Getting Started with the MGE_FIT_SECTORS Package

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Original version January 31, 2002; current version February 14, 2014

1 Introduction

These pages briefly describe the main steps that have to be performed to produce a Multi-Gaussian Expansion (MGE) fit, starting from one or more fully reduced images of one galaxy, using the method and the IDL (http://www.exelisvis.com/idl/) or Python (http://python.org/) package MGE_FIT_SECTORS (http://purl.org/cappellari/software) described in Cappellari (2002, MNRAS, 333, 400). Various references to the MGE method and its application can be found in the above paper. Figures and actual examples of MGE fits can also be found in that paper.

Additional detailed usage information is found at the beginning of each IDL procedure source code (the files are called `procedure_name.pro`), or by looking at the example procedures included in this distribution. But probably the best way to start using the MGE_FIT_SECTORS package consists of looking at the example file `test_mge_fit.pro` and running it. This file is intended be used as a template to be adapted for each specific MGE fitting problem.

2 Installation

The installation is performed by simply extracting all the files (IDL procedures and FITS images) distributed in the tarball or zip file into a directory (e.g., `mge_fit_sectors`). It is useful to add this directory to the IDL path. Some basic knowledge of IDL and version 5.0 or later are assumed. The IDL Astronomy User's Library (http://idlastro.gsfc.nasa.gov/) also needs to be previously installed (but if you can read FITS files within IDL it is probably installed already). The IDL routine BVLS is also required and should be downloaded[2] separately.

To test that the installation is working properly enter into the directory `mge_fit_sectors` (e.g., `CD, 'mge_fit_sectors'`) and type the command `TEST_MGE_FIT`. The execution of this whole script will take about 10 minutes on a 1GHz PC and will exercise almost all the package procedures by reproducing most of the figures of Cappellari (2002). Intermediate results are visualized on the screen while the fit is proceeding and the output contour files are saved in the `mge_fit_sectors` directory. The different examples can also easily be run separately, by typing the name of the corresponding procedures.

3 Concepts

An MGE fit, using the MGE_FIT_SECTORS package, consists of the following steps:

Locate the galaxy: the precise position of the galaxy center, its orientation with respect to the image axes and its 'characteristic' ellipticity have to be determined;

Get photometry: the galaxy photometry is measured along sectors, logarithmically spaced in radius and linearly in angle, on the different images that will be used to fit the MGE model; Three vectors of values R_j, θ_j, I_j (radius, angle, intensity) are obtained for each image;

Do the fit: if more than one image is used for the MGE fit, the profiles obtained from the previous step have to be rescaled, to bring them on the same intensity scale and the same spatial scale. The R_j, θ_j, I_j values for the different images are then combined into only three vectors, describing the photometry of the whole galaxy. The actual fit is then performed and the Gaussians parameters are determined;

Display results: the model fit, convolved with the proper PSF, can be compared with the images used in the fit, using contour plots.

Each of these tasks is performed with a different specific procedure.

4 The Package

We first consider the case of an MGE model with constant position angle. Four different procedures are used to perform the four tasks described in the previous section:

`FIND_GALAXY`**:** This procedure computes center, orientation and ellipticity of a galaxy image. The weighted first and second moments of the intensity distribution are used for this purpose. Alternatively standard photometric packages can be used to determine these input parameters;

`SECTORS_PHOTOMETRY`**:** galaxy photometry is measured along sectors linearly spaced in angle and covering the whole galaxy image. When attempting an initial fit to the galaxy it may be useful to restrict the fit to a smaller number of sectors (e.g., $N_{\rm sec} = 7$ for a constant position angle fit) and to a single-Gaussian PSF, to speed up things while still determining regions to be masked, sky subtraction and minimum counts level to include in the fit;

`MGE_FIT_SECTORS`**:** this is the main procedure in the package and determines the actual MGE fit by starting from the photometry measured at the previous step. The intermediate results are plotted on the screen while fitting and the values of the best-fitting parameters are printed on the screen at the end of the fit. This procedure uses instrumental units: counts for intensity and pixels units for the spatial scale;

`MGE_PRINT_CONTOURS`**:** this procedure uses the values of the best-fitting parameters determined at the previous steps and saves to a PostScript file a contour plot comparing the actual fitted image to the PSF-convolved MGE fit. Even small discrepancies in the model are easily revealed by this contour comparison.

