

# PROJECT

## 7

# GALAXIES

**Objective:** The topics covered in the previous lessons target celestial objects located in our “neighbourhood”, i.e. objects which are within our own Galaxy. However, the Universe extends much beyond the Milky Way. In this project the student will get accustomed with the different type of galaxies, the morphology and radial light distribution of elliptical galaxies.

**Observations:** This exercise requires the acquisition of two images, in B and V filters, of a number of elliptical galaxies that belong to different classes.

**Theory topics:** Types of galaxies, stellar content of a galaxy, radial light distribution in elliptical galaxies.

**Analysis:** The students will be able to measure the size of an elliptical galaxy along its two major axis. Using these measurements they will be able to classify the galaxy. In this way, they will get accustomed to the Galactic classification system. Furthermore, the students will also be able to determine the radial light distribution in elliptical galaxies, and thus familiarise themselves with the de Vaucouleurs' law.

**Contents: Galaxies.**

1. The various types of galaxies: Ellipticals, Spirals and Irregulars
2. Classification of Elliptical galaxies
3. Radial surface brightness profiles of elliptical galaxies

## GALAXIES

### 1. THE VARIOUS GALACTIC TYPES: ELLIPTICAL, SPIRALS AND IRREGULARS.

The existence of galaxies other than our own was established only 80 years ago, i.e. during the 1920s. Before that, galaxies were listed in catalogues of nebulae: objects that appeared fuzzy in a telescope and were therefore not stars. Stars within these 'celestial clouds' were already been revealed by telescope images at the beginning of the 20th century. However, it was E. Hubble who showed conclusively, for the first time, that one of the nebulae (the Andromeda 'nebula' M31) is a galaxy in its own right.

Hubble was also the first who tried to set out a scheme for classifying the galaxies. In his 1936 book, 'The realm of the Nebulae', he established a classification system (see Figure 1) which, including some later additions and modifications, it is still in use today. Hubble recognized three main types of galaxy: ellipticals, lenticulars and spirals, with a fourth class, the irregulars, for galaxies that would not fit into any of the other categories.

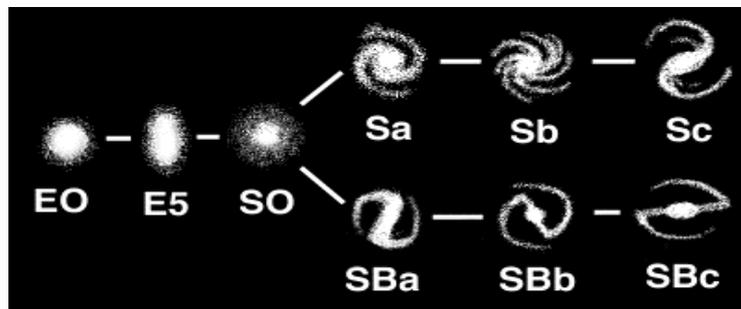


Figure 1: Galaxy classification; Hubble's scheme.

**Elliptical galaxies** (see Figure 2) have an ellipsoidal form, are smooth (i.e. they show a fairly even distribution of stars throughout) and almost featureless, devoid of structures as spiral arms and dust lanes. They are generally lacking in cool gas and consequently have few young blue stars. Ellipticals predominate in rich clusters of galaxies, and the largest of them, the cD galaxies, are found in the densest parts of those clusters (these systems can be up to 100 times more luminous than our Milky Way). Normal or 'giant' ellipticals have luminosities a few times that of the Milky Way (with characteristic sizes of tens of kiloparsecs). The stars of these bright ellipticals show little organized motion, such as rotation. Their orbits about the galaxy centre are oriented in random directions. In less luminous elliptical galaxies, the stars have more rotation and less random motion. The faintest ellipticals (with less than  $\sim 1/10$  of the Milky Way's luminosity) split into two groups. The first comprises the rare compact ellipticals, and the other group consists of the dwarf (dE) and spheroidal (dSph) elliptical galaxies.

