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Review of the doctoral dissertation of **mgr. Subhrata Dey**, Faculty of Physics, Astronomy & Applied Computer Science, Jagellonian University, entitled "Panchromatic Spectral Energy Distribution modeling of infrared bright galaxies," conducted under the supervision of prof. dr. hab. Michał Ostrowski and dr. hab. Arti Goyal:

This dissertation concerns the topic of multi-band emission processes, including star formation, in IR-bright galaxies: the author models the far-UV to radio and radio-only spectral energy distributions (SEDs) of small samples of nearby Luminous and Ultra-Luminous InfraRed Galaxies (LIRGs and ULIRGs). These galaxies play a critical role in the Universe's star formation history, particularly at high redshift ($z \sim 1-2$), and detailed analysis of nearby U/LIRGs can serve as a template for their behavior in the high- z Universe.

I evaluate this dissertation positively: The topic is relevant, as it is important for the community to develop the resources to study U/LIRGs at high redshift, as those are the locations/times when major star formation occurred. Previous studies did not have as extensive broadband SED modeling on U/LIRGs, and radio-only SEDs have been relatively lacking, i.e., frequently did not make use of a lot of data < 1.4 GHz. The dissertation's innovations include 1) using dense sampling of multi-wavelength data for SEDs; 2) demonstrating the importance of low-frequency radio data in SEDs, considering absorption and more physical models, encompassing multiple emission regions, and using the Bayesian "Ultra-Nest" algorithm; and 3) developing a new model for low-frequency radio bending to implement in the CIGALE SED-fitting code.

The dissertation contains an introduction that demonstrates the author's awareness of U/LIRGs' place in the big picture of formation and evolution of galaxies in the hierarchical model. As the emission characteristics of star-forming galaxies and AGN are inherently complex and multi-wavelength, I like the introduction's description of how the dominant radiation mechanism evolves with time. Chapters 2, 3, and 4 describe the data collection, the radio-only SED fitting methodology, and the broadband, FUV–radio SED fitting methodology, respectively. Chapters 5 and 6 cover the SED fits to a sample of LIRGs and a sample of ULIRGs, respectively.

The results for radio-only SEDs include decomposition into thermal and nonthermal emission components to better estimate star formation rates (SFRs), and identification of spectral turnovers/bends, attributed in many cases to free-free absorption. Results for far-UV to radio SEDs include the following: estimates of IR luminosity, SFRs, dust content, stellar mass, and AGN fraction; these estimates are

generally consistent with previous results. The addition of radio data to the broadband SEDs helps to constrain dust luminosity and SFR more precisely. 1.4 GHz total and nonthermal luminosities and 4.8 GHz total, non-thermal, and thermal luminosities are found to be good estimators of the recent SFR for the LIRG sample, and for ULIRGs with weak AGN. Non-thermal radio indices do not correlate with redshift, stellar mass, dust mass, or SFR. AGN fraction in ULIRGs is not observed to depend on morphological class.

There are applications for future studies of star-forming galaxies, given upcoming radio surveys from e.g., SKA, and the upcoming sparsity of far-IR observatories. In addition, the SEDs of high-redshift star-forming galaxies tend to be relatively less sampled, so conclusions about low- z sources can inform studies of star formation, AGN fraction, etc. at high z .

The results presented here have already been published in two papers published in *The Astrophysical Journal*.

I have some comments and questions which I hope can be addressed by the author:

§1: *Introduction*:

– §1.2.1, p. 9: "The contributions from fainter discrete sources ... are well-correlated with the star formation rate or stellar mass of galaxies." A citation or two here would be beneficial to the reader.

– §1.2.1, p. 9: "The accretion disk itself may contribute directly to the X-ray emission." A bit of clarity is needed here: If the author referring to thermally-emitted continuum emission, then this statement is true for Black Hole X-ray Binaries (e.g., §3.3 of Remillard & McClintock 2006, *ARA&A*, 44, 49), but not Seyfert AGN (e.g., Gierliński & Done, 2004, *MNRAS*, 349, L7). If the author is referring to a relativistically-blurred reflection component from the inner disk (e.g., J. Crummy et al., 2006, *MNRAS*, 365, 1067; J. Garcia et al., 2013, *ApJ*, 768, 146), then this is a true statement. The Turner & Miller (2009) citation listed does not seem directly relevant.

– §1.2.2, p. 10: Grammar correction needed: "Young ionizing stellar populations, emitting predominantly in the UV range."

