# Surface brightness profiles of nearby central group galaxies

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**Abstract.** Galaxy groups offer an excellent opportunity to study the impact of galaxies on their intergalactic medium (IGM), and vice versa, as the galaxy's heating process effects are more visible due to the groups' lower density and mass compared to clusters of galaxies. This project is part of an optical observational campaign to observe the Complete Local-Volume Groups Sample (CLoGS), which is a statistically-complete sample of 53 groups within 80 $Mpc$. Radio observations (GMRT & VLA), X-ray bands, and sub-mm (IRAM-30m) data are already available for the entire sample. Here, we are interested in accurate surface brightness (SB) profiles of these central, dominant elliptical galaxies in the groups as this directly relates to their stellar mass profiles. The SB profiles can be used to measure structural parameters e.g. the size of the core, contains detail of the assembly histories of the galaxies, and can ultimately be used to calculate dark matter density profiles if combined with dynamical (total) mass measurements from spectra.

## 1. Introduction

The location of dominant galaxies in the centres of the groups suggests a particularly extensive evolution history where the stellar mass is buildup through frequent mergers with smaller galaxies [1]. As SB profiles can be used to measure structural parameters and since they directly relate to the stellar mass profiles, it should display several observational signatures of how these galaxies formed. One example of a structural property we can measure from accurate SB profiles is the presence and size of cores. The formation of the most massive early-type galaxies took place by mergers of pre-existing gas free galaxies [2] and it is then suggested that the core is naturally formed as an end-point of this process. This explains why cores are found in nearly all luminous early-types [3];[4].

## 2. Data

CLoGS is an optically-selected and statistically-complete sample of groups in the nearby Universe, which is specifically chosen and studied with optical observations for this project, since radio and X-ray bands [5] are already available. This provides important physical properties of the IGM such as gas temperature and the total X-ray luminosity, both probing the environment in which the group members are located [6]. Together, the CLoGS observations can be used to investigate the role of active galactic nuclei (AGNs) in maintaining the thermal balance of the IGM, to name one example.

In order to get the SB profiles that we need, we make use of R-band (or equivalent) imaging and the Multi-Gaussian Expansion (MGE) fitting method. We apply the MGE fitting to the R-band images of 35 central group galaxies, from archival Hubble Space Telescope (HST) and Canada-France-Hawaii Telescope (CFHT) MegaCam imaging. For 12 of the 35 groups, we also present new CFHT MegaCam observations obtained in 2018/2019. We will also measure the sizes of the cores of these galaxies and correlate it with other physical properties of the galaxies and host groups.

We find that the 35 group galaxies of CLoGS have different morphologies. NGC4261, for example, is an elliptical galaxy. However, the Flexible Image Transport System (FITS) [7] image of this central group galaxy, retrieved from the Hubble Legacy Archive, shows a well defined disk of dust in the centre (see Figure 1), well known from an earlier study [8]. We find three more similar disks (refer to Figure 1). All four of these central group galaxies host radio jets [5].

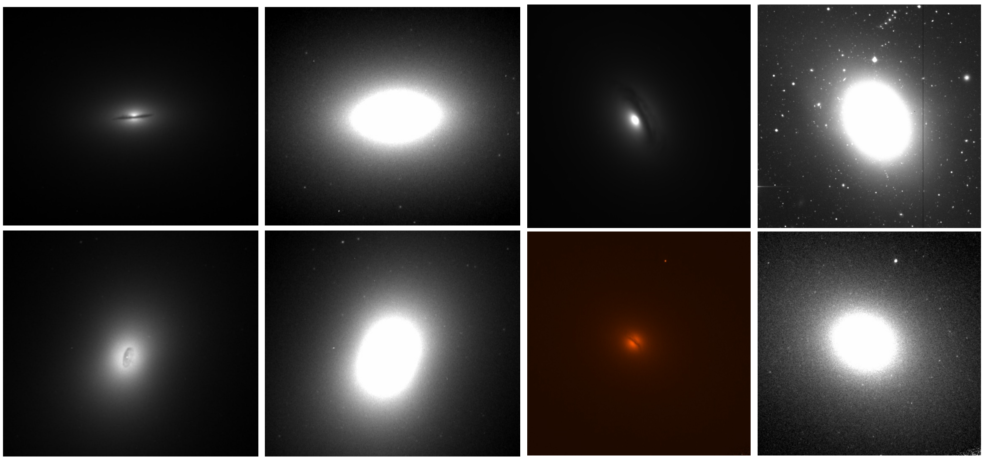

**Figure 1.** We show the four central group galaxies with two different contrast algorithms applied. *Top row, from left to right:* NGC5322 (HST) in minmax scale, NGC5322 in zscale, NGC3665 (one of the New MegaCam observations) in minmax scale, NGC3665 in zscale. *Bottom row:* NGC4261 (HST) in minmax scale, NGC4261 in zscale, NGC5127 (HST) in minmax scale (heat colour), NGC5127 in zscale.

