



# Kinematics of two spiral galaxies

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**Abstract.** We studied the kinematics of two spiral galaxies: NGC2336 and NGC2841. We calculated the rotation curve, which describes how the velocity changes along the galactic radius, and from this the corresponding mass of each galaxy.

## 1. Introduction

The motion of a spiral galaxy is due to two contributions: the bulge, which moves as a rigid body and the disk, which follows a Keplerian motion. The purpose of our research was to obtain experimentally the rotation curve of a spiral galaxy. The rotation curve describes how the velocity changes as a function of the distance from the galactic centre. Therefore, the model that we want to develop has to describe the uniform circular motion of a rigid body near the centre. This means that the model should reproduce the linear law  $v = \omega r$ , where  $\omega$  is the angular velocity and  $r$  the distance from the centre. On the other side, far from the centre, the model has to follow the Keplerian motion plus the contribution due to the dark matter. This is described by the law  $v^2 r = \text{constant}$ , i.e.  $v \propto 1/\sqrt{r}$ : the trend of the velocity, at increasing distance from the centre, is inversely proportional to the radius.

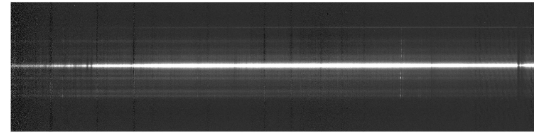
Our second purpose was to determine the total mass of the galaxy by applying the Virial Theorem:  $U + 2K = 0$ .

In order to determine the recessional and the rotation velocity of the galaxies as a function of the distance from the centre, we adopted the Doppler effect. The Doppler effect is observed whenever the emitting source is moving with respect to an observer. The wavelength emitted by a moving source is different from that emitted by the same source at rest.

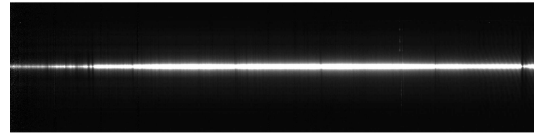
## 2. Observational data

Our analysis was carried out starting from the spectra of the two galaxies, NGC2336 and NGC2841, observed with the telescope Galileo at the Asiago Astrophysical Observatory, with an exposure time of 300 seconds. To analyse the data we used the following packages: *IRAF*, *TOPCAT* and *ds9*.

The observed spectra are shown in Figs. 1 and 2 for NGC2336 and NGC2841, respectively.



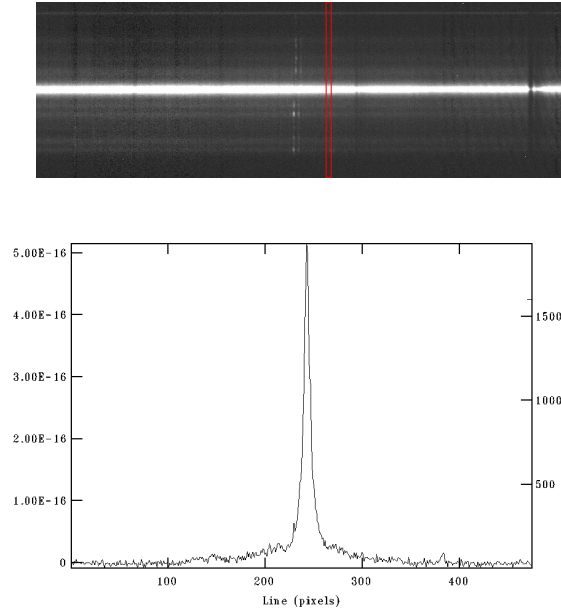
**Fig. 1.** Spectrum of NGC2336.



**Fig. 2.** Spectrum of NGC 2841.

## 3. Work description

First of all we had to determine the position of the centre of our galaxies, because in the centre the rotational velocity is zero. To estimate the position of the centre, we took into account the region of the spectrum where we saw the continuum, by using the task *implot* of the *IRAF* software and displaying the spectrum perpendicular to the dispersion, that is along the slit. We considered the maximum intensity of the continuum as the centre of the nucleus and we associated to its coordinates  $r = 0$ . Then, we plotted only the  $H\alpha$  region of the spectrum and calculated the  $H\alpha$  emission line position at different distances from the nucleus.



**Fig. 3.** Top: Spectrum of NGC 2336. The red rectangle indicates the position along the spectrum used to determine the centre of the galaxy. Bottom: plot of the region in the rectangle, orthogonal to the dispersion. The position of the peak is the position of the centre.

