Surface brightness profile determination for galaxies taken at the Observatorio UC

Néstor Espinoza, *Undergraduate Student*, PUC

***Abstract*—Using 8 exposures of 120 seconds each for three different galaxies on two different days at the Observatorio UC in Santiago, Chile, we present a study of the surface brightness profiles for a lenticular (NGC1553), elliptical (IC1459) and a spiral galaxy (NGC7205). Using standard IRAF tasks (with the aid of the `isophote` package from the STSDAS ditribution) we obtained the isophotes for our galaxies and studied how they varied with the distance from the center of the galaxy. After careful examination of our data and using a chi-square test, we found that both NGC1553 and IC1459 early-type galaxies followed a de Vaucouleurs surface brightness profile and that the NGC7205 late-type galaxy followed an exponential surface brightness profile. We also study the color gradient of our isophotes and find that our spiral galaxy shows an anomaly with respect to recent studies. A discusion on this subject is made, along with calculations using a generalized Sérsic profile.**

***Index Terms*—Galaxies, Surface Brightness Profiles, de Vaucouleurs, Exponential, Sérsic**

I. Introduction

THE study of galaxy brightness profiles (i.e. the study of the brightness of galaxies as a function of it's radii measured from the center of them) and it's correlation with the physical and morphological properties of their galaxies has been a major source of study in the past twenty years. Studies vary from stellar composition to the correlation between brightness profiles and Hubble type. For example, the correlation between the stellar population has been studied and proved to be a very good source of information on how stellar formation can be analysed in galactic disks in various studies (see de Jong, 1996 or Martin & Kennicutt, 2001, for example), but the correlation with Hubble type have been a major source of debate. Although a recent study by van der Wel (2008) shows, for instance, that there is strong correlation between morphological type and the generic Sersic brigthness profile, some limitations arise on what morphology really means, as stated in it's work. Motivated by this statement, we'll do a short review on Hubble's morphological type definitions so we can have a clear picture about the definitions on the present work.

A. Early-type galaxies

The definition of an early-type galaxy, according to Hubble's evolutionary model, is applied to elliptic (denoted by En, where n is a number from 0 to 7 that denotes the apparent ellipticity of the galaxy), lenticular (denoted by $S0$) and in modern astrophysics sometimes even to spiral Sa galaxies (see, for example, the work by Strateva et al., 2001). Except for Sa galaxies, early-type galaxies are normally composed by redder stars which have high dispersion in their velocities. In the present work, whenever we refer to early-ype galaxies we'll be refering to En and $S0$ galaxies.

B. Late-type galaxies

Late-type galaxies are applied to spiral galaxies (denoted by Sn, where n is a,b or c) and barred spiral galaxies (denoted by SBn, where n is a,b or c) according to the closeness of their spiral arms to their central bulges. In the present work, whenever we refer to late-type galaxies we'll be refering to spiral galaxies.

C. Brightness profile models

In the present work, we'll be fitting models to brightness light profiles of galaxies. It is important then to review some of the most popular parametrizations, the Sérsic profile being one of the most general and popular one.

The Sérsic profile (Sérsic, 1963) describes a general $1/n$ exponential profile, motivated by a generalization of the de Vaucouleurs (de Vaucouleurs, 1948) profile in the presence of atmospheric and instrumental dispersion and has the form:

$$-2.51\log_{10} I(r) = -2.51\log_{10} I_0 - kr^{1/n}$$

Here we encouraged the use of the form $-2.51\log_{10} I$ instead of m for magnitude, because what's measured by the magnitude it's an integrated flux in a band, not the total brightness from our source. In the present work, we'll measure m in two different bands so we'll compare how the brigtness profile changes in different filters. That being defined, we can write:

$$m = m_0 + kr^{1/n}$$

If we set $n = 4$ we get the famous de Vaucouleurs profile, initially thought by the author for elliptical galaxies and by setting $n = 1$ we get what's called the exponential profile, which is a good description of spiral galaxy disks.

The Sérsic profile has been an important model in the search for correlations between global galaxian parameters and n, such as total luminosity and scale-radius (Caon, 1993) or between black hole mass and bulge concentration on galaxies (Graham & Driver, 2007).