Figure 1 shows a few examples indicating the different morphologies for some of the central group galaxies that we have analysed. Four central group galaxies, NGC5322, NGC3665, NGC4261 and NGC5127 are shown. These different colours and scales were set in SAO ds9 for each FITS image.

*Method*

We use the MGE method [9], as implemented by [10]. This method reproduces detailed photometry, which allows for variations of ellipticity. The MGE procedure starts with determining the galaxy's average ellipticity ($\varepsilon$), the orientation (or position angle, PA), and the luminosity-weighted central coordinates $(x_{cen}, y_{cen})$. Next, the galaxy image is divided into four quadrants, and detailed photometric profiles are measured along sectors which are uniformly spaced in orientation (angle) from the major- to minor axis. The average of the SB profiles from sectors in the four quadrants are taken together, and each is then fitted as the sum of Gaussian components. The best-fitting MGE model SB is determined by convolving it with the instrumental point spread function (PSF) and comparing to the observed SB. The projected MGE surface brightness ($\Sigma$) is defined as follows:

$$\Sigma(x', y') = \sum_{j=1}^{N} I'_j exp\left[-\frac{1}{2\sigma_j'^2}(x'^2 + \frac{y'^2}{q_j'^2})\right] \tag{1}$$

with $N$ indicating the Gaussian components that the model is composed, $I'_j$ as the distance-independent surface density, $\sigma'_j$ the dispersion in units of *arcsec* along the major $x'$-axis and $q'_j$ the flattening for each Gaussian. The MGE surface density can be de-projected analytically [11] to obtain the intrinsic density $\rho_*(R,z)$ in the galaxy meridional plane, which can be still expressed as the sum of Gaussians, under the assumptions of the MGE method, and for a given inclination $i$.

The results of the MGE method can be used to convert the total counts of each Gaussian ($C_0$) into corresponding peak SB with physical units. The equation, to determine the total counts of each Gaussian, $C_0$, is defined by [10]:

$$C_0 = \frac{TotalCounts}{2\pi SigmaPixels^2 q} \tag{2}$$

with $q$ as the observed axial ratio for each Gaussian component. By making use of standard photometry formulae, the peak SB $C_0$ can be converted into SB $\mu_R$ with units of $mag \cdot arcsec^{-2}$. This is defined by the equation to a first approximation [10]; [12]:

$$\mu_R = zeropoint + 0.1 + 5log(SCALE) + 2.5log(EXPtime) - 2.5logC_0 - A_R \tag{3}$$

for all the R-band images. The parameters used are the photometric *zeropoint* (25.94 for HST images of filter F814W, 26.52 and 26.74 for MegaCam images of filters R.MP9601 and r.MP9601, respectively) in AB magnitude, a correction for infinite aperture of SB measurements (0.1), the spatial scale (0.0455 $arcsec \cdot pixels^{-1}$ for HST images of filter F814W, 0.206 $arcsec \cdot pixels^{-1}$ and 0.187 $arcsec \cdot pixels^{-1}$ for MegaCam images of filters R.MP9601 and r.MP9601, respectively), the exposure time (varying for every galaxy; from $460s$ to $2460s$), the peak SB ($C_0$) and the galactic extinction ($A_R$) [13] from the recalibration of the [14] infrared-based dust map.

## 3. Results

The MGE fitting method was applied to 35 (of the 53) central group galaxies from CLoGS. From the Hubble Space Telescope (HST) archive we obtained 16 central group galaxies, four from the Canadian Astronomy Data Centre (CADC): Canada-France-Hawaii Telescope (CFHT) as stacked MegaCam archival data and 12 from new observations with CFHT MegaCam. Only some of the results from each telescope will be presented here as examples.

### *3.1. HST images*

The MGE method was used for 16 FITS images, retrieved from the Hubble Legacy Archive. The filter of these images is F814W and is less affected by dust. Here, we present the results of the MGE fitting method for one central group galaxy, NGC0315, an elliptical galaxy. Figure 2 shows the determination

