SCIENCES SORBONNE UNIVERSITÉ

IAP

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LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

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Proposition de Projet de Recherche Doctoral, Initiative Physique des Infinis

The H_2 molecule as a tracer of feedback-driven turbulence: interpreting JWST data

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Scientific context: How galaxies form is one of the main question of contemporary astrophysics. In the current dark matter-dominated cosmological model, galaxies are assembled from the collapse of gas in virialized dark matter halos. However, predicting the physical properties of galaxies (like their star formation rates or morphologies) is still very challenging, essentially because we still do not fully understand which processes regulate the gas content in galaxies. Those processes involve a complex interplay between gravitational collapse, gas accretion via cold gas streams infalling from the cosmic web, galaxy merging, and feedback related to star formation and/or active galactic nuclei (AGN, i.e. galaxies hosting an active supermassive black hole). It is this balance between the rates of inflow, outflow, and star formation that gives the physical characteristics of the galaxies we observe today.

To grow a galaxy, baryons must cool down to form new stars, but the energy liberated by accretion and feedback from stars and black holes limits the gas cooling. *The impact of this injection of energy on the build-up of galaxies is largely unknown, and depends on how that energy is transferred to the gas*. Some of this energy is thermalized, producing halos of hot gas with long cooling timescales. Some of it is transferred as bulk kinetic energy by radiation pressure or direct mechanical impact, producing galactic winds. **Part of the kinetic energy injected on large scales by feedback is transferred to smaller scales where stars are forming, which sustains turbulence in the molecular gas**. This third point is largely ignored in current studies of galaxy formation, and only captured in cosmological simulations over a limited range of scales. Recent observations reveal that a large fraction of the mechanical energy injected by feedback is stored in a turbulent reservoir, and cascades down to small scales, where it is dissipated, in particular through H_2 lines (e.g. Guillard+2009, 2012, Lesaffre+13, Emonts+2016). Therefore, **the dissipation of feedback-driven turbulence may be a key process in regulating the gas content of galaxies because it has a strong impact on the gas cooling.**

The James Webb Telescope (JWST) is about to open a fully new perspective by allowing us to look for molecular hydrogen (H_2) lines, which are the most efficient molecular coolant of gas heated by mechanical energy. In many sources, Spitzer observations have revealed that indeed rotational lines of H_2 integrated over entire galaxies radiate, in many sources, a total power that cannot be explained by the sole reprocessing of the available UV radiative energy (e.g. Guillard et al. 2009, 2012). ***JWST will revolutionise H_2 observations***, and we hope this will help elucidating the gas physics that regulates the return of matter from disk to galactic halos and vice versa. We have started to prepare the interpretation of the upcoming data and would like to involve a PhD student in our project. ***This PhD work focuses on how feedback-driven turbulence impacts the properties of galaxies, in particular the gas cooling and their ionised, atomic, and molecular content.***

Science objectives: In astrophysical environments where large amounts of mechanical energy are involved, like AGN or galaxy mergers, H_2 lines can be unambiguous tracers of turbulent dissipation,. **However, we still miss a comprehensive model of the cooling flow across gas phases to provide a quantitative interpretation of those lines**, and derive the gas energy budget**.** ***The theoretical objective of this PhD project is to develop a physical framework where multi-wavelength observations, including H_2 line fluxes that will be measured by JWST in thousands of galaxies, are combined to quantify the cooling rates from hot-to-warm and warm-to-cold phases.***

Observationnally, the mass and energetics of the gas within each phase (ionized, atomic and molecular), outflowing or not from galaxies, and the impact of these winds on the efficiency of star formation, remain poorly constrained by observations. **JWST data will allow us to study at very high spatial resolution the energetics of the warm molecular gas through H_2 line spectral mapping**. In particular, one of the exciting possibilities is the study of the kinematics and physical state of the gas in the circum-nuclear disk and the torus, enabling us to see *whether molecular gas is entrained in the flow right from the very small scales, close to the supermassive black hole, or formed further out as a result of gas cooling.* JWST H_2 data will give us access to the gas dissipation rate and excitation, and thus will allow us to link the AGN activity and the turbulent dissipation.

Methodology: To advance our understanding of the regulation of the gas content in galaxies, both observational evidence of signatures of turbulence, as well as a physical model of gas cooling and energy dissipation are needed. In the following we detail the methodology planned to achieve the two main science objectives (observational and theoretical) of this PhD project.

1. Physical modelling: The PhD student's work will build up on the cooling flow model proposed by Bordoloi et al. (2017) to interpret observations tracing the cooling rate of hot gas in galaxies. The student will extend this modelling to the cooling down to atomic and molecular phases. This model will allow us to investigate the impact of physical parameters on the turbulent mixing between phases. Once validated, this global cooling flow model will be ingested within the physical and chemical framework of the Paris-Durham shock code developed at ENS (https://ism.obspm.fr/shock.html). This will allow us to interpret H_2 line fluxes with grids of models of shocks in irradiated molecular gas (Godard et al. 2020, Lehmann et al. 2021), and quantify the energy budget of the molecular gas in the outflow.
The student will also be offered the opportunity to work on 3D numerical simulations of cooling flows to assess the dynamical impact of thermal instability. Depending on the interest of the student we will focus the project on the model comparison with existing observations or the numerical study.