– §1.2.3: A quick note regarding the AGN torus: "The presence or absence of broad emission lines in the optical spectra of AGN, which categorizes them into type 1 or type 2 AGN, respectively, is ... related to the observer's viewing angle to the torus – face-on or edge-on, respectively." To be nit-picky, I would just add that for a clumpy torus, viewing a type 1 or a type 2 AGN is a viewing-angle-dependent *probability* (depending on whether or not there exists a clump to intersect one's line of sight to the Broad Line Region, e.g., Nenvoka et al. 2008, *ApJ*, 685, 160), while the "face-on/edge-on" dichotomy applies only for the smooth donut shape.

§2: *Data*:

– In those few individual cases where a ULIRG's AGN fraction is large, the use of non-simultaneously-obtained data may be a potential issue for IR SED constraints, given that most AGN are inherently moderately variable in their IR luminosities on timescales of several years and longer. Variations of ≥ 0.2 magnitudes are not uncommon (see e.g., Fig. 5 of S. Son, M. Kim, & L.C. Ho, 2023, *ApJ*, 958, 135). This is a potential source of mild bias to check and/or bear in mind when SED fitting; it could also contribute to relatively higher values of χ^2/dof .

§3: *Radio-only SED modeling*:

– §3.2.2: Regarding model selection: Would use of the Akaike or Bayesian Information Criteria help

here? (see e.g., §5.2 of J. Buchner et al. 2014, A&A, 564, A125)

§4: *UV/IR/Radio SED modeling with CIGALE:*

– §4.2.2 (description of single stellar populations): The Salpeter IMF was used in the CIGALE SED modeling. But out of curiosity, would alternate IMFs (such as those that flatten towards low stellar mass) have any significant impact on results?

§5: *LIRGs: radio-only SEDs; FUV–radio SEDs:*

– Are there spectra with measurements of the $9.7\mu\text{m}$ Si feature in the sample that can be used to help constrain SKIRTOR torus parameters?

– p. 58: "...residuals are often related to strong emission lines, visible for the nebular model." Were optical/UV spectra available for the targets for model constraints or for verifying the origin of such residuals?

– As listed in Fig. 5.3, many values of χ^2_{red} are formally very high; could this be an indication that systematic uncertainties were underestimated? In addition, in most cases, the data/model residuals from one point to the neighboring point are not correlated. However, 4 out of 11 LIRGs in Fig. 5.3 and 6 out of 14 ULIRGs in Fig. 6.2 display systematic trends in their data/model residuals from 70 to $600\mu\text{m}$ (decreasing with increasing λ). Is this an artefact of differing apertures? Does one need steeper-spectra dust-emission or AGN-emission components across this wavelength range?

– Sorry if I missed this, but for each target, when did the most recent burst of SF occur? (I did not see best-fit values of e.g., τ_{burst} , f_{burst} listed in Ch. 5.)

– In §5.6.9, Eq. 5.6 (estimation of SFR from $L_{1.4\text{GHz}}$), why not use $q_{\text{IR}} = 2.34$, the mean value for your sample, derived in §5.6.1?

§6: *ULIRGs: radio-only & FUV–radio SEDs:*

– In §6.6.4 and 6.6.5 (thermal fractions), it is suggested that the similarity in the values of TF between ULIRGs and LIRGs is inconsistent with the expectation that ULIRGs should have higher values of TF (due to higher SFRs), but lower values of TF in ULIRGs could be due to extra absorption of ionizing photons by dust. This seems like an arbitrary and ad hoc solution; can this mechanism please be explained more quantitatively (i.e., relatively higher dust levels in ULIRGs leading to decreases in TF to the same level as in LIRGs)?

– In §6.6.7 (Optical morphologies), Fig. 6.7c, SFR_{IR} vs. L_{dust} , the text notes that for both samples, the values derived from SED fits agree with those expected from the Kennicutt (1998) relation. However, it looks to my eyes like ULIRGs and merging LIRGs agree with this relation extremely well, while the non-merging LIRGs agree only loosely, with all targets having relatively lower SFRs (albeit only by factors of a few). Is there an explanation for this divergence?

§7: *Summary & future prospects:*

– A key application of the results is using radio-based modeling to study SFRs at high redshift. Are there any potential differences between the radio emission properties of the local and the high- z U/LIRGs that may bias such an exercise?

– A wide variety of radio emission models are needed across the U/LIRG samples. Does this fact yield any big-picture implications for galaxy evolution?

References:

– There are a few incomplete entries in the reference list, e.g., Done 2010, Reynolds & Nowak, Rosati, Turner & Miller, and Worrall.

In summary, I find the thesis work to be a valuable contribution to the field of the study of IR-bright galaxies, including measurements of star formation and assessments of their multi-band emission properties, and it meets the criteria for a doctoral dissertation. I am happy to recommend that this dissertation be admitted to a public defense.

A handwritten signature in black ink that reads "Alex Markowitz". The signature is written in a cursive, slightly slanted style.

dr. hab Alex Markowitz
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