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Evaluation of the doctoral dissertation of M.Sc. Prasad Sawant

The doctoral dissertation of M.Sc. Prasad Sawant is entitled *"Probing the baryon cycle of primordial galaxies in the ALMA and JWST era"* and was carried out under the supervision of Prof. Ambra Nanni, with Dr. Michael Romano as auxiliary supervisor. The dissertation was prepared in English. The project concerns the evolution of galaxies at their early stage, with particular emphasis on the role of the interstellar and intergalactic medium in this evolution. The basis of the considerations are observations, since we are still far from a full understanding of the processes taking place there. The very phenomenon of dust formation still escapes full theoretical understanding, and dust plays a key role in the formation and evolution of stars, in a process where these two phenomena couple non-locally.

The dissertation is written as a new whole, although the concept is largely based on the published paper *"The ALPINE-ALMA [CII] Survey: Unveiling the baryon evolution in the interstellar medium of $z \sim 5$ star-forming galaxies"* (*A&A*, 694, A82, 2025), of which M.Sc. Prasad Sawant is the first author. The entire concept of the thesis and its relation to the above-mentioned publication is clearly presented at the beginning of Chapter 4 of the dissertation: the introductory elements from this publication evolved into Chapter 2 of the dissertation, where the topic is placed in a broader context. The data forming the basis of the dissertation are now discussed in Chapter 3 in a significantly expanded way, and the research results obtained by the doctoral student and published in the above-mentioned paper are presented in Chapter 4. Chapter 5 brings new, as yet unpublished results for a sub-sample of the objects from Chapter 4, supplemented with new observations from JWST. Conclusions and further research perspectives are presented in the final, sixth chapter. Below I discuss the chapters in this order.

Chapter 1 constitutes an introduction to the issue of dust evolution and its coupling with stellar evolution in the early Universe. The issue is very complex, since dust production is a result of stellar evolution, but stars also destroy dust, and the intermediary in these processes is not only the interstellar but also the intergalactic medium. The author briefly outlines the beginnings of the Universe and the ΛCDM cosmological model, and then proceeds to describe the key, and at the same time very complex, process of star formation. The introduction presents the historical background and the basic concepts, such as the initial mass function and the problem introduced by metallicity through the ability of plasma to cool. It also discusses the stage of reionization of the intergalactic medium associated with the formation of the first generations of stars. The effect must depend significantly on the inhomogeneity of the matter distribution already at this stage. One remark of mine – the possible role of active galactic nuclei was not mentioned. The author then discusses the dependence of the star-formation rate on redshift and, emphasizing its uncertainty for $z > 2$, links it with the determination of the dust content in galaxies. Next, he carefully discusses the properties of the multiphase interstellar medium and its active role in star formation. The summary presents the baryon budget in the Universe and a schematic model of its circulation. In the description the author refers both to earlier works and to the most recent results (the bibliography is very extensive). A separate, detailed thread is the description of emission lines and their role in determining the properties of matter in early galaxies. Emission lines are later used in the results presented in the dissertation, but it might have been worthwhile to mention in a few sentences the tracing of the medium's properties through the study of absorption lines. It is interesting why the [CII] 158 μm line is so intense. The chapter ends with a discussion of the properties of dust, crucial for the further parts of the dissertation, including an explanation of the distinction between extinction and attenuation. The chapter concludes with a list of problems that should be solved and which M.Sc. Sawant dealt with in his scientific work. In summary, I liked this chapter very much.

Chapter 2 presents in detail certain aspects of the method used to obtain the results. Here there is a general description of broadband spectral modeling methods, and the equations describing the evolution of gas and dust, which appear in the original published paper. The chemical evolution equations are essentially based on the equations from Nanni et al. (2020), but they were simplified from the integral form to an integrated form in a characteristic timescale τ_{main}, which might have been explained in some way. This timescale does not appear earlier. The outflow rate in equation 2.1 is parameterized by the SFR, which is intuitively clear, whereas the same parametrization appears in the inflow term of mass into the galaxy, which does not seem obvious. Such inflow is rather determined by the galaxy's environment, and I missed some justification here. The whole system of equations describing the evolution of individual components (gas fractions, dust fractions) is of course very complex and certain simplifications are necessary. In order to link the model with observations, the equations are formulated so as to provide information about the total dust mass and the luminosity of the object, making it possible to couple with broadband spectral modeling and confrontation with observational data.

In the following part of the work the author discusses the radiation arising in the galaxy (its components are stars, free gas and dust) and various approaches to modeling this process. In the later part of the dissertation (Chapter 4) the CIGALE code will be used.
There is an additional section on the role of active galactic nuclei in shaping the galaxy's spectrum. The role that AGN may play in the very evolution of the galaxy (so-called feedback) – through the possibility of regulating the star-formation rate (both positive and negative feedback may occur) – is not mentioned. And it is not taken into account in the results presented in Chapter 4.

I miss in this chapter an explanation of equation (20) from the original published paper by Sawant et al. The equation itself appears in Chapter 4, as equation 4.4, but again without additional explanation. Why does the final result come from (weighted) averaging over the model parameters, and not simply from the best fit? Combining probabilities can of course be justified, but it is not necessarily so. In the author's view, do all these parameters represent evolutionary scatter, or is the justification different?

Part of the modeling is explained only in Chapter 4, in particular the fact of using an infrared spectral template, which was surprising to me, since the selected objects come from fields covered by the Spitzer and Herschel instruments.

