Stellar velocity dispersion of luminous compact galaxies at intermediate redshift

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ABSTRACT

We present the stellar velocity dispersion measurements for five luminous compact galaxies (LCGs) at z = 0.5–0.7. These galaxies are vigorously forming stars with an average star formation rate of ~40 M⊙ yr⁻¹. We find that their velocity dispersions range from ~137 to 260 km s⁻¹, while their stellar masses range from 4 × 10⁹ to 10¹¹ M⊙. If these LCGs evolve passively after this major burst of star formation, their masses and velocity dispersions, as well as their evolved colours and luminosities, are most consistent with the values characteristic of early-type spiral galaxies today.

Key words: galaxies: evolution – galaxies: kinematics and dynamics – galaxies: starburst.

1 INTRODUCTION

Luminous compact galaxies (LCGs; Hammer et al. 2001) are starburst galaxies at intermediate redshifts mostly detected in both ultraviolet and infrared wavelengths. They are characterized as having small effective radii (R_e < 5 kpc), high luminosities [M_Λ(B) ≤ −20] and strong emission lines. Hammer et al. (2001) observed a representative sample of LCGs selected from the CFRS fields using the intermediate resolution (R > 600) spectrograph FORS1 and FORS2 on the VLT/Kuyen telescope. The spectra revealed some strong absorption lines (Ca II K and H, G band, Fe I and Balmer lines) as well as narrow and intense emission lines ([O II]λ3727 Å, [O III]λλ4868, 5007 Å Balmer lines). The spectrophotometric analysis of these galaxies (Hammer et al. 2001; Gruel 2002) has shown that they are likely to be composed of three different stellar populations. The youngest population presents strong emission lines ([O II]λ3727 Å Balmer lines), indicating present-day active star formation and subsolar metallicity. A second stellar population was formed within the last few hundred million years. It is characterized by a solar metallicity and the presence of Balmer lines in absorption. The third population, older than 5 Gyr, exhibits solar metal abundances and strong metallic absorption lines (calcium, iron lines, O band, titanium, etc.; Gruel 2002).

Almost all LCGs analysed by Hammer et al. (2001) have large extinction coefficients (A_v ~ 1.5), yielding average extinction-corrected star formation rates SFR ~ 40 M⊙ yr⁻¹ (which is ~10 times higher than those estimated from the ultraviolet fluxes; Hammer et al. 2001; Gruel 2002). Some LCGs show morphological irregularities and/or close companions, as revealed in Hubble Space Telescope (HST) images (Hammer et al. 2001; Zheng et al. 2004). These observations suggest that LCGs could be undergoing violent star formation events similar to those occurring in close interacting systems. Hammer et al. (2001) concluded that these LCGs might be the progenitors of the bulges of spirals galaxies forming inside-out.

A new parameter to shed light on the local counterparts of LCGs is the galaxy’s kinematics. Measurements of the Hβ emission-line velocity widths for the LCG sample of Hammer et al. (2001) show low velocity widths of ~70 km s⁻¹, suggesting that they might be low-mass objects (~10⁹ M⊙). Hα velocity widths for a handful of LCGs, measured with ISAAC at the VLT (Tresse et al. 2002), show a ‘double horn’ profile characteristic of rotation. Puech et al. (2006) also used integral spectroscopy to measure the velocity field for some LCGs using GIRAFFE at the VLT. However, because of the small apparent size of these objects, the velocity map extends only over very few spaxels.

The most reliable measurement of galaxy kinematics is the stellar velocity dispersion from absorption lines. In this paper, we present the first velocity dispersion measurements from absorption lines for five LCGs at intermediate redshift. We constrain our study to the spectral range that includes the Balmer lines ([Hα], [Hβ], [He I]), the calcium doublet Ca II K and H and the G band. In Section 2 we present the data set for our galaxy sample. In Section 3, we describe the methods used to measure the velocity dispersion, the photometry and the stellar masses of these galaxies. Section 4 contains the results and a discussion. We assume the following cosmology in this paper: H₀ = 70 km s⁻¹ Mpc⁻¹, Ω_m = 0.7 and Ω_Λ = 0.3.

