Chapter

Dark Matter within the Milky Way

Aleksander Kaczmarek and Andrzej Radosz

Abstract

Dark matter is an invisible substance that seems to make almost 85% of all the mass and roughly 26% of mass-energy content of our Universe. We briefly present the history of its discovery, and we discuss the main attempts to resolve the problem of the origin of dark matter. Those attempts are as follows: dark matter particles (WIMPs), unseen astrophysical objects (MACHOs), or interactions of dark matter with ordinary (luminous) matter. We also introduce a different approach claiming no need for existence of the dark matter (MOND) and recent findings about the ultra-diffuse galaxies. Finally we present 21-cm line observations of neutral hydrogen in the Milky Way made by using 3 m in diameter radio telescope in the Astronomical Observatory of the Jagiellonian University. These studies yield rotational curve of our galaxy. Rotational curve we obtained is compared to those present in literature and constitutes a proof of presence of dark matter in the Milky Way.

Keywords: dark matter, WIMP, MACHO, MOND, rotational curve, ultra-diffuse galaxies, gravitational lensing, milky way

1. Introduction

In 1933 Fritz Zwicky [1] indicated a problem related to the galaxy cluster Coma. Galaxy cluster studied by Zwicky appeared to contain some 400 times more matter than an ordinary, visible, i.e., luminous matter. The content of the luminous matter was estimated form the amount of light emitted by the cluster. However, there was no response for that finding. Only 40 years later in 1970s the problem was rediscovered and concerned almost all of the galaxies. Research of Vera Rubin discovered that the galaxies rotate in a way that cannot be explained by taking into account visible, luminous matter. Today we know that most of the matter in the Universe is dark. Various attempts to resolve the problem of the existence of a mysterious form of matter, dark matter, have been taken ever since. One such idea is to find a particle to possibly complete the standard model. The most important property of such particle would be that it is not a subject to electromagnetic force; hence the dark matter is invisible in all electromagnetic wavelengths. In order to detect such particle, sensitive detectors are built, but still final conclusion has not been made. Another attempt of explaining the problem of missing matter was based on the assumption of existence of astrophysical objects such as black hole or dim brown dwarfs. This idea has rather been discredited as the abundance and masses of such objects are too small comparing to the amount of the matter that is missing. On different grounds stands the idea of modifying gravity in low acceleration regime. Modified Newtonian dynamics (MOND) proposed by M. Milgrom in 1983 is a phenomenological approach attempting to provide explanation of rotation of galaxies without invoking hidden matter at all. Yet such an approach seems to be in tension with recent findings of van Dokkum et al. about the ultra-diffuse galaxies. There appear to exist galaxies devoided of dark matter—then what about MOND predictions? This contribution is completed with the rotational curve of the Milky Way determined with 3 m in diameter radio telescope in the Astronomical Observatory of the Jagiellonian University. Obtained rotational curve is flat which indicates the presence of dark matter in the halo of our galaxy.

2. The dark matter problem

The term "dark matter" (DM) was introduced due to the contribution by Fritz Zwicky as early as in 1930s of the twentieth century. Studying the Coma cluster (of galaxies) located 320 million light-years away, Zwicky estimated [1] masses of the galaxies that make up this cluster based on the amount of light they emit. It turned out that such an amount of (*luminous*) matter wasn't large enough to explain the trajectories and velocities of those galaxies. Zwicky claimed then that the gravitational attraction exerted by the luminous matter was not enough to hold the cluster together and if there wasn't some kind of additional, nonluminous matter that provide extra gravity force, the galaxies would fly apart. These findings seemingly intriguing by themselves had not been taken seriously by scientific community. And only findings of Vera Rubin [2], some 40 years later, led to the formulation of the fundamental and still unresolved problem. Rubin studied rotational curves of galaxies. Rotational curve of a galaxy is a plot presenting how the orbital velocity of objects in this galaxy changes with increasing distance from the galaxy's center (see **Figure 1**). It turned out that the shapes of the curves did not comply with the theoretical predictions based on the mount of matter estimated due to the emitted light.