Manuscript received November 28, 2010.

N. Espinoza is with the Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica de Chile, Santiago, Chile. Phone: +(56) 09 987749956, e-mail: nsespino@uc.cl.

II. The Data

A. Image obtention

We took images of 3 different galaxies on two different days at the Observatorio UC using the 40 cm MEADE telescope with a SBIG ST-L-1001 3 CCD Camera. On the first day (October 27th) we observed the NGC7205 galaxy (RA: 22:08:34, DEC: -57:26:33 (J2000)) taking eight expures of 120 seconds each in two filters (R and V). The second day (November 4th) we observed the NGC 1553 (RA: 04:16:10, DEC:-55:46:48 (J2000)) and IC 1459 (RA:22:57:10, DEC:-36:27:44, (J2000)) galaxies taking eight expures of 120 seconds each in two filters (R and V).

B. Data reduction

We performed standard bias, dark and flat corrections on our images and sky-substracted them using the median value of the image as the sky-level value. Then, we used the `isophote` IRAF package (from the STSDAS distribution) to obtain the isophotes of our galaxies. The first step to do this was to determine the centers of our galaxies, so we examined visually the images to obtain an estimate of the physical pixel coordinates of the center. The `ellipse` task on the `isophote` package provides an algorithm not only to find the centroid, but also to find the ellipticity and the position angle of our isophotes so a good estimate of those parameters is important for the iteration to converge properly. We also where very careful to inspect visually our images in order to know the exact position of objects that could interfere in the calculation of our isophotes such as stars or bad pixels, and did a mask on every science image with the interactive mode of the `ellipse` task.

After seting up the initial parameters, we did our isophote extraction in two different ways. The first one was letting the geometric iteration parameters (ellipticity, position angle and center of the ellipse) to change freely as we extracted our isophotes and the second one was to constrain the ellipticity and the position angle using the previously iterated geometric parameters. We chosed to call this last method the “bayesian” method, because we are using some information that we already know: for our elliptical galaxies, we know they have elliptic shape, so the ellipticity and position angles must be geometric constants on the isophotes we extract. This last method had to be used on the spiral NGC7205 galaxy, because the algorithm didn’t converge properly. Images of the extracted isophotes are shown on Figure 1.

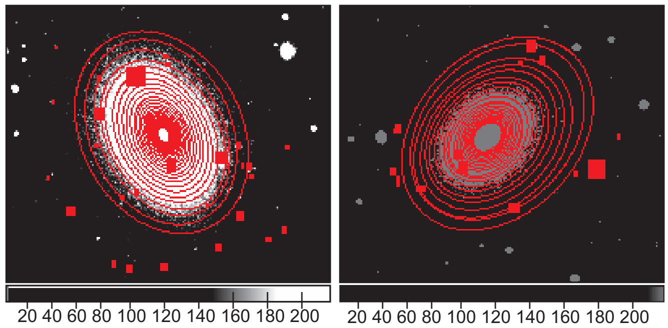

Fig. 1. Images of the obtention of our isophotes on NGC1553 (left) and IC1459 (right) . The masking of bright objects is denoted on the image by red squares and rectangles.

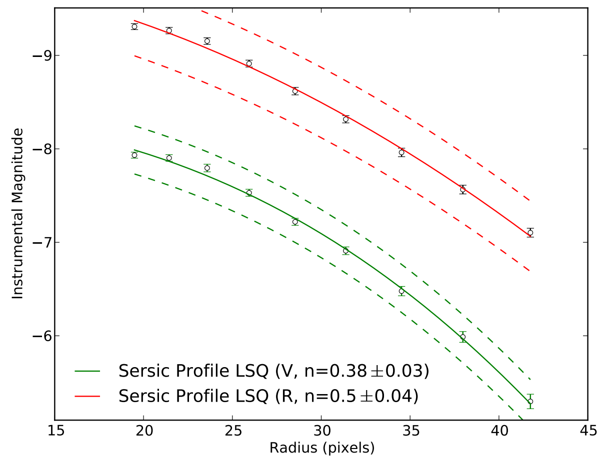

Fig. 2. Sérsic profile fit for the NGC7205 spiral galaxy for the two bands present on our photometry. The n index is shown and the $3-\sigma$ confidence interval on our fit given by our magnitude at the center is also denoted by dashed lines.

