DARK MATTER IN THE CLASSROOM

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Content

Introduction

In 2012, the Higgs boson was found. In September 2015, the experimental confirmation that gravitational waves actually exist became an international sensation. Although Einstein predicted their existence over 100 years ago, we didn't have the needed technology to prove it until now. Over 90% of the matter in the Universe belongs to the“dark matter”[2]. There are a lot of exciting scientific discoveries made in the recent years. A lot of scientists look for answers to interesting scientific questions but all of these things cannot be found in the Physics and astronomy schoolbooks.

Goals

The aim of this project is to give the students the opportunity to become explorers, to get familiar with one of the methods of how the Universe is examined and also to understand how scientists came up with the idea about dark matter.

In order to achieve all these things, we decided to complete the following tasks:

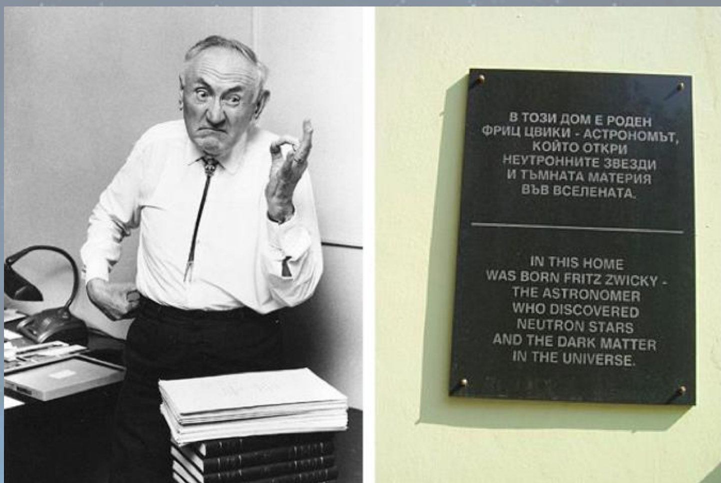
1. Build the rotation curve of the galaxy and, using the data from it, estimate the mass of the inner galaxy.

2. Observe how hydrogen is distributed in the galaxy by using a fixed galactic longitude and changing the galactic latitude.

3. Creating a map of the first quadrant of the Milky Way.

4. Creating a worksheet for a practical physics activity, in which the students will be able to build a rotation curve using the data from SRT.

Historical and scientific background



http://offnews.bg

The first name which comes to mind when we mention dark matter is Fritz Zwicky. In 1933, he publishes the results of his research on the velocities of the Coma Cluster of galaxies. These velocities were so high that the cluster should have fallen apart. Zwicky expresses his hypothesis about the existence of a large quantity of invisible mass that attracts and holds galaxies together through gravitation.

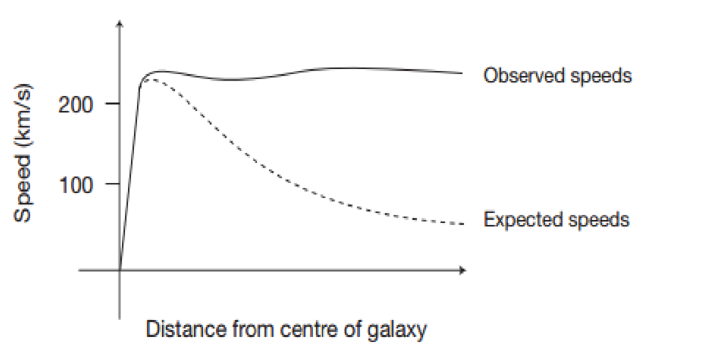
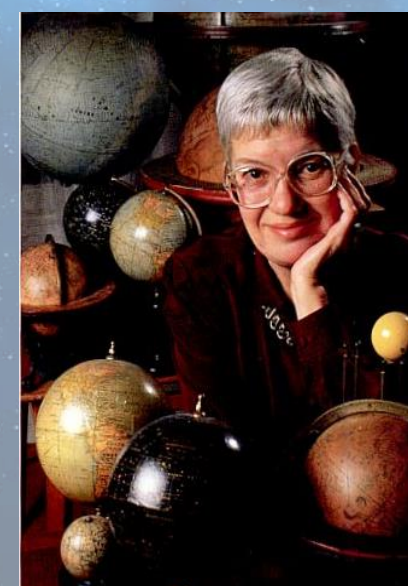


Figure 6 Expected and observed orbital speeds for stars in Andromeda. The expected speeds are based on the assumption that the vast majority of Andromeda's mass lies within the galaxy's core where most of the stars are found.

[5]

Dark matter is mostly associated with the name of Vera Rubin and her colleague Kent Ford.

In the 60s of the 20th century, they estimated with great accuracy the orbital velocities of the stars in Andromeda. The rotation curve they built differed from what they had expected.



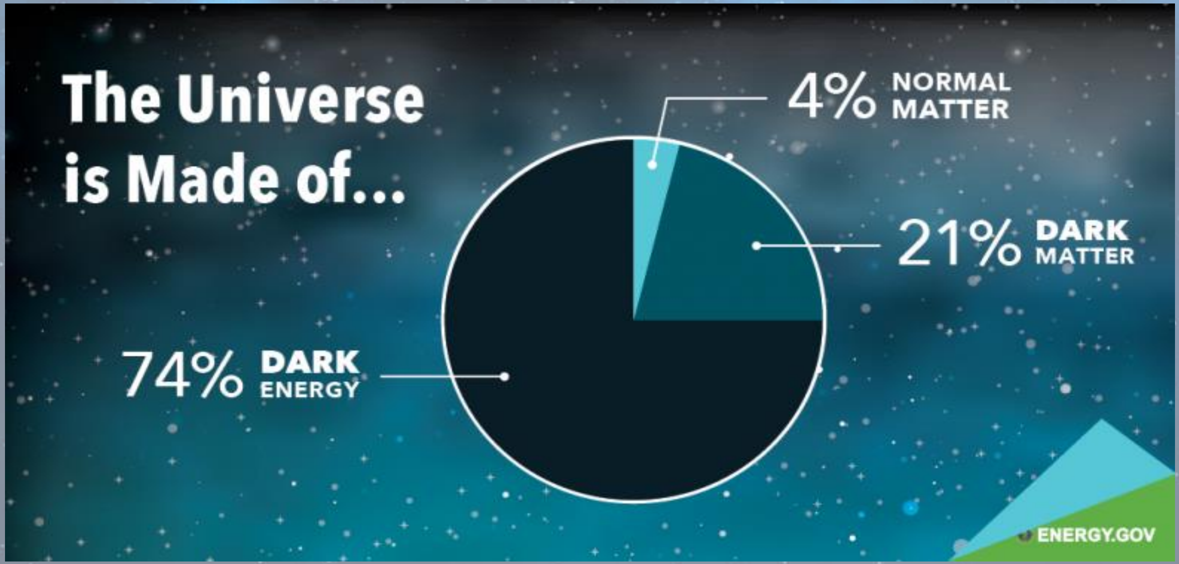
[5]

In 1975, at the meeting of the American Astronomical Society (AAS), Rubin and Ford explained the form of the rotation curve with the presence of a relatively dark galactic halo whose mass is more than 50% of the mass of the galaxy.

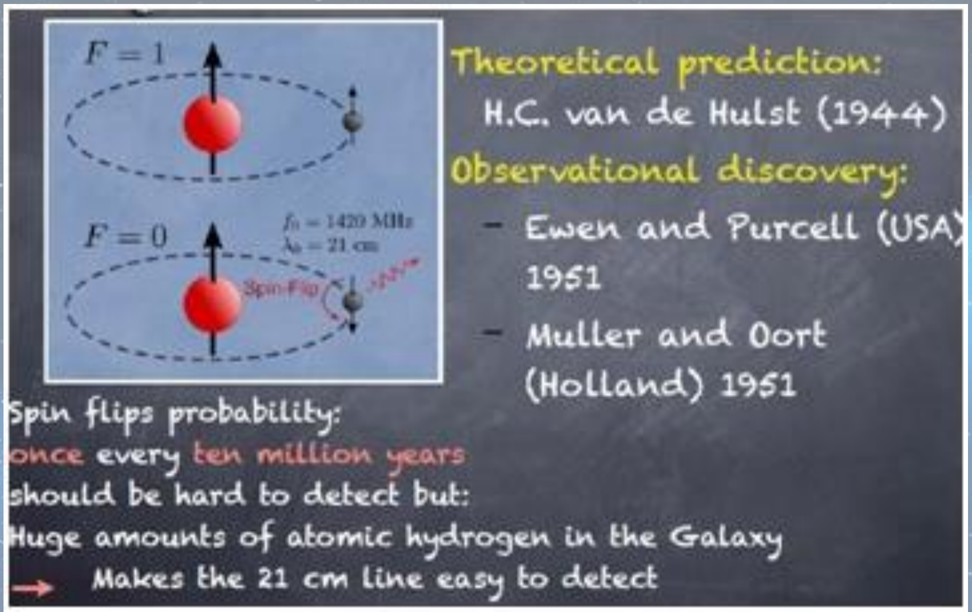
Later, independent evidences for the existence of dark matter appeared. Part of them are the strong gravitational lensing and the Angular Cosmic microwave background fluctuations.