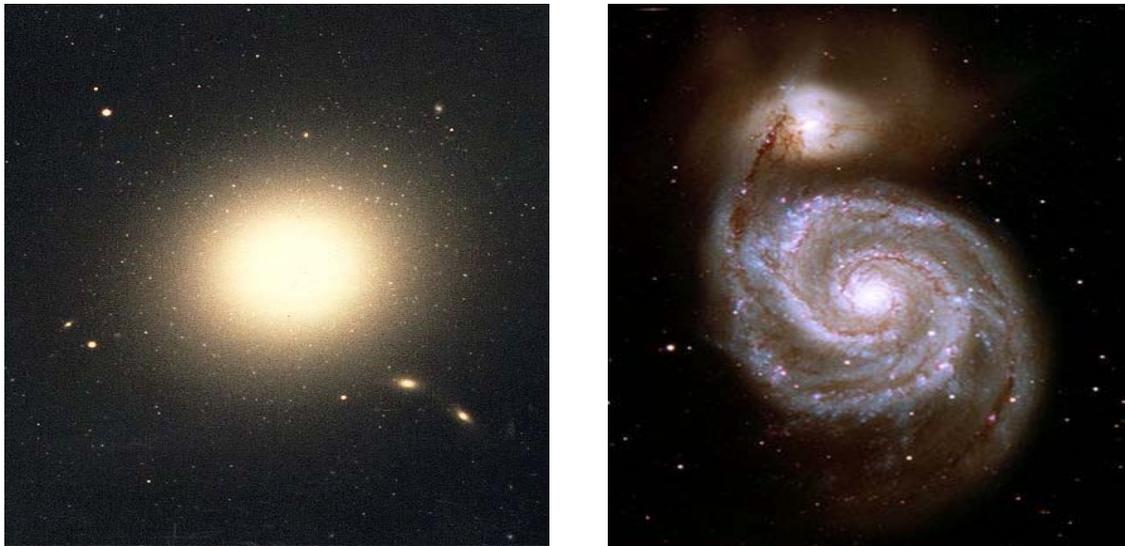


Figure 2: An elliptical (M87) and a spiral (M49) galaxy (left and right hand panel, respectively).

**Lenticular galaxies** are labelled S0, and they form a transition class between ellipticals and spirals: they lack extensive gas and dust, and prefer regions of space that are fairly densely populated with galaxies (like ellipticals). They also have a thin and fast rotating stellar disc in addition to the central elliptical bulge (like spirals), although the disc lacks any spiral arms or extensive dust lanes.

**Spiral galaxies** are named for their bright spiral arms, especially prominent in the blue light. The arms are outlined by clumps of bright, hot, young O and B stars, and the dusty gas out of which these stars form. About half of all spiral and lenticular galaxies show a central linear bar: the barred systems SB0, SBa, SBb, SBc (and SBd) form a sequence parallel to that of unbarred galaxies. Along the sequence from Sa to Sc (and Sd) spirals: a) the central bulge becomes less important relatively to the disc, b) the spiral arms become more open, c) the fraction of gas and young stars in the disc increases, d) the luminosity, on average,

decreases, and e) the speed at which the disc rotates decreases, on average. Consequently, the galaxies are less massive as well. At the end of the spiral sequence, there exist the Sm and SBm classes, which are also called as the *Magellanic spirals*, named for their prototype, which is our neighbour *Large Magellanic Cloud*.

Hubble placed all galaxies that did not fit into his other categories in the ***Irregular*** class. Today we use that name only for the small blue galaxies which lack any organized spiral or other structure. The smallest of the irregular galaxies are called *dwarf irregulars*. They differ from the dwarf spheroidals by having gas and young blue stars.

## 2. CLASSIFICATION OF ELLIPTICAL GALAXIES

The traditional galaxy classification schemes have been based on the visual examination of a small number of libraries (catalogues) of galaxy images. These images are usually taken in the B (or 'photographic') band. As a result, colours are not included in the class-defining criteria. Furthermore, galaxies in these catalogues have been selected on the basis of their apparent magnitudes: in many cases the defining libraries were designed to include all galaxies brighter than some given apparent magnitude. This criterion effectively ensured that the galaxy classification was defined in terms of rather luminous galaxies, that are actually not at all typical of the generality of galaxies in the Universe. Finally, most published galaxy classifications are the result of a subjective assessment of a picture by a human being. In fact, many times two astronomers will place the same spiral galaxy in different (albeit adjacent) classes. This is not usually the case with ellipticals, as there exists an 'objective' way to classify them.

Ellipticals vary in shape from round to fairly elongated in form. They are labelled by the Hubble type **En**, where the number **n** describes the apparent axial ratio (**b/a**) by the formula:

$$n=10 [1 - (b/a)], \quad (1)$$

where **a** and **b** represent the length of the semi-major and semi-minor axis, respectively, of the galaxy *isophotes*.

