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Formation and evolution of the stellar content of galaxies in the J-PAS era

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Abstract

Our first goal is to explore the potential of the Javalambre Physics of the Accelerating Universe Astrophysical Survey (J-PAS) to study the formation and evolution of the stellar content of galaxies up to $z \sim 1$. For this aim, we have tested and developed a new set of techniques and tools, including spectral energy distribution (SED) fitting and Artificial Neural Network (ANN) codes, to constrain a wide range of galaxy properties (e.g. age, metallicity, extinction, stellar mass, equivalent widths, etc.) by solely using the photometric data from the miniJPAS survey. Our results point out that our techniques along with J-PAS-like data are able to yield reliable stellar population parameters. In fact, we demonstrate that these properties can be used to conduct a large variety of modern and ambitious research projects such as the cosmic evolution of the star formation rate (SFR) density, the role of environment for quenching galaxies, the non-universality of the initial mass function (IMF), the radial variation of the stellar content properties of galaxies in clusters, and the evolution of the luminosity and stellar mass densities since intermediate redshift.

1 Introduction

During the last decades, state-of-the-art multi-filter surveys imaging large areas of the sky with a combination of narrow, intermediate, and even sometimes broad bands (e.g. [14, 1, 3]) offer a complementary and alternative pathway to tackle a lot of topics in Astronomy, such as galaxy formation and evolution studies ([4, 5, 6, 7, 9]). These kinds of surveys typically offer very large samples of galaxies across large areas of the sky without any selection effect other than the depth of the detection band. Indeed, multi-band imaging opens the possibility of performing pixel-by-pixel studies of galaxies, as long as these are larger than the point spread function (PSF) of the system, that is, without pre-selection or aperture effects due to the use of fiber or integral field spectrographs. All this motivates us to explore the potential of such surveys and the development of methodologies to address the assembly and distribution of the stellar content of galaxies up to $z \sim 1$.

Very recently, the Javalambre Physics of the Accelerating Universe Astrophysical Survey (J-PAS, see [1]) started to image more than 8000 $\deg^2$ of the northern sky making use of the wide-field JPCam camera and its unprecedented photometric system (see [1, 2]). This photometric system comprises 54 narrow-band filters with a full width at half maximum of $FWHM\sim$ 145 Å (equally spaced every 100 Å), two high-pass filter extending to the UV and near-infrared ends, and one broad band ($i_{\rm SDSS}$), which results in an effective optical range of 3500–9300 Å. Thanks to this configuration, the typical photometric redshift (photo-z in the following) errors of J-PAS galaxies are expected to be of the order of $\sigma_{\rm NMAD} = 0.013$ with an outlier rate of $\eta = 0.39$ at $r < 23$ (see [11]). In this regard, we expect that more than $\sim 5\,200$ galaxies per $\deg^{-2}$ will exhibit an accuracy of $\sigma_{\rm NMAD} = 0.003$ and $\eta = 0.05$, which can be used for detecting baryon acoustic oscillations. In the meantime, the J-PAS collaboration members have been using a previous survey referred as miniJPAS (further details in [2]) for testing the potential of J-PAS and performing a first scientific exploitation of the data. In brief, miniJPAS comprises a stripe of 1 $\deg^2$ in the AEGIS field with the J-PAS photometric system and the JPAS-Pathfinder camera, whose photometric catalogue is complete at $r_{\rm SDSS} = 23.6$ and $r_{\rm SDSS} = 22.7$ for point-like and extended sources, respectively. For our particular aims, we primarily used the miniJPAS dataset to set constraints on the precision and accuracy of the stellar population properties of J-PAS-like galaxies, as well as to perform a first data exploitation and prepare all the techniques and methodologies until its first data release. All this with the ultimate goal of performing galaxy evolution and formation studies of various kind up to $z \sim 1$.

2 Determination of stellar population properties in J-PAS

Our analysis techniques for the determination of the stellar population properties of galaxies are mainly based on SED-fitting codes combined with the use of Artificial Neural Networks techniques (ANNs). In our group, we are making use of the SED-fitting codes of both MUFFIT (MUlti-Filter FITting code) and BaySeAGal ([4] and [9], respectively) to constrain the commonly used galaxy properties of age, metallicity, extinction, stellar mass, rest-frame luminosities, star formation history (SFH), etc. along with uncertainties. For the analysis, MUFFIT adopts non-parametric composite models of stellar populations (mixtures of two simple stellar population models, i.e. combinations of SSPs) and the full photo-z probability distribution function (zPDF) provided by the J-PAS collaboration (details in [11]), whereas BaySeAGal adopts a parametric SFH (delayed-τ model) and the zPDF maximum.