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2 DATA

2.1 Sample selection

The galaxy sample was selected from three Canada–France Redshift Survey (CFRS) fields: CFRS 0000+00 (Le Fevre et al. 1995), CFRS 0300+00 (Hammer et al. 1995) and CFRS 2230+00 (Lilly et al. 1995). Intermediate-redshift LCGs were selected using criteria defined by Hammer et al. (2001): size (r1/2 ≤ 5 h−1 Mpc), luminosity [MAB(B) ≤ −20.0], redshift (0.5 ≤ z ≤ 1) and the presence of a major star formation episode characterized by an [O II]λ3727 Å emission line with an equivalent width EW([O II]λ3727 Å) ≥ 15 Å. This results in a sample of 32 LCGs, or 29 per cent of the most luminous [MAB(B) ≤ −20.0] galaxies found in the three CFRS fields (Gruel 2002). We observed 22 of these galaxies with the FORS/R600 and I600 spectrograph at the European Southern Observatory 8-m VLT/Kueyen at a resolution of FWHM = 5 Å (Hammer et al. 2001; Gruel 2002). The typical exposure times were 12 000 s per object.

We reduced the spectroscopic data by using the MEASURE software described in Gruel (2002).

In this paper, we analyse a subsample of the LCGs with the highest signal-to-noise ratio (S/N) and the strongest absorption lines, for which measurements of stellar velocity dispersion are feasible.

3 METHODS

3.1 Velocity dispersion measurements from the absorption lines

Velocity dispersion was measured with the program MOVIE, included in the REDUCEME software package (Cardiel et al. 1998). The instrumental resolution of our LCG sample is FWHM ∼ 5 Å (σins ∼ 100 km s−1). The lowest velocity dispersion measurable with this instrumental resolution is σ ∼ 70 km s−1 for spectra with S/N > 10 (Matković & Guzmán 2005). Thus, we selected galaxies from our LCG subsample with S/N ≥ 10 per resolution element. The S/N criteria reduced the LCG sample to only five objects. The final sample is given in Table 1.

Because the original aim of the observations was to analyse emission lines, we did not observe stars that we could use as templates. Therefore, we created our own series of stellar templates with the same instrumental resolution as the LCGs.

We used stellar templates from the MILES spectral stellar library (Sánchez-Blázquez et al. 2006; Falcón-Barroso et al. 2011), which includes stars observed between 2001 July and 2002 December in La Palma (Spain) at the Isaac Newton Telescope. These templates are the basis of our galaxy template. Because their resolution is higher (∼2.5 Å FWHM) than our sample of galaxies (R = 600), we convolved them with a Gaussian kernel. The characteristics of the Gaussians used for the convolution were determined from the difference between the instrumental resolution of the galaxies and the stellar data base. The instrumental/spectral resolution of the individual LCGs was determined from the sky spectrum obtained with the same slit as the spectrum of the galaxy. The intrinsic dispersion of the instrument is given by

\[ \sigma_{\text{inst}} = \frac{\text{FWHM}_{\text{sky}}}{2.35} \times \frac{1}{\lambda} \times c. \]

The value of the Gaussian function used to broaden the stellar template is the quadratic difference of the instrumental resolution of our observations and that of the stellar library:

\[ \Delta \sigma = \sqrt{\sigma_{\text{inst}}^2 - \sigma_{\text{inst}}^2} \]

(see Fig. 1).

The use of a stellar data base to build stellar templates by convolving the instrumental resolution to one’s own observations has already been successfully demonstrated for early-type galaxies by Treu et al. (1999, 2001a,b). These studies proved that at any given S/N and resolution, there is a lower limit to the velocity dispersion that can be measured. Typically, this limit stands at half the instrumental resolution of a given galaxy spectrum at low S/N (Bender, Burstein & Faber 1992). All measurements with a S/N < 10 per resolution element are deemed unreliable. Treu et al. (2001a) and Matković & Guzmán (2005) quantified the errors for different S/N and a range of velocity and showed that the systematic error for a galaxy with S/N ≥ 10 and a velocity dispersion of 150 km s−1 is ∼15 per cent.

![Figure 1. Example of one stellar spectrum (22.0637) (solid line) with the best broadened stellar template fit (dashed line) obtained with MOVIE. The different absorption lines used are labelled.](http://example.com/figure1.png)
Velocity dispersions for the galaxies were measured using the MOVEL and OPTEMA algorithms described by González (1993). The MOVEL algorithm is an iterative procedure based on the Fourier quotient method (Sargent et al. 1977) in which a galaxy model is processed in parallel to the galaxy spectrum. The main improvement to the procedure is introduced through the OPTEMA algorithm, which is able to overcome the typical template mismatch problem by constructing, for each galaxy, an optimal template as a linear combination of stellar spectra of different spectral types and luminosity classes.