III. Data analysis

We performed three different least squares fits using the PYTHON implementation of the Levenber-Marquardt algorithm[1] for each of our galaxies. The first one was letting every parameter of the Sérsic profile to freely converge, the second was constraining $n = 4$ on the Sérsic profile to get the de Vaoucoulers profile and finally we did an exponential profile fit letting $n = 1$. The first one is made to check whether our estimate using the Bayesian Method used to constrain the geometrical properties of our early-type galaxies is good enough to be considered on our analysis.

[1] http://cars9.uchicago.edu/software/python/mpfit.html

A. Sérsic profile fitting

The results on each galaxy can be seen on Figure 2, 3 and 4 for NGC7205, NGC1553 and IC1459, respectively.

On our early type galaxies, as we discussed in the Data reduction section, we also did a Bayesian Method to obtain the isophotes by contraining the geometrical properties of our galaxies. The results of the fits are shown on Figures 5 and 6 for NGC1553 and IC1459, respectively.

After examining and comparing our residuals, we finally continue our analysis with the three galaxies using the Bayesian methods because they give plausible error estimates for our curves.

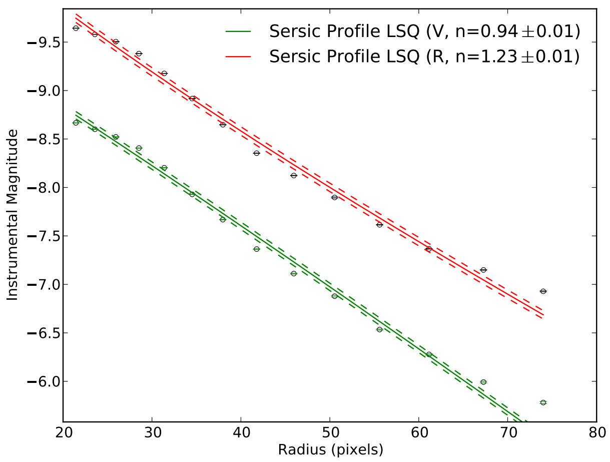

Fig. 3. Sérsic profile fit for the NGC1553 lenticular galaxy for the two bands present on our photometry. The n index is shown and the $3-\sigma$ confidence interval on our fit is also denoted by dashed lines. Note the deviant points far away from the center.

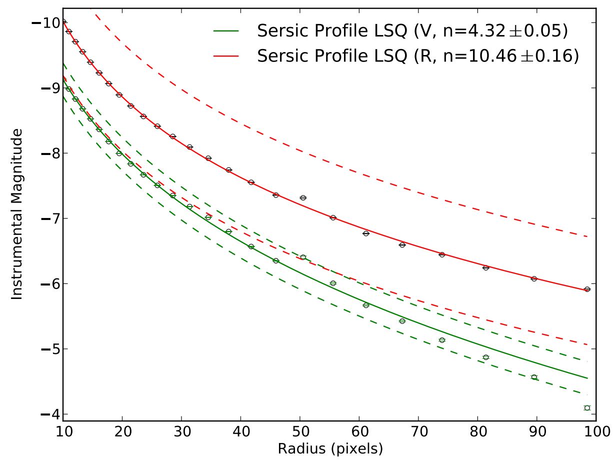

Fig. 4. Sérsic profile fit for the IC1459 ellipticcal galaxy for the two bands present on our photometry. The n index is shown and the $3-\sigma$ confidence interval on our fit is also denoted by dashed lines.

B. de Vaucouleurs and Exoponential profiles fit

We performed de Vaucouleurs and Exponential profile fits to our three galaxies by letting n fixed to 4 and 1, respectively. We obtained values for the O-C curve (observed minus computed) and chi-square values for each fit. The results are shown on Table I.

According to the obtained information, we show the corresponding fits to the models that gave the lowest chi-squared values for NGC 7205, NGC 1553 and IC 1459 on Figures 7, 8 and 9 respectively.