Contours of constant *surface brightness* on a galaxy image are called *isophotes*.

The *surface brightness* of a galaxy, **I(x)**, is the amount of light per square arcsecond on the sky at a particular point **x** in the image. Consider a small square patch of side **D** in a galaxy that we view from a distance **d** (so that it subtends an angle  $\alpha=D/d$ ). If the combined luminosity of all the stars in this region is **L**, and their apparent brightness **F(=L/4πd<sup>2</sup>)**, then, since by definition **I(x)=F/α**, then

$$I(x)=L/4\pi D^2. \quad (2)$$

The units for **I** are **mag/arcsec<sup>2</sup>**.

**Exercise 1:** In a galaxy at a distance of  $d$  Mpc, what would be the apparent B magnitude of a star like our Sun? In this galaxy, show that  $1''$  on the sky corresponds to  $5d$  pc, and hence that the surface brightness  $I_B=27$  mag/arcsec<sup>2</sup> is equivalent to  $1 L_{SUN}$  pc<sup>-2</sup>.

Coming back to the issue of elliptical galaxy classification, equation (1) shows that this can be achieved through the use of a quantitative classification criterion.

The isophotes of most elliptical galaxies are remarkably close to being true elliptical. The ratio  $b/a$  quantifies how far the isophot differs from a circle. In fact, the *ellipticity*,  $\epsilon$ , of an elliptical galaxy is defined as:  $\epsilon = 1 - b/a$ .

The point is that, for most ellipticals, the ellipticity is fairly constant, the position of the centre and the direction of the long axis remain stable, irrespective of the optical band we use, or the brightness of the isophotes we have chosen. As a result, the classification of elliptical galaxies is usually pretty robust. For example, E0 galaxies appear circular in the sky (i.e.  $a \sim b$ ) and the short axis in an E5 galaxy is half the size of the long diameter, in all optical bands. The index  $n$  is usually rounded to the nearest whole number. Finally, the Hubble type of an elliptical galaxy depends on our viewing direction.

### 3. RADIAL SURFACE BRIGHTNESS PROFILES OF ELLIPTICAL GALAXIES

The light in elliptical galaxies is much more concentrated toward the centre, than it is in the discs of spirals. We can plot the surface brightness on the major axis of the image of an elliptical galaxy against radius  $R$ .

For most of the luminous and mid sized elliptical galaxies (i.e. those brighter than about  $3 \times 10^9 L_{SUN}$ ), the formula:

$$I(R) = I(R_e) \exp\{-7.67 [(R/R_e)^{1/4} - 1]\}, \quad (3)$$

provides a fairly good description for their surface brightness profile. The radius  $R_e$  is called the *effective radius*. The circle of radius  $R_e$  includes half the light of the galaxy. This relationship was discovered by de Vaucouleurs in 1948, hence it is known as the *de Vaucouleurs  $R^{1/4}$  law*.

**Exercise 2:** Show that the above formula yields a total luminosity of:  $L \approx 7.22 \pi R_e^2 I(R_e)$

(remember that  $\int_0^\infty e^{-t} t^7 dt = \Gamma(8) = 7!$ ).

**Exercise 3: Use a table of incomplete  $\Gamma$  functions to show that half of this light in an elliptical galaxy comes from within radius  $R_e$ . Study of elliptical galaxies using images from Skinakas observatory.**

The objective of this project is to determine the Hubble type of elliptical galaxies that you have observed with the Skinakas 1.3 m telescope, and to study the radial distribution of their surface brightness profile along their major axis.

We assume that you have acquired V band images of a few elliptical galaxies, and the necessary bias and flat field frames. So, the first step is to:

1. Calculate a mean bias frame and subtract the bias from the V-band images (both of your objects and of the flat fields)

and then, for flat-fielding:

2. Take all the V-band flat-field images, add them together and divide the sum by the mean value of the sum. This will give an averaged flat-field whose mean is unity. Divide the galaxy images by the scaled flat-field image.

Then,

### **a) for the classification of the galaxies**

you will need to use appropriate software that will be able to draw a 'plot of the isophotes' of the galaxy at hand. Here we will assume that you are familiar and can use the *IRAF* software package.