This image from the NASA/ESA Hubble Space Telescope shows the galaxy cluster MACS J1206 .

Today scientists reckon that normal matter constitutes only 4% of the Universe.

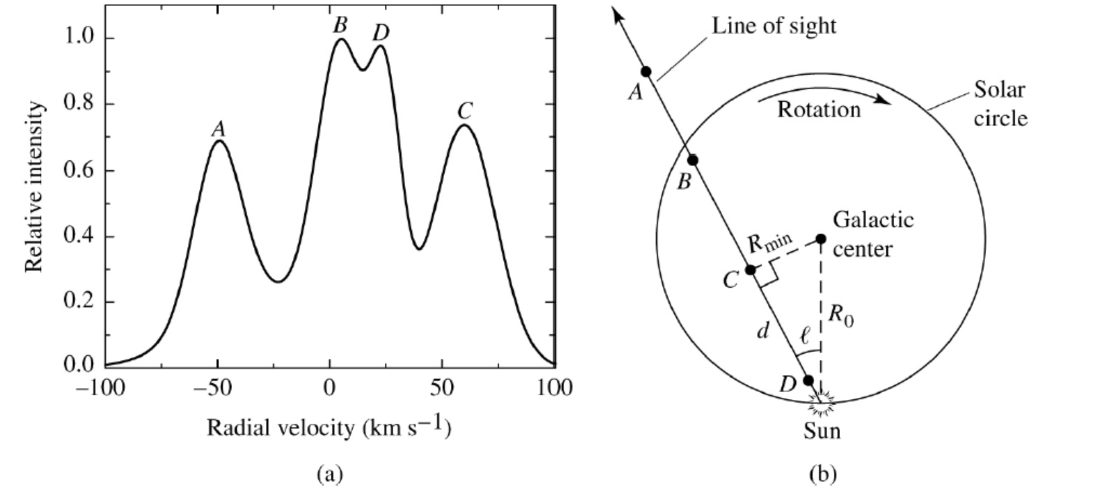


The story of radio waves H21 is remarkable. In 1944, the Dutch astronomer Hendrik Christoffel van de Hulst theoretically predicts the possibility that the electron in the hydrogen atom can change its direction of spinning and emit radio waves with a wavelength of 21 cm.



The probability of this event happening to a hydrogen atom is 1 in 10 million years. However, the number of hydrogen atoms in the Universe is huge and this kind of events happen often. In this project, with the help of this spectral line and the Doppler Effect, the velocity of the orbital movement of the stars around the Galactic centre is being defined. [6]

For the building of a rotation curve, the radial velocities of the clouds of hydrogen and their distances (R) to the centre of the galaxy are needed. The radial velocities are being determined by the spectrums of emission and the Doppler Effect. The software in EU HOU calculates them by the so-called tangent-point method. This method only works for Quadrants I and IV, namely the inner Galaxy (R < R0). [1]



(a) Plot of Hydrogen 21-cm emission along a line-of -sight from the Sun. (b) A diagram showing the positions of the 4 Hydrogen clouds (A,B,C,D) relative to the Sun. Note that the cloud with the smallest *R* (cloud C) has the largest radial velocity

[1]

The rotation curve can be used to determine the mass M of the substance that is in a sphere with a radius R. After enforcing Newton’s law and the second law of mechanics, we see:

$$F = \gamma \frac{M.m}{R^2} = m.a = m.\frac{V^2}{R}$$

$$M = \frac{V^2}{\gamma} R$$

γ – gravitational constant

Before we describe our work, let's present EU HOU SRT Network

EU HOU SRT Network is a network of robotized radio telescopes, which helps students to put their knowledge into practice and make their own observations of the Milky Way from a distance. The intensity of emission of the 21-centimeter line of neutral hydrogen is being measured in terms of various longitudes (*l*) and latitudes (b).

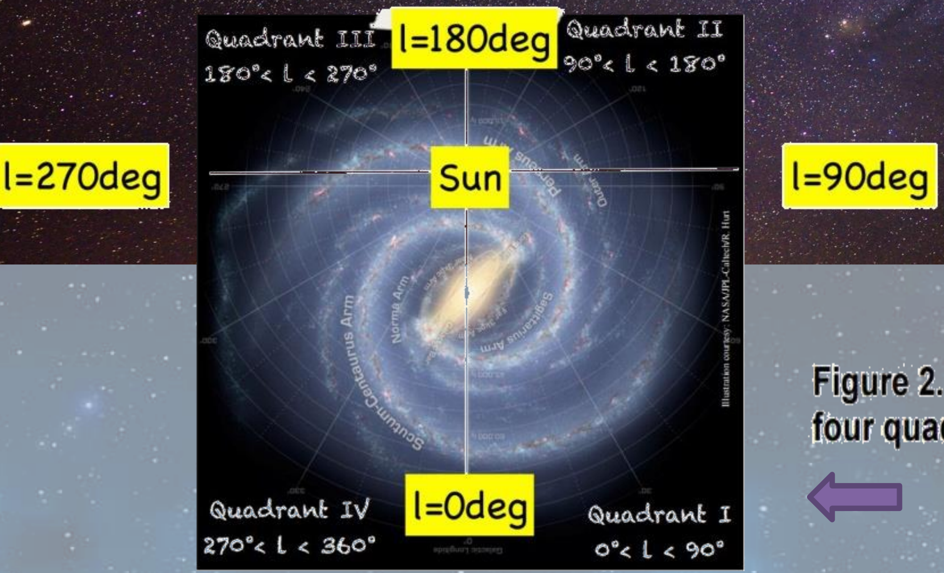
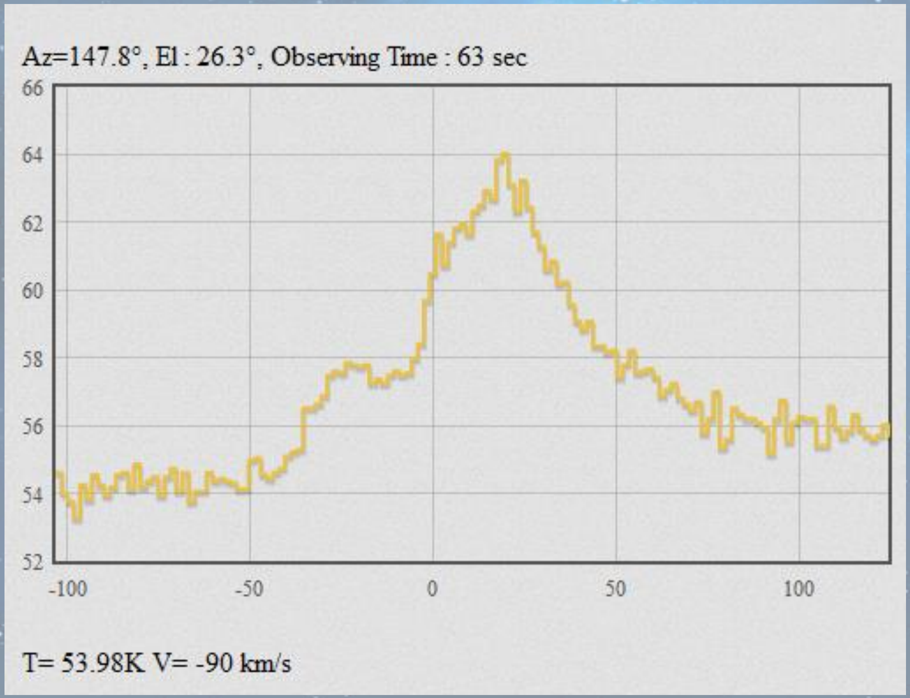


