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SALT and SUNBIRD: Young massive star clusters and superwinds in strongly star-forming galaxies

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An overview of ongoing research on luminous infrared galaxies, LIRGs, is presented. A sample of approximately 40 such strongly star-forming galaxies have been studied with adaptive optics imaging using VLT and Gemini, and the galaxies then followed-up with a uniform SALT spectroscopic survey. Two different long-slit configurations were used, often with multiple slit orientations. The project investigates the LIRG histories, their stellar populations and abundances, and the gradients thereof, galaxy wide gas inflow and outflows, and their super star cluster population characteristics. Some early results are presented with motivation for the various aspects of this large SALT survey.

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1. Introduction: The SUNBIRD survey

Luminous infrared galaxies (LIRGs, $10^{11}L_\odot \leq L_{IR} \leq 10^{12}L_\odot$) in the local Universe combine strong dusty star-formation (SF) with various levels of nuclear activity. They are more diverse regarding morphology, mode and location of SF than ULIRGs ($L_{IR} \geq 10^{12}L_\odot$) which tend to be remnants of gas rich major mergers with a centralised starburst and AGN. Local LIRGs appear to be closer analogs of the bulk of high-z SF [1]. The nearby cases are thus a very interesting laboratory to study universal processes of galaxy transformations, the evolution and sequence of SF in these objects, its triggering, SMBH growth and interplay with the hosts. In the SALT project presented here we concentrate on the metallicity and SF (history) of LIRGs as a function of interaction stage and environment, on galactic scale gas flows, and use super star clusters as tracers of triggered extreme star formation.

We recently finished a survey of approximately 40 LIRGs using adaptive optics (AO) NIR imaging with VLT/NACO, Gemini/ALTAIR/NIRI, and the superb wide field capability of multi-conjugate AO on Gemini/GEMS. These instruments deliver images with a spatial resolution perfectly complementing archival HST optical data. The survey is dubbed *SUperNovae and starBursts in the InfraReD*, *SUNBIRD*, for the twofold science aim: we searched for very obscured core-collapse SNe close to the nuclei of star-forming galaxies to determine the total SFR in the local universe (see e.g. [7, 4, 14]) and study the LIRGs themselves using SALT, which often provides constraints for the SN characteristics as well. The sample galaxies are at distances ranging from 40 to 180 Mpc, they are at various stages of merging, interaction, or isolation and provide a statistical representative sample of nearby LIRGs.

The science of SUNBIRD/SALT survey, in particular, concentrates on the galaxies themselves. We completed a uniform spectroscopic survey of the targets using RSS through several SALT semesters from early 2012 through to end of 2014. Two setting were used. With $R \approx 1000$, the PG900 grating served as a stellar population, metallicity, and gas-phase ionisation information generator. Nearly all important emission and absorption lines needed for the analysis were obtained in one setting from $[OII]\lambda 3727$ to Hα. The PG1800 grating yielding $R \approx 3500$ at the Hα+[NII] region was our main kinematics/dynamics tool, while also providing the redder emission lines ($S[II]\lambda 6731$) for gas densities, and the Na D doublet for cool ISM characteristics and gas flows. Many targets were observed with two slit positions covering either major and minor axes, or aligning the slits across interesting morphological features based on the AO-imaging, or over companion galaxies.

2. Goals of the survey with early results

The analysis of the SALT data are still ongoing. Two PhD theses and a post-doc project have been involved at various stages and different aspects of SUNBIRD. In the following, we present motivation for the different aspects of the science being done with the data, and in some cases show first and/or early results.

2.1 Super star clusters

The part of the project furthest along is that of studying the super star clusters (SSCs). They