The appropriate *IRAF* command to draw a plot of a galaxy isophotes is:

***contour 'image'***

where 'image' is the name of your '.FITS' image file. As usual, the command

***help contour***

will print, on the computer screen, a text file which explains how the command works, and which are the important command parameters. The parameter values can be modified by the use of the command

***epar contour***

which edits the parameter file of the command. In this exercise, it is important to create two 'contour plots'.

Use the command ***imexamine*** and move the cursor on the galaxy image close to the apparent centre of the galaxy. Press the '**a**' button, and the approximate x- and y-axis pixel values of the galaxy centre (say *x\_gal* and *y\_gal*) will appear on your computer screen.

Then, move the cursor away from the galaxy, and from any other stellar images, and press the '*m*' button. In this way, you can determine the 'background sky' value of your image. Repeat a few times, and calculate the average 'sky' value (say  $I_{\text{sky}}$ ).

Now, edit the contour parameter file, and modify the '*ncontours*' parameter value to something like 5-10. Then, run the *contour* command, but considering just a small region around the galaxy central part:

```
contour 'image'[x_gal-10:x_gal+10, y_gal-10: y_gal+10]
```

***What is the shape of the galaxy isophotes close to its centre?***

Repeat, but this time, plot the isophotes of the whole galaxy by using [*x\_maxleft*: *x\_maxright*, *y\_maxdown*: *y\_maxup*] in the command above. The pixel coordinates *x\_maxleft*, *x\_maxright*, *y\_maxdown*, and *y\_maxup* correspond to the left, right, down and up 'outermost' pixels from the galaxy centre, and are supposed to define a region which includes the whole galaxy image, up to the point where the galaxy light merges with the background sky light.

***How do the outermost galaxy isophotes look like? Do they look similar to the central isophotes? If not, can you provide one possible explanation?***

By changing the value of the parameter '*device*', you can now print the second contour plot. Use the three outermost contours to estimate *a*, *b* (in pixels) and hence *n*.

***Do the n values change? What are your conclusions?***

Having classified the galaxies, you can now proceed to examine

### ***β) the radial surface brightness profile***

of the galaxies along their major axis.

With the help of the isophotes plot you can determine the approximate (*x\_maxleft*, *y\_maxdown*) and (*x\_maxright*, *y\_maxup*) pixel coordinates of the galaxy major-axis. The IRAF command

```
pvector image x_maxleft y_maxdown x_maxright y_maxup
```

will allow you to either plot or print in a file the data from the galaxy image along the vector which the (*x\_maxleft*, *y\_maxdown*) and (*x\_maxright*, *y\_maxup*) pixel coordinates define, i.e. along the galaxy major-axis. The choice of plotting or printing in a file the data values along

the major axis is determined by choosing the appropriate values for the command parameters 'vec\_output' and 'out\_type'.

Another important command parameter is 'width' which determines the number of pixels, perpendicular to the vector, to average. Run the command with *width=1, 3, and 5*.

***How does the radial profile change? Can you explain why?***

Run the *pvector* command with *width=3* and store the results in a text file. Using your favourite plotting software programme, plot the results.

The x-axis in this plot will show the distance, in pixels, along the major-axis, while the y-axis shows the light that was collected on the CCD, in a region with size  $1 * \text{width pixel}^2$ , along the major-axis, in ADU units (*I\_gal*). This is not equivalent to surface brightness, as you need to divide these numbers by the area of the region where you collect the light from. However, since the region area is the same for all points, this is not necessary, for our purposes.

In order to construct the radial light profile of the galaxy, you should identify the point along the major axis where *I\_gal* is maximum (*I\_gal,max*) and accept it as the galaxy centre. Then, using a simple Fortran programme, you should:

- a) estimate the distance of each point, on either side from the galaxy centre (say  $R_+$  and  $R_-$ , in pixels)
- b) estimate the average 'light' of the points with  $R_+=R_-$  (i.e.  $I_{\text{ave}}(R) = [I_{\text{gal}}(R_+) + I_{\text{gal}}(R_-)]/2$ )  
and
- c) subtract the contribution of the sky light ( $I_{\text{final}}(R) = I_{\text{ave}}(R) - I_{\text{sky}}$ ).

You can now plot  $\log(I_{\text{final}})$  as a function of  $R^{1/4}$ .

***How does the plot look like at small radii? Can you provide an explanation for this?***

***How does the plot look like at larger radii?***

***What are your conclusions?***

***Can you provide an estimate of the parameter  $R_e$ ?***