For this study, the error in the velocity dispersion measurement was statistically determined by bootstrapping. Using a Gaussian noise model, 100 pseudo-spectra were randomly simulated in the range given by the galaxy error spectrum. The error of the velocity dispersion measurement was obtained from the statistical distribution of the 100 pseudo-spectra measurements.

Different effects limit the precision or the ability to measure galaxy velocity dispersion. Stellar template mismatch is one such limiting factor. This effect occurs when the star template used to fit the galaxy spectrum is not representative of the real stellar population of the galaxy. Creating a galaxy template from a stellar library can be impossible; the stellar library does not contain every stellar type and one of the main stellar populations that composed the observed galaxy can be missing. As this template is a first guess to start the velocity dispersion measurement, no numerical criteria are used to avoid template mismatch. It is possible to help the software to make this first guess by removing some extra features (see below) or by limiting the number of stars in the library to the number presenting the most important features for the velocity dispersion measurement. We removed every galaxy spectrum from our sample when an important template mismatch at the initial step was visually detected, even if the S/N was over 10. To test the impact of a small initial template mismatch (no visual detection and \( \chi^2 \) greater than the template automatically created by the software), we forced the software to use specific templates, thus creating an artificial template mismatch. The measurement of the velocity dispersion with this mismatch showed an error of \( \sim 5 \) per cent in the dispersion measurement.

In our case, another effect is introduced by the convolution of the instrumental resolution of the stellar templates to that of the LCGs. The effect of this modification was intensively tested with galaxies of well-known velocity dispersion. An elliptical galaxy from the Coma cluster was changed and the velocity dispersion measured with the templates convolved to a slightly different one. The procedure was repeated with a pseudo-instrumental resolution modified up to \( \pm 3 \) Å in 0.05-Å steps. An error of 0.1 Å in the difference of resolution introduces an error of 5 per cent in the velocity dispersion measurement. The error in velocity dispersion increases more strongly with a higher error in resolution. At \( \pm 0.1 \) Å, the error is \( \sim 5 \) per cent, while at \( \pm 0.2 \) and \( \pm 0.5 \) Å the errors are \( \sim 10 \) and \( \sim 22 \) per cent, respectively, in the dispersion measurement. The instrumental resolutions of the galaxies were measured using different lines from the sky spectrum, extracted at the same time as the LCG spectra with the same polynomial (Gruel 2002). The resolution measured from the different lines was stable at \( \pm 0.1 \) Å along the spectrum.

Small emission lines tend to fill the Balmer lines (our major features), changing the global shape of the absorption features. To quantify the influence of this contamination, the emission lines in our sample were masked and the velocity dispersion was measured without them. We also observed that if not removed entirely, an artefact can appear at the continuum subtraction step for the strongest emission lines, such as \([\text{O} II]\lambda 3727\,\AA\) or \(\text{H}\beta\), and for bad sky subtraction features. As a result, these lines were erased manually. Both effects were quantified (measured with and without the lines) with an error of 2 per cent for the strong emission line \([\text{O} II]\lambda 3727\,\AA\) and 5 per cent for the emission inside the Balmer lines. For galaxy 03.0645, where the absorption lines were weaker and were contaminated by inside emission, the inside emission lines were also removed. This led to an increased error in the velocity dispersion.

To emphasize the strongest or the most useful absorption lines, the analysis has been restrained to the wavelength range \(\lambda \lambda [3570, 4400]\,\AA\). The best absorption lines present in the spectra were used: the Balmer lines (H10, H9, H8, H7, H6, H5, H4), Ca ii K and H and the G band. These restrictions have no effect on the measurement and improve the continuum subtraction.

In summary, the error analysis has shown that the accuracy of velocity dispersion measurement is principally limited by the noise in each galaxy spectrum. Our LCG sample was thus restrained to galaxies with S/N > 10. The second limiting effect is the possible mismatch in resolution between the stellar templates and the galaxies. This effect was minimized by adjusting the stellar resolution to the galaxy spectra. Still, an error of 10 per cent was found for a typical error of 0.1 Å. The average template mismatch was evaluated at around 5 per cent. Finally, the error resulting from the presence of strong emissions lines, a purely numerical error, was found to have minimal impact, with a value of less than 2 per cent.