Figure 1 illustrates this discrepancy. When being close to the center of the galaxy, the plot agrees with what one would expect: the rotational curve increases

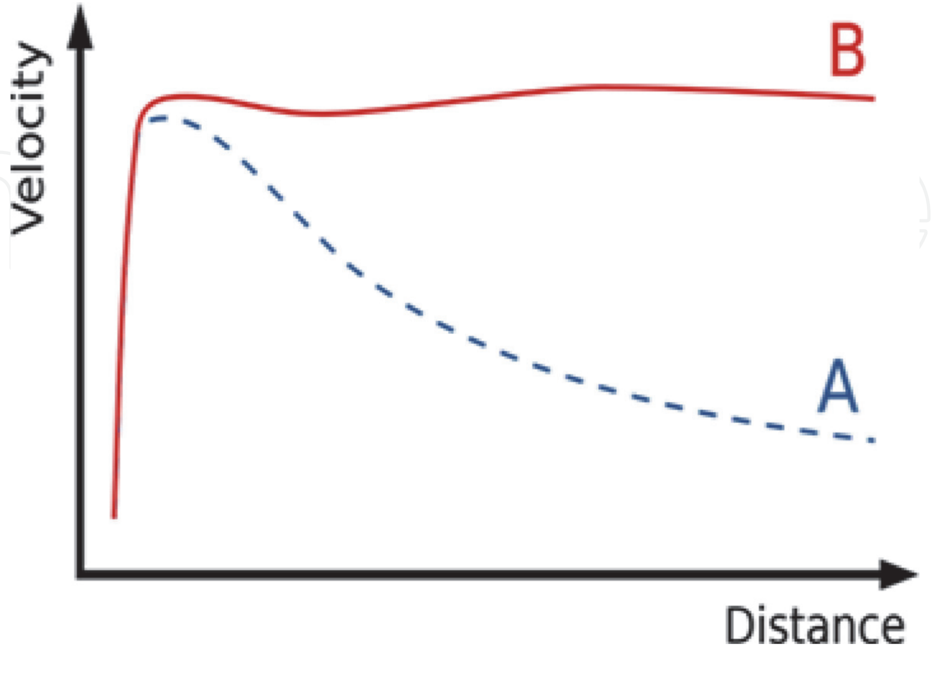

Figure 1.
Figure schematically representing discrepancy between observed (B) and predicted (A) rotational curves of galaxies that indicates presence of dark matter in halos of such galaxies. Credit: PhilHibbs, Wikipedia, https://pl.wikipedia.org/wiki/Krzywa_rotacji_galaktyki#/media/Plik:GalacticRotation2.svg, Creative Commons Attribution-Share Alike 3.0 Unported license.

rapidly that reflects an obvious fact that the velocity of a test object (a "star") increases as the effective gravitational force is growing (at a given radius, only the mass enclosed within a sphere of that radius is relevant in terms of excreting gravitational force—Newton's Shell Theorem). Past a certain distance though (when increasing a distance from the massive center of galaxy does not enclose adequately bigger amounts of mass), the effective force of gravity should decline (as R^2 will increase faster than the mass enclosed in a sphere of a radius being that distance from the center so the force of gravity will decline) which should result in lower orbital velocities.

Vera Rubin and Kent Ford published their first rotational curve in paper [2]. They presented there the rotation of Andromeda based on spectroscopic survey of emission regions applying neutral hydrogen, Hα, and [NII] λ6583 emission lines. Further works, see, e.g., [3], revealed that most of the galaxies have rather flat rotational curves like the one in **Figure 1**. The fact that more distant stars have almost constant velocity attracted the attention of scientists. The circular velocities of the stars are due to gravity which plays the role of centripetal force. Combining Newton's law of gravity with an expression for centripetal force yields the following relation:

$$\frac{GM}{R^2} = \frac{V^2}{R}, \tag{1}$$

where G is universal gravitational constant, M is mass exerting a gravitational force, V denotes velocity of a (test) object orbiting mass M, and R is the distance between them. One obtains from Eq. (1)

$$M = GV^2R. \tag{2}$$

Since G is constant and V appears to be constant as we can see in rotational curves (see **Figure 1**), it would mean that the mass of a galaxy increases linearly with the distance from its center:

