Using the MAST virtual observatory to study light profiles in elliptical galaxies

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In this paper we use high quality images from the M.A.S.T. Virtual Observatory to elliptical galaxies with redshift $z < 0.02$ to explore the differences between the classic de Vaucouleurs $r^{1/4}$ and Sérsic $r^{1/n}$ surface light profiles. With the data obtained from the light profiles fits for a sample of 20 elliptical galaxies, we study the fundamental plane of elliptical galaxies. The Fundamental Plane involves several physical quantities of the galaxy such as luminosity, dispersion velocity and effective radius. While it is known that the Sérsic profile gives a better physical description of an individual galaxy, it was surprising that this data does not fit the Fundamental Plane for a sample of galaxies as well as the classical de Vaucouleurs fit does.

Keywords: Virtual observatory; elliptical galaxies; surface light profile; fundamental plane.

En este artículo usamos imágenes de alta calidad del Observatorio Virtual MAST, de galaxias elípticas con un corrimiento al rojo de $z < 0.02$ para explorar las diferencias en el ajuste al perfil de brillo superficial dados por de Vaucouleurs $r^{1/4}$ y Sérsic $r^{1/n}$. Con los datos obtenidos por estos ajustes a una muestra de 20 galaxias elípticas, estudiamos el Plano Fundamental de galaxias elípticas. El Plano Fundamental involucra varias cantidades físicas de una galaxia como su luminosidad, velocidad de dispersión y radio efectivo. Aunque es conocido que el perfil de Sérsic da una mejor descripción de una galaxia individual, fue una sorpresa encontrar que para la muestra completa los datos obtenidos por el perfil de de Vaucouleurs se ajustó mejor al Plano Fundamental.

Descriptores: Observatorio virtual; galaxias elípticas; perfil superficial de luminosidad; plano fundamental.

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1. Introduction

Traditionally, in astronomical research, the data has been obtained in big observatories on top of mountains. However, the number of astronomers has increased and the observing time has become more scarce. On the other hand, the amount of digital data generated by the observatories is getting larger and larger, mainly because after the research of the astronomers, the data just sits there unused. For example, if an astronomer takes images of a hundred elliptical galaxies for a project in galactic cannibalism, the same data could be used by another astronomer looking for supernovae without the need of going to an observatory. This situation and the development of faster computer systems, produced the concept of the Virtual Observatory (VO). The VO can be seen as a huge database of astronomical data. This database can be accessed in multiple ways to retrieve the desired data in a short time. This represents a new opportunity for researchers and students as it provides access to a huge quantity of data of high quality. In this paper we set to find out how easy it is in reality to access high quality data.

2. Theory

Elliptical galaxies appear to be simple objects at first view. Just a smooth blob of light, sometimes round, sometimes very elliptical. However, the reality is quite different. For instance, the light profile of the galaxy can give us information on its shape, size and brightness. One of the most successful descriptions on the surface brightness is the de Vaucouleurs' Law [1] which fits to a $r^{1/4}$ surface light profile:

$$I(r) = I_e e^{-7.67[(\frac{r}{r_e})^{\frac{1}{4}} - 1]} \qquad (1)$$

Here, the effective intensity I_e is defined as $I(r_e)$, where r_e is the effective radius that contains half of the galaxy luminosity. However, as the quality and resolution of the images increased, a more general description has become more useful. This is Sérsic's Law.

$$I(r) = I_e e^{-b_n[(\frac{r}{r_e})^{\frac{1}{n}} - 1]} \qquad (2)$$

This $r^{1/n}$ profile was proposed by Sérsic [2] in 1968 and revisited by Caon, Capaccioli and D'Onofrio [3]. When $n = 4$, this equation becomes de Vaucouleurs' Law. The term $b_n = 2n - 0.327$ was proposed by Capaccioli [3] from results of numerical fits. Besides the better fit of Sérsic Law, one of the most interesting results are the correlations between Sérsic parameters (n, r_e, I_e) and galactic properties such as absolute magnitude and size of the galaxy.