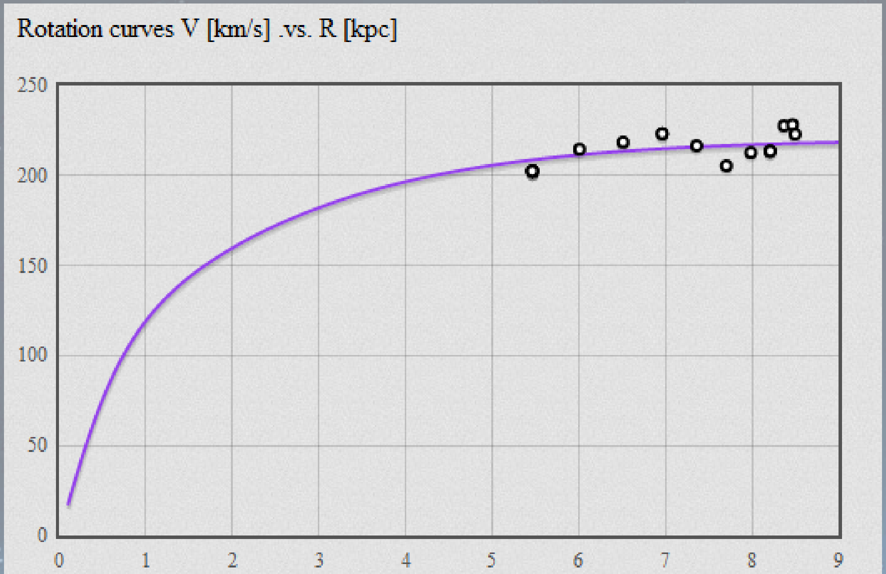
Figure 2. Diagram showing the definition of Galactic longitude and the four quadrants. The sense of rotation is clockwise in this diagram.

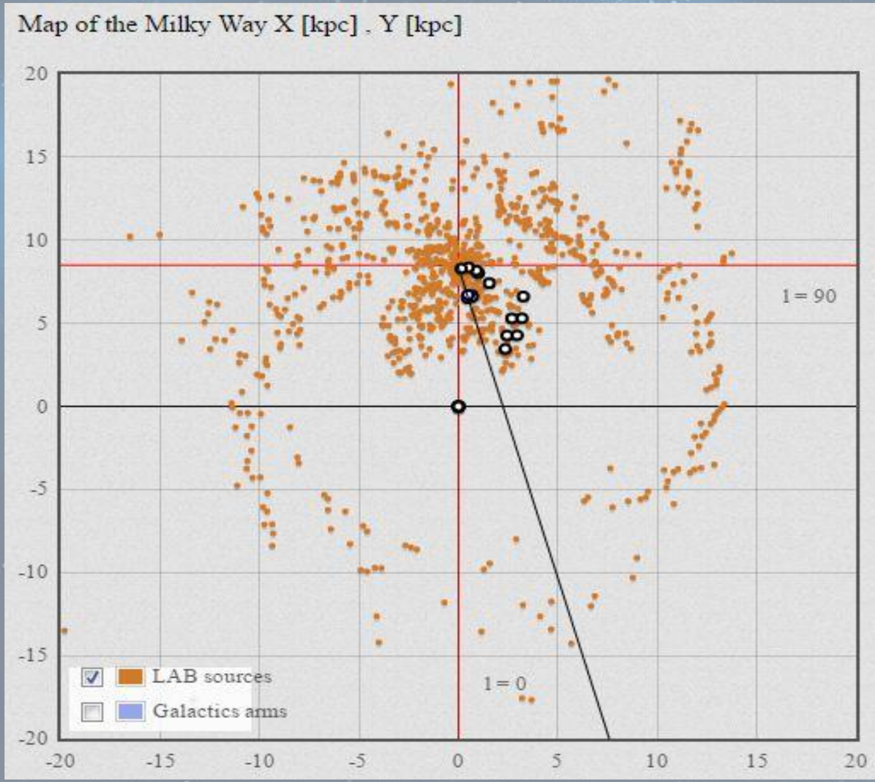
In the site www.euhou.net, there is a built-in software that processes the data of observation and:

- draws up the relation between the intensity of the radiation (temperature) and the velocity the emitted hydrogen for the particular measuring.



- draws up a rotation curve of the galaxy in which the velocity is measured in km/s and the distance - in kpc;





- draws up a map of the Milky Way;

Task 1 - Building a rotation curve

id | user gpcheshumen | l | b | Date | all

3/6 | 20

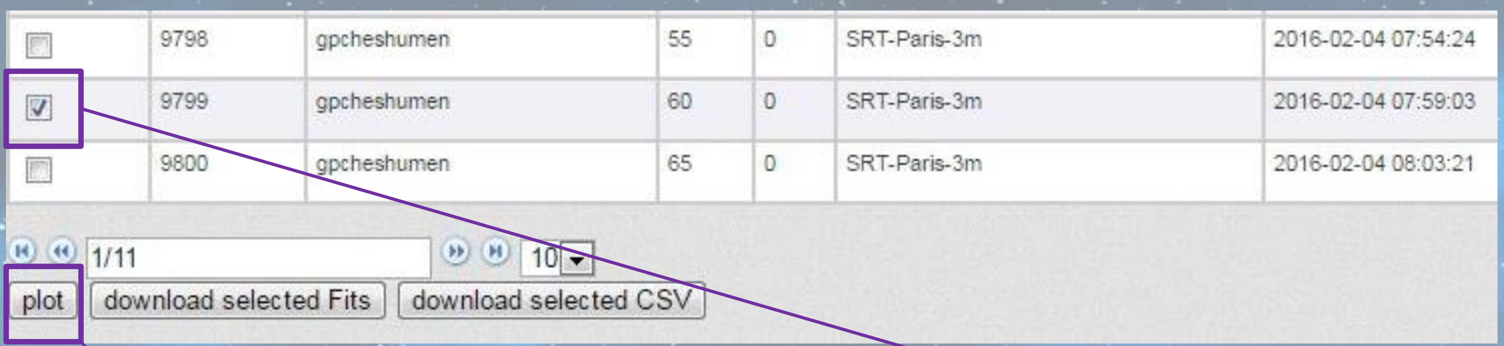
	num	user	l	b	radio telescope	Date
	11126	gpcheshumen	87	0	SRT-Paris-3m	2016-11-10 12:21:46
	11127	gpcheshumen	85	0	SRT-Paris-3m	2016-11-10 12:24:53
	11128	gpcheshumen	83	0	SRT-Paris-3m	2016-11-10 12:28:55
	11129	gpcheshumen	81	0	SRT-Paris-3m	2016-11-10 12:34:46
	11130	gpcheshumen	79	0	SRT-Paris-3m	2016-11-10 12:40:40
	11131	gpcheshumen	77	0	SRT-Paris-3m	2016-11-10 12:43:40
	11132	gpcheshumen	75	0	SRT-Paris-3m	2016-11-10 12:47:10
	11133	gpcheshumen	73	0	SRT-Paris-3m	2016-11-10 12:50:10
	11134	gpcheshumen	71	0	SRT-Paris-3m	2016-11-10 12:54:15
	11135	gpcheshumen	69	0	SRT-Paris-3m	2016-11-10 12:57:15
	11136	gpcheshumen	67	0	SRT-Paris-3m	2016-11-10 13:00:47
	11137	gpcheshumen	65	0	SRT-Paris-3m	2016-11-10 13:04:52
	11138	gpcheshumen	63	0	SRT-Paris-3m	2016-11-10 13:09:42
	11146	gpcheshumen	75	0	SRT-Krakow-3m	2016-11-17 12:06:50
	11151	gpcheshumen	65	0	SRT-Krakow-3m	2016-11-17 12:21:13
	11152	gpcheshumen	60	0	SRT-Krakow-3m	2016-11-17 12:24:32
	11153	gpcheshumen	55	0	SRT-Krakow-3m	2016-11-17 12:29:21
	11154	gpcheshumen	50	0	SRT-Krakow-3m	2016-11-17 12:33:23
	11155	gpcheshumen	45	0	SRT-Krakow-3m	2016-11-17 12:36:19
	11156	gpcheshumen	40	0	SRT-Krakow-3m	2016-11-17 12:38:00

For the realization of the task, we reserved observation time for the telescopes in Paris and in Krakow and carried out several measurements on

10.11.2016
17.11.2016
18.11.2016;