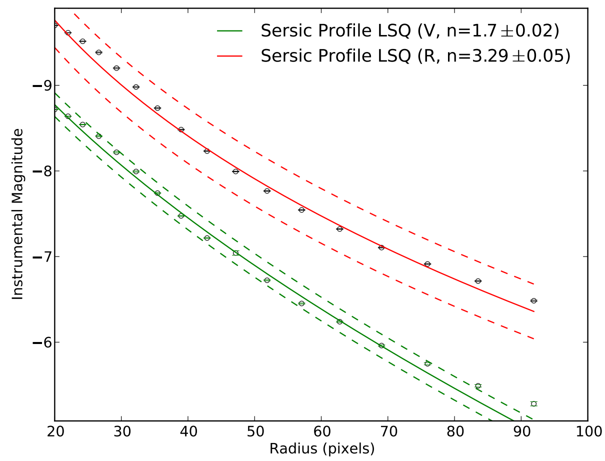

Fig. 5. Sérsic profile fit using the Bayesian Method for the NGC1553 lenticular galaxy for the two bands present on our photometry. The n index is shown and the $3-\sigma$ confidence interval on our fit is also denoted by dashed lines.

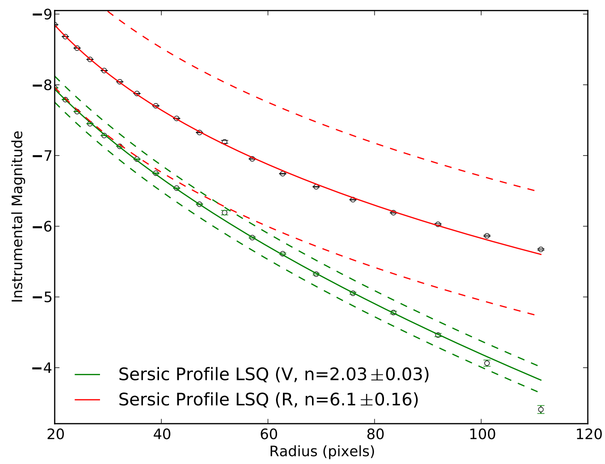

Fig. 6. Sérsic profile using the Bayesian Method fit for the IC1459 ellipticcal galaxy for the two bands present on our photometry. The n index is shown and the $3-\sigma$ confidence interval on our fit is also denoted by dashed lines.

Galaxy	Model	χ^2_R	χ^2_V
NGC 7205	de Vauc.	124.78	179.86
NGC 7205	Exp.	49.63	90.84
NGC 1553	de Vauc.	5428.85	5183.21
NGC 1553	Exp.	31619.36	6446.97
IC 1459	de Vauc.	766.52	1285.83
IC 1459	Exp.	39322.03	5177.55

TABLE I

DATA OBTAINED AFTER ADJUSTING MODELS TO OUR DATA. THE R AND V SUBSCRIPT DENOTE VALUES OBTAINED FROM THE RESPECTIVE R AND V FILTERS.

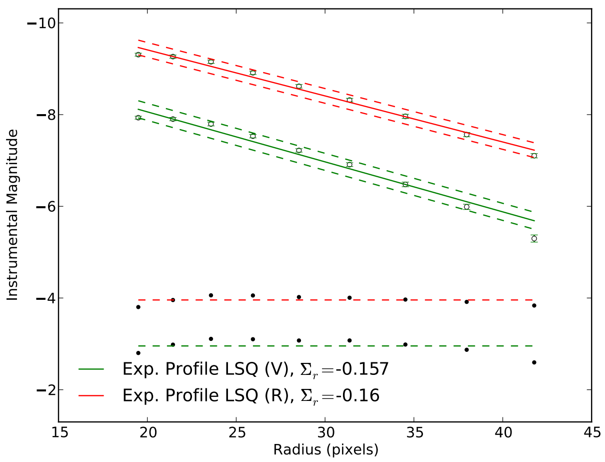

Fig. 7. Exponential profile adjusted to the NGC7205 galaxy brightness profile data. The O-C curve for each fit according to it's color is shown with an offset from 0 for visualization. We also present Σ_r, the mean of the residuals.