If we model an elliptical galaxy as a sphere of particles, then the Virial Theorem (VT) may be used to study it. From the VT, several relations have been found, including Tully-Fisher [4], Freeman Law [5] and Faber-Jackson [6]. Using this relations the Fundamental Plane (FP) was obtained:

$$L \propto \sigma_0^{\alpha} r_e^{\beta} \qquad (3)$$

In this equation we have the luminosity L, the velocity dispersion σ_0 which is related to the virial properties of the galaxy, and the effective radius r_e we obtain from the surface light profile. Looking at the equation, we ask ourselves: *Which effective radius should we use, the one that fits the de Vaucouleurs profile, or the more general $r^{1/n}$? Will there even be a difference?* We think there will be a difference for a sharper profile, where the light is more concentrated at the center of the galaxy, the effective radius will be smaller. A more gentle slope in the profile will give us a larger effective radius. With this reasoning, we see that the de Vaucouleurs profile sometimes will give values below or above the given by Sérsic. We saw that using a small sample of high resolution images of elliptical galaxies is a quick way to find out if there are differences. To obtain this type of images in short time, a Virtual Observatory is the best way to do it.

The Multimission Archive at STScI is a NASA funded project to support and provide to the astronomical community a variety of astronomical data archives, with the primary focus on scientifically related data sets in the optical, ultraviolet, and near-infrared parts of the spectrum. Of special interest to us, is the High Level Science Products (HLSP). These are community contributed images and spectra. This data is fully processed (reduced, cleaned of cosmic rays, etc), so it is ready for scientific analysis. The access is simple. Right in the webpage http://archive.stsci.edu/ is a search box. We simply introduce the name of the object (for example, NGC 1399) and it will tell us if there are HLSP available for download.

The data used in this work came from the Hubble Space Telescope (HST). The images were captured with the Wide Field Camera which has four CCDs. Three of this CCDs are arranged in an L-shaped array with a resolution of 0.1" per pixel. The filter used is F814W with an approximate wavelenght of 0.8 microns. This filter is commonly used in galactic studies because it is not severely affected by dust existence.

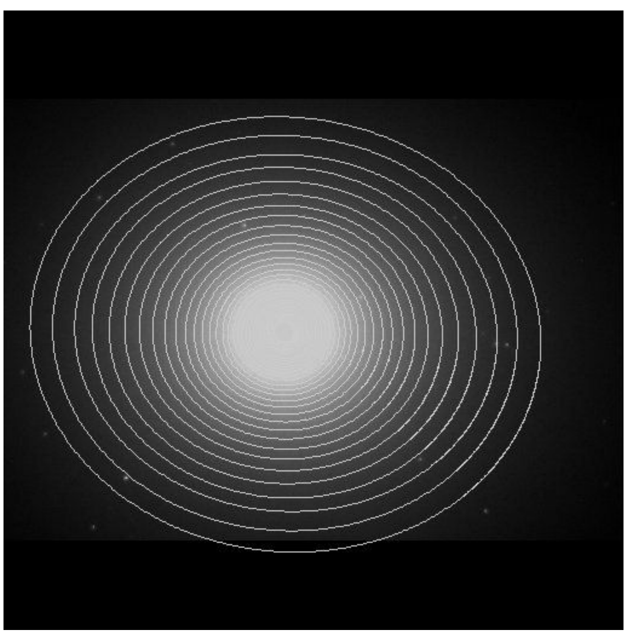

FIGURE 1. Ellipse fitting using the *ellipse* task from IRAF, for NGC 1427. Each ring has the same value in brightness (isophote). Image from STScI.

3. Results

The galaxies were selected with the next criteria:

1. They are part of the New General Catalog (NGC),
2. They should be true elliptical galaxy. In the preliminary sample we found two that were the results of mergers and did not give a clean fit for the light profile (each previous core produced a bump in the profile), even when they appeared to be ellipticals,
3. The galaxy must be near to us so it presents a big angular size in terms of pixels to get more resolution for the light profile fitting. Most galaxies in the SDSS have an angular size around 5 pixels in contrast to over 30 pixels in MAST and will not show a big difference between the two profiles as there are too few data points,
4. They are well known and there is a lot of information of them in Hyperleda (http://leda.univ-lyon1.fr/). From Hyperleda we used the apparent magnitude, absolute magnitude and velocity dispersion, and
5. It must have a HLSP image, and it should not be overexposed.

We started with over 30 galaxies, but the last criteria reduced the sample to 20 galaxies. It is expected that as times goes by, more and more data will be available as HLSP. One of the benefits of using images of the HLSP, is that they are ready for analysis. Typical astroimaging reduction (cosmic rays, flat sky, dark current subtraction, etc.) is already done for us.

Once we obtained the images, we used the *IRAF* software for the analysis. We used it because it has a special task to fit elliptical isophotes to an image (Fig. 1), and construct a table of information of several parameters including intensity, radial distance from the center, ellipticity among many others. The isophotes are regions that have the same pixel values. It is possible using this table, to reconstruct a model of the galaxy. This is useful in some cases to find inner structure such as multiple cores or bars and can be done by simple substracting the model from the real image.