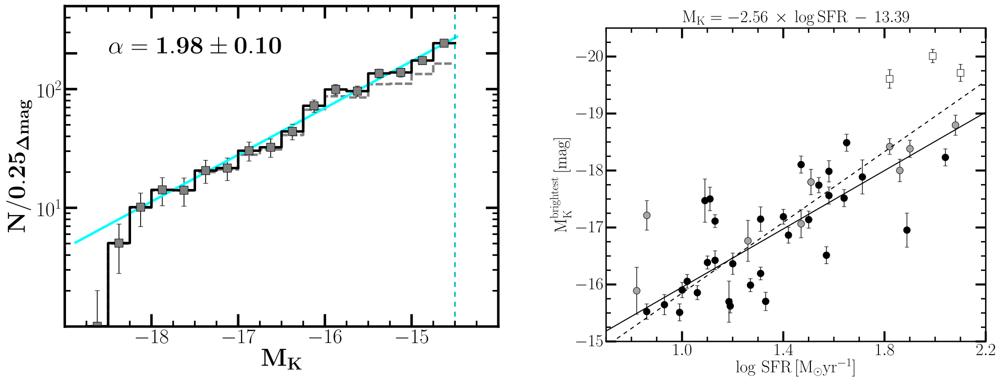

Figure 1: *Left:* K-band SSC LF of the whole LIRG sample. The single power-law fit of the data points is represented by the solid line while the vertical line marks a completeness level of -14.5 mag. *Right:* A correlation is seen between the NIR brightest star cluster magnitude and the SFR of the galaxy. A weighted linear fit to all the data, including the three most distant targets at $D_L > 150$ Mpc shown as open squares, is represented by the dashed line. The solid line fits the $D_L \leq 150$ Mpc targets labeled as circles; those at $D_L \leq 100$ Mpc are black and those at $100 < D_L \leq 150$ Mpc are grey.

represent the youngest and most massive form of known gravitationally bound star clusters in the Universe, and are found in abundance especially in environments that trigger strong and violent star formation - such as interacting LIRGs. How do these environments exactly produce star clusters of masses $> 10^6 M_\odot$? A very interesting question about SSCs is their connection to Globular Clusters (GC). Are SSCs the GC progenitors? Their masses are similar. If so, where and why do they disappear, since GCs in the modern day universe are not nearly as abundant in galaxies? It is clear they disrupt and dissolve rapidly, but in which environments do they survive?

We are studying the SSC populations in our sample as a function of SFR and type of host galaxy, interaction stage, etc., in an effort to constrain cluster mass functions, the formation, evolution, and disruption of SSCs, which all have relevance to star formation laws in general. As a first step we studied the K-band Luminosity Functions (LF) - a sub-sample was published in [9]. We constructed the K-band SSC luminosity functions (LFs) of the sample. The values of the power-law slopes range in between $\alpha = 1.5 - 2.4$. The median and average of the indices are 1.86 ± 0.24 and 1.92, respectively [11]. Out of the 34 constructed CLFs, 65 % have flatter distributions with $\alpha < 2$. Fitting a single power-law function to the LF of the *combined* dataset down to a $M_K = -14.5$ mag gives a slope $\alpha_1^{con} = 1.98$ with a formal uncertainty of 0.10 (left panel of Fig. 1).

One of the most important results of this work revealed that starburst galaxies have shallower slopes than normal spirals where $\alpha \approx 2.4$ [19]. We suggest that strongly star-forming galaxies such as LIRGs host SSCs that are disrupted in a way depending on their mass or environment. This would result in a smaller value of the power-law index α of the cluster LF. In fact, we find a weak correlation between α and the SFR. Note, however, that star clusters with different ages were binned together while drawing the LFs, and a better way to study the mass-dependencies is to construct true mass functions (MF) and to determine their ages. Another interesting avenue we are pursuing is to investigate whether or not the values of α vary with the different merging stages

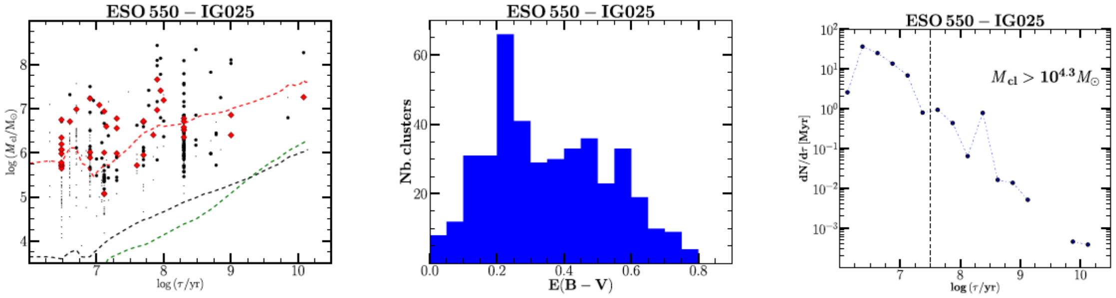

Figure 2: Mass and age modelling of SSCs in the case of ESO 550-IG025. *Left:* The cluster age-mass planes from the χ^2-fit. Black points are the objects with $\sigma \leq 0.35$ in all four $UBIK$-images, whereas the dots are those below the error cutoff but in UBI-filters only. The dashed lines denote the photometric detection limits ($\sim 80\,\%$) considering B- (green), I- (black), and K-band (red) evolutionary tracks. *Middle:* The distribution of best-fit extinctions of the SSC candidates. SALT spectral information about metallicities and extinctions in different areas of the galaxy are used as constraints in the SSC modelling. *Right:* Star cluster frequency dN/dτ as a function of age. Three different lower mass limits were considered to derive various formation rates of the observed clusters.

of our targets.