$$M(R) \sim R. \tag{3}$$

As we know most of galaxies including the Milky Way have a bright massive center, a *bulge*, with majority of stars placed in that range and possibly a supermassive black hole in the middle. The farther away from the center, the fainter the regions are, i.e., less stars hence less matter is present, and linear dependence (3) is almost impossible to be obeyed. Computer simulations show that the galaxies move in a way we can observe them only if there is another than ordinary, luminous, form of matter, namely, dark matter. The amount of dark matter should be as large as almost five times more than the amount of ordinary matter. This is in agreement with calculations made within lambda-cold dark matter model (Λ-CDM) and the data from Wilkinson Microwave Anisotropy Probe (WMAP) [4] as well as Planck mission [5]. Λ-CDM model is a parametrization of the Big Bang cosmological model in which the Universe contains three major components: first, a cosmological constant denoted by lambda (Greek Λ) and associated with *dark energy*; second, the postulated *cold dark matter* (abbreviated CDM); and third, *ordinary matter*. It is often referred to as the standard model of Big Bang cosmology because it is the simplest model that provides a reasonably good description of the content of the Universe. WAMP was a satellite designed to map the cosmic microwave background (CMB) radiation over the entire sky in five frequency bands. The agreement between Λ-CDM model and the data from WAMP is good enough, which supports the validity of this model [4, 5]. The Λ-CDM model indicates that the matter the

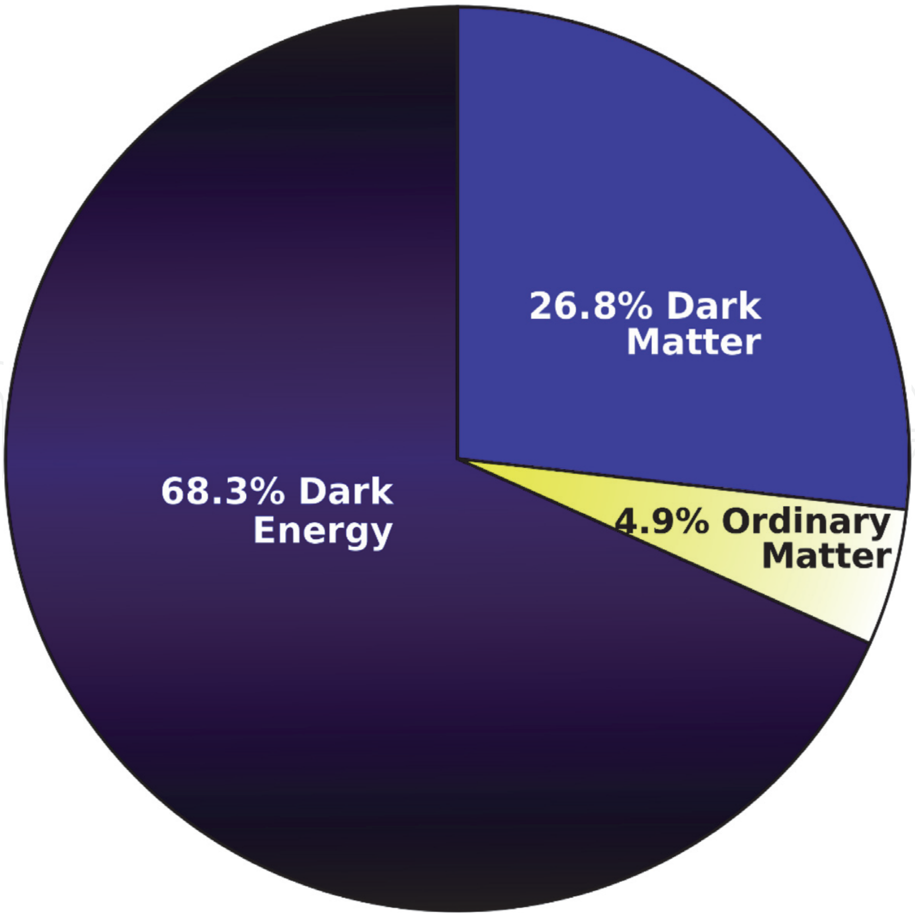

Figure 2.
Estimated distribution of matter and energy in the universe based on Planck data. Credit: ESA, Planck reveals an almost perfect Universe.

stars (and us) are made of is just a tiny part of the mass-energy content of the Universe (see **Figure 2**).

