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## Report on the Doctoral Thesis Manuscript of Mr. Prasad Sawant

Dissertation Title: Probing the baryon cycle of primordial galaxies in the ALMA and JWST era

This thesis presents a thorough and technically accomplished well-structured investigation of the ALPINE galaxy survey based on 158  $\mu\text{m}$  [CII] and dust continuum from ALMA observations. Mr. Sawant tackles a long-standing astrophysical challenge of understanding the gas and dust properties of galaxies at  $z \sim 4$  to 6. By applying a chemical evolution model alongside SED fitting techniques, the study investigates the evolving ISM conditions in early galaxies. The work builds from a background in dust production and dust evolution modeling establishing the motivation for the main focus of his work, which culminates in a major recently published article (Swant et al. A&A 694 2025). Overall, the manuscript is polished and coherent, and contributes meaningfully to some of the enduring questions surrounding the physics of the evolution of galaxies across cosmic time.

Chapter 1 provides a clear and well-structured introduction to science behind the nature of galaxies at the cosmic noon being investigated, by first exploring possible variations in the stellar IMF in star forming galaxies, using multiwavelength observations from the ALPINE ALMA survey. Motivated by the inability of standard chemical evolution models assuming a Chabrier IMF and maximal dust production, to explain the observed dust and gas reservoirs in these galaxies, Mr. Sawant brings to light the question of whether a top-heavy IMF could provide a better explanation to the observations. Particular emphasis is placed on galaxies near the star-forming main sequence, examining their star formation rates, metallicity, and dust content within the broader context of the evolving baryon cycle. The introduction chapter effectively draws this research within ongoing efforts to understand early galaxy evolution during the final stages of cosmic reionisation. The introduction sets a compelling and well-motivated research agenda, connecting key questions about the IMF, early star formation, and dust production in galaxies.

Chapter 2 outlines a comprehensive methodological framework for interpreting the ISM properties of the ALPINE galaxies by integrating chemical evolution modelling with SED fitting. These complementary approaches work together to interpret the observed properties of the galaxy sample: chemical evolution models track the buildup of stars, metals, and dust through inflows, outflows, star formation, and feedback processes, incorporating assumptions about the IMF, star formation histories, and dust production sources (e.g. SNe and AGB stars), and are calibrated against observed metallicities and dust masses. In parallel, SED fitting techniques are used to derive key galaxy properties from multi-wavelength observations, using approaches ranging from simplified modified blackbody fits and empirical templates from spectral libraries to physically motivated dust grain models and full panchromatic codes like CIGALE and MAGPHYS. Together, these approaches provide a coherent strategy to interpret the observed properties of these galaxies and test theoretical models of the evolution of the ISM. This chapter nicely outlines a robust and balanced method that bridges theoretical modelling and observational data, setting the stage for the scientific analysis of the thesis.

Chapter 3 discusses the importance of assembling a statistically robust and representative sample of high- $z$  star forming galaxies (SFGs) to study their ISM properties, reviewing the observational challenges posed by

dust-obscured SFGs, which are often missed in optical surveys, due to dust obscuration, and explains the important role of IR and mm observations in overcoming these limitations. The chapter first introduces the COSMOS survey, a deep multi-wavelength field covering 2 square degrees, which has enabled detailed studies of typical SFGs  $z=4-6$ . Central to this survey and to Mr. Sawant's thesis is the ALPINE survey, which used ALMA to observe the [CII] FIR line, a key tracer of star formation and gas content, in a sample of 118 galaxies with spectroscopic red shifts, and combines archival data to model the physical ISM conditions. ALPINE is intended to provide measurements of star formation rate, stellar masses, dust content, and the cosmic star formation rate density, to establish a comprehensive picture of high- $z$  SFGs.