We also correlated the luminosity of the brightest cluster to the host SFR [10]. We found a positive correlation between the brightest cluster magnitude and the galaxy SFR (right panel of Fig. 1). It can be expressed as $M_K^{brightest} = -2.56 \times \log \mathrm{SFR} - 13.39$. We discussed statistical interpretations of the relation, in particular the size-of-sample effect. This simply means that it is more likely for more luminous clusters to form in an environment with extreme star formation activity. However, we also showed that the scatter in the relation is smaller than expected purely from statistics, thus hinting that physical interpretations may also be needed to explain the relation and its scatter. The effects of the galactic environments on cluster formation efficiency, or/and possibly other internal cluster effects such as the mass-luminosity relation are likely to play an important role. Apart from an estimate of the star cluster physical properties, determining the exact roles of the environments and the galaxy reddening would be the next steps required to fully understand the relation. For this step, SALT spectra are needed to provide the host galaxy properties.

The second phase of the SSC project requires the mass and age determinations of the thousands of detected SSCs. Our own NIR photometry is combined with HST optical images, whenever available, and new star cluster catalogues are derived based on optical detection. We compared Yggdrasil and Starburst99 SSP models [20, 6] with the observed SEDs to fit the cluster age, mass, and extinction of starburst-dominated galaxies. A large fraction of the star cluster populations have ages younger than 30 Myr. The cluster masses of the interacting systems are generally between $10^4 - 10^8\,M_\odot$ (an example is provided in Fig. 2). Such values are quite massive compared to the mass ranges associated with star clusters hosted in more quiescent environments. At least one of the LIRGs has its star cluster population disrupted in a mass-dependent manner. A similar case, also using the combination of HST imaging and SALT spectroscopy, is seen in a curious case of SSCs in a starburst ring in a small early type galaxy (see [2, 17]). We look for such physically interesting signals from the turnover in the LFs, any truncation of the cluster MFs, and the distribution of the cluster frequency in age (right panel of Fig. 2). The next steps of this work would be to correct the cluster mass functions from observational incompleteness and to derive accurate values of Γ on global and local scales.

2.2 Metallicities and stellar populations

The nuclear metallicities of (U)LIRGs are under-abundant compared to other galaxies of similar luminosity and mass, presumably because lower metallicity material from the outskirts of the progenitor galaxies flows in during the interaction [13]. Simulations predict that both central abundances and the magnitude of metallicity gradients are anti-correlated with gas richness and SFR of the progenitors and also that these relations change over interactions stages. Observations, however, are scarce to-date. There is only one study measuring abundance *gradients* in interacting (U)LIRGs [12]. Our sample is larger, and we are able to correlate the gradients with environment, merger stage, and the onset of strong SF. We will check whether the environmental divide of LIRGs found in [15] extends to their metallicities. Metallicity gradients are connected to gas outflows and inflows, which are key aspects of galaxy evolution thought to both trigger and quench SF in core regions. Indeed, both neutral and ionised gas flows are ubiquitous in our data set.

In deriving the spatially resolved metallicities, we use, iteratively, the latest calibrated empirical strong-line methods. Only in one or two cases the temperature sensitive [OIII]λ4363 is detected and a direct method of abundance calculations is possible. Spatially resolved information on line ratios across the galaxies is also important in disentangling SF and any AGN contributions, since shock heated gas can masquerade as AGN signal when mixed with SF.

Deriving the histories of stellar populations is a central goal of the SUNBIRD/SALT project. The lower resolution PG900 spectra are ideal for the purpose. While on-going SF characteristics and gas-phase metallicities are based on emission lines, the full RSS spectrum is modelled to find characteristic ages, histories, and metallicities and extinctions of the underlying stellar populations. The spectral stellar population fitting packages ULySS [5] and STARLIGHT [3] are used with various input population synthesis templates. This part of the project is described in more detail by [8] in these proceedings.