On the other hand, the J-PAS filter set comprises a large number of narrow bands that allows us the detection of emission lines in a wide redshift range. However, and owing to the J-PAS resolving power (equivalent to $R \sim 60$), when a flux excess resulted from nebular emission is detected, eventually we are not able to discern the contribution of each of the emission lines contained in the band by a traditional way (e.g. Hα and [NII], [OIII] and Hβ). For this reason, we worked on ANN algorithms for both the identification of emission line galaxies (ELGs) and constrain the equivalent widths of Hα, Hβ, [NII], and [OIII] up to $z = 0.35$ (details in [12]). These ANN models were confronted and trained with synthetic photometry obtained from SDSS, MaNGA, and CALIFA high-quality spectra.

Moreover, we have been working on complementary methodologies to extend our analysis techniques to study the stellar content of spatially-resolved galaxies. For this aim, we created the tool `Py2DJPAS` that automatically downloads the multi-band images of spatially-resolved galaxies from the J-PAS database, to subsequently carrying out a PSF homogenization, masking of foreground/background sources, and segmentation of the different regions of these galaxies (details in [15]). The fluxes obtained from the different regions and bands will be used as inputs of our SED-fitting codes and ANN models to explore the distribution of the stellar population properties across galaxies.

3 Stellar population studies in the J-PAS era

After the SED-fitting analysis of all the miniJPAS galaxies, our results point out that we are able to constrain stellar population properties of galaxies with a similar precision that those obtained by spectroscopic surveys of similar signal-to-noise ratio (S/N, further details in [9]). As a reference, the expected precision for the age and stellar mass of miniJPAS galaxies with $S/N \sim 10$ is of the order of 0.07 ± 0.03 dex and 0.16 ± 0.07 dex, respectively. We also find that the miniJPAS galaxies exhibit a bimodal distribution of galaxies (i.e. quiescent and star-forming galaxies, [5]) in the stellar mass versus $u_{\mathrm{JAVA}} - r_{\mathrm{SDSS}}$ rest-frame colour diagram. This is more remarkable after correcting this colour for extinction, which reveals that the stellar population properties of galaxies are tightly related to their position in these kinds of diagrams (see also [6]). Finally, the cosmic evolution of the star-formation rate density obtained by our SED-fitting results and the miniJPAS galaxies at $0.05 \leq z \leq 0.15$ is in very good agreement with results obtained in previous works with spectroscopic data (see left panel in Fig. 1). Therefore, there is evidence that the use of proper techniques with this kind of data combined with other approaches as the fossil record methods can yield very potential studies involving stellar evolution properties of galaxies in a wide redshift range.

Thanks to the observing strategy of large-scale multi-filter surveys and the great J-PAS photo-z precision, a huge number of galaxy clusters and groups (along with all their galaxy members up to the limiting magnitude of the catalogues) are going to be detected with a low contamination of foreground and background sources. This allow us to explore the role of environment on galaxy evolution with great detail up to $z \sim 1$. In [10], we found that the fraction of quiescent/red galaxies is higher in galaxy groups than in the field by a factor that ranges from < 10 % to 60% at stellar masses of 10^{10} and $10^{11.5}$ $M_{\odot}$, respectively. Moreover, the fraction of miniJPAS star-forming galaxies in the field that are quenched per unit of time or galaxy quenching rate (R_i) relies on redshift (see right panel in Fig. 1). On the other hand, there is a massive galaxy cluster in miniJPAS dubbed mJPC2470-1771 ($R_{200} \sim 1300$ kpc, $M_{200} \sim 3 \times 10^{14}$ $M_{\odot}$, and $z = 0.29$) that allowed us to study the distribution of the integrated stellar population properties of galaxies as a function of the cluster-centric radius (see [16]). After the SED-fitting and ANN analyses of the cluster members, we conclude that there is also an excess in the fraction of red galaxies with respect to the field, which in turn typically lie on the inner parts of the galaxy cluster. In fact, only half of the galaxies within the $0.5 \times R_{200}$ region are star forming, while the less massive, blue and young galaxies are mainly placed at a cluster-centric radius larger than $0.5 \times R_{200}$ (see Fig. 2).