Chapter 4 explores the evolution of gas and dust using the chemical evolution models calibrated against ALPINE survey data, examining how factors, such as IMF, galactic outflows, and dust production and destruction processes, affect the ISM cycle in these galaxies. The findings of this chapter have been reported in a recently published Sawant et al. 2025 paper and show the importance of outflows in regulating gas content, the dominant contribution of Type II Supernovae in dust production for older galaxies, and the growing importance of grain growth in the ISM in intermediate-age galaxies. While a standard Chabrier IMF explains most observations, a top-heavy IMF better fits the dustiest and youngest galaxies, although some cases remain unexplained. Comparisons with other dust models confirm challenges in accounting for the large dust masses in young, low-mass galaxies, demonstrating possible gaps in current dust formation theories and observational constraints. The chapter concludes by emphasising the need for improved models and future data, particularly from JWST, to better probe IMF variations and ISM conditions. This chapter delivers a well-integrated and sound analysis, combining chemical evolution models with observations and evaluating the results within current literature. It also acknowledges some limitations and uncertainties of dust prescriptions and observations.

Chapter 5 builds on modelling results that attribute dust in older systems largely to Type II SNe, while ISM grain growth is essential for intermediate age galaxies. However, even a top-heavy IMF fails to account for the high dust masses seen in the youngest galaxies with the highest sSFR. Comparisons with other studies in the literature reveal similar shortcomings in explaining rapid dust buildup at early times. To address these limitations, this chapter introduces a followup study using JWST NIRSpec observations from the CRISTAL program, which gives spatially resolved constraints on dust attenuation, star formation rates, metallicity, and IMF variations through diagnostics such as H $\alpha$ , UV continuum, and MIR features. These data will be used to test whether top-heavy IMFs or alternative dust formation mechanisms are needed to explain early galaxy evolution. This chapter successfully lays out a clear, targeted observational strategy using JWST, thereby setting the stage for resolving some of the most persistent uncertainties in high- $z$  galaxy formation and evolution.

Chapter 6 synthesises the thesis findings and places them within the broader context of galaxy evolution. A primary conclusion in this work is that using ALPINE observations of [CII] and dust continuum, demonstrates that chemical evolution models can reproduce dust in older systems, while younger galaxies remain challenging to explain, even when invoking a top-heavy IMF. Looking ahead, Mr. Sawant describes the role of JWST CRISTAL data, particularly from NIRCam and NIRSpec, which will bring spatially resolved diagnostics such as H $\alpha$ /UV ratios and gas phase metallicities, providing some early indications of IMF variations and bursty star formation. The study of 98 ALPINE galaxies shows persistent tensions in dust production theories and challenges the universality of the IMF. Ultimately the work calls for more refined dust models and emphasises the urgency to push the limits of current cosmological theory.

Overall, the thesis offers a solid investigation of dust and gas evolution in high- $z$  galaxies, using ALMA [CII] and dust continuum data from the ALPINE survey, combined with SED fitting and chemical evolution modelling. Across the chapters, the study systematically addresses the observed dust budget, the difficulty in reconciling standard models with young, dusty galaxies, and the potential need for a variable, possibly top-heavy, IMF. Mr. Sawant's study lays the ground work for incorporating early JWST observations describing how spectral diagnostics from JWST will test IMF variations and dust production scenarios. The work is timely, well-structured and makes a valuable contribution to our understanding the early evolution of gas and dust during the final stages of the epoch of reionisation.

Following my review of the individual chapters and the overall thesis manuscript, I would like to pose some comments and questions that aim to understand some modelling choices, explore broader implications of Mr. Sawant's findings and get his views on future directions in this field.

1. In Mr. Sawant's models, dust growth in the ISM is an important mechanism. But even with this process, the youngest ALPINE galaxies still have under-predicted dust masses. Would increasing the dust growth efficiency (i.e. shortening the accretion timescale,  $\tau_{\text{acc}}$ ) help close this gap? How do the assumed  $\tau_{\text{acc}}$  values compare with empirical constraints from local galaxies, for example, such as those derived in Galliano et al. (2021) based on the DustPedia local galaxy sample?

Are there current or upcoming JWST observations or ALMA diagnostics that could help constrain ISM conditions, to better inform  $\tau_{\text{acc}}$  in these early ALPINE galaxies?

2. Mr. Sawant mentions in the last chapter that recent detections of galaxies at  $z \sim 14$  may stress test the  $\Lambda$ CDM model. What specific assumptions or predictions of  $\Lambda$ CDM are being challenged by these observations?

