Constraining Feedback in Low-mass Galaxies with JWST Observations

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Scientific context

In the standard ΛCDM model, galaxies grow through the accretion of gas which flows down the potential well of dark matter (DM) halos, themselves growing as their gravity pulls more and more matter from large-scale filaments. It is now well established that without any regulating process, this scenario leads to galaxies with stellar masses at best an order of magnitude too large compared to observations. This situation is particularly critical in low-mass objects, where observations suggest that less than 1% of the gas available to a DM halo is locked up in stars. Feedback from massive stars is the key to this puzzle. At the scales of the interstellar medium (ISM), massive stars regulate star formation by injecting energy through radiation, supernova (SN) explosions, or cosmic rays. This feedback may be strong enough to expel most of the gas out of galaxies and shut down star formation completely in the least massive ones. At intermediate scales, galactic winds and energetic radiation interact with accretion flows and reduce their efficiency. At larger scales, radiation from massive stars reionized the Universe and maintained the intergalactic medium (IGM) warm, effectively stopping the growth of small galaxies and inhibiting further condensation of gas in low-mass dark matter structures.From the observational viewpoint, constraints on feedback are indirect and often derived for massive galaxies, which are more easily observed. It is however clear that low-mass galaxies are most strongly impacted by feedback, and that the detailed study of their star formation activity will yield strong constraints on the nature and strength of feedback mechanisms.

The project

The James Webb Space Telescope (JWST) has now reached its final destination at the L2 point and will start its science operations early this summer. Our team leads the science case of low-mass galaxies in two accepted programs with the JWST, which will allow us to make a breakthrough in this field by: (a) measuring the abundance of star-forming galaxies in the early Universe down to the faintest luminosities ever achieved, and (b) assessing the feedback-induced burstiness of the star formation histories of low-mass galaxies at intermediate redshifts ($z = 1$-3). This project is at the crossroads of several research ares of IPI, including the formation of the first galaxies, the feedback induced by stellar radiation and supernovae explosions, and the reionization of the Universe. It will build on the scientific synergy between observational constraints from the JWST and theoretical models of galaxy formation to tackle one of the most important challenges in observational cosmology. It will significantly contribute to engaging the French scientific community in the exploitation of the JWST.

A- The prevalence of low-mass galaxies at early epochs

The abundance of low-mass star-forming galaxies during the Epoch of Reionization (EoR), as traced by the very faint end of the UV luminosity function (LF) at $z > 6$, is determined by the ability of small galaxies to accrete gas and by their efficiency at converting it into stars. The accretion is strongly affected by reionization, a form of large-scale radiative feedback, while the efficiency of star formation is the result of ISM-scale feedback processes. The shape and amplitude of the UV LF at the faint end and their evolution through the EoR are thus excellent probes of feedback. Constraining the faint-end of the UV LF is extremely challenging, and state-of-the-art estimates diverge at $M_{UV} > -15$ mag. The main limitations here are *(a)* the limited depth of HST observations, *(b)* large uncertainties associated with high magnification factors of gravitational lensing. On the theoretical side, great numerical efforts have been made to produce quantitative predictions of the UV LF, but there remain order-of-magnitude disagreements between simulations

Our accepted JWST program (UNCOVER) will obtain deep NIRCam and NIRSpec observations of the A2744 lensing cluster, which will reach 2-3 magnitudes deeper than the Hubble Frontier Fields observations. Therefore, measuring the exact shape of the faint end of the LF will no longer rely on highly-magnified sources and associated uncertainties. Following on our work in the Frontier Fields (Atek et al. 2018), these observations will enable us to measure the exact shape of the faint end of the LF from z~6 out to z~10 and down to magnitudes as faint as $M_{UV} \sim -12.5$ mag. In parallel, we will compare our results with the state-of-the-art cosmological simulations SPHINX, which include subgrid models for star formation and radiation feedback in low-mass galaxies, where this mode of feedback has been shown to dominate. The comparison to observations will put strong constraints on the effects of feedback models and other effects (cosmic rays, formation of H_2 and dust) on the abundance of faint galaxies.