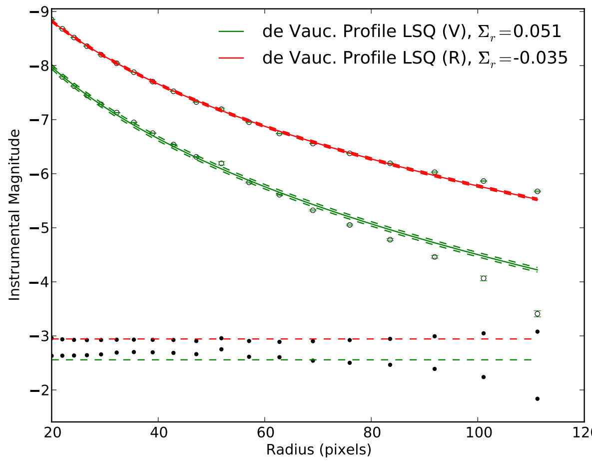

Fig. 9. de Vaucouleurs profile adjusted to the IC1459 galaxy brightness profile data. The O-C curve for each fit according to it's color is shown with an offset from 0 for visualization. We also present Σ_r, the mean of the residuals.

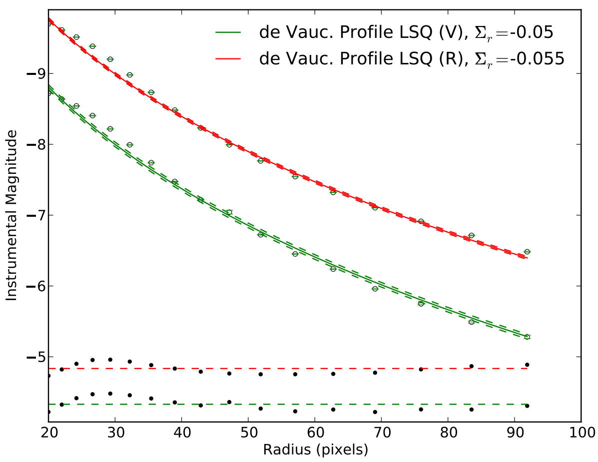

Fig. 8. de Vaucouleurs profile adjusted to the NGC1553 galaxy brightness profile data. The O-C curve for each fit according to it's color is shown with an offset from 0 for visualization. We also present Σ_r, the mean of the residuals.

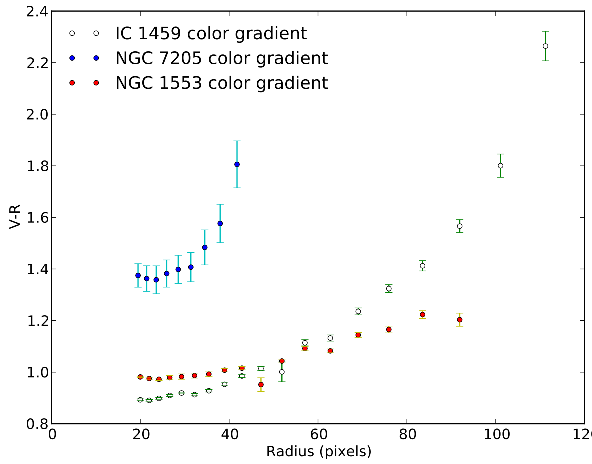

Fig. 10. The color gradient for our three galaxies are shown for comparison on blue (NGC7205), red (NGC 1553) and white (IC 1459).

C. Color gradient obtention

We obtained the color gradient (V-R v/s radii) for our three galaxies, where the error propagation was made using the sum of the variances on each instrumental magnitude. The results are shown on Figure 10.

IV. Discussion

A. Brightness profile determination methods

According to our results, using the Bayesian Method seemed the most reliable method for the obtaintion of our brightness profile curves, at least for our early-type galaxies. This can be seen comparing Figures 3 and 5, where the Bayesian method for the obtention of the brightness profile gave us a more realistic -statistically significant- interval to work on (i.e. the fit and it's sigma-error gives us an interval where the data fits properly). On the other hand, the use of this method on the late-type galaxy was just a matter of convergence, and we don't find any reasonable argument to show that this method has to work on all spiral galaxies. If we are searching for isophotes, that is, lines of equal (or similar, for the iteration to converge) light intensity, this method might only work close to the central bulge, but the search for elliptic isophotes on the exterior part of the galaxy seems as an oversimplification of the problem that can lead to errors on our conclusions about the stellar population, mainly because if there are elliptical isophotes present on the spiral galaxy they are just a part of the galaxy: the study of the spiral arms (i.e.

the study of the star-formation catalisators) is obviated. For this reason, we have to be very clear that our isophote obtention for our spiral galaxy is just a part of the galaxy (the disk), not the global picture of it.