Figure 3 shows an example of the lower resolution RSS data, a spectrum of the star-forming galaxy ESO 221-008 which exhibits some blue compact dwarf type characteristics. Modelling in this case reveals two strong peaks of starbursts, a very recent one on top of a 100–200 Myr old population. Morphologically this galaxy breaks up into hundreds of super star clusters, with possible recent merging activity consistent with the starbursts.

2.3 Gas flows

Galaxy scale gas flows are an essential part of the modern picture of galaxy evolution (e.g. [18]). Many key observables need gas outflows and/or inflows in the models explaining them in the cosmological build-up of the galaxy population seen today — these include for example the deficit of galaxies at both the high and low mass ends of the mass function, the origins of metallicity gradients and the mass-metallicity relation, relations between bulge and SMBH mass, interplay of the enrichment of the intergalactic medium and cool accretion feeding star formation, and so on.

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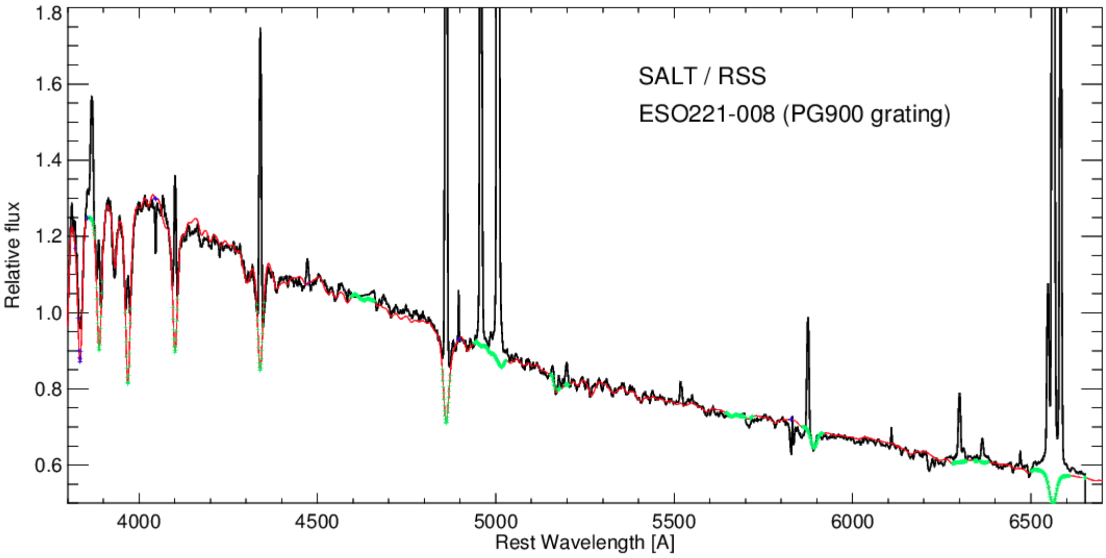

Figure 3: SALT/RSS spectrum of one of the galaxies in the SUNBIRD sample. The black curve is the data, while the red one shows a best-fit Starlight continuum model. The wavelength sections shown in green are blocked out from the fit due to emission lines. The end results is a 1/5 Solar metallicity irregular system, likely merging, with a strong 6 Myr old starburst on top of another burst 100–200 Myr ago, while most of the mass is in a much older central concentration.

Though there has been a considerable effort in characterising gas flows in X-ray, optical, and sub-mm, the physical details of the flows beyond the main bodies of galaxies as a function of galaxy type, SFR, and environment are still remarkably sketchy.

The higher resolution SALT/RSS spectra were taken specifically to study the complex gas flows of our LIRG targets. The primary goal is to characterise the kinematics of both the warm and cool gas. Multiple Gaussian fits to the emission lines reveal distinct components of the ISM. The right panel of Fig. 4 shows an example of a two component fit to the central area of a galaxy. Relatively narrow line components such as here are due to large HII regions. In this case the bluer component is outflowing with some 350 km/s offset from the systemic central velocity and has shocks contributing to the line ratios.

Though not seen in the example above, a very ubiquitous feature in our sample is a *broad* velocity component of the Hα line indicating strong superwinds up to many hundreds of km/s, often over the whole body of the galaxy and beyond. The line ratios of the broad high velocity components often suggest shock contribution and contain information on gas mixing processes.