3. Possible solutions and even more problems

3.1 Wimps

Hypothetical particles that constitute the dark matter are called WIMPs which stands for weakly interacting massive particles. All the matter that we know (and us) is made of baryonic matter, i.e., the matter is made of baryons. WIMPS would be a new type of particles beyond the standard model. Those should be massive, subject to the gravitational force, and possibly other forces that are comparable to the weak force. One such candidate for WIMP could be a stable supersymmetric particle. Supersymmetric model has a particle of this property which was even called a "Wimp Miracle," but we have not yet observed any trace of supersymmetry, moreover, Wimp Miracle in any of the particle colliders. WIMPs also should not interact via electromagnetism; hence the DM is not visible in any wavelength. We only can "see" the DM due to its gravitational interactions, which are strong enough to cause a phenomenon known as gravitational lensing.

3.1.1 Gravitational lensing

This phenomenon is observed when the light rays passing near a very massive object are deflected (due to the curvature of space–time produced by this object) in such a way that a distant observer observes it lensed. **Figure 3** illustrates gravitational lensing: the stretched structures are distant galaxies, whose light was bent by the DM between them and the observer. This allows to calculate the mass required to cause such phenomenon [6]. Large aggregations of massive DM particles are able to produce such image letting us to know it's out there.

3.2 MACHOs

Massive astrophysical compact halo objects (MACHOs) was another hypothesis invoked to explain the presence of large amount of nonluminous matter in galactic halos. Those, contrary to the WIMPS, would have been regular astrophysical objects emitting little or no radiation such as black holes, neutron stars, as well as brown dwarfs and unassociated planets, which drift unseen through interstellar space providing extra gravity. Thorough investigations have shown that this concept rather fails to explain the expected amount of the DM. One way to detect MACHOS' influence, as described in [7], is to look for events of microlensing caused by them. Such microlensing would cause observable apparent amplification of star's flux. In [7] it was shown that the number of such events is far too less that would have been expected. That rules out MACHOS as the candidates for DM. Moreover, the studies of abundance of baryons created in the Big Bang show that baryon density is consistent with the mean cosmic density of matter visible optically and in X-rays. It implies that most of the baryons in the Universe are visible but not dark and that most of the matter in the Universe consists of nonbaryonic DM [7].

3.3 MOND

In the former sections, we have discussed the attempts of solving or explaining the problem of the missing matter. That is to find or to claim existence of unknown, invisible substance. Yet there is another idea based on a different assumption. In 1983 Milgrom [8] proposed an idea that maybe it is the theory that needs to be

Figure 3.
An image of gravitational lensing obtained with Hubble space telescope showing a distant image of galaxies which had been stretched due to the warping of space–time caused by a massive object between them and the observer. Credit*: ESA/Hubble https://www.spacetelescope.org/images/potw1506a/.*

modified rather than an invisible matter to be found. Modified Newtonian dynamics (MOND) is an empirically motivated modification of Newtonian dynamics at low accelerations, suggested as an alternative to dark matter concept [8, 9]. In Ref. [8] Milgrom considered the possibility that Newton's second law does not describe the motion of objects under the conditions which prevail in galaxies and systems of galaxies. Newton's laws have been tested in high-acceleration environment like the Earth or the solar system. The stars in the outer parts of the galaxies move in the circumstances of extremely low accelerations compared to what we know from everyday life. To illustrate how small such accelerations might be, let us calculate the acceleration of average star (the Sun) located on the suburbs of average galaxy (the Milky Way):

$$a = \frac{V^2}{R} = \frac{\left(220\ \frac{km}{s}\right)^2}{8.5\,kpc} \approx 1.845 \times 10^{-10}\frac{m}{s^2} \tag{4}$$

Milgrom proposed then a generalized form of Newton's second principle, claiming the inertia term not to be simply proportional to the acceleration of an object but being rather a more general function of it:

$$m \cdot \mu(a/a_0)\vec{\boldsymbol{a}} = \vec{\boldsymbol{F}}. \tag{5}$$

In expression (5) m is gravitational mass, a is acceleration, a_0 is some acceleration constant, and μ is a nonlinear function with the following properties:

$$\mu(x \gg 1) \approx 1, \mu(x \ll 1) \approx x \tag{6}$$

The acceleration constant is found to be $a_0 = 1.2 \pm 0.2 \times 10^{-10}\,\frac{m}{s^2}$ [8]. Phenomenological success of MOND is that applying it produces flat rotation curves of galaxies as observed and that this simple law is sufficient to make predictions for a broad range of galactic phenomena.

