Galaxy Physical Properties in View of Euclid - *Literature Review*

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1 INTRODUCTION TO GALAXY FORMATION AND EVOLUTION

Galaxy formation is the result of many factors: dark matter, gas and stars, as well as the cosmology in which these lie. Through observationally probing the properties of galaxies at a variety of distances, it is possible to unlock key information about the processes of formation and evolution over cosmic time, in tandem with theoretical modelling. For example, accurately age dating galaxies can be valuable in helping to understand the state of the universe at very specific snapshots. Another example of observational probes to cosmology would be the evolution of galaxy mergers over cosmic time: which gives an idea of the evolution of DM halos and thus some more constraints on selecting a viable cosmological model (e.g. ΛCDM, ΛWDM etc.).

The study of galaxy formation and evolution has been studied observationally, through many different surveys: VIMOS-VLT Deep Survey (VVDS), CANDELS, COSMOS, DEEP2, GOODS, SDSS to name just a few.

Even for surveys with a cosmological motive, e.g. BOSS, eBOSS, DES, LSST, WiggleZ and Euclid, galaxy properties must be determined in order accurately probe cosmological parameters.

The field of study that is galaxy formation and evolution is still a comparatively young one, but has grown at an incredible rate due to the efforts of its contributors as well as the interest from cosmology

2 STELLAR POPULATION SYNTHESIS

Stellar population synthesis (SPS) has been a valued technique in the field of astrophysics used to model the behaviour of galaxies (or any other stellar population for that matter). Originally ideated by Beatrice Tinsley during the late 1960's and 1970's, the concept of modelling stellar populations by using stellar evolution as a basis to constrain properties of the whole population is an ingenious way to probe extragalactic populations which can't be resolved in single stars.

Since simple populations such as those by Renzini & Voli (1981), the quality and accuracy of stellar population models has grown to become a great analogue from which to compare and understand observations. Such is the case in the converse, allowing for the make-up of galaxies, and stages of stellar evolution to be fleshed out into the complex systems we recognise them to be today. One notable example of this is shown in Maraston (2005), in which Maraston presents a new evolutionary population synthesis (EPS) code which crucially improves the quality of observational correlation in opposition to the contemporary norm by placing much more emphasis on the TP-AGB phase of stellar evolution. Another is displayed in Renzini & Buzzoni (1986), in which the entire basis for which we understand post-main sequence stages was found to be more aptly evaluated through 'fuel-consumption theory'. These are just a couple of examples of how the field of galaxy formation and evolution has been advanced in the last 30 years.

3 SPECTRAL ENERGY DISTRIBUTION (SED) FITTING

For probing cosmology, as well as drawing accurate galaxy physical properties, obtaining accurate redshifts is crucial in order to recognize the rest-frame spectra of galaxies. Using spectroscopic methods, this is fairly simple and reliable. However, the time consumption of spectroscopy makes it infeasible in some larger surveys. Although SDSS has achieved this, note that the median galaxy sample redshift is $z \sim 0.1$. It is valuable, then, to develop a method of constraining accurate redshifts based on photometry. This idea has been used notably by Baum (1962), Couch et al. (1983) and Koo (1985) for low redshifts. Increased interest came with the development of larger-scale high-z surveys (e.g. Hubble Deep Field (HDF)). *Empirical training set* methods of photometric redshift techniques were developed to meet this demand (Connolly et al. 1995, 1998; Wang et al. 1998). However, problems arose in the flexibility in filters with this method: each time a new filter set is chosen, the desired parameters must be recalculated on a newly selected set of real spectra. Additionally, the bright training set didn't instill much confidence in its ability to determine the redshifts of fainter (and potentially higher-z) galaxies.

This is where the idea of *SED fitting* comes in. SED fitting takes into account the overall spectrum of an object as well as key features within it (e.g. Lyman break at 4000 in rest-frame). 'Observed' (or indeed, model) spectra are directly compared to known templates in the same bands, and a best-fit is drawn. A popular example of this is *HyperZ* (Bolzonella et al. 2000), which is still widely used today for fitting procedures. The core of the fitting success is based purely on the χ^2 of the template vs. observed:

$$\chi^2(z) = \sum_{i=1}^{N_{filters}} = \left[\frac{F_{obs,i} - b \times F_{temp,i}(z)}{\sigma_i}\right]$$

where $F_{obs,i}$, $F_{temp,i}$ and σ_i are the observed and template fluxes and their uncertainty in filter i, respectively, and b is a normalization constant.

By fitting a template SED to observations, one can infer galaxy properties (e.g. age, metallicity, SFR, redshift) based upon the input physics used to create the template with the lowest χ^2. This elegantly allows one to create *full* spectra based upon data from a few photometric bands.