Can Mr. Sawant speculate on whether current semianalytic or hydrodynamical models can accommodate these very early galaxies issues with minor tweaks, or do they point to deeper problems with  $\Lambda$ CDM (e.g. dark matter properties, initial conditions, etc)?

With JWST now pushing the red-shift frontiers, what kind of observations would best help validate or cast doubt on  $\Lambda$ CDM predictions about early structure formation?

3. Section 2.2.4 discusses the importance in considering AGN emission and the difficulty in quantifying possible contributions due to the degeneracies between AGN and star formation in the observations and SED modelling. At  $z \sim 5$ , AGN feedback may not yet dominate in many low-mass to intermediate mass systems, but for galaxies with high sSFR and large stellar masses (and large dust masses), can AGN feedback be important enough to consider in the modelling? If so, how can this be constrained in the modelling or with other observations?
4. Mr Sawant's study models the SFHs of ALPINE galaxies using delayed- $\tau$  models and their truncated versions to account for potential quenching. The recent CLOUDY modeling of the JWST and ALMA observations of Veraldi et al (2025) introduces an additional dimension to SFH characterisation through the burstiness parameter,  $k_s$ , which they relate to the gas and star formation surface densities. Their result suggests that emission properties, and even inferred ISM conditions, may depend sensitively on whether galaxies are smoothly evolving or experiencing bursty episodes. Given this, how might incorporating more bursty SFHs, or explicitly varying  $k_s$ , impact the conclusions about dust and gas properties in Mr. Sawant's study of ALPINE galaxies? Is there a path to reconciling the SED-based modelling with the ISM constraints derived from this type of CLOUDY modelling?
5. How strongly can IMF variations be disentangled from short-term burstiness in SFHs when interpreting elevated  $H\alpha/UV$  ratios?

What observational diagnostics beyond  $H\alpha/UV$  and  $[CII]/\text{dust}$  could be used to robustly test IMF variations at  $z \sim 5$ ? Which diagnostics are most promising to break degeneracies?

Could stochastic SF activity (e.g. in the past 10-20 Myr) mimic the signatures of a top-heavy IMF?

6. Do the  $[CII]$  line profiles in ALPINE show evidence of feedback? (e.g. broad wings) consistent with stronger SNe activity from a top-heavy IMF?
7. The Sawant et al. study uses global quantities of  $M_{\text{gas}}$  and  $M_{\text{dust}}$  to constrain chemical evolution and IMF variations. If dust and gas do not occupy the same physical volumes, this could bias the observed  $sM_{\text{gas}}$  and the model fits if, for example  $[CII]$  is extended and dust is compact. How might the spatial mismatch between

[CII] and dust continuum emission affect the reliability of global gas and dust mass estimates, and thus inferred IMF variations?

8. The Palla et al. (2024) study explores the effects of metallicity and dust evolution in REBELS galaxies, concluding that while extreme dust production mechanisms are not required, different metallicity scenarios lead to different dominant dust formation channels (e.g. AGB vs. SNe dominance). Mr. Sawant's investigation, also confronts difficulties reproducing dust-to-stellar and dust-to-gas ratios in certain cases. Based on the findings from Palla et al., to what extent can mismatches in Mr. Sawant's model predictions be attributed to assumptions about metallicity, and how might incorporating non-parametric SFHs or metallicity-dependent gas calibrations, as used in Palla et al, inform or revise the thesis conclusions? How sensitive are Mr. Sawant's thesis conclusions to those assumptions? How might incorporating JWST constraints (or other telescope observations) break degeneracies in SED modelling and eventually sharpen conclusions about the origin and evolution of dust in the early universe?

These questions arise naturally from the strengths of Mr. Sawant's thesis and are intended to extend, rather than critique, the work already presented. In summary, I find the dissertation to be a significant and timely contribution to the field. It meets the standards expected of a doctoral thesis and I support the progression of Mr. Prasad Sawant to the next stage of the public defence. I would like to nominate Mr. Sawant for distinction.

Sincerely,



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