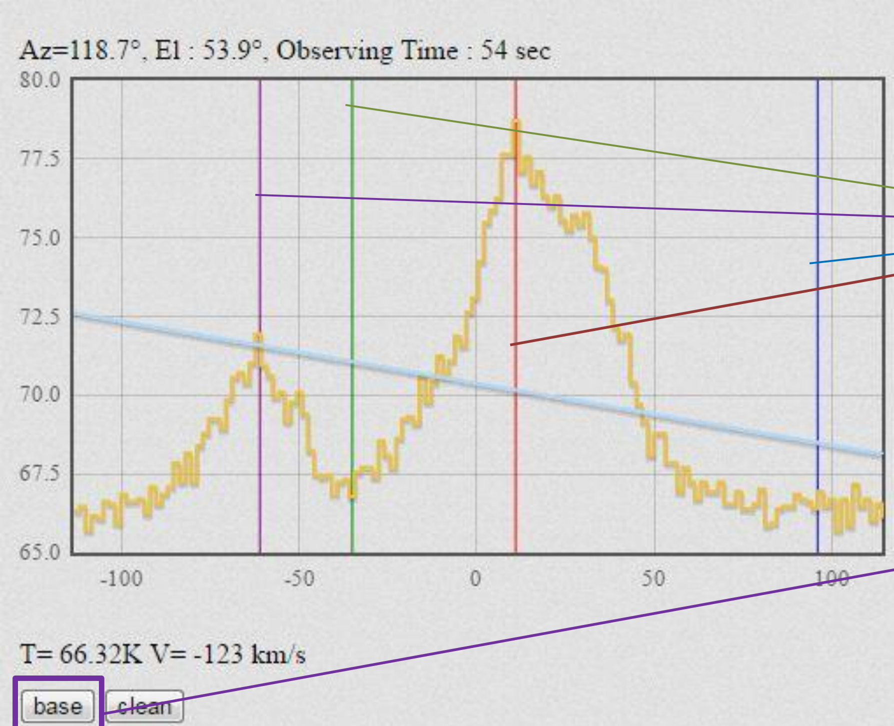
For our first aim – to build a rotation curve, we set the galactic latitude b=0 and changed the galactic longitude (*l*) from 0^o to 90^o.

Here is how we measured the velocity and the distance:



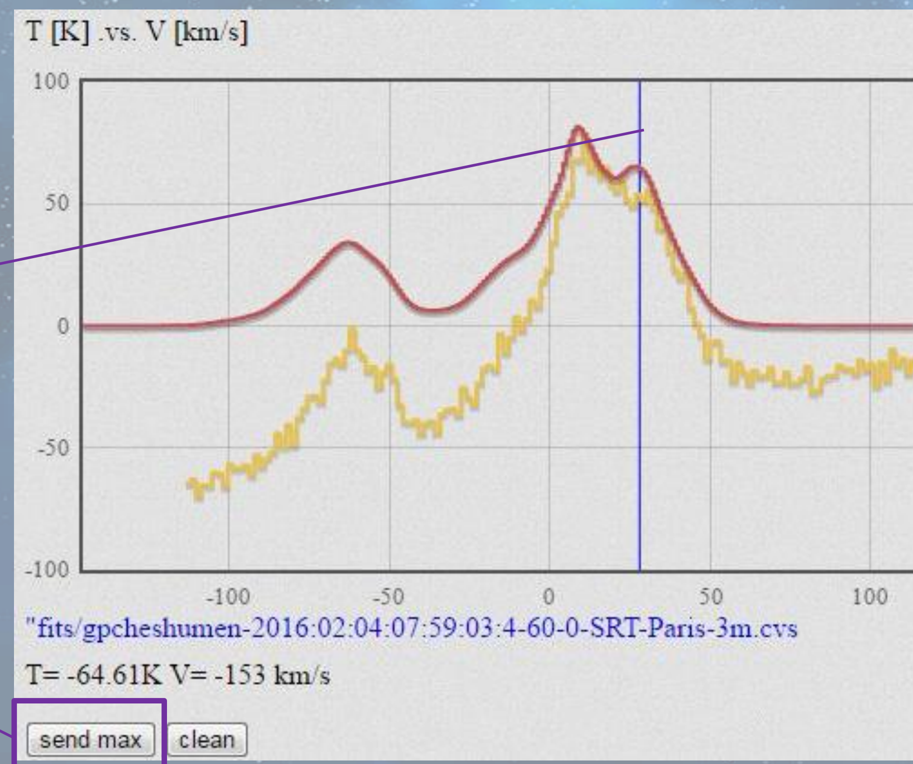
① Tick off the data you want to process.

② Click “plot”.



③ Mark a total of 4 peaks and drops .

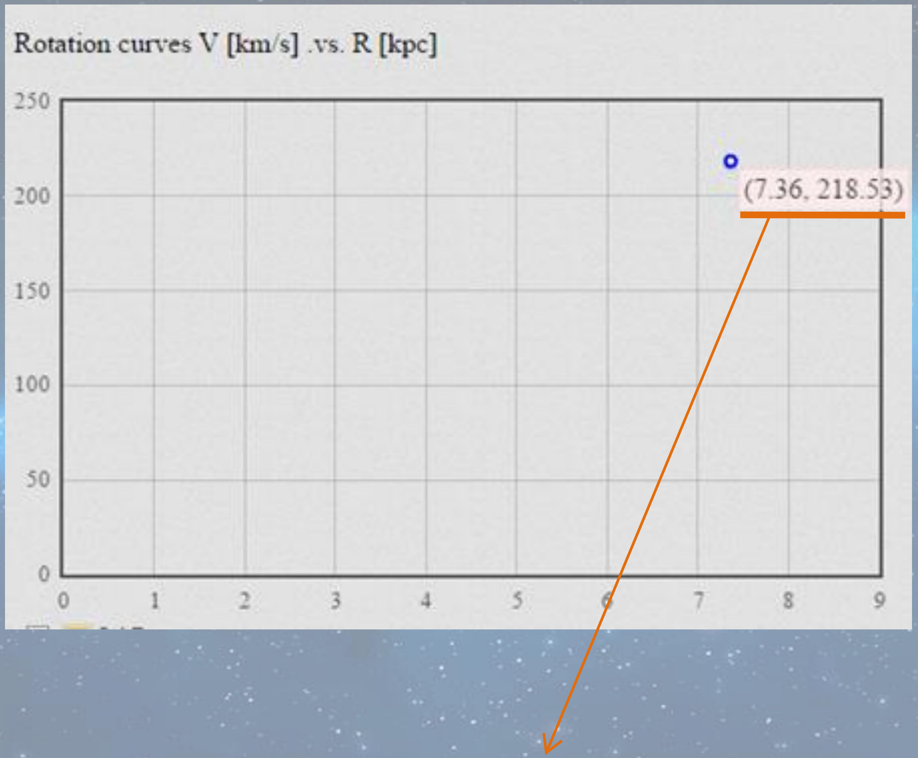
④ Click "base".



⑤ Find the furthest peak that is on the right and select it.

⑥ Click on "send max".

The result:



⑦ Click on the dot to see the distance from the Galactic centre and the velocity.

$R = R_0 . \sin(l)$

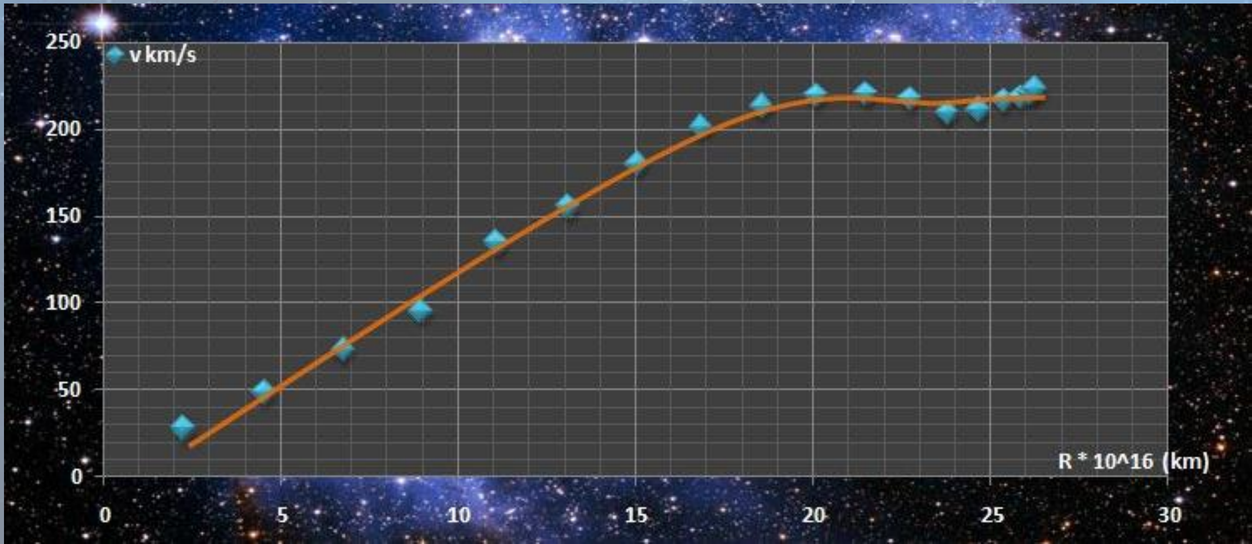
The results from the measures can be seen on this scale:

l	R (km) * 10^16	v km/s
5	2,290744	27
10	4,560472	48
15	6,798676	73
20	8,98434	95
25	11,101702	134
30	13,135	155
35	15,068472	180
40	16,886356	201
45	18,575517	213
50	20,12282	219
55	21,517757	220
60	22,74982	217
65	23,808501	209
70	24,685919	211
75	25,400463	216
80	25,870696	218
85	26,170174	220
90	26,27	223

We took the velocity from ⑦.