**Table 1.** Coordinates of the centre for our galaxies in pixels

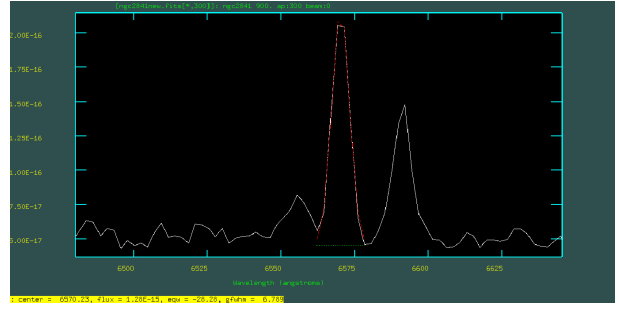
|         | X    | Y   |
|---------|------|-----|
| NGC2336 | 1542 | 243 |
| NGC2841 | 1468 | 241 |

**Table 2.** Intervals of wavelengths for [NII] emission

|                 | NGC2336 | NGC2841 |
|-----------------|---------|---------|
| $\lambda_{min}$ | 6597    | 6563    |
| $\lambda_{max}$ | 6621    | 6583    |

We noticed that the  $H\alpha$  line is not always well visible in the central regions because it is often absorbed by the underlying stellar absorption. To overcome this problem, we decided to base our calculations on the forbidden line [N II]6584 Å for both galaxies. With the software DS9 we identified the range of wavelengths in which we detected this emission line (see Table 2).

In Fig. 4 we showed the emission peaks. Overlapped, in red, there is the Gaussian fit, applied to measure the peak positions.



**Fig. 4.** Emission lines fitted with a Gaussian function (red dashed line).

**Table 3.** Main results for the two galaxies

|                                            | NGC2336 | NGC2841 |
|--------------------------------------------|---------|---------|
| Redshift                                   | 0.0072  | 0.0021  |
| Recessional velocity [km s <sup>-1</sup> ] | 2142    | 630     |
| Distance [Mpc]                             | 28.6    | 8.4     |
| Conversion factor [pc/"]                   | 138.44  | 40.65   |

### Data elaboration

Knowing that the emission wavelength of [N II] rest frame is  $\lambda = 6584\text{Å}$ , and considering that the rotational velocity is zero in the galactic centre, we calculate the recessional velocity for the whole galaxy using the following equation:

$$v = \frac{\lambda_{oss} - \lambda_0}{\lambda_0} \cdot c \quad (1)$$

where  $\lambda_{oss}$  and  $\lambda_0$  are the observed wavelength and the laboratory wavelength, respectively. As an example we applied eqn. (1) to NGC2841:

$$v = \frac{6597.85 - 6584}{6584} \cdot c = 630 \frac{\text{km}}{\text{s}}. \quad (2)$$

Dividing the recessional velocity by Hubble's constant ( $H_0 = 75 \text{ km/s/Mpc}$ ) we obtained the distance of the two galaxies, expressed in Mpc. This is necessary to calculate the conversion factor from pixels to parsecs. The scale of the CCD we used to obtain the spectra is  $1''/\text{px}$ . This means that one pixel corresponds to one arcsecond, therefore we did not need to transform pixels into arcseconds before converting them to parsecs.

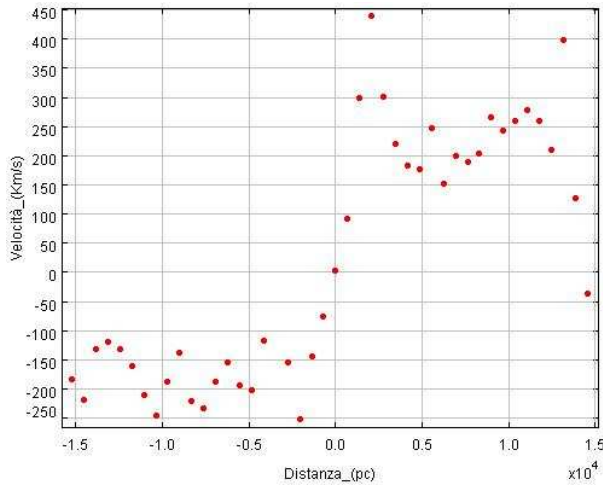
In order to calculate the conversion factor, we divided the distance by 206265":

$$\text{scale factor} = \frac{d}{206265} \left[ \frac{\text{Mpc}}{''} \right] = 40.66 \left[ \frac{\text{Mpc}}{''} \right] \quad (3)$$

