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Review of the doctoral thesis of Gabriele Riccio entitled „The star formation activity of galaxies: multi-wavelength constraints based on Spectral Energy Distribution fitting”

Summary of the thesis

Star formation rate (SFR), the measure of the rate at which a galaxy is forming stars, is a key parameter in characterisation of galaxy evolution.

Chapter 2 presents the test of the spectral energy distribution (SED) fitting based on simulated data from the Large Synoptic Survey Telescope (LSST) in order to learn which parameters can be derived reliably. The author found that due to the lack of ultraviolet and mid-infrared coverage, these data will be insufficient to measure SFRs, but they are an accurate proxy for stellar masses. This leads to the conclusion that the relation between stellar mass and attenuation may be used to aid the SFR estimation.

Chapter 3 presents the analysis of low-mass X-ray binaries (LMXBs) in globular clusters (GCs). The author found more LMXBs in red and bright GCs and that a red GC is more likely to host an LMXB if it is closer to the centre of a galaxy.

In Chapter 4 the author modelled X-ray emission detected by the eROSITA satellite in order to confirm the correlation between X-ray luminosity and SFR.

Contribution to the field

The recommendation how to use the LSST data will be useful, because most of the galaxies uncovered with its survey will not have detections at other bands with other telescopes. The analysis presented in this thesis allows the determination of important galaxy properties accurately.

The thesis presents the first analysis of LMXB in GCs in the intra-cluster medium, as opposed to GCs inside galaxies. This allowed the author to draw a conclusion about the LMXBs formation channel in GCs depending on the host-galaxy environment. It would be advantageous for the thesis to elaborate on the importance of this finding for the understanding of the formation of XRBs and galaxy evolution in general, i.e. how these results can be used in these contexts.

eROSITA is a new mission, so the value of the SFR-L_X analysis is that it allows the further multi-wavelength studies. In particular, it is quantified in the thesis that the completeness corrections are crucial for the investigation of every relation involving X-ray luminosity derived from these data, especially beyond low redshift.

Below I point out the weaknesses of this thesis with the aim of helping to improve the future work.

Metallicity used in the SED modelling

Table 2.2 lists the parameters used in the SED modelling, stating that the Solar metallicity was adopted for all models. Metallicity is almost impossible to be constrained from the broad-band photometry, but a more accurate measurement of other parameters (and especially their uncertainties) are obtained if this parameter can have a wider range of values. In this way the age-metallicity degeneracy is taken into account. This is especially important at the upper end of the considered redshift range ($z = 2.5$), at which we cannot expect all galaxies to have the Solar metallicity. This issue should be at least acknowledged in the thesis.

Sample selection

In terms of the sample selection, I have the most severe reservation for section 2.9.1 which describes the outlier selection. The author removes from the sample galaxies for which the stellar mass estimation from the full SED modelling disagrees with that from modelling the optical bands only. Then in the main analysis it is found that the stellar mass estimation from the full SED modelling agrees with that from modelling the LSST bands only, which are in the optical. This sounds like a circular argument and the agreement may be a mere consequence of removing galaxies for which the estimates disagree. In the real-case scenario this outlier selection will not be possible, because then there will be no full SED modelling, just the LSST modelling. The fraction of removed galaxies is low, so probably this does not influence the results, but it would be worth adding a description of what would happen if these galaxies were kept in the analysis.

In section 2.4.3 passive galaxies are defined as those with specific SFRs of $\log(\mathrm{sSFR}/\mathrm{yr}^{-1}) < -11$. The main-sequence evolves with redshift, so the passive galaxy cut should also go up with redshift, in a similar way, as the starburst selection evolves. However, I acknowledge, that the number of passive galaxies in the sample is low, so this would not change any of the results.

In section 2.5.1 only galaxies detected in all six LSST bands are analysed. This selection removes red galaxies (dusty and/or old). It would still be valuable to investigate how LSST will perform for them with several non-detections.

Finally, I was not convinced that cutting the parent sample to include only the main-sequence galaxies is adequately justified. Again, it would be interesting to see how the fit to the LSST photometry would perform for starburst and passive galaxies, even if they constitute only a small fraction of the parent sample.