We transformed the distance from kpc to km.

With the help of the data in this chart, we built this rotation curve. It is obvious that with getting more and more distant from the Galactic centre, the velocity stays approximately constant, as it is in Rubin and Ford's rotation curve.



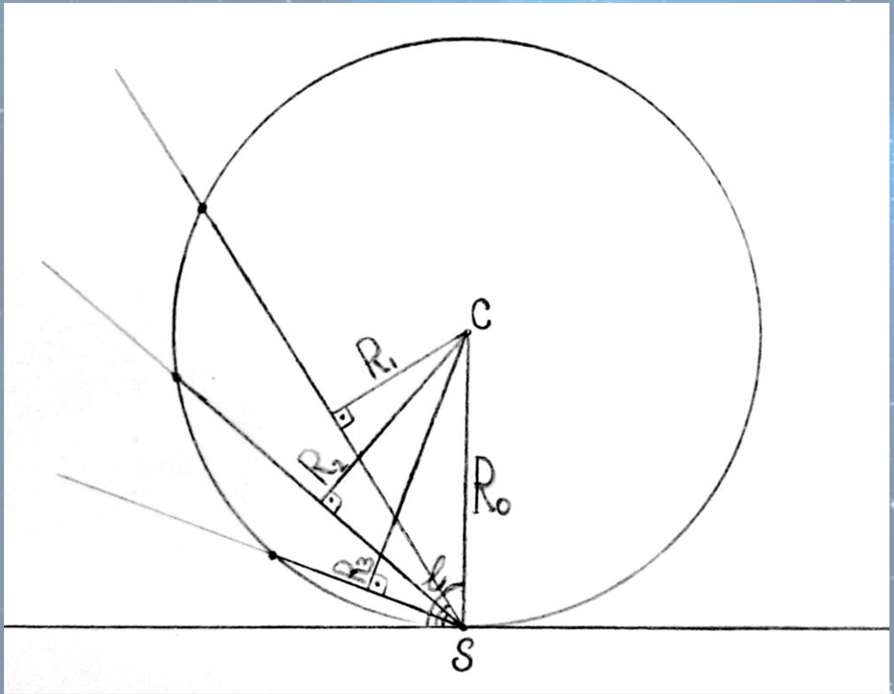
Determining the mass of the inner galaxy

The rotation curve of a galaxy can be used to determine the mass of the inner galaxy using some simple equations of the Newtonian physics.

$$M = \frac{V^2}{\gamma} R$$

For this calculation, it is assumed that the mass of the galaxy is spherically symmetric, which in accordance with the authors of the quoted source is admissible. [1]

For the valuation of the mass that is contained in a sphere with radius R_0 , we had to evaluate the velocity of the spinning of the Sun around the Galactic centre. The question was what had to be the galactic longitude to get this velocity? We made the following draft that presents the change of R with the approaching of the galactic longitude to 90^0 .



We got the limit: $\lim_{l \to 90^o} Rn = R_o$,

where R_0 = 8,5 kpc is the distance from the Sun to the Galactic centre.

This way we concluded that for the valuation of the mass of the inner galaxy we had to measure the velocity with galactic longitude $l=90^0$.

From the data brought out from the rotation curve, we reported the following values:

$$V = 224 km/s = 224.10^3 m/s$$

$$M = \frac{V^2}{\gamma} R$$

$$R = 8{,}5 kpc = 8{,}5.10^3 pc.3{,}09.10^{16} m$$

$$\gamma = 6{,}67.10^{-11} \frac{Nm^2}{kg^2}$$

We got the following values of the mass of the inner galaxy:

$$M = \frac{R.V^2}{\gamma} = \frac{8{,}5.3{,}09.10^{19}\,m.224^2.10^6\,\frac{m^2}{s^2}}{6{,}67.10^{-11}\,N\,\frac{m^2}{kg^2}} \approx 1{,}98.10^{41}\,kg \approx 2.10^{41}\,kg$$

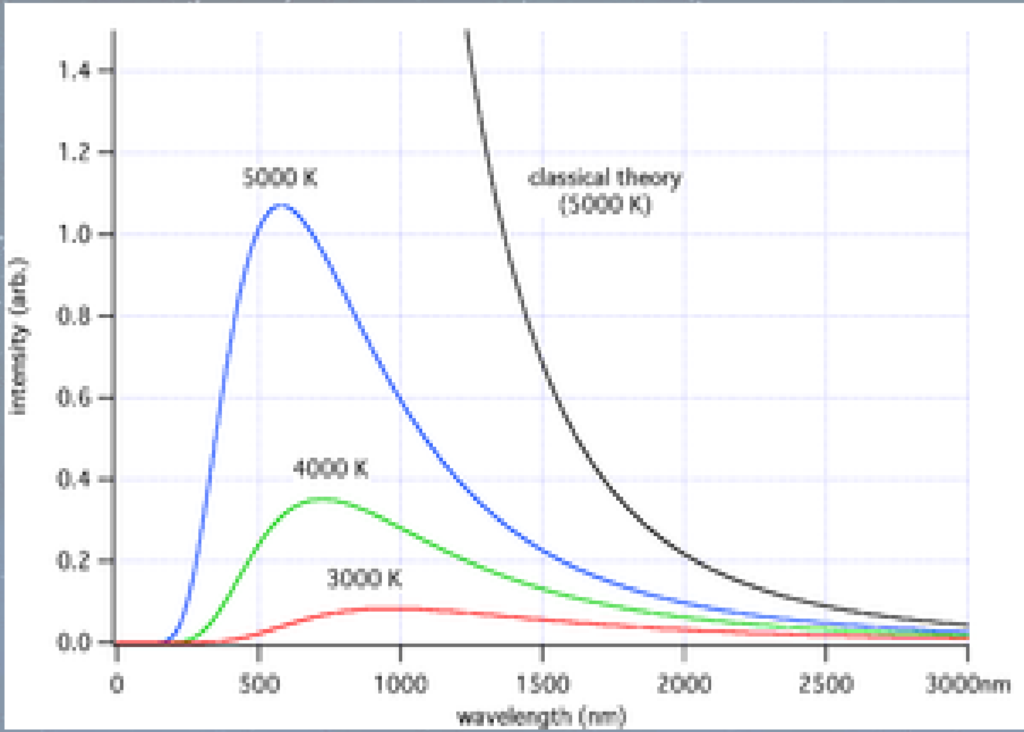
In order to be able to estimate if our result is reliable, we divided it by the mass of the Sun $M_{\odot}=2.10^{30}$kg .

$$N = \frac{M}{M_{\odot}} = \frac{2.10^{41}\,kg}{2.10^{30}\,kg} \approx 10^{11}\,suns$$

In order of magnitude, this result is in accordance with the valuation of the general number of the stars in the Milky Way.

2. Task - Observing the distribution of the hydrogen in the galaxy

While conducting our observations using different galactic longitudes, we saw that we could make observations using different latitudes, too. The question was what information about the galaxy we would receive in this way. We could feel that there is a proportionality between the surface temperature which could be measured with the software, and the quantity of the emitted hydrogen atoms, but we had to support our assumption with facts.