Chapter 3 presents the history of studies of star-forming galaxies at the earliest possible stage of the evolution of the Universe. It then discusses the ALPINE Survey, originally carried out several years earlier by a large team and first presented in Le Fèvre et al. (2020). This survey provides the observational basis for the work performed by the doctoral student and presented in Chapter 4. The survey originally presents results for 118 star-forming galaxies in the redshift range 4–6. The observations obtained with ALMA include the [CII] 158 μm line as well as the far-infrared continuum. The description given in the dissertation very clearly summarizes the source selection process, in a more concise and transparent way than the original paper by Le Fèvre et al. In particular, it immediately emphasizes the focus on two fields – COSMOS and ECDFS – because of the availability of multi-wavelength data. The chapter also discusses the ALPINE-CRISTAL and ALPINE-CRISTAL-JWST surveys (PI: Faisst), whose results are still in preparation. The doctoral student's preliminary results from the ALPINE-CRISTAL-JWST survey are presented in Chapter 5.

Chapter 4 contains a further discussion of the method and the actual results from the ALPINE ALMA-[CII] survey. The subject of Sawant's research was 98 objects from this survey, since that many satisfied the imposed observational criteria. In the analysis the author gave proper attention to the upper limits appearing for some of the measured parameters. The analysis method is presented in clear diagrams, and the assumed parameters or their ranges are listed in a table. The individual errors in parameter determination are large (e.g., Fig. 4.6), but the sizeable number of objects in the sample ensures that observed trends are visible.

All the objects were modeled, which made it possible to test a description of their evolution. Objects older than 600 Myr were relatively easy to model and not very sensitive to assumptions about the IMF shape. On the other hand, modeling younger galaxies (below 300 Myr) imposed strong constraints on the evolutionary scenario. The required IMF shape had to be top-heavy (with a predominance of massive stars relative to the standard model), and with efficient dust formation. It was also necessary to allow for significant mass outflow from the galaxy in order to explain the observed decrease in gas and dust relative to stellar mass with galaxy age. These results are very interesting.

It was very good that the author included here an example of the spectral modeling of one of the objects. Indeed, one can see a considerable gap in the data around where the emission peak falls (Fig. 4.4), though there is one point there, and this shows the importance of the assumed/determined dust temperature. The tests included in the thesis regarding the assumed SED shape (Fig. 4.2) suggest that it does not matter much for stellar or dust mass, though it may for the star-formation rate – here the scatter is large, and without an additionally assumed infrared spectral shape the values are much smaller.

In the summary of this chapter (Sect. 4.5) I am struck by the conclusion that dust should form mainly in the interstellar medium, and not in AGB stars. The doctoral student cites in this context the work of Alger et al. (2024), where the authors discuss in some detail the physics of this phenomenon – on the one hand the coagulation of dust grains in the dense ISM phase, and on the other the accretion of mantles onto dust grains, changing their optical properties. Thus this may indeed work, and at the same time constitute an argument for a very strong inhomogeneity of the ISM in young galaxies, which may connect with the earlier-mentioned by the doctoral student phase of reionization of the intergalactic medium as a result of such an inhomogeneous galaxy structure.

Chapter 5 is the outline of a new, very interesting work based on the ALPINE-CRISTAL-JWST survey. For a selected sub-sample from the ALPINE survey, observations were carried out with JWST in order to determine their spectra in the ultraviolet, optical and near-infrared in the rest frame of the objects. The author performed a detailed analysis of the images and spectra, identifying active regions of the galaxies. An example spectrum (Fig. 5.4) covers the range of the Hα and Hβ lines. Having at his disposal additional spectral information, the author repeated the broadband SED fitting using a newer version of the CIGALE code, but I do not know why this time excluding the far-infrared. This probably made the correct assessment of the dust role more difficult. Nevertheless, attenuation was basically taken into account, and the new element was additionally the inclusion of binary systems in the study, which was not applied in the previous chapter. The effect of the presence of binaries becomes visible in the SED modeling – the presence of binaries for some reason (honestly, I do not know why) enforces a much stronger role of attenuation. The description of the data analysis is detailed, showing the author's diligence in approach and his way of overcoming the various difficulties at this stage. In particular, a key measurement was the Hα-to-FUV ratio, and with its help the application of constraints on IMF models. In general, M.Sc. Sawant favors the so-called top-heavy model, but the exact results depend on the object, and thus, as other authors have already suggested, the IMF is not universal, and further detailed analysis of the dependence of the IMF on the dust content and on earlier strong starburst activity is necessary. The new observational data now make it possible to begin testing this.

Chapter 6 contains a brief summary of the dissertation – what has been achieved, and what remains to be studied in the issue under discussion. In particular, M.Sc. Sawant is not (and rightly so) yet fully satisfied with the description of dust formation at high redshifts and with the interpretation of the large scatter in the IMF associated with the dust formation process in very young galaxies. But the forthcoming new observational data provide the basis for further progress in this direction.

Summary

The dissertation concerns issues of great importance for astrophysics in the context of the early stages of galaxy evolution, at redshifts 4–6. The work is valuable, interesting, and of high scientific standard. The starting point is excellent observational data, obtained by an international team, but subsequently modeled by the doctoral student. The results show that dust formation is coupled with star formation, that mass outflow from young galaxies is an important element of their evolution through the relative decrease of gas and dust observed in somewhat older objects. A very important element emphasized by the doctoral student is the strong inhomogeneity in the mass distribution of young galaxies, which significantly influences their evolution and the scatter of properties, including the initial mass function of newly forming stars.

The work is editorially very carefully prepared, containing a list of abbreviations, a list of figures and tables, and the individual chapters are adorned with interesting and nicely formatted quotations.

In summary, the reviewed dissertation meets all the criteria appropriate for doctoral theses, which justifies the request for acceptance of the doctoral dissertation, admission to public defense, and continuation of the procedure of the doctoral degree of M.Sc. Prasad Sawant.

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