Explanation of the SFR overestimation

In section 2.5.2 the author states that the overestimation of SFRs when using only the LSST data is the lack of ultraviolet (UV) data, so at higher redshifts the situation improves due to the LSST bands being shifted to the rest-frame UV. This is inconsistent with the results presented in section 2.5.3: for GALEX-detected galaxies, adding the UV data only marginally improves the overestimation. I suspect that the way CIGALE (or SED-fitters in general) works is the reason for the overestimation. Maybe the priors are set to give too much weight for solutions with high dust attenuation (and therefore high resulting SFRs). High-redshift galaxies are on average more dusty, so for them this is not a problem. IRAC data at $z \sim 0$ corresponds to wavelength regime connected with dust-obscured star formation (hot dust and PAHs), so adding this filters gives the missing information of how much light is obscured and results in better SFR estimates (Fig. 2.9). Adding IRAC fluxes at higher redshift does not change anything because they correspond to the rest-frame optical.

This scenario can be tested by fitting $z \sim 0$ galaxies with set of filters which would correspond to the LSST rest-frame wavelength coverage for $z \sim 2$ galaxies (only rest-frame ultraviolet). If the scenario put forward in the thesis (that the UV data is important) is correct, then in this experiment there should be no SFR overestimation for these $z \sim 0$ galaxies.

Why adding SPIRE fluxes does not improve the overestimation is a bit strange, but it may be due to low signal-to-noise of these data. The comparison of full and LSST-only SED models on Fig. 2.5 shows that the far-infrared peak in the LSST-only case is too high only by 50%, so this overestimation can still persist even when the SPIRE data are added, which then does not improve the SFR estimation. This can be easily tested by generating SPIRE data with better signal-to-noise ratios (for example similar to those for IRAC data) and checking if with such data the SFR overestimation disappears.

SFR mock analysis

I do not understand the reliability test presented in section 4.5.1. How were galaxies 'with known physical parameters' generated? Was CIGALE used to generate photometry from the best-fitting model and then to re-fit this new photometry? If so, then this is not a proper test, because if one starts from similar photometry twice, then one is guaranteed to obtain similar results.

A similar comment applies to section 4.6.3, when mock analysis for X-ray luminosities of various components is presented. It is not sufficiently described how this analysis was performed.

The use of SFRs from Hα

I find the analysis of the SFRs from Hα in section 4.5.3 not robust enough. In particular I disagree with the statement that "the majority of the galaxies that scatter from the 1:1 relation are classified as Seyfert or LINER". Fig. 4.6 shows that SFGs and composite galaxies follow exactly the same trends as the two other classes. Therefore, I do not think that SFRs from Hα should be used instead of those from the SED modelling.

The scatter of the main-sequence

The dividing line between the starbursts, normal and quiescent galaxies is somewhat arbitrary. However, adopting a dividing line of 1.3 dex (a factor of 20), as done in Section 4.5.4 is a huge overestimate. The scatter of the main-sequence is not that big, it is usually measured at 0.2–0.3 dex (a factor of ~ 2). In other words, a galaxy ten times above the MS is clearly a starburst, and that a factor of ten below the MS is clearly passive, as opposed to the selection adopted by the author.

This distinction is important for the analysis, because later the star-forming and passive galaxies are treated differently, so this needs to be corrected.

Minor comments

I have several minor comments.

- The section numbering mentioned at the end of section 2.2 is wrong. This repeats in other parts of the thesis, so I suspect some of the labels are defined multiple times.
- In Fig. 2.6 the dashed lines are at ± 2 dex, so they represent a hundred, not two times above and below the main-sequence. They should be at ± 0.3 dex. A similar comment applies to Fig. 4.7. There the caption correctly states that the lines are 1.3 dex above and below the main-sequence, but the labels are "x1.3" which suggests a factor of 1.3.

Conclusion

I conclude that this thesis represents a valuable contribution to the field of galaxy evolution and star formation and therefore I recommend granting the doctoral degree to Gabriele Riccio.

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