Astrophysics

Galaxy dynamics and dark matter

Alejandro José Florido Tomé

1 Introduction

In this practice, NGC 2841 has been studied in different wavelengths with program ds9.

The goal is to obtain its dynamical, atomic gas and stellar masses, from which dark matter proportion in the galaxy will be obtained.

2 Background

If we have a mass m doing a circular orbit of radius r around a mass M_{dyn} with a velocity v_{rot}, we can use Second Newton's Law:

$$mv_{rot}^2/r = GM_{dyn}(<R)m/r^2, \quad (1)$$

so, clearing from the equation what we want:

$$M_{dyn} = \frac{v_{rot}^2 r}{G}. \quad (2)$$

Taking the next values for the constants: $G = 6.674 \cdot 10^{-11}\ m^3/kg \cdot s^2$, $M_\odot = 2 \cdot 10^{30}\ kg$, $1\ kpc = 3.0857 \cdot 10^{19}\ m$, we can rewrite the previous equation as:

$$M_{dyn} = \frac{v_{rot}^2 r}{G} \cdot \frac{3.0857 \cdot 10^{19} m}{1 kpc} \cdot \frac{1 M_\odot}{2 \cdot 10^{30} kg} = $$
$$= 2.31 \cdot 10^5 \left(\frac{v_{rot}}{km \cdot s^{-1}}\right)^2 \left(\frac{r}{kpc}\right) M_\odot. \quad (3)$$

The rotation velocity of the galaxy v_{rot} does not correspond with the one measured, $v_{rot,measured}$, because of the inclination $i = 65,3\ degree$ of the galaxy, such that they are related by:

$$v_{rot} = \frac{v_{rot,measured}}{sin(i)}. \quad (4)$$

By other part, we will measure the velocity-integrated flux of the HI line, S_{HI}, essential to obtain the atomic gas mass present in the galaxy:

$$M_{HI} = 2,36 \cdot 10^5 \left(\frac{D}{Mpc}\right)^2 \left(\frac{S_{HI}}{Jykms^{-1}}\right) M_\odot, \quad (5)$$

with D=14,1 Mpc the distance of the galaxy.

And it's possible to obtain the stellar mass of the galaxy with:

$$M_{star} = 14,5 L_{3,4\mu m}[M_\odot], \quad (6)$$

where the luminosity is given by:

$$L_{3,4\mu m} = 2,75 \cdot 10^7 \left(\frac{S_{3,4\mu m}}{Jy}\right) \left(\frac{D}{Mpc}\right) L_\odot. \quad (7)$$

3 Methods and results

We had been following the steps detailed in the practical exercise given in Prado. This consists on using ds9, a program such that, with some pictures of a galaxy in different wavelengths (in this case, the galaxy is NGC 2841), It's possible to obtain the rotation velocity of the object, its radius, ... Let's explain by parts what we have been doing.

3.1 Dynamical mass

First of all, we use the MOM1 picture, a map of the mean velocity of the HI. We introduce as regions ellipses and a line. The line must cross the entire galaxy, and the ellipses of different radius must have the same relation that $d_{max} = 6,9\ armin$ and $d_{min} = 2,3\ armin$, that is 6,9/2,3=3. To put these elements at the right places, we must consider the position angle=153, minus 90, for being the angle used by ds9; and the coordinate of central position of NGC 2841: $RA = 09:22:02.6$, and $declination = +50:58:35$. We can save this region, allowing us to use the same regions without doing the same later (see Figure 1).

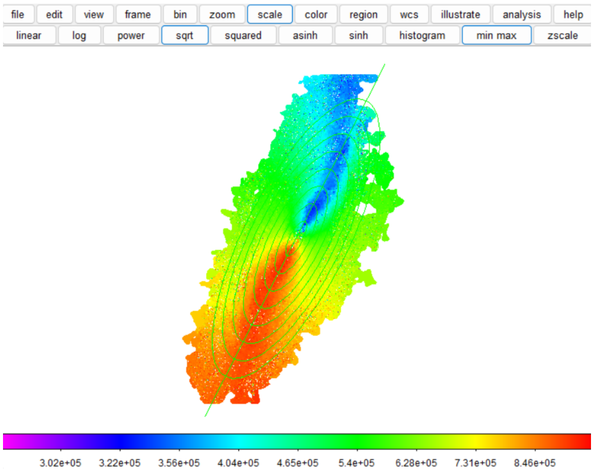

Figure 1: Measure of the mean velocity of the HI of NGC 2841, where bigger values means reddish colors, and lower values means bluish colors. Ellipses and the line have been introduced with the coordinates of the galaxy center.