Once a satisfactory MGE fit has been obtained the model has to be converted in physical units and then deprojected using e.g., the equations given in Cappellari (2002).

The last three procedures above have an equivalent one for the MGE fit of galaxies presenting isophote twists. The corresponding procedures names are obtained by adding the suffix `_TWIST` to the above procedures names.

5 Converting to Surface Density

The conversion from the Gaussian parameters printed by the `MGE_FIT_SECTORS` procedure to physical quantities that can be used in a dynamical model is done with standard methods, but experience from a number of users has shown that an actual worked example may be useful.

We performed an MGE fit to an HST/WFPC2/F814W image of IC1459, with our `MGE_FIT_SECTORS` package. The exposure time of the image was `EXPTIME`=460 s, obtained with `GAIN`=15. The PC CCD was used as reference for the intensity and for the spatial `SCALE=0.0455` arcsec pixels^{-1}. This means that the intensity measurements obtained by `SECTORS_PHOTOMETRY` on the WFPC2 mosaic image were scaled to match the ones on the PC CCD, taking the different pixel areas into account, and similarly was done for the measured radii. No changes were made to the measurements obtained for the WFPC2/PC CCD. This same scaling is also done e.g. by the example procedure `WFPC2_MGE_FIT`. The following parameters were obtained for the best-fitting Gaussians by the `MGE_FIT_SECTORS` procedure:

TotalCounts	SigmaPixels	qObs
8198.48	0.38000	1.000000
44161.1	5.88124	0.899775
215881.	13.5803	0.672745
348640.	21.8192	0.815558
1.26569×10^6	46.0376	0.681965
2.17338×10^6	82.7561	0.775966
1.97307×10^6	149.808	0.714511
3.86588×10^6	246.401	0.738354
4.41886×10^6	478.825	0.732588
8.42750×10^6	870.403	0.733947
2.76482×10^7	2777.72	0.774998

The TotalCounts of each Gaussian can be converted into the corresponding peak surface brightness C_0 (in counts pixels^{-1}) using equation (1) in Cappellari (2002)

$$C_0 = \frac{\text{TotalCounts}}{2\pi\ \text{SigmaPixels}^2\ \text{qObs}}. \tag{1}$$

This is the only MGE-specific part of the conversion, while the following steps are common to other parametrizations of the stellar surface brightness.

The surface brightness C_0 in counts pixels^{-1} can be converted into a Johnson-Cousins I-band surface brightness μ_I in mag arcsec^{-2} using standard photometry formulas. In the case of the WFPC2/F814W filter the equation is to a first approximation (Holtzman et al. 1995, PASP, 107, 1065)

$$\begin{aligned}\mu_I = 20.840 + 0.1 + 5\log(\texttt{SCALE}) \\ + 2.5\log(\texttt{EXPTIME}) - 2.5\log C_0 - A_I.\end{aligned} \tag{2}$$

Here 20.840 is the photometric zeropint, 0.1 is a correction for infinite aperture to be applied for surface brightness measurements, and A_I is the extinction in the I-band.

Finally one goes from the surface brightness μ_I in mag arcsec^{-2} to the surface density I' in $L_\odot \mathrm{pc}^{-2}$ with the equation[1]

$$I' = \left(\frac{64800}{\pi}\right)^2 10^{0.4(M_{\odot,I}-\mu_I)}. \tag{3}$$

[1] The surface brightness and surface density are independent on distance. Without loosing generality we assume 10 pc where the apparent and absolute magnitudes coincide by definition. At 1 pc one arcsec corresponds to a linear scale of $\frac{2\pi}{360^\circ \times 3600}$pc $= \frac{\pi}{648000}$pc, while at 10 pc one arcsec corresponds to $\frac{10\pi}{648000}$pc. This implies that a surface brightness of $\mu_I = M_{\odot I}$ mag arcsec^{-2} corresponds to a surface density of $\frac{1 L_{\odot I}}{(\frac{10\pi}{648000}\mathrm{pc})^2} = \left(\frac{64800}{\pi}\right)^2 L_{\odot I}$pc^{-2}.

