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Review of the PhD Thesis
"Probing the Baryon Cycle of Primordial Galaxies in the ALMA and JWST Era" **by Prasad Sawant**

The PhD thesis "Probing the Baryon Cycle of Primordial Galaxies in the ALMA and JWST Era" by Prasad Sawant was prepared under the supervision of dr hab. Ambra Nanni, with the auxiliary supervisor dr Michael Romano from the National Centre for Nuclear Research, Poland. The dissertation consists of six chapters, including the Introduction and the Conclusion sections, and is written in English. The work concerns about 100 main-sequence galaxies at redshift $z \sim 5$, included in the ALPINE survey probing the [C II] 158 µm emission line, which is a key diagnostic for star formation processes in high-redshift galaxies. The author, in particular, models the broad-band spectral energy distribution (SED) together with the chemical composition of the targeted systems, using data from the far-infrared to the UV/optical range to constrain the evolution of gas and, especially, dust in the studied galaxies.

The dissertation is meticulously prepared, with careful editing and very good English. Occasionally, however, some statements may sound slightly off. For example, in the Introduction, section 1.1, the sentence *"Modern cosmology posits that the Universe is governed by the ΛCDM paradigm, which describes it as …"* is somewhat misleading. A paradigm is a theoretical framework used by scientists to describe and interpret reality, not something that physically governs how the Universe works. The physical Universe is governed by the actual laws of physics: gravity, quantum mechanics, etc. The ΛCDM (Lambda–Cold Dark Matter) model is our current best description of those laws on cosmological scales, which in fact has recently faced several challenges. For these reasons, instead of making categorical statements such as *"Following the Planck epoch …, it [the Universe] transitioned into the inflationary epoch, during which space expanded exponentially…"* (section 1.2.1), it would be preferable to write that it is widely *believed*, within the framework of the ΛCDM paradigm, that following the Planck epoch the Universe transitioned into an inflationary phase, etc.

Chapter 1 of the dissertation provides an introductory summary of structure formation and evolution in the Universe within the ΛCDM paradigm. The author introduces and discusses in detail the Initial Mass Function (IMF) of stars, the Epoch of Reionization (EoR), the Star Formation Rate Density (SFRD), the physics of the Interstellar Medium (ISM) including a brief overview of ISM diagnostic emission lines, in particular the prominent far-infrared [C II] 158 µm line arising from singly ionized carbon, and finally the phenomenology and physics of cosmic dust, with extended comments on the difficulties and relevance of including dust in galaxy modeling frameworks, especially at high redshifts. This chapter is a pleasure to read, offering a comprehensive summary with an exhaustive list of references, and clearly defining and introducing all the major terms, processes, and problems. Here I have only a couple of critical comments, which are very minor:

- In section 1.3, the author states that *"The ISM is comprised of the diffuse mixture of gas and dust that occupies the space between stars within galaxies."* The author omits here cosmic rays and magnetic fields, which are both in approximate pressure equilibrium with ISM gas, at least in systems like the Milky Way. While not directly relevant to the scope of the dissertation, this should be acknowledged, as the evolution and structure of the ISM (including dust grains!) are shaped by these two additional constituents, in particular via stellar feedback, where cosmic rays and magnetic fields are pertinent players.
- In the same section, it is written that *"The other portion of baryons thus reside in low-density gas, the hot and warm phases of the IGM, the warm-hot intergalactic medium (WHIM), and the hot plasma filling galaxy clusters and groups which is challenging to detect in emission."* This is misleading, since while the WHIM and diffuse IGM are indeed challenging to detect in emission, the hot intracluster plasma is routinely observed in X-rays.

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- In section 1.4, the author writes *"However, reverse shocks in supernovae can destroy both newly formed and pre-existing dust."* If pre-existing dust in the ambient ISM/CSM is meant here, that is destroyed mainly by the forward shock, not the reverse shock, which propagates inward through the expanding SN ejecta (in the ejecta's frame).

Chapter 2 of the thesis contains a basic description of the "methodologies employed throughout" the research of the author. It begins with Section 2.1, in which the method for modeling the chemical evolution of the ISM, including its gaseous and dust fractions, is presented, following Nanni et al. (2020). In particular, for the baryonic gas evolution, a simple "rate equation" (or "continuity equation") of the form dM/dt = sources-sinks is given, with various source and sink terms representing the ejection of gas by the stellar population, gas astration (i.e., conversion into stars), gas outflowing and inflowing from the ISM (presumably via stellar feedback processes and accretion, respectively), and metal depletion from the gas phase into dust grains. Using this framework, an analogous equation is then formulated for dust species, including dust enrichment from stars, dust destruction by SN explosions, dust growth in the ISM, etc. Various terms representing these processes are set by introducing efficiency factors, parameterizations, and approximate terms, in order to capture the very complex chemical evolution of the ISM. This is therefore a purely phenomenological modeling approach, which at best can demonstrate the self-consistency of the model being built, rather than capture dust physics from first principles; however, given the complexity of the problem, no other approach is truly feasible.