3.2 Photometry

The \( B, V, I \) and \( K \) photometry for our sample were obtained from the CFRS catalogues (Hammer et al. 1995; Le Fevre et al. 1995; Lilly et al. 1995). The absolute AB magnitudes and rest-frame colours were derived from the best fit to the photometric data of models from Bruzual & Charlot (1993, 2003). The errors were derived using Monte Carlo simulations and were estimated to be \( \sim 0.14 \) and \( \sim 0.2 \) mag for the magnitudes and colours, respectively. Note that all the values were transformed to the concordance cosmology used in this paper.

3.3 Measurements of stellar mass

The stellar masses were calculated using the code described in Cristóbal-Hornillos et al. (2005) and Hempel et al. (2011), based on the idea of Guzmán et al. (2003). The ages and masses were determined by fitting the observed photometry (\( B, V, I \) and \( K \) bands) to the modelled flux obtained from the convolution of a redshifted library of synthetic galaxy spectra with the filter transmission functions.

A two-component synthetic model, consisting of a young instantaneous burst and an exponentially declining SFR, was considered. Models were built using the stellar population predictions of Bruzual & Charlot (2003), considering different ages for both components (as indicated in Table 2). The models depend on several parameters: the initial mass function (IMF), metallicity, \( A_V \), extinction law, mass, SFR, and age. We considered the same IMF, metallicity, \( A_V \) and extinction law for both old and young components. Therefore, a total of nine parameters (given in Table 2) define the two-component population model. To handle this degenerate problem, we first made simulations (Cristóbal-Hornillos 2005) to understand the influencing parameters on the stellar mass determination. We considered a modelled luminous compact blue galaxy (LCBG) with the mean parameters of Guzmán et al. (2003) and placed it at \( z = 0.5 \), \( \alpha = 0.8 \).
and $z = 1.1$, adding realistic photometric uncertainties (0.03, 0.06 and 0.1 mag for each redshift). For the simulations, we considered the $U$, $B$, $V$, $I$, and $K$ bands. We saw that extinction and metallicity were the parameters that had the most influence on the final stellar mass. Increasing the amount of extinction tended to decrease the inferred stellar mass. Because of the extinction–age degeneracy, a younger and less-massive underlying component increased the extinct flux in the rest-frame ultraviolet bands. Similarly, a lower metallicity also increased the stellar masses. Other parameters, such as SFR, extinction law and IMF, had little effect on the estimates of masses. In our study, the best models ($\chi^2 < \chi^2_{\text{min}} + 1$) deviated by less than a factor of 2 in the inferred stellar masses.

We fixed certain parameters by using measurements from the real spectra. The extinction $A_V$ was measured from the Balmer decrement between $H_{\beta}$, $H_{\alpha}$, and $H_{\gamma}$ emission lines, and infrared flux when available. In the initial approach, we used the Large Magellanic Cloud extinction law for all the galaxies. For one of these, 03.1540, the models could not fit the stellar energy distribution (SED) correctly. The effect was reduced by using the Calzetti law (Calzetti et al. 2000) for the extinction law, but the fit still did not reproduce the expected SED. The mass determined for this galaxy was at the upper limit and was probably overestimated. This LCG was also detected by the Infrared Space Observatory (ISO), and it is considered peculiar in terms of both its extinction and star formation.

For the fitting process, the ranges considered for the different parameters are shown in Table 2. The $\chi^2$ is calculated from the difference between the observed and modelled photometry as in the following equation:

$$\chi^2 = \sum \sigma_j \left( \frac{F_{\text{mod}} - F_{\text{obs}}}{F_{\text{obs}}} \right)^2.$$

Here, the weights $\sigma_j$ in each filter are given by $1.086/\sigma_{m_j}$, where $\sigma_{m_j}$ is the error in magnitudes. At each iteration, once the model parameters are fixed, the fitting process determines which combination of stellar masses and ages for the components produces the best $\chi^2$ fit to the observed photometry. A simultaneous fit to the two-component model is performed. We attempted an alternative approach, in which first we fitted the young burst component to the blue-band photometry, and then we fitted the residuals to the underlying component. Such an approach seemed reasonable because the bluest/reddest bands were expected to be dominated by the young/old components. However, the results were found to depend strongly on which of the two components was fitted first (i.e. if we first fitted the young component, then too much near-infrared flux was assigned to the component, yielding a low total mass).