The SigmaPixels is trivially converted to arcsec by multiplying by `SCALE`. Adopting an absolute magnitude for the Sun in the I-band $M_{\odot,I} = 4.08$ mag, the final results for the (distance independent) Gaussian parameters, ready to be used in a dynamical model, are:

I'_j ($L_{\odot,I}$ pc^{-2})	σ'_j (arcsec)	q'_j
727874	0.0172	1.000
18191	0.268	0.899
22306	0.618	0.672
11511	0.993	0.815
11226	2.09	0.681
5243.0	3.77	0.775
1577.4	6.82	0.714
1105.6	11.2	0.738
337.28	21.8	0.732
194.31	39.6	0.733
59.276	126	0.774

This is for example the input format used by the routines of the Jeans Anisotropic MGE (`JAM`) package of Cappellari (2008, MNRAS, 390, 71).

From the fitted values, the total luminosity of each Gaussian is also easily obtained as

$$L_j = 2\pi I'_j \sigma'^2_j q'_j \tag{4}$$

(the galaxy distance is needed). Starting from these values the deprojection from the surface density to the intrinsic density, adopting the MGE assumptions, is performed both in the axisymmetric or triaxial case, using the equations in Section 2 of Cappellari (2002).

For example, if the galaxy is assumed to be axisymmetric, and considering that the luminosity L_j does not change with projection, all that is needed for deprojection are the two formulas ($i = 90$ is edge-on):

$$q_j = \frac{\sqrt{q'^2_j - \cos^2 i}}{\sin i}, \qquad \sigma_j = \sigma'_j, \tag{5}$$

where primed symbols correspond to projected quantities and non-primed ones to intrinsic quantities.

The following relation between the peak surface density I'_j of each Gaussian (typically in $L_\odot \mathrm{pc}^{-2}$) and the intrinsic density I_j (typically in $L_\odot \mathrm{pc}^{-3}$), is also sometimes useful:

$$I_j = \frac{I'_j \; q'_j}{q_j \; \sigma_j \; \sqrt{2\pi}}, \tag{6}$$

This relation is obtained by the obvious requirement that the total luminosity of a Gaussian does not change during projection (see equations [1] and [6] in Cappellari [2002]).

6 Troubleshooting

Experience on a large number of objects has shown that virtually all the unsuccessful fits (e.g., generally presenting data-model discrepancy in the contour plot) to galaxies that clearly *can* be fitted by an MGE model, are solved by correcting one of the following problems:

- improper masking of stars or dust regions in the image: use `BADPIXELS` keyword in `SECTORS_PHOTOMETRY`;
- improper sky subtraction: make sure that the profile is asymptotically close to a power-law in the other parts, or measure the sky level in other standard ways;
- inclusion in the fit of too low and noisy intensity values (in the galaxy outer parts): set the keyword `MINLEVEL` in `SECTORS_PHOTOMETRY`;
- incorrect relative calibration of the different frames (in the case of multiple images): properly scale the images. Make sure that the profiles for the different images merge smoothly into one single profile;
- inaccurate alignment of the model with the galaxy major axis: check the input position angle. Small misalignments of model and data are easily visible from the contour plots;

In particular no improvement has ever been observed by e.g., increasing the number of sectors utilized in the fit and it has been *never* necessary to edit starting guess by hand.

If all the above issues have been solved, and it is still not possible to obtain a good fit, one can use the fully linear algorithm by setting the keyword `/LINEAR` in the `MGE_FIT_SECTORS` procedure. This procedure is guarantee to converge to the global χ^2 minimum. If no good fit can be obtained in this way, this means that the galaxy can *not* be fitted with an MGE model (with positive Gaussians): this can happen e.g. with strongly peanut shaped bulges.

A fit with negative Gaussians can still be attempted, by setting the keyword `/NEGATIVE` in the `MGE_FIT_SECTORS` procedure, but one has to be careful with cancellations effects while computing any numerical quantity from the obtained MGE model.