Next, the derivation of dust luminosity and masses is presented. This part is harder to follow, as the introduced equations appear somewhat out of nowhere with no justification. For example, eq. 2.10 should simply be introduced as the standard optically thin dust emission formula, and the function *B(T)* should be defined as the Planck function at dust temperature *T*. The following equation, 2.11, meanwhile, presents the dust emission formula with the Planck function averaged over the variable radiation field of H II regions, but the function *U* and index *α* are never properly introduced (in fact, not until Section 4.3.2, much later in the thesis).

The author also states: *"I neglected the contribution of PAHs at these longer wavelengths and consider the equilibrium temperature for dust grains for dust species."* This is most likely justified, since PAHs emit predominantly in the mid-IR (≈3–20 μm) and contribute negligibly at far-IR/sub-mm wavelengths, where the emission is dominated by larger grains in thermal equilibrium. Still, more quantitative statements on the expected level of PAH contribution at different wavelengths of the infrared continuum could be valuable.

Then, in Section 2.2, an overview of galaxy SED fitting techniques and approaches found in the literature is presented, with an in-depth discussion of various aspects such as the inclusion of infrared dust emission or the AGN component. Such fitting is nowadays typically performed using codes like CIGALE, which are based on the energy balance approach and estimate the physical properties of the studied systems, with associated uncertainties, typically employing Bayesian inference. The relation between Sections 2.1 and 2.2 is at this point, however, a bit vague.

Chapter 3 describes the available data on high-redshift Dusty Star-Forming Galaxies (DSFGs), in particular the ALPINE survey, which provides a representative and statistically robust sample of such objects. The author notes that detecting DSFGs, which are relatively rare and predominantly found at redshifts $z>1$, remains challenging due to instrumental limitations. These limitations are largely overcome by the ALMA Large Program to Investigate [C II] at Early Times (ALPINE), a survey aimed at detecting the [C II] 158 μm fine-structure line and the associated FIR continuum emission in about one hundred star-forming galaxies within the redshift range $4.4<z<5.9$, selected from either the Cosmic Evolution Survey (COSMOS) or the Extended Chandra Deep Field South (E-CDFS).

Chapter 4, according to the author, is an "adapted version" of the refereed publication Sawant et al. (2025). It is my understanding that the previous chapters of the dissertation (Chapters 2 and 3) were also, at least in part, based verbatim on this publication, with possible updates and extensions. It is not clear to the referee whether the procedure of splitting an already published paper into various parts that then become parts of the dissertation is the correct practice, or whether the published work should instead be included in the thesis exactly as it appears in the journal (Astronomy & Astrophysics). I will therefore only note this issue here, assuming everything is formally correct.

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The presented work concerns modeling the baryon evolution in the ISM of galaxies from the ALPINE survey. The main goal of the modeling is to estimate physical parameters, including stellar, gas, and dust masses, as well as star-formation rates, of the studied systems. For this purpose, the galaxy SEDs were modeled with the CIGALE code, and the dust emission was handled through the composite IR template constructed by Burgarella et al. (2022) from a sample of about 30 high-redshift ALMA-detected galaxies (predominantly ALPINE galaxies). The author investigates whether and how the inclusion of this template affects the main conclusions, by comparing SED fitting of the targets with and without the IR template, and also by means of a mock analysis. The author concludes that, overall, when using the IR template the parameters are *"better constrained, especially in the derivation of dust masses"*. This is to some extent expected and, moreover, in my opinion, does not necessarily prove the robustness of the approach.