While doing the fitting, we observe that there are a couple of problems. At the center of the image, the CCD sensor may be saturated and this gives us a plateau in the profile. In the outer part of the galaxy the problem is how to know where the galaxy ends and where the background light starts. This presents a catch-22 because if the image has a low exposure time, then the center will be all right while the outer part will be lost. If we increase the exposure to have a better grasp on the real size of the object, then most of the center will be saturated. From the HLSP we used images with a slight saturated center. A python program was used to do the fittings in both light profiles. The program did a non-linear fit using a

Levenberg-Marquardt routine. With this, we obtained the effective radius, the luminosity of the galaxy, and in the Sérsic fit, the n parameter. The non-linear fit was used because the term I_e depends on r_e and might introduce a bias if we do a linear fit.

For the fitting, the program took in consideration the next parameters:

1. The sky value, needed to determine where the galaxy ends. It is done in a case by case basis,

2. Apparent magnitude of the galaxy (taken from the Hyperleda database),

3. Velocity of the galaxy. Also taken from Hyperleda and needed to get the distance to the object. For this, the Hubble constant value of $H_0 = 71 + -4$ (km/s)/Mpc from WMAP '03 was used,

4. A scale parameter used to convert from angular size in pixels, to kpc. The CCD of the HST camera has a resolution of $0.1''$ per pixel.

In all the cases the Sérsic profile was the better fit. If we compare the errors, we also observe that the Sérsic fit was the most consistent too (Fig. 2).

Now, we calculated the parameters for the FP to do the comparison. The FP equation was transformed into a lineal one:

$$\log(L) = \alpha \log(\sigma_0) + \beta \log(r_e) + \gamma \qquad (4)$$

TABLE I. Errors for the Fundamental Plane fit. From the values we see that de Vaucouleurs was a better fit to the Fundamental Plane. The R^2 values the closer to 1.0 the better they are.

	Std. Error	R^2	Adj. R^2
Sérsic	0.303	0.632	0.588
de Vaucouleurs	0.269	0.709	0.675

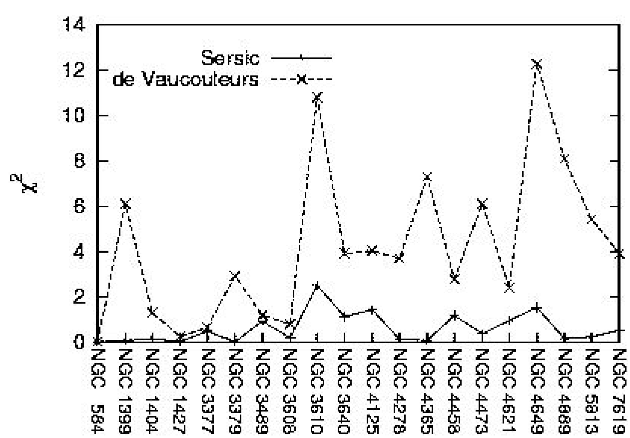

FIGURE 2. χ^2 value for each light profile fit, and galaxy. Straight line are the Sérsic fit and the dotted line is from de Vaucouleurs'. It is clearly seen that Sérsic is more consistent and with less error.

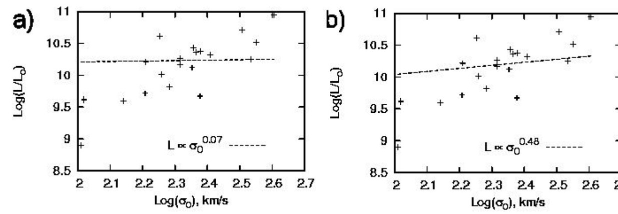

FIGURE 3. Luminosity versus Velocity Dispersion. Left is Sérsic and right de Vaucouleurs. The data points are the same because they do not come from the light profile fit, while the slope is different because the FP fit was not the same.

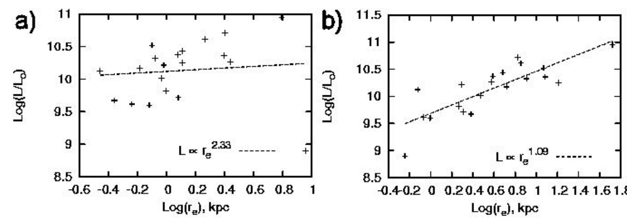

FIGURE 4. Luminosity versus Velocity Dispersion. Sérsic (on the left) has more dispersion on the fit, and has less range in the x-axis. de Vaucouleurs gave a better fit to the FP.