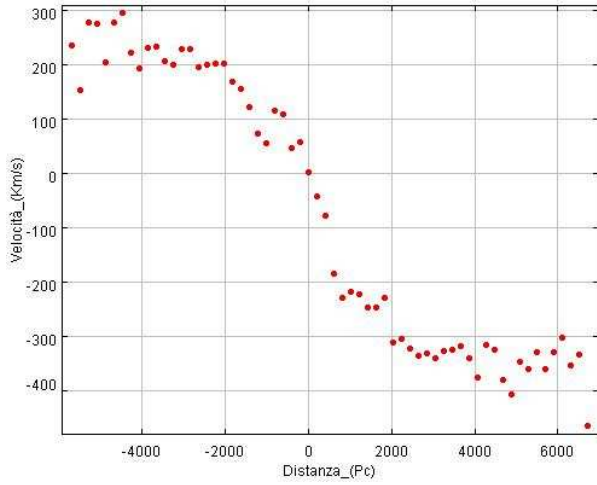
All the results are summarized in Table 3.

We obtained the distance from the galactic centre expressed in pc by using the relation:

$$r(\text{pc}) = r('')d(\text{pc})/206265''.$$



**Fig. 5.** NGC2336: velocity of each point of the galaxy along the slit as a function of their distance from the centre.



**Fig. 6.** NGC2841: velocity of each point of the galaxy along the slit as a function of their distance from the centre

In this way we calculated the velocity of each region of the galaxy along the major axis, referred to the centre, by applying the redshift formula (eqn. 1) to the observed wavelength of [NII], and by subtracting the central recession velocity. The relations between the observed velocity and the distance from the centre for the two galaxies are shown in Figs. 5 and 6.

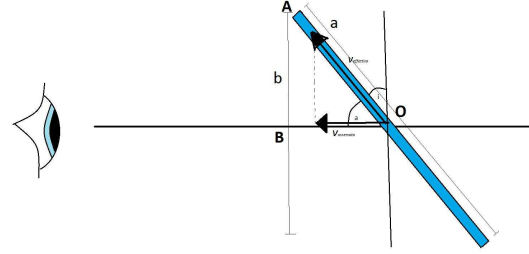
### Correction to the velocities

Until this point, we did not take into account the fact that the observed galaxies are inclined. For this reason, the measured redshift of the [N II] emission is only the component along the line of sight of the rotation velocity.



In order to calculate the inclination angle, we considered the triangle **OAB** (see Fig. 7), and we applied the properties of the right triangle:

$$\frac{b}{2} = \frac{a}{2} \sin \alpha, \quad b = a \cos i, \quad i = \cos^{-1} \frac{b}{a}$$



**Fig. 7.** Components of the rotation velocity.

The inclination angles of our galaxies are:

$$i_{NGC2841} = 1.128 \text{ rad}, \quad \text{and} \quad i_{NGC2336} = 1.046 \text{ rad}$$

In order to calculate the deprojected velocity, we applied the right triangle properties to the triangle **OAB**, where the observed velocity,  $v_{oss}$ , is along the cathetus **OB**, and the effective velocity,  $v_{eff}$ , along the hypotenuse **OA** (see Fig. 7). In this way we obtained the relation:

$$v_{eff} = \frac{v_{oss}}{\sin i}.$$

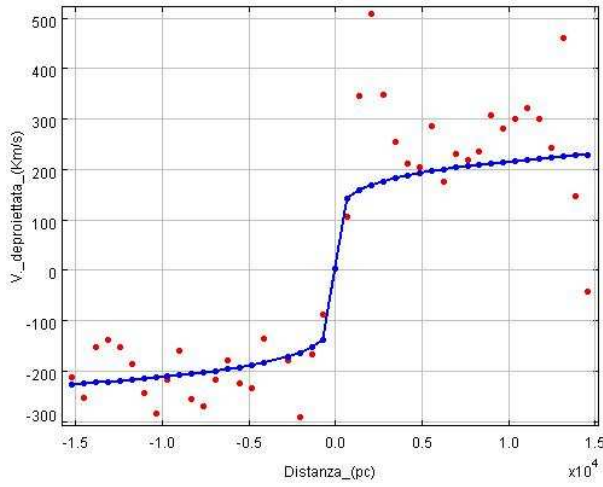
### Construction of mathematical models

After calculating the real velocities along the major axis of the galaxy, we wanted to reproduce the observed rotation curve of the two galaxies adopting a mathematical model, in order to better analyse our results.