The upper age was defined as the age that a galaxy, which formed at $z = 4$, would have at the $z$ observed using our adopted cosmology.

| Parameter                      | Range            |
|--------------------------------|------------------|
| Age of recent burst            | $10^7 - 5 \times 10^8$ yr |
| Age of underlying population   | $2 \times 10^8 - 2 \times 10^{10}$ yr |
| IMF Salpeter (1955)            |                  |
| Mass of stars: lower and upper limits | 0.1 and 100 $M_\odot$ |
| $A_V$                          | Fixed            |
| Extinction law                 | Fixed            |
| Metallicity                   | $0.4Z_\odot$, $Z_\odot$ |
| SFR (underlying)              | $r = 1.0$ Gyr    |
| SFR (burst)                   | Instantaneous    |

Also, the lifetimes of the stars producing most of the ionizing photons are typically $3 - 5 \times 10^6$ yr; after $10^7$ yr, the production rate of ionizing photons drops by over 99 per cent (Charlot & Longhetti 2001).

To estimate the evolution of these galaxies to $z = 0$, the code fits the galaxy at the observed redshift. We have considered the fitted models as they continued to evolve until $z \sim 0$, and we have assumed that all gas in the fitted galaxy had been used to produce stars.

In the models, we assume a passive evolution for our LCGs, which are experiencing their last starburst and will not have any mergers. This last hypothesis is sustained by Conselice, Blackburne & Papovich (2005), who have shown that the major merger rate decrease since $z \sim 1$. Under these conditions, the velocity dispersion and masses are independent of the evolution of the galaxies, and the colour and luminosity will be determined by the single evolution of the best fit of the observed SED. The evolved point, used later in this paper, was calculated from the models after evolution (see Fig. 2).

### 4 RESULTS AND DISCUSSION

The velocity dispersion measurements and the stellar mass estimates are listed in Table 1. The velocity dispersions from the absorption lines of the LCGs range from $\sim 137$ to $260$ km s$^{-1}$ with a median of $\sim 180$ km s$^{-1}$. The two galaxies with the highest velocity dispersion (03.1349 and 03.1540) are ISO galaxies. Hammer (1999) have shown that galaxies detected by the ISO tend to be large and massive, and they are found mostly in interacting systems that yield strong SFRs ($> 10^3 M_\odot$ yr$^{-1}$).

In Fig. 3, we compare the star masses and $M_B$ and $(U - V)$ colours of LCGs with the different types of nearby galaxies.

The data used for comparison include several different types of galaxies taken from the Sloan Digital Sky Survey (SDSS) stellar...
mass catalogue (Kauffmann et al. 2003). We remark that this catalogue does have some degree of mismatch within a 1-arcsec radius with the Data Release 4 (DR4) catalogue we used for the magnitude and colours. We removed all objects whose cross-correlation yielded a different plate identification number, a different fibre identification number, a different modified Julian Date, discrepancies in the redshift or a large error in the measurement of the mass or the velocity dispersion. Our final selection includes ∼94 per cent of the initial sample.

Fig. 3 summarizes the results of our analysis. The data points are the five LCGs studied in this paper: grey points denote the observed value and white points denote the model predictions after passive evolution. The triangle corresponds to the object whose SED, which was determined by our stellar mass code, did not fit its photometry values. Therefore, its estimated evolution is very uncertain. The crosses in the colour–σ diagram are H II galaxies (see the figure caption). The grey shading shows the density plots for different SDSS galaxies. The separation in to different galaxies types, shown in the three columns, was done by colour selection, following Fukugita, Shimasaku & Ichikawa (1995).

The upper row is the $M_*$ versus σ diagram, the middle row is the $L$ versus σ diagram and the lower row is the colour versus σ diagram. About ∼5 Gyr ago, the five LCGs had stellar masses and velocity dispersions consistent with those characteristic of today’s population of early-type spheroids and spiral galaxies. Their luminosities and colours, however, are similar to the most luminous, bluest local H I galaxies. Assuming that the stellar masses and velocity dispersions of these LCGs remain approximately constant, and that they are undergoing their last burst of star formation, simple evolutionary synthesis models predict that these objects will evolve passively to best resemble the typical luminosities and colours of early-type spiral galaxies. Our measurements of velocity dispersion and stellar mass, combined with this simple evolutionary prediction, are consistent with the proposed link between LCGs and massive spiral galaxies (Hammer et al. 2001).

We note that our results are not necessarily inconsistent with previous works, suggesting that another class of intermediate redshift star-forming galaxies (the so-called LCBGs) might evolve into today’s population of low-mass spheroidal galaxies (Guzmán et al. 2003; Koo et al. 2005; Noeske et al. 2006). The LCGs in our sample have a luminosity similar to the 15 per cent of brightest objects in the LCBG samples studied by Koo et al. (2005) and Noeske et al. (2006).

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