3.4 Ultra-diffuse galaxies

Recent studies of van Dokkum et al. [10, 11] have uncovered new class of object referred to as *ultra-diffuse galaxies*. NGC1052-DF2 and NGC1052-DF4 are large, faint galaxies with an excess of luminous globular clusters, and they have a very low-velocity dispersion. Velocity dispersion is the dispersion of radial velocities about the mean velocity for a group of objects. Low-velocity dispersion indicates that the galaxy has little or no dark matter. NGC1052-DF2 was studied with the Keck Cosmic Web Imager (KCWI), a new instrument on the Keck II telescope that was optimized for precision sky-limited spectroscopy of low surface brightness phenomena at relatively high spectral resolution. The spectroscopy data was used to describe kinematics of the galaxy. This result was based on the radial velocities of globular clusters that were assumed to be associated with the galaxies. It was claimed in Ref. [10] that taking observational uncertainties into account, the determined intrinsic velocity dispersion is consistent with the expected value found for the stars alone and lower than expected from DM halo (see **Figure 4**). The dynamical mass of NGC1052-DF2 determined in [10] was $1.3 \pm 0.8 \times 10^8 M_{\odot}$, and the stellar mass, i.e., luminous matter, was found to be $1 \pm 0.2 \times 10^8 \mathrm{M}_{\odot}$.

To give a reader some intuition and place this in some context, it is worth to notice that the stellar mass of the Milky Way found in [12] was $6.08 \pm 1.14 \times 10^{10} M_{\odot}$. It is broadly accepted in literature, and as will the following section

