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Review of the Doctoral Dissertation by Mahmoud Hamed, entitled
"Dust Attenuation in Dusty Star-Forming Galaxies Using Spectral Energy Distribution"

The doctoral thesis of Mr Mahmoud Hamed, completed under the supervision of dr hab. Katarzyna Małek with the auxiliary advisor Junais, addresses a general problem related to correcting the observed UV/optical radiative output of cosmologically distant star-forming galaxies for dust attenuation. Specifically, the author focuses on determining the appropriate attenuation law to be used for different systems based on their evolutionary stages and other fundamental physical properties. The main body of work relies on modeling the broad-band (FIR—to—UV) Spectral Energy Distribution (SED) of galaxies, which includes the direct and dust-reprocessed starlight; in some cases, the diffuse synchrotron emission of the interstellar medium (ISM) at radio wavelengths is also considered. Through such detailed modeling, various fundamental properties of galaxies are estimated, such as their stellar and dust masses, star formation rates (SFRs), etc.

The thesis is written in English and is based on three first-author, peer-reviewed papers (Hamed et al., Astronomy & Astrophysics, 2021, 2023a,b), which comprise Chapters 2—4 of the dissertation. The thesis has been meticulously edited, and the overall English is of a high standard. However, a few confusing passages can still be found, e.g., *"Another crucial measurement in the context of galaxy evolution is the SFR. It is the most important baryonic event in galaxies, since stellar evolution is required in order to form the building blocks of galaxies."* (Section 1.3.2).

In the first introductory Chapter of the thesis, the author provides a brief overview of the multi-wavelength emission of galaxies, ISM dust attenuation and emission, as well as various methods enabling estimation of the

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main parameters of galaxies, such as stellar masses. This chapter is well-written; however, some sections appear to be too concise. For example, the author could provide more information on the PAH emission features (S1.1.3). Referring to stellar mass or SFR as “physical observables” (S1.4) is also questionable to some extent, as these parameters are not directly observable but are instead inferred or calculated based on the available data.

One issue is the absence of any mention in the introduction section regarding the non-thermal emission of star-forming galaxies, particularly the ISM-related gamma-ray production or the synchrotron radio emission. Additionally, my main comment pertains to S1.1.2, where the author explains the difference between dust attenuation and extinction as *“Loss of light due to absorption or scattering along the line of sight is referred to as extinction, whereas attenuation encompasses both extinction and the effects of obscure stars and scattering back into the line of sight.”* This explanation lacks precision. While it is true that attenuation includes the scattering of photons into the observation beam, the crucial aspect is that it considers multiple sources along the line of sight, which can be influenced by different columns of dust. In other words, the attenuation *“is defined as net loss of starlight that is due to complex radiative transfer effects of the underlying dust extinction properties and spatial distributions of dust and stars”* (Seon & Draine, 2016, ApJ, 833:201). Since the impact of ISM dust on the observed starlight of distant galaxies is a central focus of the submitted thesis, this issue could benefit from a more detailed and precise explanation.

Chapter 2 of the submitted thesis presents a study of a massive main-sequence galaxy Astarte and its less massive companion, Adonis, at a redshift of z~2. The radio—to—UV SEDs of the targets have been constructed using photometric data from various facilities, including CFHT, VISTA, Subaru, Spitzer, Herschel, and VLA. The SEDs were modelled using the CIGALE code developed by Boquien et al. (2019), with specific prescriptions for star formation history and dust emission, as well as with dust attenuation laws from either Calzetti et al. (2000) or Charlot et al. (2000; referred to as C00 and CF00, respectively). Through this modeling, the author estimated the stellar and dust masses of the two galaxies, as well as their SFRs. The analysis concluded that the massive post-starburst Astarte is currently undergoing quenching following an earlier starburst activity. In contrast, the lower-mass companion, Adonis, exhibits a strong starburst activity based on its measured SFR.

In addition, the author conducted an analysis of the 2.7mm ALMA data for the targets and successfully detected the CO(3-2) line at the redshift and position of Astarte. However, the author's statement in the thesis on page 30, claiming that *“The size of the CO disk is ~74 kpc”*, appears to be incorrect. Considering that a source at redshift z~2, marginally resolved by ALMA with a beam size of 0.78" x 0.56", would correspond to a physical scale of no more than ~8 kpc,

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the reported size seems inconsistent. If this is not a typographical error, it has implications for the estimation of the dynamical mass as presented in equation 2.3, resulting in a significant decrease, particularly by one order of magnitude, for a given disk inclination angle.

In Chapter 3 of the dissertation, the author investigates the correlations between dust attenuation laws and various physical parameters of dusty star-forming galaxies (DSFGs) at high redshift, detected using ALMA and Herschel in the COSMOS field. The selection of targets involved cross-matching the ALMA and Herschel Extragalactic Legacy Project (HELP) catalogs, while additional selection criteria were applied based on the quality of available multi-wavelength data. This included high signal-to-noise ratio ALMA detections enabling for proper image deconvolution, and good-quality images with the matching (sub-)arcsecond angular resolution from the third data release of Subaru's Hyper Suprime-Cam (HSC) y-band deep field continuum maps. In total, the final sample comprised 122 galaxies with high-quality SEDs within the redshift range of $1 < z < 4$, including 43 systems with spectroscopic redshifts.