Now, keeping our attention on the intersection between the ellipses and the radius, we can move our mouse to this place, and take the value of the mean velocity in this point. So we can do this to all the ellipses, and we will have the mean velocity as a function of the radius. The radius will be in the ellipse region file in arcsec. To pass it to kpc, we need to multiply. With this steps, we can finally do a graphic with the mean velocity and the radius (see Figure 2).

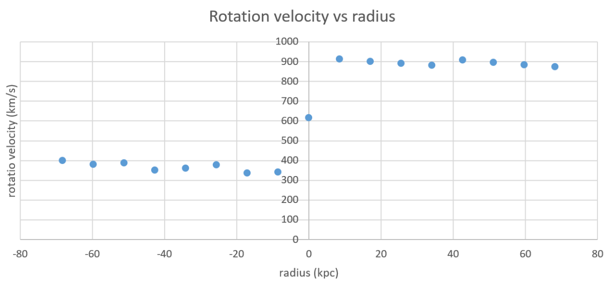

Figure 2: Rotation velocity of NGC 2841 versus its radius.

From Figure 2, we can obtain the mean rotation velocity. We have, for the -r and r, two values of the mean velocity, let's call it v_{max} and v_{min}, so, for $|r|$, mean rotation velocity as a $|r|$ function will be $v_{max} - v_{min}$ (see Table 1). Then, the mean rotation velocity will just be the mean value, given by $v_{rot,measured} = 536,099\ km/s$.

As the galaxy has a inclination $i = 65,3\ degree$, this velocity is not the real one. The real one is given by equation 4, so $v_{rot} = 590,088\ km/s$. With it, it's possible to obtain the dynamical mass of the galaxy as a function of r using equation 3 (see Table 2).

We can also obtain the systemic velocity derived from the redshift due to the expansion of the universe. For NGC 2841, z=0,00213, so, taking $c = 3 \cdot 10^8\ m/s$:

$$v_{sys} = zc = 639\ km/s. \tag{8}$$

3.2 Atomic gas mass

In second part, we will use the MOM0 image (map of the velocity-integrated flux of the HI). We have to open the ellipse and line region used before, such that we need the velocity-integrated flux of the HI line. We want it unities at $(Jy \cdot km/s)$, and we obtain it at $(Jy \cdot km/beam \cdot s)$. To do it, we must multiply by $(10^{-3} \cdot \frac{pixel-size-hi^2}{beam-x \cdot beam-y})$, where $pixel-size-hi = 1,5$" looking at header, and $beam-x = 6,06$" and $beam-y = 5,79$" given in the practical exercise.

To measure the velocity-integrated flux of the HI line S_{HI}, we select the different ellipses, and take the pixels sum of the ellipses n_{pix}, and the are related by:

$$S_{HI} = n_{pix} \cdot 10^{-3} \cdot \frac{1,5^2}{6,06 \cdot 5,79}, \tag{9}$$

whose values are given at Table 1. Using equation 5, we can obtain the atomic gas mass of the galaxy (see Table 2).

3.3 Stellar mass

Finally, we use the WISE 3,4 μm file. Here, 1 pixel=1,375", and we put again the ellipses and line region. We are going to measure, for each ellipse, the mean value (m_{value}) (Jy/pix) and the number of pixels (n_{pixel}). But there is always a background to have in account, with a value, taken from an ellipse outside the galaxy, $m_{back} = 1,559 \cdot 10^{-5}\ Jy/pix$.

Then, the flux at $3,4\ \mu m$, $S_{3,4\mu m}$, will be:

$$S_{3,4\mu m} = (m_{value} - m_{back}) \cdot n_{pixel}, \tag{10}$$

whose values are given in Table 1. We will be able to calculate the luminosity and the stellar mas with equations 7 and 6, respectively (see Table 2).

3.4 Visible and dark matter mass

With the dynamic, atomic gas and stellar mass, it's known that the visible mass, M_{vis}, is given by:

$$M_{vis} = M_{HI} + M_{star}, \tag{11}$$

(see Table 2) such that:

$$M_{dyn} = M_{vis} + M_{DM}, \tag{12}$$

with M_{DM} the dark matter mass, the value that we are looking for.