The whole procedure of finding the optimal values of the model parameters (initial gas masses, efficiencies of galactic inflow and outflow, dust growth efficiency in the ISM, etc.) for the analyzed galaxies, as presented in Section 4.3, is rather complicated and opaque, and the visual representation shown in Figure 4.3 does not necessarily help in this respect. It seems that, at first, N physical parameters are derived using CIGALE, while M models are generated based on the baryonic evolution model of Nanni et al. (2020; Section 2.1 of the dissertation). The resulting MxN matrix of predicted parameters is then subjected to chi-square minimization, from which the probability for each of the M models is calculated. Next, the mean of each of the N parameters is computed by weighting each model by its probability. With this procedure, the author proceeds in Section 4.4 to discuss the modeling results regarding particular model parameters (age, gas-to-star and dust-to-star mass ratios, mass inflow and outflow efficiencies, etc.) and model ingredients (Chabrier IMF vs. top-heavy IMF). These constrain the physical processes influencing gas and dust production and consumption in the ISM of the studied galaxies, including the relative importance of various dust sources (SN II vs. SN Ia vs. AGB stars vs. dust growth in the ISM), and the role of galactic inflows and outflows in shaping the chemical composition of the systems.

I believe the main conclusion is that combining SED fitting with chemical evolution modeling of the ISM can reproduce many of the observed properties of the ALPINE galaxies, but only when a non-standard (in particular: top-heavy) IMF is allowed in some cases. The author also notes that adopting a variable IMF — i.e., one that is allowed to vary with environment, redshift, or physical conditions, instead of being assumed universal — may help resolve tensions in dust, gas, and metallicity constraints.

The idea of a variable, non-universal IMF is further discussed in **Chapter 5**, which incorporates new James Webb Space Telescope (JWST) observations of ALPINE galaxies, in particular using the Hα-to-UV ratio method for a subsample of 18 ALPINE galaxies recently observed with JWST in near infrared. This, in my understanding, is still preliminary work in progress, but it is highly relevant due to the inclusion of the newest JWST data and the latest iteration of the CIGALE code. At this point, I will only note that while the main idea of a variable IMF seems generally quite reasonable, the concern is that allowing for a non-universal IMF within the broader framework of phenomenological modeling — which already involves many free parameters, arbitrary assumptions, approximate parameterizations of complex physical processes, and phenomenological correlations between multiple parameters — risks making the models even less predictive, particularly given the still relatively limited spectral coverage of high-redshift galaxies, even with JWST. Finally, **Chapter 6** summarizes the main conclusions of the thesis and outlines prospects for future work.

All in all, I believe that the PhD dissertation submitted by Prasad Sawant is a very good one. It showcases the author's technical skills in the field of galaxy modeling, particularly regarding baryonic chemical evolution and dust physics. Despite several critical points raised above in my review — which are either minor or reflect my personal perspective on a field in which I am not myself an expert — this is a solid piece of work, with an extensive list of citations to the most relevant and recent literature on the topic. The scientific results presented in the thesis, and published in the refereed paper Sawant et al. (2025), are highly relevant, as understanding baryonic evolution in galaxies in general, and in high-redshift galaxies in particular, especially in the context of dust production, remains one of the central topics in modern astrophysics. The author employs state-of-the-art observational data and numerical codes, and successfully navigates this complex and difficult problem. Accordingly, the dissertation fulfills the requirements for a PhD thesis, and I recommend its admission to public defense.

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Podsumowując, stwierdzam, że rozprawa doktorska złożona przez Prasada Sawanta jest bardzo wartościową i dopracowaną pracą naukową. Ukazuje ona zarówno umiejętności techniczne, jak i szeroką wiedzę autora w dziedzinie modelowania galaktyk, w szczególności w zakresie barionowej ewolucji chemicznej oraz fizyki pyłu. Pomimo kilku krytycznych uwag zawartych powyżej w mojej recenzji — mających charakter marginalny bądź odzwierciedlających mój osobisty punkt widzenia w obszarze, w którym nie jestem specjalistą — należy podkreślić, iż jest to znaczące dokonanie naukowe, oparte na bogatej liście odniesień do najistotniejszej i najnowszej literatury przedmiotu. Wyniki badawcze przedstawione w pracy, a także opublikowane w recenzowanym artykule Sawant i in. (2025), mają istotne znaczenie, gdyż zrozumienie ewolucji barionowej w galaktykach zarówno ogólnie, jak i w szczególności w przypadku galaktyk o dużym przesunięciu ku czerwieni, zwłaszcza w kontekście produkcji pyłu, pozostaje jednym z kluczowych zagadnień współczesnej astrofizyki. Autor umiejętnie wykorzystuje najnowocześniejsze dane obserwacyjne i kody numeryczne, podejmując się z powodzeniem analizy złożonego i trudnego problemu badawczego. W świetle powyższego stwierdzam, że rozprawa w pełni spełnia wymagania stawiane pracom doktorskim i rekomenduję jej dopuszczenie do publicznej obrony.

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