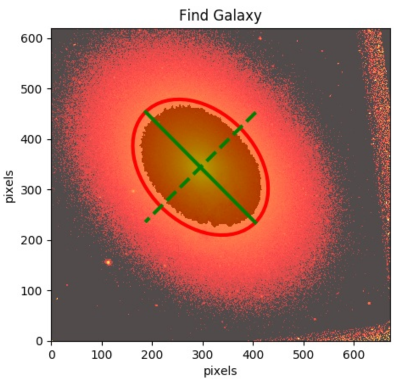


**Figure 2.** This procedure computes the centre, orientation and ellipticity of NGC0315.

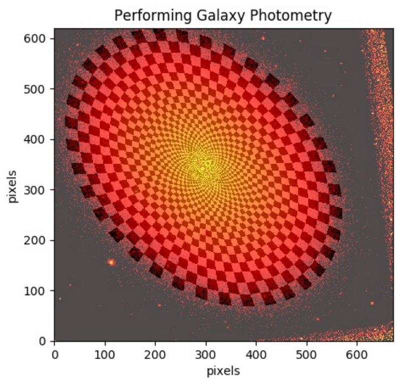


**Figure 3.** Galaxy photometry is measured along sectors linearly spaced in angle and covering the whole image.

of the precise position of the galaxy's centre as well as the orientation with respect to the image axes

($PA = 44.8deg$) and the ellipticity ($\varepsilon = 0.283$). The galaxy image of NGC0315 is then divided into four quadrants. For the next step of the method, Figure 3 shows detailed photometric profiles measured along (uniformly spaced) sectors in orientation from the major- to minor axis.
The next step of the method is shown by Figure 4 where the best-fitting parameters at the end of the fit are shown. Here, the best-fitting model Gaussians are shown, as well as the deviation from the observed data. This third step takes the average of the SB profiles together, from sectors in all four quadrants, and each is then fitted as the sum of Gaussian components. From the fitting method's output results, it was found that NGC0315 can be described with three nonzero Gaussian components.

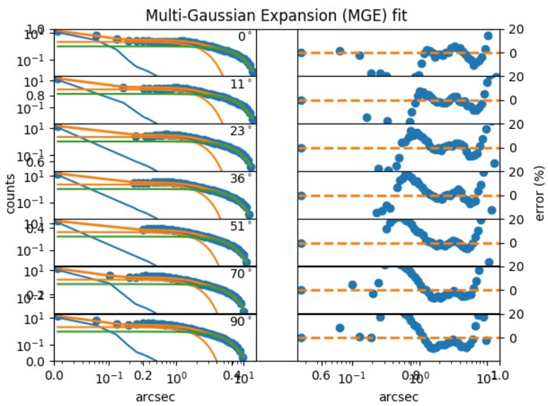


**Figure 4.** The MGE fit is determined by starting from the photometry at the previous step. *Left:* The best-fit model (solid line) fitted on the counts (blue circles) varying for Gaussian components (in colours of blue, green, orange and yellow). *Right:* The error percentage, showing the goodness of fit of the MGE for NGC0315.

After the best-fitting parameters have been determined from the previous step, the fitting method will use these parameters to produce contour plots that compares the PSF-convolved MGE fit model to the actual (original) fitted image, making use of instrumental units of counts (for intensity) and pixels (for the spatial scale). These results are shown by Figure 5.

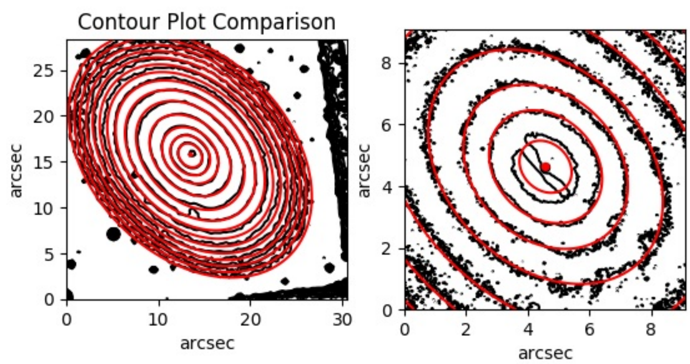


**Figure 5.** Contours (red colour) expand from the centre outwards. *Left:* PSF-convolved MGE fit. *Right:* MGE fit on original image.*Left:* Contours are superimposed on the MGE fitting model convolved with the PSF. *Right:* Contours are overlaid on the central part of the (original fitted) image of NGC0315 that has been extracted and plotted at high resolution.

*3.2. MegaCam archival images*
Four R-band images were analysed with the MGE fit method, from the Canadian Astronomy Data Centre (CADC): Canada-France-Hawaii Telescope (CFHT) Science Archive. Stacked MegaCam data was used.

The specific filters for the R-band are R.MP9601 and r.MP9601. Image Reduction and Analysis Facility (IRAF) was used to copy a portion of the CFHT R-band FITS image, consisting of the central group galaxy from a wide field image. Here, we present only the final results of the MGE fitting method of one central group galaxy NGC3613, an elliptical galaxy, as an example.
Figure 6 is the output results of the third step of the MGE fitting method - showing the best-fitting parameters at the end of this fit. The average of the SB profiles taken together were fitted as the sum of Gaussian components. From the fitting method's output results, it was found that NGC3613 can be described by five nonzero Gaussian components. The instrumental units used are the same as indicated previously.