2. Observations: The PhD student will immediately have access to datasets from JWST guaranteed time observations, MIRI MRS & NIRSPEC IFU spectral-imaging of nearby galaxies with AGN and starburst-driven outflows. P. Guillard is co-PI of this program and the student will reduce and analyse the data. Those sources also well-known for the extreme brightness of his H_2 lines (Ogle et al. 2010), which, with JWST, will be resolved spatially and spectrally. Building on our experience in interpreting Spitzer Telescope data, this is a unique opportunity to develop this expertise in the context of active galaxies. Then, the student will be given the opportunity to work on an accepted open-time program "Closing in on the launching sites of AGN outflows" (GO1, co-PI : P. Guillard) ID: 01670**,** which will sample 6 AGN with diverse luminosities and outflow rates. The student will participate to the reduction of the imaging and spectroscopy data of the MIRI instrument, and will lead the scientific exploitation of the H_2 spectral data, which will make it possible to trace the mass, kinematics and the excitation of the molecular gas in the outflows.

Why is this PhD project relevant for the "Physique des Infinis" initiative? This thesis fits nicely within the scientific framework of the IPI, precisely because we propose to tackle the long-standing issue of the feedback loop regulating the gas content of galaxies, from an original observational and theoretical perspective. Indeed, the proposed PhD project connects the microphysics and chemistry at very small scales (turbulent dissipation) to the study of the energetics of the large scale gas reservoirs impacted by supermassive black holes in active galaxies.

Thesis supervision and collaborations: The PhD student will work with a team of astrophysicists from IAP and ENS, involved in several JWST proposals where H_2 will be observed in various astrophysical contexts and on a wide range of physical scales. The PhD candidate will benefit from this rich environment and will contribute to the team expertise. The project builds on our recognized expertise in modelling of the interplay between the dynamics, the physics and chemistry of interstellar matter, in particular H2. The PhD supervisor, **Pierre Guillard** (**ADS link**) studies the physics of galaxies (stars, gas, dust) and is a member of the JWST MIRI instrument Science and Test teams, P.I. of the commissioning activities related to the Point Spread Functions of the MIRI imager, and co-P.I. of a Guaranteed Time Observation project on nearby galaxies. He also has experience with photo-ionization models and shock models to explore the physics of cooling and to predict observables such as H_2 spectral lines. He has co-supervised 2 thesis (N. Cornuault, 2014-2017, 20% and Suma Murthy 2018-2021, 50%) and 4 postdocs at 50%. **Pierre Lesaffre (ADS link**) has supervised 3 thesis and is an expert of the numerical modelling of the coupling between interstellar chemistry and magnetohydrodynamics. He has contributed to several publicly available codes such as MESA (stellar evolution), Zeus3D (3D MHD), Paris-Durham (1D MHD shock models including chemistry) and recently published an interface (CHEMSES, Lesaffre+2020) between RAMSES and Paris-Durham which brings to 3D MHD the flexibility and chemical richness of the Paris-Durham code.

Provisional calendar over the 3 years

Year 1: Bibliography, understanding of the subject - Getting familiar with GTO JWST data, reduction and analysis tools - Building of a simple cooling flow model of ionised and atomic gas.

Year 2: Ingesting the cooling flow model into the Paris-Durham shock code framework - Interpretation and modelling of the JWST H2 line data - start of writing of the first paper(s) and follow-up proposals.

Year 3: finishing up paper(s) - start of data analysis and interpretation of follow-up data if successful - thesis manuscript and completion.

PhD candidate profile: We seek a highly-motivated student with good programming skills (mostly python) and interests in the physics of interstellar matter, galaxy evolution, numerical experiments and/or data reduction.

Short list of references: Bouché et al. 2010, ApJ, 718, 1001 — Bordoloi et al. 2017, ApJ 848, 122 — Flower, Pineau des Forêts, 2015, A&A, 578, 63 — Lesaffre et al. 2020, MNRAS 495, 816 — Falgarone, E., Zwaan, M., Godard, B., et al. 2017, Nature, 548, 430 — Godard, B., Pineau des Forêts, G., Lesaffre, P., et al. 2019, A&A, 622, A100 — Guillard, P., Boulanger, F., Pineau des Forêts, G., & Appleton, P. N. 2009, A&A, 502, 515 — Lehmann, A., Godard, B., Pineau des Forêts, G., Vidal-García, A., & Falgarone, E. 2021, in press — Lehmann, A., Godard, B., Pineau des Forêts, G., & Falgarone, E. 2020, A&A, 643, A101.