Pforr et al. (2012, 2013) show how fitting codes (here, *HyperZ*) can be used in tandem with *mock* galaxies. EPS codes such as that of Maraston (2005) (M05) can be used to make synthetic SEDs with known physical properties (age, metallicity, reddening, mass, SFR) to be treated as observed data. SED fitting can then be carried out, and through comparing the input physics to the derived properties, the robustness of observations and fit can be understood. The use of mock observations here allows one to test the robustness of prospective observations, due to being able to use the proposed filters of a certain observation (this is discussed further in Section 4).

Pforr et al. (2013) concludes that a *broad* wavelength coverage is crucial in the robustness of determining galaxy properties when redshift is unknown. This is because strong spectral features (e.g. Lyman break) are key in finding a good fit, and such features will be easier found with a larger wavelength coverage so that these can be observed at the rest-frame (especially when considering a wide range of redshifts). Quantitatively, the effect of wavelength coverage when recovering redshift can be seen in Figure 4 of Pforr et al. (2013). Interestingly, for some higher-z observations, it is found that sometimes neglecting some filters can help with the recovery of some physical properties. For example, star formation rate can be misconstrued due to a phenomenon known as *outshining* discussed in Maraston et al. (2010) and neatly illustrated in Figure 12 of the paper. This affect is explored more directly in relation to SED fitting in Pforr et al. (2012), and can be seen in Figure 8 of this paper.

4 OBSERVATIONAL EFFORTS

Since HDF-N and HDF-S in particular, the idea of photometrically resolved spectra has gained a lot of interest as a more efficient way to get many redshifts efficiently from a larger survey. This was, in fact, the aim of *HyperZ*. Since then, many other SED fitting codes have been developed (e.g. *FIREFLY*, *GOSSIP*, *pPXF*), some of which employ a 'Bayesian inference' method to determine properties, as well as neural-networks.

Looking forward, *Euclid* (a ESA survey with the primary objective of probing weak lensing and large-scale structure), will observe ~10 billion objects out to z ~2 over 15,000 deg^2 of extragalactic sky. Reference spectra will be observed to match 50 million of these objects using the on-board slitless spectrograph. Due to the high-z nature of Euclid's survey, it will be particularly valueable to the fields of galaxy formation and evolution (lookback time ~ 10^{10} years). Naturally, this much data at high redshift will be invaluable to the community, and is unprecedented.

There is potential caveats to the nature of Euclid, however. Particularly, in the broadband filter coverage (see Figure 1), which has taken some secondary consideration in comparison to the resolution of data. This is due to prioritising resolution over coverage since the objective is primarily to calculate galaxy shear. This is problematic for scientists interested in inferring galaxy properties with the data, for the reasons discussed in Pforr et al. (2013) and in the SED fitting section here. To counter this, ~1,000 nights of ground-based observations are planned on several world-class telescopes to complement the gaps in the photometry.

Many other observations have been tested like HDF (one example in DES (Guarnieri et al. 2019)) to pre-emptively simulate results in the relevant broadband filters and find out what kind of results are expected, as well as some idea of the best SED fitting codes to use. Using the Euclid filters to see what kind of results could be obtained on a simulated data prior would be a useful exercise in considering these same questions for its data. This prospective look at the specific Euclid filters is yet to be produced in the literature.

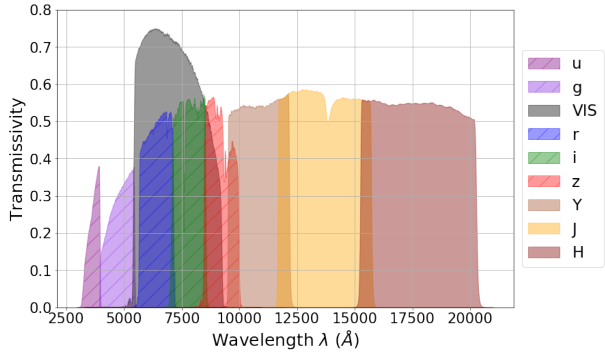

Figure 1. *Euclid* photometric bands. Note that *u, g, r, i* and *z* bands will be observed through complementary ground observations (shown as hatched regions here). Euclid will observe in *VIS, Y, J* and *H* . Note also that *VIS* will be too wide to contribute to the resolution of photo-z, and is there to provide morphology information for galaxy shear calculations. Thanks to Claudia Maraston for the filter data.

Gaining an idea of the properties that could be inferred from the real data, as well as a discussion on the best methods by which to make the most of this data, would be of value to the scientific community, whom intend to use this data. Euclid is set to launch in June 2022.

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