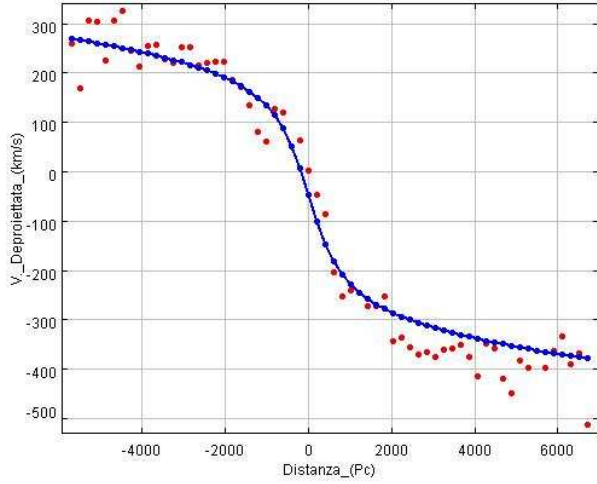
Observing the trend of the curves shown in Figs. 5 and 6, we noticed that, in the region near the galactic centre, the motion can be described by solid body rotation, because the velocity increases proportionally to the distance from the centre. On the other side, in the external regions, where we supposed a Keplerian motion (because the galaxy is not a rigid object), the velocity tends to be constant. This suggests the presence of dark matter, which cannot be seen, but affects the most external regions of the galaxy.

The mathematical model we used to fit our curves was taken from literature:

$$v(r)_{model} = \frac{ar}{(r^2 + c_0^2)^{\frac{p}{2}}}$$



**Fig. 8.** NGC2336: rotation curve.



**Fig. 9.** NGC2841: rotation curve.

#### 4. Results

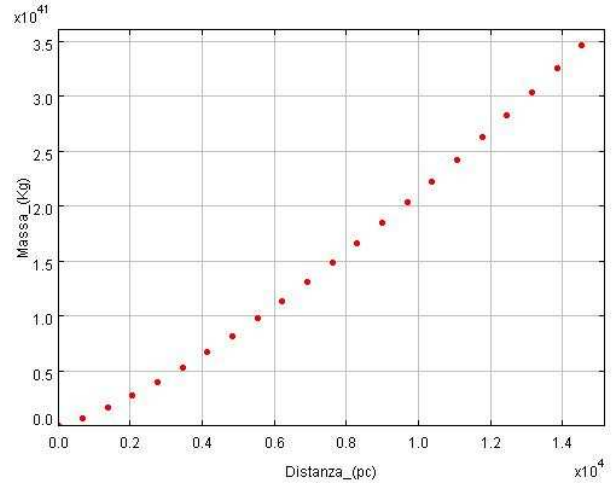
As final step of our work, we calculated the mass of the galaxies by using the velocities obtained from the mathematical model and applying the Virial theorem. The Virial theorem states that, for a stable, self-gravitating, spherical distribution of equal mass objects (stars, galaxies, etc), twice the total kinetic energy of the objects plus the total gravitational potential energy is equal to zero:

$$U = -2K$$

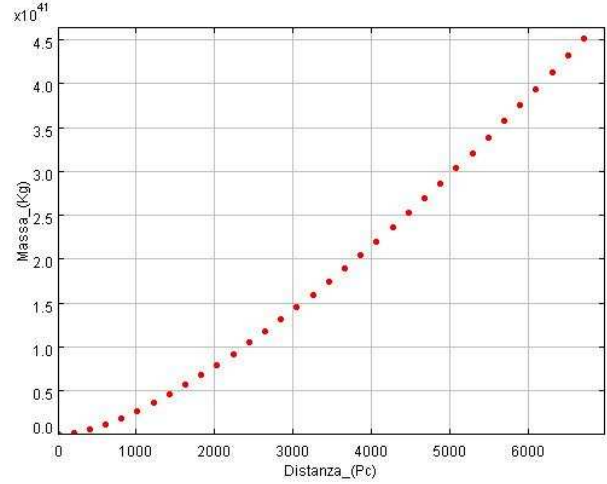
$$G \frac{mm'}{r} = 2 \frac{1}{2} m' v^2$$

$$m = \frac{rv^2}{G}$$

By looking at the plot for the masses, Figs. 10 and 11, we can see an increasing of the mass as function of the



**Fig. 10.** NGC2336: mass of the galaxy as a function of distance from the centre.



**Fig. 11.** NGC2841: mass of the galaxy as a function of distance from the centre.

radius, since we calculated the mass inside each radius previously found.

The mass values corresponding to the galactic radii are:

$$M_{NGC2841} = 4.0 \times 10^{41} Kg$$

$$M_{NGC2336} = 4.1 \times 10^{41} Kg$$

these values correspond approximately to  $2 \times 10^{11} M_{\odot}$ .