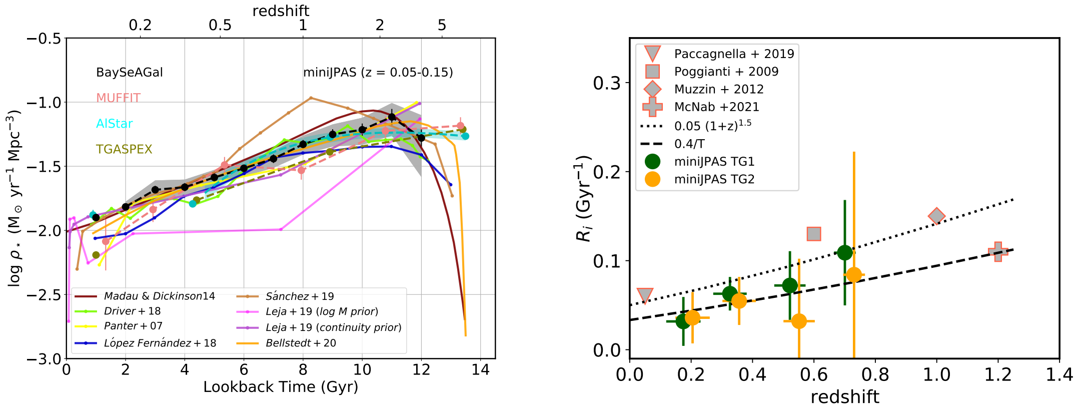

Figure 1: *Left panel*, cosmic evolution of the star formation rate density obtained from miniJPAS galaxies at $0.05 \leq z \leq 0.15$ with MUFFIT and BaySeAGal (coral and black dots, respectively). *Right panel*, evolution with redshift of the galaxy quenching rate of miniJPAS galaxy groups for two definitions of transition galaxies. Figures from [9, 10], respectively.

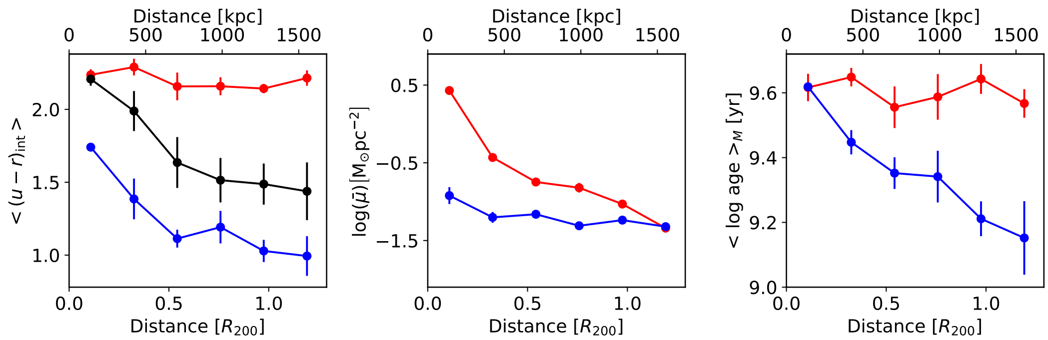

Figure 2: Stellar population properties as a function of the cluster-centric radius in the miniJPAS galaxy cluster mJPC2470-1771. *From left to right*, $(u - r)$ rest-frame colour corrected for extinction, stellar mass surface density, and mass-weighted age for star-forming and quiescent galaxies (blue and red lines, respectively). Figure from [16].

By the ANN algorithms, we were able to study the EWs of the ELGs in miniJPAS (see [13]). In particular, we focused our research on the simultaneous measurements of the Hα, Hβ, [OIII], and [NII] emission lines, which limited our work up to $z = 0.35$. Otherwise, the Hα would be redshifted out of the wavelength range imaged by the J-PAS photometric system, but this means that other emission lines may explored at higher redshift. According to the so-called BPT diagrams, we identified around 1800 ELGs in the miniJPAS footprint that were classified as star-forming (80 %), composite (14 %), Seyfert (5 %), and LINER (1 %) in good agreement with other spectroscopic works (e.g. those based on SDSS spectra, see left panel in Fig. 3). The ionization mechanisms were also explored via WHAN diagrams and the cosmic evolution of the SFR density obtained from Hα and Hβ EWs of miniJPAS galaxies is in good agreement with previous studies (details in [13]).

Furthermore, we carried out preliminary tests to explore the non-universality of the IMF. For this aim, we recently updated the MUFFIT code to include the IMF slope (Γ, where a Salpeter-like IMF equals 1.3) as another free parameter. Firstly, we tested the results obtained by other authors using IMF-sensitive indices and we ran MUFFIT with one red massive galaxy (ID 2470-10239) at the nearby universe (i.e. a spatially-resolved candidate likely presenting an excess of low mass stars according to spectral indices). As a result, we found that this galaxy's SED is compatible with a bottom-heavy IMF, especially in their inner parts (see right panel in Fig. 3). However, the number of spatially-resolved, red, and massive galaxies is very limited in miniJPAS as to confirm this fact in a statistical way.