Helping us with the values of Table 2, we can obtains the Figures 3 and 4.

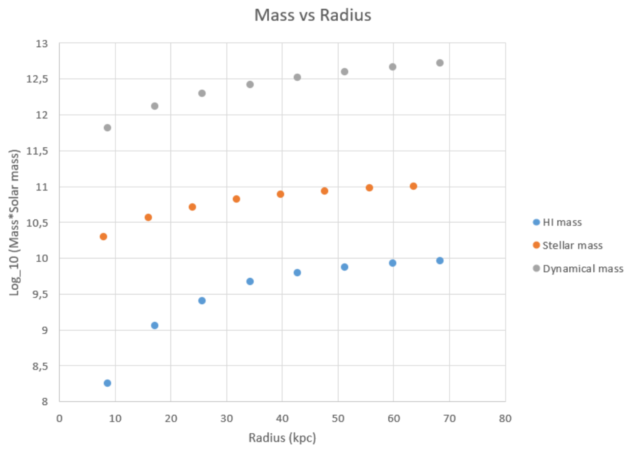

Figure 3: Logarithm of dynamical, HI and stellar mass versus the radius.

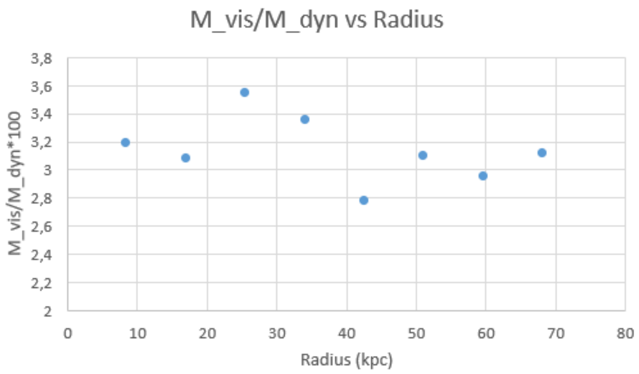

Figure 4: Percentage between visible and dynamic mass versus the radius.

From Figure 3, It's clear that there are more stellar than atomic gas mass, because of the evolution of the galaxy; and from Figure 4, that the percentage of visible mass is around 3,5%, leaving the rest, the no visible mass, for the dark matter: about 96,5% for NGC 2841.

4 Discussion and conclusions

From Figure 4, we can conclude that, in NGC 2841, about 96,5% of the galaxy is dark matter. This is logical because is the mean source of its gravitational force, and the reason why the mean velocity does not change with the radius (see Figure 2).

This proportion mass remains almost constant with the radius, and It is a amount expected for this type of galaxies.

Although, it's a proportion too big: it is possible that I have made some mistake, probably in the conversion from arcsec to kpc in each case. Nevertheless, one thing is clear: dark matter explains Figure 2, the rotation curve, a strong experimental evidence of its presence.

5 Tables

Rotation velocity (km/s)	Radial distance (kpc)	$S_{3,4\mu m}$ (Jy)	S_{HI} ($Jy \cdot km \cdot s^{-1}$)
616,538	0,000	-	-
570,576	8,533	1,264	3,831
563,023	17,067	1,199	24,716
512,627	25,600	1,099	54,213
520,229	34,133	0,989	100,978
557,205	42,667	0,843	135,121
508,171	51,200	0,663	162,817
504,454	57,733	0,471	184,389
472,065	68,267	0,256	197,527

Table 1: Rotation velocity of the galaxy, flux at $3,4\mu m$ and velocity-integrated flux of the HI line as functions of the radial distance.

M_{dyn} ($\cdot 10^{12} M_{\odot}$)	Radial distance (kpc)	M_{HI} ($\cdot 10^{9} M_{\odot}$)	M_{star} ($\cdot 10^{10} M_{\odot}$)	M_{vis} ($\cdot 10^{10} M_{\odot}$)
0,777	8,533	0,179	2,029	2,047
1,514	17,067	1,159	3,732	3,838
1,883	25,600	2,544	5,253	5,507
2,585	34,133	4,738	6,687	7,161
3,707	42,667	6,339	7,848	8,482
3,700	51,200	7,639	8,712	9,476
4,254	57,733	8,651	9,507	10,372
4,258	68,267	9,268	10,021	10,957

Table 2: Dynamical, atomic gas, stellar and visible mass as functions of the radial distance.