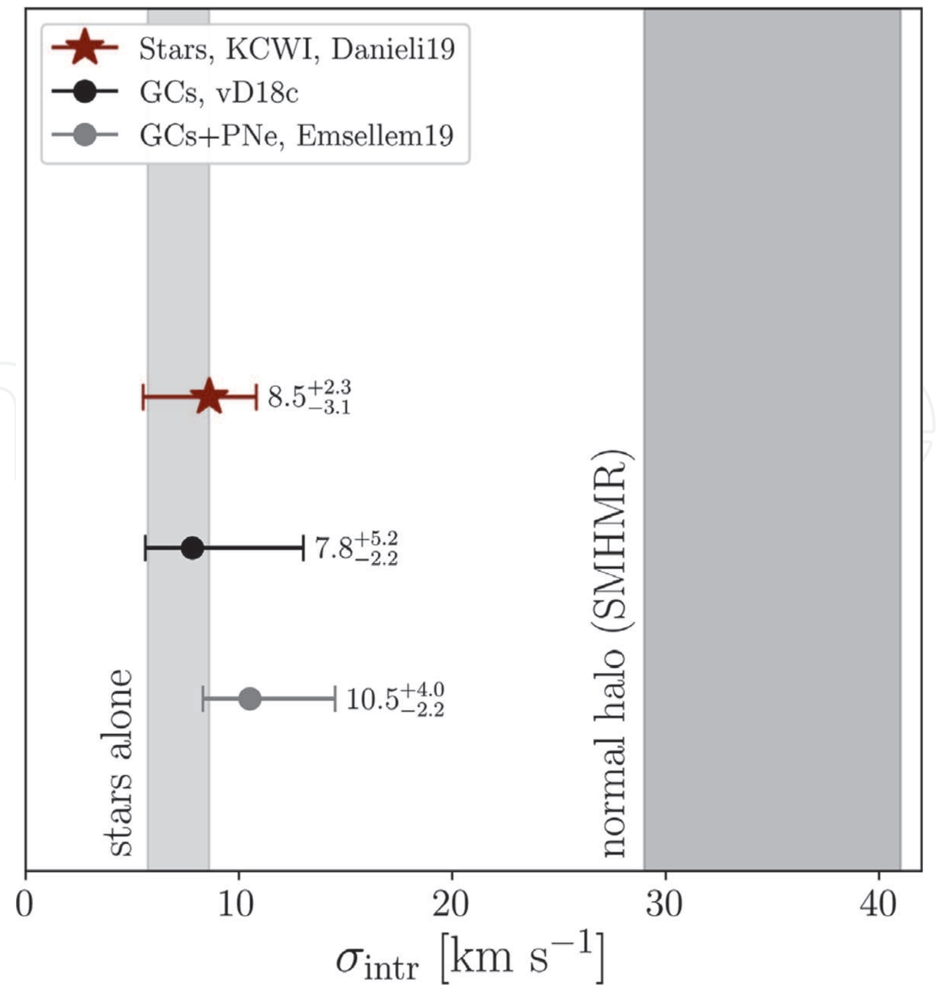

Figure 4.
Constraints on the intrinsic velocity dispersion of NGC1052-DF2. The result found in [8] (red dot star) is consistent with two other studies mentioned by authors and shows that such velocity dispersion indicates lack of the dark matter. Credit: *[10].*

present, the Milky Way contains big amount of the dark matter. The velocity dispersion of our galaxy is 75 km/s [13]. The NGC1052-DF2 is about 100 times lighter than the Milky Way; however, the velocity dispersion of NGC1052-DF2 was found to be only roughly 8.5 km/s [10]. If the galaxies can be formed and exist without the dark matter, i.e., the dark matter is not present in all existing galaxies, then the attempts to explain their dynamics by applying MOND might be at risk.

4. Detection of dark matter

4.1 Gravitational interaction with ordinary matter

In 2012 Moni Bidin et al. [14] published a paper in which they estimated surface mass density in the solar neighborhood. Results obtained match the expectations of visible matter alone without the need of adding the dark matter component. The difference between the measured mass of matter (derived in this study) and the mass of visible matter (i.e., mass of matter that is estimated in the independent way based on the amount of emitted) provides an estimate of the amount of DM in the volume under analysis, and constraints on the shape of the DM halo can be derived. The fundamental basis for this measurement is the application of the Poisson–Boltzmann and Jeans equations to a virialized system in steady state. This allows to estimate either the local density at the solar position or the surface density (mass per unit area) of the mass within a given volume. Authors in Ref. [14] derive analytical expression for surface density as a function of distance from the galactic disk plane Σ(Z) to estimate the surface mass density between 1.5 and 4.5 kpc distance from the galactic disk plane using data from of the kinematics studies of about 400 red giants kinematics. The authors in [14] claimed that the estimate of the surface mass density matches the expectation of visible mass alone and the degree of overlap between the two curves is striking. There is no need for any dark component to account for the results: the measured Σ(Z) implies a local DM density $\rho_{\odot DM} = 0 \pm 1\, M_\odot \cdot 10^{-3} pc^{-3}$ a. Further the authors in [14] compared this results with models of DM disk present in literature such as Ref. [15] hereafter OM; Ref. [16] hereafter SMH, which is standard DM halo model; or Ref. [17]—the model with minimal local DM density—hereafter MIN. Comparison of these findings is presented in **Figure 5**. Authors in Ref. [14] claim that the OM model is excluded at 8 sigma confidence level, SHM at 6 sigma, and even MIN model at 4.1 sigma. (Sigma confidence level says how many values lie within the number of standard deviation of the mean. For example, in particle physics there is a convention of a five-sigma effect being required to qualify as a discovery, that is to say that 99.99994% of the values must lay within 5 standard deviations of the mean; 8 sigma is even higher confidence level). Authors conclude that the measurement of the mass surface density at the solar galactocentric position between 1.5 and 4 kpc from the galactic plane accounts for the visible mass only. The DM density in the solar neighborhood, extrapolated from the observed curve of Σ(Z), is at variance with the general