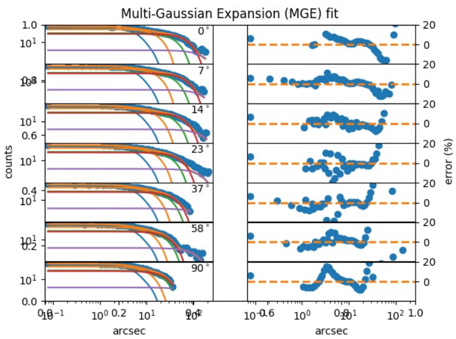


**Figure 6.** Determines the MGE fit of NGC3613 by starting from the photometry at the previous step. *Left:* The best-fit model (solid line) fitted on the counts (blue circles) varying for Gaussian components (in colours of blue, green, orange an yellow). *Right:* The error percentage, showing the goodness of fit of the MGE.

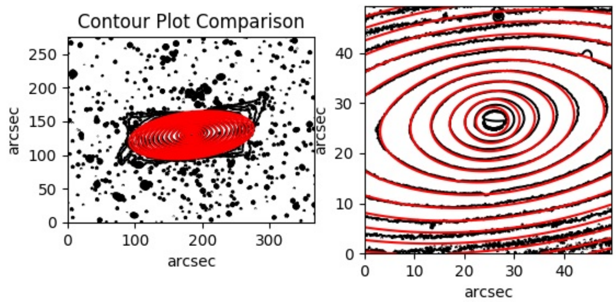


**Figure 7.** Contours, indicated in red colour, expand from the centre outwards. This visual comparison ensures that the MGE fitting routine focuses on a small central part of the galaxy so that the best-fitted parameters could be produced. *Left*: PSF-convolved MGE fitted model. *Right*: Contours are overlaid on the (original fitted) image of NGC3613 as plotted at high resolution.

*3.3. New MegaCam observations*

New images were observed with CFHT MegaCam for 12 groups. IRAF was used to copy a portion of the FITS image, consisting of the central group galaxy. After this, the same MGE fitting was executed. Here, we also present only the final results of the MGE fitting method of the central group galaxy, NGC0410, an elliptical galaxy, as an example. For the third step of the method, Figure 8 shows best-fit model (solid line) fitted on the counts (blue circles). After the average of the SB profiles was taken, it was fitted as the sum of Gaussian components (different coloured solid lines) - from which NGC0410 can be described with five nonzero Gaussian components. The plot is shown in Figure 8, and the instrumental units that were used are the same as for Figures 4 and 6.

## 4. Conclusions

For this project, we have used the MGE fitting method in order to get accurate SB profiles of 35 central group galaxies (of the CLoGS sample) of which the results of only three are presented in this article, as examples.
We firstly show the surprising result that four elliptical central group galaxies show disks of dust in the

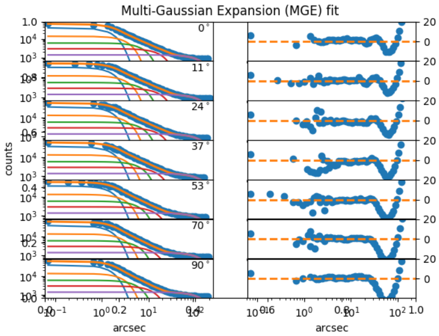


**Figure 8.** *Left:* The best-fit model (solid line) fitted on the counts (blue circles) varying for Gaussian components (different coloured solid lines). *Right:* The error percentage, showing the goodness of fit of the MGE.

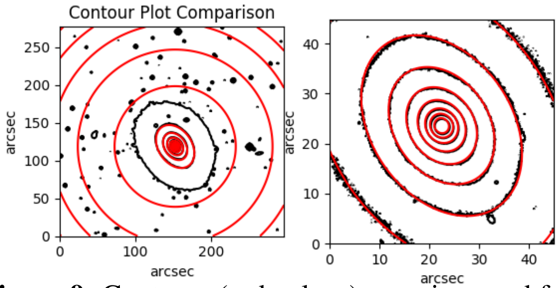


**Figure 9.** Contours (red colour) superimposed for the PSF-convolved MGE fitted model (left) and overlaid on the (original fitted) image (right) of NGC0410. This comparison shows us that the contour lines are superimposed well onto the original observed image, focusing on the central part of the galaxy.

centre, of which one (NGC4261) was previously known and described in an earlier study [8]. We find a range of morphologies for the 35 central group galaxies ranging from clear spiral arms and bulges to round elliptical galaxies.

The MGE fitting method is effective for these central galaxies, and we will in future work also fit broken power-laws to compare the results in order to get accurate SB profiles we need, and measure size of cores.

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