Regarding the cool gas component, it is determined using Na D absorption. This feature traces neutral gas flows near the wind base and we can compare these with emission line tracers of the warm ionised outflows. If the wind is significantly mass loaded — essential for feedback models — we then expect HII emission from the entrained gas. We measure kinematics as a function of distance to chart the development of the wind — e.g., cosmic ray pressure could allow winds to accelerate above escape speed outside of the main bodies of starbursts. Na D is often seen blue-shifted with respect to the disk of the galaxy. An example is shown in the left panel of Fig. 4, a very distinctive double feature blue-shifted approximately 300 km/s from the systemic velocity of the galaxy. The profile of the doublet can be fitted to measure the optical depth, and the outflowing gas mass, and the mass loading factor, which combined with the SFR are crucial parameters for feedback effects in galaxy evolution.

To constrain wind models further, it is important to establish where the winds originate and how far they actually reach, as well as the presence and kinematics of tidal debris — these features have not been studied systematically to date in (U)LIRGs.

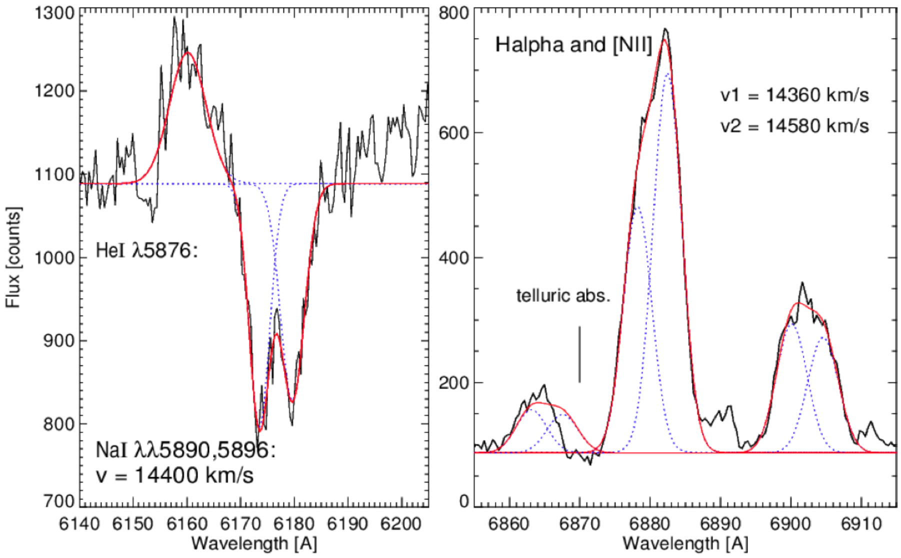

Figure 4: Gas flows in IRAS 19115-2124, a pilot study of LIRGs using RSS [16]. *Left:* Na D absorption doublet showing that the cool neutral ISM is outflowing from the galaxy at approximately 300 km/s line-of-sight velocity. *Right:* The Hα region from the same galaxy, showing the blue wing of the ionised gas approximately matching the outflowing neutral gas velocity, and indicating shock heating, while the bulk of the Hα emission originates from the gas disk at the systemic velocity. Black curves are data, blue shows individual velocity components, and red the total fit.

2.4 Overall evolution of the LIRGs

To put together the picture of the evolution of the LIRG systems, their kinematic and dynamic state are determined from the higher resolution spectra and combined with the stellar population information. An example of the analysis is the case of the very first SALT/RSS observation during early commissioning of the instrument, a LIRG system. An unexpected third minor component which dominates the SF of the whole galaxy system was found [16]. SF characteristics/histories are correlated to the dynamics of the components and kinematics of the interactions including the nuclei and tidal features, as well as characteristics of the inflows and outflows of both cool and ionised gas. The age/spatial distributions of the SSCs will add an important constraint on the evolutionary picture. Individual exciting cases may be followed up by Fabry-Pérot observations.

3. Summary

Luminous IR-galaxies provide a useful laboratory to study a variety of key phenomena related to galaxy transformation. These include star formation triggering, interplay between starbursts and super massive black hole growth, the effects of interactions between galaxies and feedback processes related to galaxy wide winds. The SUNBIRD/SALT project studies these processes with a sample of approximately 40 LIRGs. The data set include adaptive optics imaging and spectroscopic observations using SALT/RSS. The SALT data are specifically used to determine the metallicity, extinction, and stellar populations characteristics of the sample, to study the gas inflow and outflows of both cool and warm ISM, and to provide constraints on the modelling of photometry of the super star cluster populations found in the host galaxies. Among the various paths of science being analysed with the data currently, we for example see globular clusters being born and destroyed, and see star formation quenching happening in detail.

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