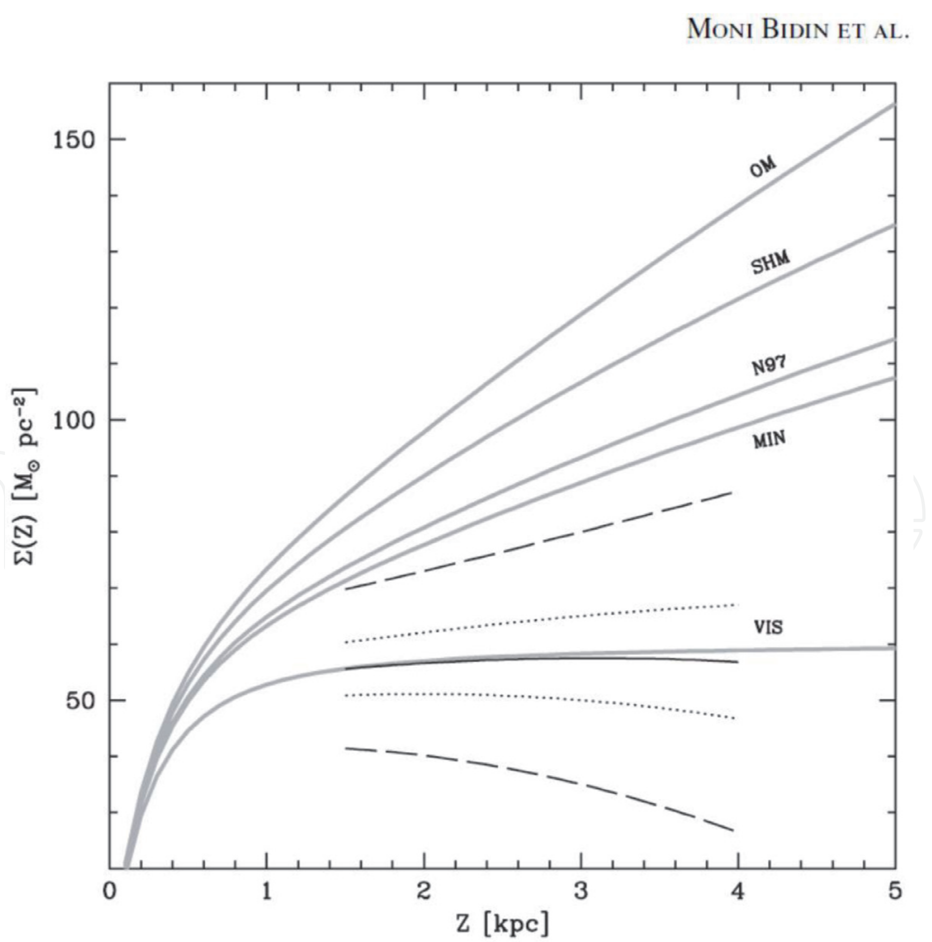

Figure 5.
Observational results for the surface mass density, as a function of distance from the galactic plane (black curve), compared to the expectations of the models discussed in the text (thick gray curves). The dotted and dashed lines indicate the observational 1σ and 3σ strip, respectively. Expectations for the known visible mass are indicated by the thick gray curve labeled as VIS. Credit: *[14].*

consensus that it must be in the range $5 - 13\, M_\odot \cdot 10^{-3} pc^{-3}$ (e.g., [18, 19]). Lack of DM is observed by using measurements of the thick disk kinematics and is independent of the choice of data, because very similar results were obtained by means of other kinematical results in the literature. It is clear that the local surface density as measured in Ref. [14], extrapolated to the rest of the galaxy, cannot retain the Sun in a circular orbit at a speed of $\sim$220 km s^{-1}. A deep missing mass problem is therefore confirmed by this study, and this finding tells us that indirect attempts to detect the dark matter by investigating its interactions with ordinary matter in that way have a little chance of success.