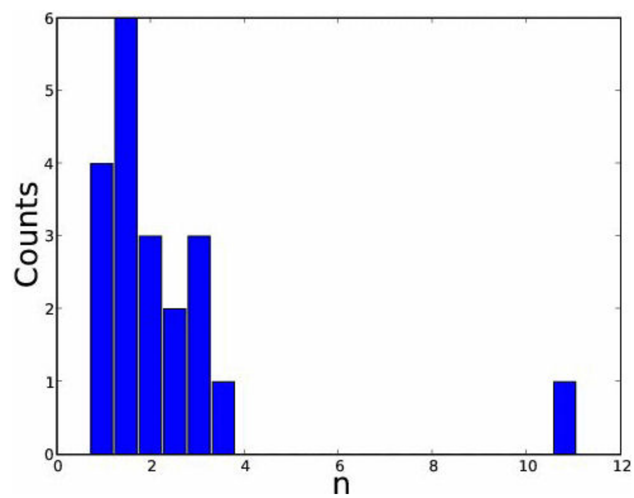

FIGURE 5. Sersic's index histogram. There is no preference for $n = 4$ that corresponds to de Vaucouleurs, but we can see a peak around $n = 2$ in this sample.

With the Fundamental Plane expressed like this, we used the method of linear regression to obtain the coefficients. The equation for the Fundamental Plane using the Sérsic data is $\log(L) = 0.07 \log(\sigma_0) + 2.33 \log(r_e) + 4.70$. For de Vaucouleurs was $\log(L) = 0.48 \log(\sigma_0) + 1.09 \log(r_e) + 7.31$. The errors are presented in the Table I.

The better fit for the FP was de Vaucouleurs, even when the fits for the effective radius were not as good as Sérsic's. Another thing we can see, is that for the Sérsic fit, the effective radius has a bigger presence, and the velocity dispersion is barely taken in account. At the moment, we do not have an explanation as to why this happened. In the graphic of luminosity against dispersion velocity (Fig. 3) there are no differences. After all, neither of these parameters depend on the fit used. In other words, is the same data for both cases.

However, when the effective radius is involved there is a difference (Fig. 4). In the Sérsic case, the data has more dispersion in the y-axis (as the errors in the fit tell us), and has less range in the x-axis. An explanation is that most of the galaxies in the sample had a Sérsic index < 4 so the effective radius was smaller and the luminosity more concentrated in the center of the galaxy. For de Vaucouleurs, the effective radius spreads over a wider range. Plotting dispersion velocity and effective radius give us a similar result.

Another interesting result is found when a histogram (Fig. 5) is made of the values obtained for n. Blanton [7] using a bigger sample from SDSS, finds a peak in the distribution around $n \sim 1$, also for close galaxies. It is clear that there are no preferences for a $n = 4$ in the light profiles.

4. Conclusions

The most important result, is that it is possible and very convenient to use data from a VO. With a broadband Internet connection, the data can be obtained in just one day. It was interesting to observe a difference in the Fundamental Plane using the Sérsic fit. One should expect that because the Sérsic profile follows more precisely the shape of the galaxy, it would be more useful to describe it with the classical FP. There are other studies [7,8] in which they find similar results and hint that using a spherical model for an elliptical galaxy is no longer enough to describe the physical properties given the information on the real three dimension shape that can be obtained using high resolution images. Another thing to consider, is that the Fundamental Plane contains information of the virialization of the galaxy. The light profiles, as the name implies, only give information on the visible mass of the galaxy. Perhaps the difference observed between the fits is another favor of the ΛCDM scenario, because the effective radius was calculated from the visible mass of the galaxy and into the Fundamental Plane the total virialized mass is taken in account. Finally, we can not exclude the possibility that the FP equation may be better fitted if we use the velocity dispersion as the independent variable, because a dependence between the luminosity and the effective radius may exist. A comparison should be made in the future, hopefully with a bigger sample. Besides a new sample, the use of techniques to use high dynamic range images stacking several images of different exposures, will give us more information for the light profile fit. There is a lot of work ahead, because the sample used is very limited and very near to us to fully understand the evolution of elliptical galaxies. A similar line of work can be extended to study Compact Groups of Galaxies at a farther distance, because elliptical galaxies may be the result of the merger of the member of a Compact Group and present physical differences at different redshifts.

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