The spectrum of emission of the intensity of an absolutely black body is described by Wien’s law and can be presented graphically in this way. [4]

For the waves with shorter wavelength of the order of nanometers, the connection between the temperature and the intensity is clearly not linear. This connection plays an important role for the creation of the quantum theory at the beginning of the 20^{th} century, but, for our observations, the waves with longer wavelength are more important than those with a short one. When we have waves with longer wavelength like λ =21 cm, we can use the Rayleigh-Jeans law from which we can conclude that the intensity of light I is proportional to the temperature T.

$$I \sim T$$

With a fixed wavelength λ =21 cm, the intensity I of the light, the energy, passing for a given time through a given space, gives us the formula:

$$I = \frac{N.E_1}{S.t} \sim T$$

where N is the number of photons, E_1 is the energy of one photon with λ =21 cm, S is the area, t is the time.

From the mechanism of emission of H21, it becomes clear that one hydrogen atom emits one photon. Consequently, the number of photons N actually gives us the number of hydrogen atoms N, which have emitted a photon with a wavelength equal to 21cm. The number of these atoms N is proportional to the total number of all the atoms N_{total}, which fall into a given line of sight.

$$\mathbf{N}_{total} \sim N \sim T$$

That leads us to the conclusion that the temperature of emission is proportional to the quantity of the emitted hydrogen into a given line of sight.

We conducted our observations on 18.11.2016 with 35° and 65° galactic longitude and changed the galactic latitude from 0 to 90° (when we had the opportunity to). We measured the "temperature" of the radiation with a given galactic longitude and we presented the data using tables and graphics:

Observation with longitude *l*=35°

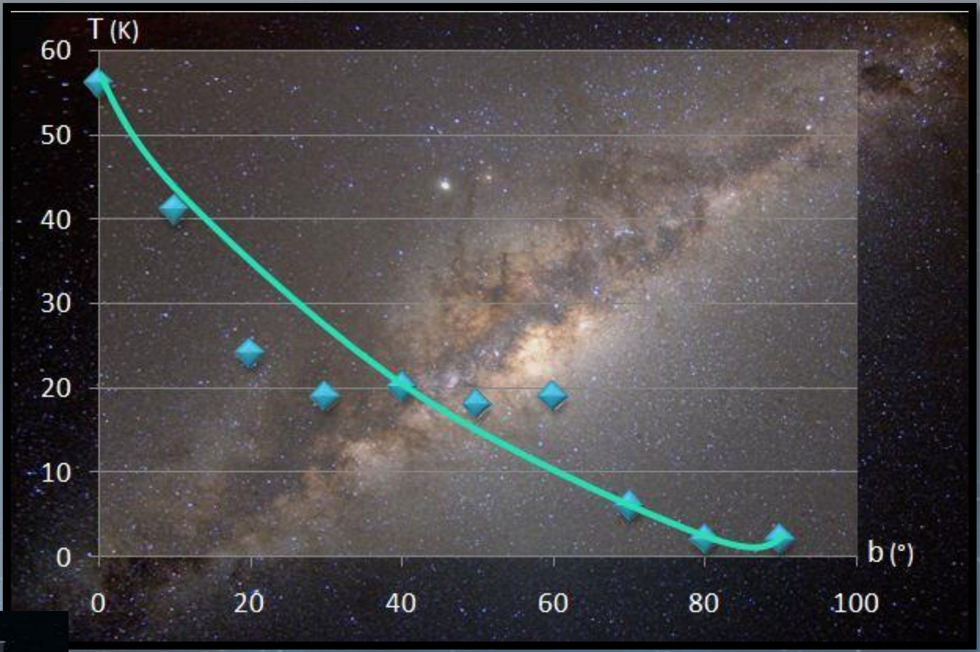
b (°)	T(K)
0	55,55
10	41,46
20	24,43
30	19,2
40	19,98
50	17,68
60	18,79
70	6,21
80	1,96
90	1,96

Observation with longitude *l*=65°

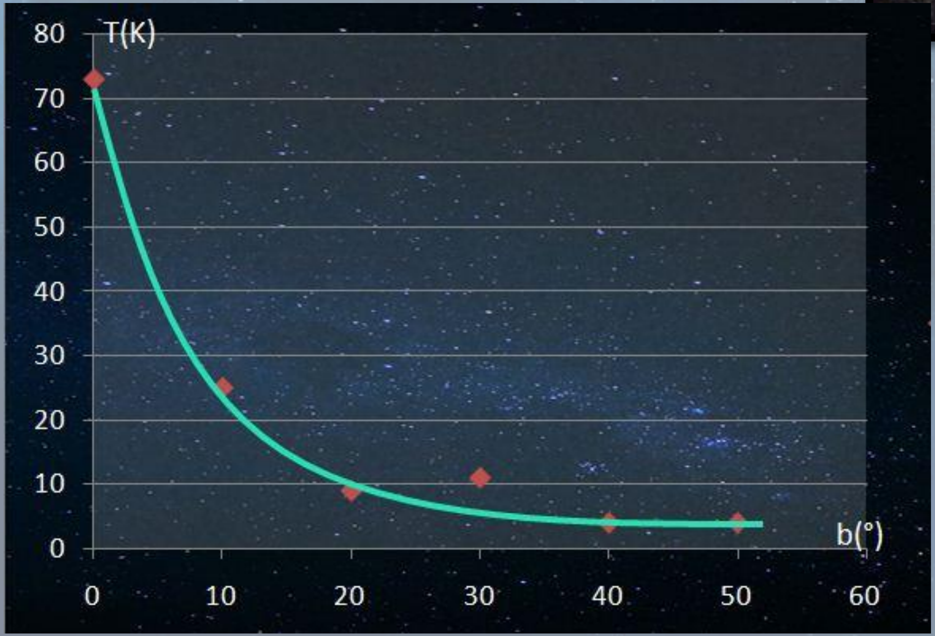
With this galactic longitude it wasn't possible for the radio telescope to make measures further than b=50 °.

b(°)	T(K)
0	73
10	25
20	9
30	11
40	4
50	4

Graphic with galactic longitude *l*=35°



From the graphics, it can be seen that, with the increase of the galactic latitude, the temperature of emission decreases rapidly and tends to the temperature of the Cosmic Microwave Background.