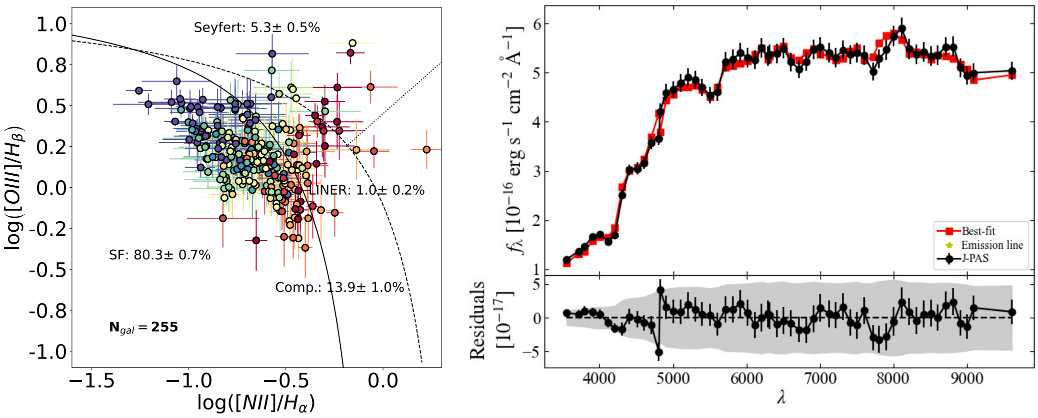

Figure 3: *Left panel*, BPT diagram obtained with the ANNs developed in our group for miniJPAS galaxies at $z \leq 0.35$ and errors lower than 0.2 dex. Redder colours illustrate more massive galaxies (figure from [13]). *Right panel*, SED of a red and massive miniJPAS galaxy (black solid line, ID 2470-10239), best-fitting model (red solid line), and residuals obtained with MUFFIT, which is compatible with a bottom-heavy IMF of slope $\Gamma = 2.0 \pm 0.5$.

Finally, we developed a robust and statistical methodology to include both the J-PAS zPDF and the stellar population parameters obtained from our codes to ultimately constrain the evolution of the stellar mass and luminosity functions of galaxies up to $z \sim 0.7$ (details in [8]). This makes the most of the MUFFIT code and it accounts for all the uncertainties and correlations of the involved parameters, the spectral-type classification, the sample completeness, selection bias, etc. Making only use of the MUFFIT results, the cosmic evolution of the stellar mass and B-band luminosity functions and densities obtained for the miniJPAS galaxies are in good qualitative and quantitative agreement with results from both spectroscopic and deeper photometric surveys (see Fig. 4).

Once the J-PAS survey is finished, this will include millions of ELGs and regular galaxies, $\sim$ 100k spatially-resolved galaxies at $z < 0.1$, hundreds of thousands of groups and thousands of clusters of galaxies at $z < 1$ that will allows us to perform very promising studies involving stellar population properties, environment, and emission lines; which can be used to carry out galaxy evolution and formation studies in a reliable and statistical way up to $z \sim 1$.

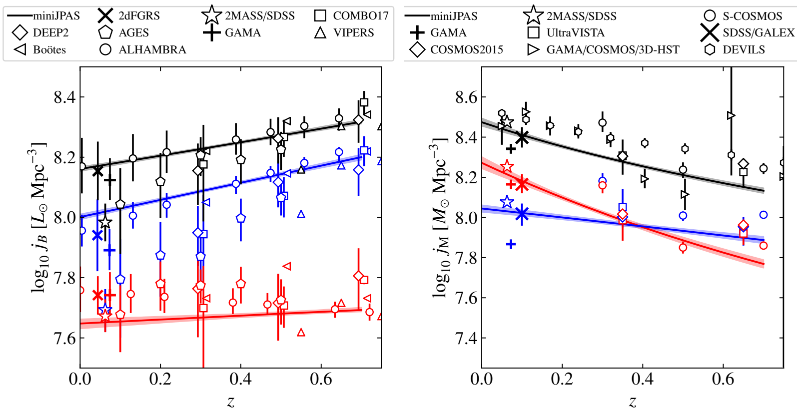

Figure 4: Evolution of the B-band luminosity and stellar mass densities for all, quiescent, and star-forming miniJPAS galaxies (black, red, and blue, respectively). Figures from [8].

Acknowledgments

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