B. Brightness profile fit determination

The obtention of a generalized Sérsic profile on our data gaved us a clue about the brightness profiles on our galaxies. According to these profiles (which minimized globally the χ^2 value), our spiral NGC7205 galaxy was closer to being part of an exponential profile, but the other two galaxies didn't give certain intervals to think about a de Vaucouleurs profile (although the n values where big enough for them to not even consider an exponential profile). According to Sérsic, his generalized $1/n$ model was motivated mainly to investigate the profile change given the atmospheric variations from ground based data. Motivated by this, we performed a χ^2 test for our data and concluded that, as we thought and saw on the Sérsic profile fit, the NGC7205 galaxy showed an exponential surface brightness profile (as expected). On the other hand, the IC1459 and NGC1553 galaxies are most likely to follow a de Vaucouleurs profile (as was expected too). However, as mentioned, the overall χ^2 is reduced on every band and every galaxy by a Sérsic profile.

It is important to note that given our selected profiles for our galaxies, every O-C data showed a systematical sinusoidal-like error, probably due to atmospheric variations (see Figures 7,8 or 9).

C. Color gradient for our galaxies

As shown on Figure 10, the NGC7204 spiral galaxy and the IC1459 elliptical galaxy follow a similar trend. They seem to get exponentially redder as we go far from the center, which seems contrary to modern observations (C.Z. Liu et al., 2009). However, we can explain this in therms of the star formation of the galaxy and the obtention of our isophotes: we obtained the information of a galaxy that has an inclination of, aproximately, 45 deg. from us. That being said, we can think of the reddening as an effect of the dust contained on the disk of the spiral galaxy (i.e., we are observing at a denser dust layer). It is also interesant to note that the lenticular NGC1553 galaxy followed a lower stepened reddening towards the edges, which we think can be a good advisor on the diference between galaxy morphologies (although further studies are needed for this to be confirmed).

V. Conclusions

The obtention of the surface brightness light curves was successful and showed to be easier for early-type galaxies than for the late-type galaxy present on our work. Our chi-square test gaved us an important tool to determine that our early-type galaxies followed a de Vaucouleurs profile and that our late-type galaxy followed an exponential profile. The Sérsic profile fit provided an excellent tool to determine the best-fit to our data and to gives us a clue on how well-behaved in comparison to the proposed models was our data.

We also performed a color gradient analysis to our galaxies and found that our late-type galaxy differed from recent observations made with the Sloan Digital Sky Survey. We believe that possible explanations for this are the uncovered dust layer present on the galaxy, given that the observation inclination angle with respect to it was $45°$ which also attenuated the variations on our data, which is clear from the error bars on our color gradient.

References

[1] R.S. de Jong, *Near-infrared and optical broadband surface photometry of 86 face-on disk dominated galaxies. IV. Using color profiles to study stellar and dust content of galaxies.*, Astronomy and Astrophysics, 313 (1996), pp. 377-395

[2] C. Martin and R. Kennicutt, *Star formation thresholds in galactic disks*, The Astrophysical Journal, 555 (2001), pp. 301-321

[3] Arjen van der Wel, *The morphology-density relation: a constant of nature*, Formation and Evolution of Galactic Bulges Proceedings IAU Symposium No. 245, 2007 M. Bureau, E. Athanassoula & B. Barbuy, eds.

[4] I. Strateva, Z. Ivezić, G. Knapp, V. Narayanan, M. Strauss, J. Gunn, R. Lupton, D. Schlegel, N. Bahcall, J. Brinkmann, R. Brunner, T. Budavári, I. Csabai, F. Castander, M. Doi, M. Fukugita, Z. Györy, M. Hamabe, G. Hennessy, T. Ichikawa, P. Kunszt, D. LAmb, T. Mckay, S. Okamura, J. Racusin, M. Sekiguchi, D. Schneider, K. Shimasaku and D. York, *Color Separation of Galaxy Types in the Sloan Digital Sky Survey Imaging Data*, Astron.J. 122 (2001) 1861-1874.