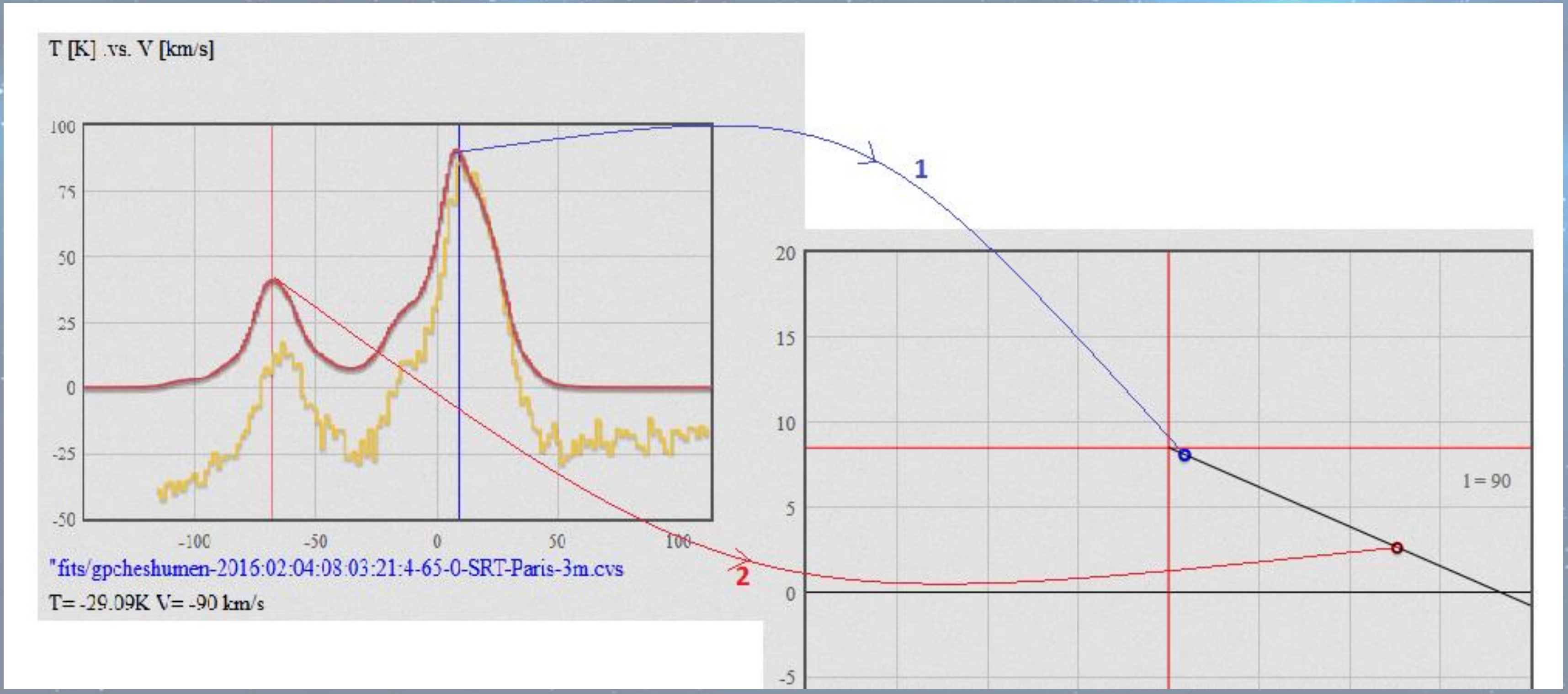


Graphic with galactic longitude *l*=65°

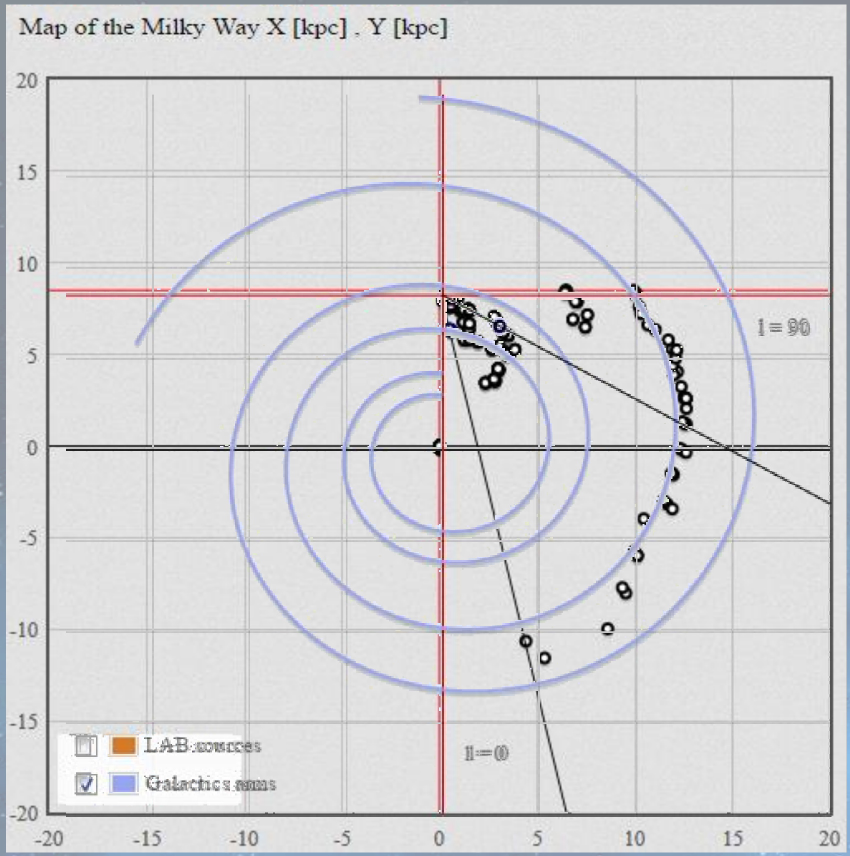
When we have in mind that the number of hydrogen atoms is in a direct ratio to the temperature, these graphics are another proof that the emitting substance in the galaxy is located predominantly on one plain.

3. Task – Creating a map of the first quadrant of the Milky Way

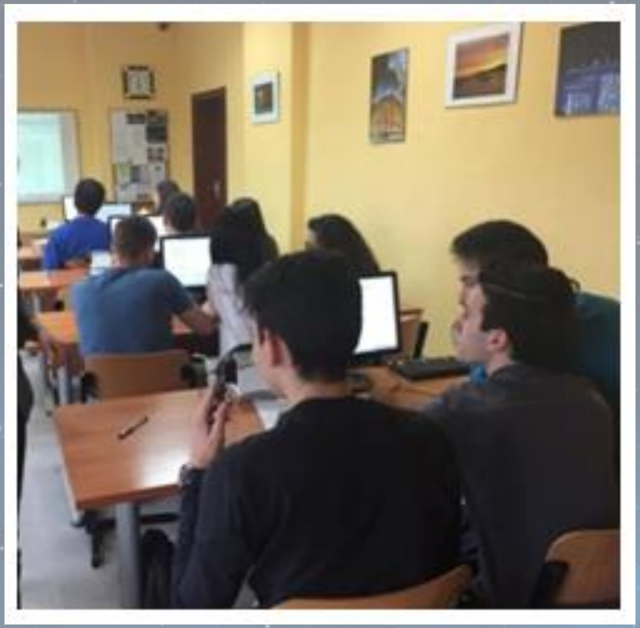
For the building of the rotation curve of the Galaxy, we use the peaks which are in the furthest right side of the T=T(V) graphic. When we click on the peak and press the button ”send max”, the software gives us the location of the emitting hydrogen cloud in the plain of the galaxy (see the blue arrow on the scheme) . But in the graphic T=T(V) there are other peaks, too. We wondered what they can be useful for, so we decided to test them. As we did so, the software presented their distance to the Sun in the same line of observation, given by the chosen galactic longitude – see the red arrow 2 in the scheme.



That is how we found out that the software presents a map called a Map of the Milky Way. It gives us the distribution of emitted matter in the plain of the galaxy. We built the graphics T=T(V) again, using the data from our observations, but this time we used all the peaks. We got the following map of the emitting matter in the first quadrant of our galaxy:

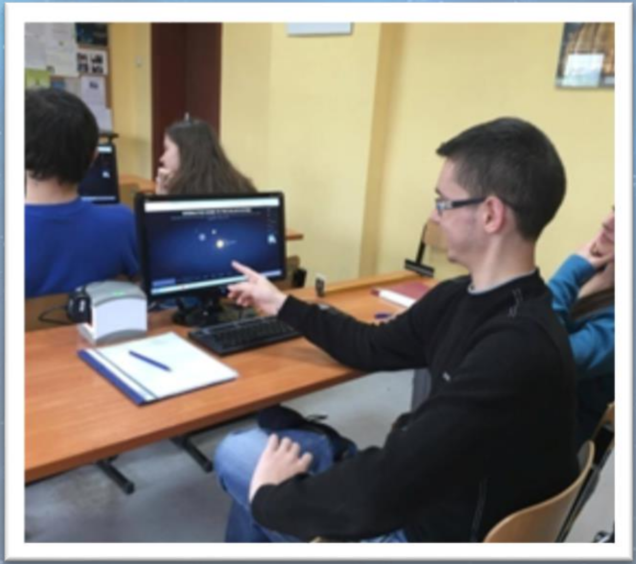


This map and the way in which we can obtain it give us the answer to one question, which we, and for sure, a lot of other people, ask themselves: How did the scientists conclude that the Milky Way is a spiral galaxy when nobody has seen its spiral arms and its “bar”?



In the next pages, we propose our idea for a practical activity, in which students can build a rotation curve of the galaxy for one period. This activity has been tested at school. After we tested it, we had a discussion with the students who did it. We dicussed whether all of them could understand the tasks, the logic of the questions, the way they were formulated, and the way the information was presented.

We took all the suggestions into account and worked hard in order to improve the activity until we finally created the one that we present here. We have to thank our classmates, Simeon Boichev and Damyan Boichev, who created and uploded on YouTube a video which is a guide on how to work with the software.



Building a rotation curve of the Milky Way

Gravitational attraction is one of the fundamental interactions in nature. Gravity controls the motion of all cosmic bodies, including the motion of the planets in the Solar System. The mass of the Sun is more than 99% of the mass of the whole system and it has a leading role in gravity ratio[5].

Accurately enough, we can consider that every object from the system, which finds itself in a definite distance “R” from the Sun, is predominantly attracted by the objects inside this radius. This attraction decreases when getting further and further from the Sun and changes the velocity of the orbital motion of the planets.

