data (astropy, spectral-cube), including photometry, simple modeling and statistical comparison.

Skills developed:

- Astrophysics of the interstellar medium and galaxies.
- Multi-wavelength data analysis.
- Scientific programming (Python) and image processing.
- Synthesis of results and scientific writing.

References:

- Azimlu et al. 2011, Astronomical Journal 142, 139
- Bagetakos et al. 2011, Astronomical Journal 141, 23
- Bahé et al. 2016, Monthly Notices of the Royal Astronomical Society 456, 1115
- Block et al. 2006, Nature 443, 832
- Boomsma et al. 2008, Astronomy and Astrophysics 490, 550
- Brinks & Bajaja 1986, Astronomy and Astrophysics 169, 14
- Chemin et al. 2009, Astrophysical Journal 705, 395
- Koch et al. 2025, Astrophyiscal Journal Supplements 279,35
- Nieten et al. 2006, Astronomy & Astrophysics 453, 459
- Shaji et al. 2025, Astronomy & Astrophysics under revision, 2025arXiv250710549A