[5] J. L. Sérsic, *Influence of the atmospheric and instrumental dispersion on the brightness distribution in a galaxy*, Boletin de la Asociacion Argentina de Astronomia, 6 (1963), p. 41

[6] G. de Vaucouleurs, *Recherches sur les Nebuleuses Extragalactiques*, Annales d'Astrophysique, 11 (1948), p. 247

[7] N. Caon, M. Capaccioli, M. D'Onofrio, *On the Shape of the Light Profiles of Early Type Galaxies*, R.A.S. Monthly Notices, 265 (1993), n. 4, pp. 1013, 1993

[8] A. Graham, S. Driver, *A Log-Quadratic Relation for Predicting Supermassive Black Hole Masses from the Host Bulge Sérsic Index*, The Astrophysical Journal, 655 (2007), Issue 1, pp. 77-87

[9] C.Z. Liu, S.Y. Shen, Z.Y. Shao, R.X. Chang, J.L. Hou, J. Yin & D.W. Yang, *The color gradients of spiral disks in the Sloan Digital Sky Survey*, Research in Astron. Astrophys., 9 (2009), Issue 1, pp. 1119-1130

VI. Apendix

Here we present the codes used on the present work.

A. Sersic Profile: The Curve fit

```
from pylab import *
from readcol import *
from mpfit import *

def myfunct(p,fjac=None,x=None,y=None,err=None):
model=p[0]+p[1]*x**(1/p[2])
status=0
return([status,(y-model)/err])

def LSQFit(filename,p0):
row,r,I,Ierr,Pvar,rms,e,eErr,PA=readcol(
        filename,twod=False)
        M=-2.51*log10(I)
        Merr=sqrt((((-2.51)/(I*log(10)))*Ierr)
        **2)

        fa = {'x':r, 'y':M, 'err':Merr}
        p0 = [18.1,-3.0,3.9]
        m = mpfit(myfunct, p0, functkw=fa)
        print 'Parameters:'
        print 'Cut-off magnitude:',m.params[0],
        '+-',m.perror[0]
        print 'Sersic free param:',m.params[1],
        '+-',m.perror[1]
        print 'Sersic n index:',m.params[2],'+-'
        ,m.perror[2]
return(r,M,Merr,m)
def Plotter(r,M,Merr,p,pe,marker,curve,plotname):
plot(r,M,'o',markerfacecolor=marker,
        markersize=4)
        errorbar(r,M,yerr=Merr,fmt=None,ecolor=None)
        s=arange(min(r),max(r),0.001)
        plot(s,p[0]+p[1]*s**(1/p[2]),'-',color=curve,
        label=plotname)
        plot(s,(p[0]+pe[0]*3)+(p[1])*s**(1/(p[2])),
        '--',color=curve)
        plot(s,(p[0]-pe[0]*3)+(p[1])*s**(1/(p[2])),
        '--',color=curve)



rV,MV,MerrV,mV=LSQFit("B_IC1459V.dat",[-12.0,0.4,1.6])
pV=mV.params
peV=mV.perror
figure()

print Plotter(rV,MV,MerrV,pV,peV,'white','green','Sersic
Profile LSQ (V,n='+str(round(pV[2],2))+'$\pm$'+
str(round(peV[2],2))+')')

rR,MR,MerrR,mR=LSQFit("B_IC1459R.dat",[-12.0,0.4,1.6])
pR=mR.params
peR=mR.perror
print Plotter(rR,MR,MerrR,pR,peR,'white','red','Sersic
Profile LSQ (R,
n='+str(round(pR[2],2))+'$\pm$'+str(round(peR[2],2))+'


legend(loc=0,frameon=False)
xlabel('Radius (pixels)')
ylabel('Instrumental Magnitude')
ylim(max(array([max(MR),max(MV)]))+0.2,min(array([min(
,min(MV)]))-0.2)
show()
```

B. gdds

sds