***Ex.1 Open*:** http://theplanets.org/orbit/

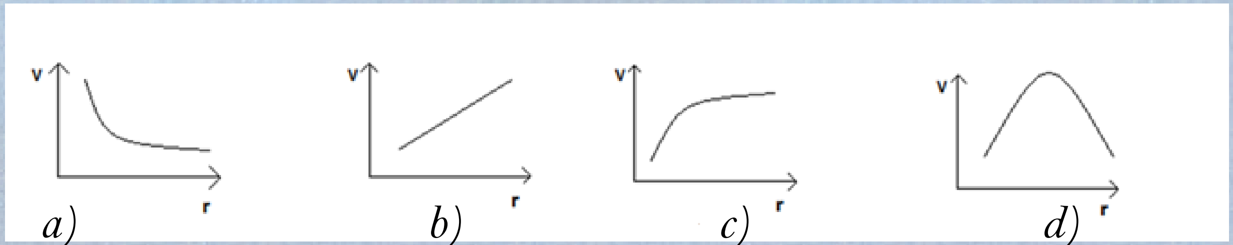
• If “r” stands for the distance from the Sun, place <, > or = for the following quantities*:*

r Mercury ….. r Earth…… r Jupiter…… r Neptune;

• Observe how the velocity of the movement of the planets changes with getting more distant from the Sun.
Place < , > or = :

V Mercury…..V Earth…..V Jupiter ……V Neptune

• Mark with red the graphic presenting the alteration of the orbital velocity of the planets with getting more distant from the Sun.

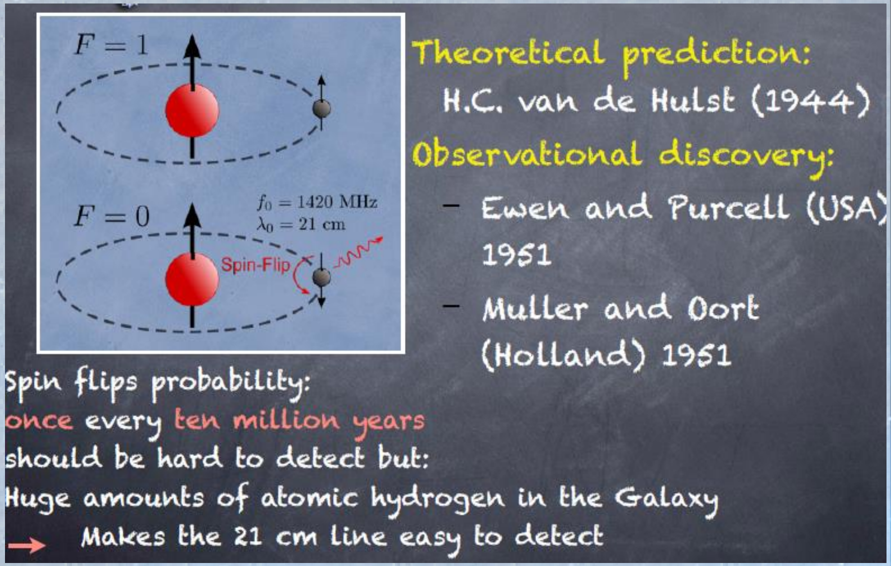


Ex.2 Let’s take a look at the Milky Way. The visible matter in the Universe is mainly consisted of hydrogen. What is the spectrum of emission of the strongly rarefied clouds of neutral hydrogen**?**

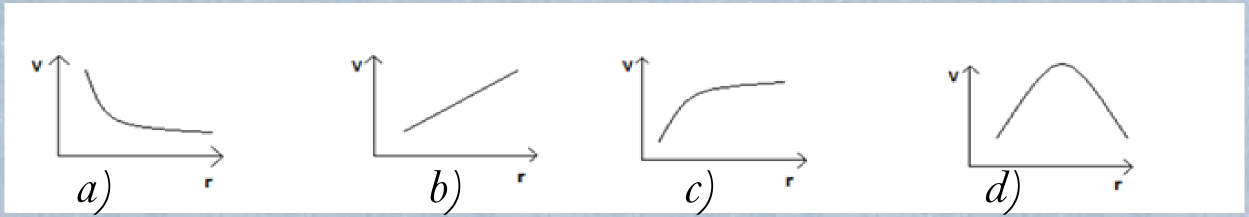
a) linear; b) striped; c) continuous;

Electromagnetic waves, which are being emitted or consumed by the hydrogen, carry valuable information. In 1944, the Dutch astronomer Hendrik Christoffel van de Hulst theoretically predicts the possibility that the electron in the hydrogen atom can change its direction of spinning and emit radio waves with a wave length of 21 cm.

Pay attention to the probability of this event happening to a hydrogen atom. Yet, the number of hydrogen atoms in the Universe is huge and this kind of events happen often. With the help of this spectral line and the Doppler effect the velocities of the orbital movement of the stars around the galaxy centre can be defined. In the Solar System, as well as in galaxies, gravitation “connects” and controls the velocity and the objects in them.



b) Which graphic, at your guess, represents the change in the velocity of the movement of the stars with the increasing of their distance from the center of the galaxy?



Now you will have the opportunity to check your assumption. You are going to build a rotation curve of the Milky Way – a graphic, which presents the change of the velocity of the stars with their rising distance from the Galactic centre. You will use data that has been received from two of the radio telescopes in "Pierre and Marie Curie University" in Paris. The observations are made at the request of our own high school.

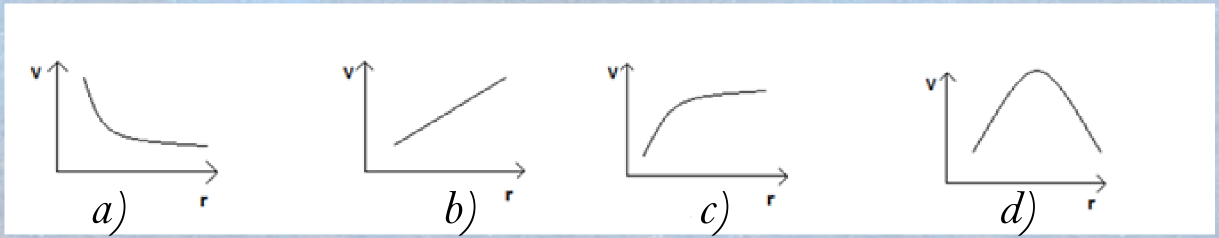
Open: https: //www.youtube.com/watch?v=suQiT6YE6Eo and make yourself familiar with the video quidance.

Start work by opening http://euhou.obspm.fr/public/archive.php

Congratulations! You built a rotation curve of the galaxy! On the graphic, the distance to the Galactic centre is given in kpc – a unit of distance equal to 3.10^{16} km.

c/ Take a photo of the curve and place it here;

d/ Take a look at the shape of the curve that you got from your experiments. Which of the graphics below is most accurate?



e/ Is your answer from 2d) identical with the answer in 2b)?

Yes ***No***

f/ If your answer is "**No**", make a guess why there are differences.

And what is the "true story" of the rotation curves of the galaxies you can see here:

http://vbox7.com/play:7c444780&p=user&id=781279

Notes

The ways in which we can build the rotation curve of the Milky Way and evaluate the mass of the inner galaxy are based on ideas from "Understanding the Rotation of the Milky Way Using Radio Telescope Observations", Alexander L. Rudolph.

The observation of how matter is distributed in the galaxy when we change the Galactic latitude and the observation of the distribution of matter along the line of sight are an idea with which we came up with while working on the project.

We reached the conclusion that $\lim_{l \to 90^o} Rn = R_o$ and $N_{total} \sim T$ by ourselves.

In the project, we used data only from observations conducted by students. Such observations can be made by every school.

Conclusion

There is nothing more satisfying than the feeling you get when you make a discovery. For this reason, our team chose to bring this satisfaction back to school and to "revive" the spirit of astronomy in class, which had been hidden in plain sight for a long time.

Most of us started at ground zero in terms of our knowledge in astronomy and observed how we made progress every single day. We began to believe that conducting observations with radio telescopes, working with data and analyzing the results from the observations can all become one exciting addition to the learning process during our Physics and Astronomy classes.

Sources

1. Understanding the Rotation of the Milky Way Using Radio Telescope Observations; Alexander L. Rudolph Professor of Physics and Astronomy, Cal Poly Pomona Professeur Invité, Université Pierre et Marie Curie (UPMC)
2. http://euhou.obspm.fr/
3. COSMOS; An Advanced Repository Foe Science Teaching And learning
4. Wikipedia
5. https://www.perimeterinstitute.ca/
6. Our Current View of The Milky Way; Anne-Laure Melchior; Université Pierre et Marie Curie
7. http://vbox7.com/play:7c444780