The effective circularized radii of the galaxies on the ALMA and HSC y-band images, referred to as Re(ALMA) and Re(UV) respectively, were measured using the GALFIT package. The remaining physical parameters of the targets were estimated through SED fitting with the CIGALE code, utilizing various dust attenuation laws, namely C00, CF00, and Lo Faro et al. 2017 (referred to as LF17). It was observed that the C00 attenuation curve resulted in lower stellar masses compared to the other two attenuation models. However, the derived SFRs and dust masses showed relatively little sensitivity to the specific attenuation law used. Additionally, the author noted that the simplest C00 attenuation law appeared to be statistically favoured by galaxies with relatively small star-to-dust radii ratios. On the other hand, more complex CF00 or LF17 attenuation laws seemed to be required for galaxies with Re(UV)/Re(ALMA) > 3, indicating compact dust emission and extended stellar emission systems.

The main result of the analysis is the observed variation in the ratio of Re(UV) to Re(ALMA) across the redshift range in the analyzed sample of DSFGs, with a peak occurring around the cosmic noon ($z\sim2$). However, based on the error bars shown in the right panel of Figure 3.11, this effect does not appear to be statistically significant. Moreover, no statistical analysis supporting the claimed redshift evolution of the Re(UV)/Re(ALMA) ratio has been provided. In this context, my main comment/question pertains to whether the effective radii measured directly on the y-band HSC images of heavily dust-obscured galaxies are meaningful. It is worth considering whether the optical/UV maps of DSFGs should first be corrected for dust attenuation using ALMA templates before conducting the analysis with GALFIT.

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Finally, Chapter 4 of the dissertation focuses on the analysis of the IRX-β relation in star-forming galaxies at intermediate redshifts of $0.5 < z < 0.8$. The galaxies were selected from the VIMOS Public Extragalactic Redshift Survey (VIPERS), and additional photometric data from GALEX, Herschel, and Spitzer telescopes were incorporated. Systems with active nuclei or poor-quality data were excluded, resulting in a sample of 1,049 galaxies. Among them, 592 sources had far-infrared Herschel detections, and all galaxies possessed spectroscopic redshifts. For the selected systems, various properties were derived and measured. Gas-phase metallicities were determined from the detected emission lines, stellar masses and SFRs were estimated using SED fitting with CIGALE, Sersic indices and galaxy inclinations were directly measured from i-band CFHT images, and the galaxy environment was quantified through the galaxy density contrast (representing the difference between the local density at a comoving distance around each source and the mean density at a specific redshift).

The IRX-β relation represents a correlation between the UV spectral slope β, which serves as an indicator of dust attenuation, and the infrared excess (IRX), defined as the ratio between the IR and UV luminosities. In the analyzed sample of galaxies, the author estimated β by fitting a power-law function to the SED of each target in the rest-frame wavelength range of 0.126μm — 0.260μm. On the other hand, the IRX parameter was directly estimated from the SED fitting process by dividing the returned total IR luminosity by the FUV luminosity for each source.
It is important to note an inconsistency in the definition of IRX throughout the dissertation. For instance, in equation 1.6, it represents a simple luminosity ratio, while later in Section 4, it is defined as the logarithm of this ratio (equations 4.8-4.10). Subsequently, it is denoted as “log(IRX)” in the axis labels of Figures 4.5 and onwards.

In their analysis, the author observed a strong dependence of the IRX-β relation on gas-phase metallicity, as well as a significant correlation with the compactness of the galaxies quantified by the Sersic indices. However, no dependencies were found on the dust mass, galaxy inclination (edge-on vs. face-on systems), or galaxy environment. It remains unclear to the reader, on the other hand, what specific types of dependencies between the IRX-β relation and other galaxy parameters are being claimed or investigated. For instance, at one point, the author suggests that the scatter around the IRX-β correlation is determined by a range in metallicity. However, the provided Pearson correlation coefficients below demonstrate only a strong positive correlation between the stellar mass and the IRX parameter, or between the stellar mass and the β slope. Consequently, the most massive and metal-rich systems indeed occupy the top-right region in the β-IRX diagram, but the issue of a spread around the IRX-β relation, remains an open problem.

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Overall, despite the aforementioned comments and critical remarks, I consider Mr. Mahmoud Hamed's doctoral thesis to be a highly valuable contribution to our understanding of the broad-band emission of star-forming galaxies and their evolution. The three first-author papers, which form the core of the dissertation, undeniably demonstrate the PhD candidate's profound and well-established knowledge, particularly regarding the ISM dust attenuation problem. The candidate showcases familiarity with recent techniques in spectral analysis and modeling, utilizing state-of-the-art data from large astronomical surveys. I anticipate that Mr. Mahmoud Hamed's future research in the expanding and prominent field of galactic astronomy will have an even more significant impact within the scientific community. Therefore, I strongly recommend the acceptance of this dissertation for a public defense.

Signed by /
Podpisano przez:

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