B- Bursty star formation as a tracer of feedback

The feedback from stellar radiation and SNe is directly reflected in the star formation histories (SFHs) of low-mass galaxies. Indeed, while massive galaxies grow with steady star formation, low-mass galaxies seem to go through a stochastic process with a succession of short bursts of star formation and suppression by stellar feedback. The duty cycle and amplitude of SFR bursts hence give unique insight into stellar feedback. From a theoretical standpoint, in spite of recent progress in implementing physical models of feedback in zoom-in simulations focusing on a handful of galaxies, results are divergent. For instance, the resulting SFH parameters, such as duration of bursts or time-interval between them (the duty cycle), vary widely. Consequently, it is unknown whether simulations are close to reality. Therefore, observational constraints of the SFH of low-mass galaxies can provide crucial diagnostics to test feedback models.

This part of the project will use a sample of thousands of galaxies from our accepted large JWST program (PASSAGE) to constrain feedback in low-mass galaxies, down to stellar masses of $10^7 M_\odot$., 30x less massive than our current HST measurements. Using Balmer lines, we will map short timescale variations in SFR(Hα)/SFR(UV) as a function of galaxy properties at the peak epoch of star formation in the Universe (z=1-3). In combination with state-of-the-art stellar population modeling tool (BEAGLE), we will constrain the SFH in low-mass galaxies. To understand the physics regulating the stochasticity of star formation, we will test the observed parameters against existing and next-generation SPHINX simulations running to z~3.

Supervision and partnership

This doctoral project relies on a close and timely collaboration between the IAP team with a focus on deep JWST observations, and the CRAL team with an expertise in simulations. The student will be supervised by two IAP researchers, S. Charlot (HDR) and H. Atek (who will pass his HDR in the first year of this project), and CRAL reseracher J. Blaizot (HDR). **H. Atek** at IAP is an expert in the study of early star-forming galaxies and their contribution to reionization using gravitational lensing (Atek et al. 2014a,b, 2015a,b, 2018). He has led high-redshift science in several international projects (e.g. BUFFALO, WISP) focusing on the nature of low-mass galaxies at high redshift (Atek et al. 2011, 2014c, 2021). He is now leading the scientific exploitation of the research areas of BURST in two accepted JWST programs, UNCOVER and PASSAGE, which will obtain more than 600 hours of observations. He will provide the team with his expertise in JWST observations and analysis since he is co-leading a national effort to prepare the French extragalactic community to analyze JWST data and submit observing proposals (http://www.iap.fr/jwst-edls). **S. Charlot** at the IAP has a world-renowned expertise in galaxy evolution models (GALAXEV, BEAGLE) and the preparation of JWST observations (NIRSpec JADES team). **J. Blaizot** has a unique expertise in numerical simulations of galaxy formation using radiative hydrodynamical simulations. He also works on constructing detailed mock observations from high-resolution simulations with our own RASCAS code (Michel-Dansac et al., 2020, http://rascas.univ-lyon1.fr), which we recently used to carry out a detailed comparison of SPHINX and the observed Lyman-alpha and UV luminosity functions in Garel et al. (2021).

Work plan

The student would preferentially have interest and general knowledge in galaxy formation and evolution, and show skills in programming tools such as python. The desired profile will be mostly observational, with interest in numerical simulations.

Year 1: the student will work on the first JWST observations to select high-redshift galaxies and construct the most precise galaxy luminosity function to date. The writing of the first paper is expected to begin at the end of the first year. The student will also write follow-up observing proposals targeting very high-redshift galaxies.

Year 2: the second part of the project is to interpret these constraints using cosmological simulations and infer the implications on the nature and strength of feedback needed to match the prevalence of low-mass galaxies at early epochs. A second article is expected at the end of the year.

Year 3: the student will analyze the stochastic nature of star formation in low-mass galaxies with observations from the PASSAGE program and stellar population models. They will compare these star formation histories with the SPHINX simulations, which will be the subject of a third article before writing the thesis manuscript.

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