4.2 Direct detection

The experiments that aim at the direct detection due to scattering do not agree with each other yielding different constraints on the mass of the DM particles. The DAMA/LIBRA experiment [20] is the only one to claim positive result of detection which however has not been yet confirmed by the other groups (detectors). The aim of this experiment is detecting low-energy recoil photons from the scintillator crystals of thallium-doped sodium iodide NaI(Tl) placed in the detectors under the ground. Such photons would be emitted when the DM particle collides with one of the scintillators. If what we know about the DM is right, then since the Earth orbits the Sun, the DM particles should pass through the planet and hence have a chance to collide with those of the detectors. The idea of the experiment is that if one takes into account the revolution of the Earth around the Sun and the revolution of the Sun around the center of our galaxy, then the signals coming from the collisions should be modulated as in June the relative velocity of the Earth and the DM flux is the biggest hence yielding the biggest number of collisions. The data collected from the phase II of the experiment have all traits required to claim the presence of the DM in our part of the galaxy. The annual modulation is present only in the events concerning the photons with energies exactly within the energetic range theoretically predicted for the DM particles. Yet the DAMA/LIBRA is a singular case. Several groups have been working to develop experiments aiming at reproducing DAMA/LIBRA's results using the same target medium. To determine whether there is evidence for an excess of events above the expected background in sodium iodide and to look for evidence of an annual modulation, the COSINE-100 experiment [21] uses the same target medium to carry out a model-independent test of DAMA/LIBRA's claim. Their results from the initial operation of the COSINE-100 experiment were published in [21], and no excess of signal-like events above the expected background in the first 59.5 days of data from COSINE-100 has been observed. Assuming the so-called standard DM halo model, this result rules out spin-independent WIMP–nucleon interactions as the cause of the annual modulation observed by the DAMA/LIBRA collaboration. Another such experiment is the XENON100 experiment that searches for electronic recoil event rate modulation by measuring the scintillation light from a particle interacting in the liquid xenon. The results of this experiment published in [22] also exclude the DAMA/LIBRA results.

4.3 Others

We will present here very briefly the other two methods of detection of DM:

- *Production of DM particles in colliders*—If the DM particles were created, for instance, in LHC, they would escape through the detectors unnoticed (due to their non-electromagnetic nature). However, they would carry away energy and momentum, so one could infer their existence from the amount of energy and momentum "missing" after a collision. The LHC also search for existence of supersymmetric particles which are one of the candidates for DM particle.

- *Searching for products of annihilation of its particles*—Indirect detection. This experiments search for the products of the self-annihilation or decay of DM particles in outer space. For example, in regions of high DM density (e.g., the center of our galaxy), two DM particles could annihilate to produce gamma rays or standard model particle–antiparticle pairs. Alternatively if the DM particle is unstable, it could decay into standard model (or other) particles. These processes could be detected indirectly through an excess of gamma rays, antiprotons, or positrons emanating from high-density regions in the galaxy or others.

5. Milky way rotation curve

DM manifests its existence through the shape of rotational curves of galaxies, in particular, through the rotational curve of our own galaxy, the Milky Way. This is what motivated us to take a glimpse on that topic and to compare results to those present in literature [23]. We have studied the rotational curve of Milky Way with radio telescope located in the Astronomical Observatory of the Jagiellonian University provided by EU-HOU project (EU-HOU project was founded with support from the European Commission, grant 510,308-LLP-1-2010-FR-COMENIUS-CMP. https://www.astro.uni-bonn.de/hisurvey/euhou/LABprofile/).

5.1 The method

This 3 m in diameter telescope runs observations on 1420 MHz frequency which is the emission line of neutral hydrogen. When the hydrogen atom undergoes a transition from the state of higher energy when the spins of the proton and the electron are parallel to the state of lower energy that is when the spins are antiparallel, emitted photon is equivalent to radiation roughly 21 cm wavelength in vacuum (see **Figure 6**). Even though such process occurs very rarely, given the abundance of the hydrogen in the Universe (i.e., 74% of its baryonic mass), it is a common phenomenon. Hence the hydrogen is also present in the interstellar space around the stars, and radio observations yield information on how the matter is distributed inside the galaxy, and knowing the Doppler shift of the observed radiation, one can calculate the velocity of the hydrogen cloud from which it comes from. This in turn gives us an idea how the hydrogen and the nearby matter move within the galaxy, i.e., orbit around its center. Knowing the velocities and distance of such hydrogen clouds, one can plot the rotational curve of the galaxy. This is called tangent point method. Thus using the data obtained from the telescope, the Doppler equation:

$$V_r = \frac{f_0 - f}{f_0} \cdot c \tag{7}$$

one can calculate the source's velocity (speed) relative to us (V_r). f_0 is the frequency emitted by the hydrogen atom, f is the frequency the radio telescope receives, and c denotes the speed of light. The frequencies registered by the radio telescope are of course slightly different than 1420 MHz which is the frequency of emitted photon as measured at the lab and as emitted by the hydrogen atom.

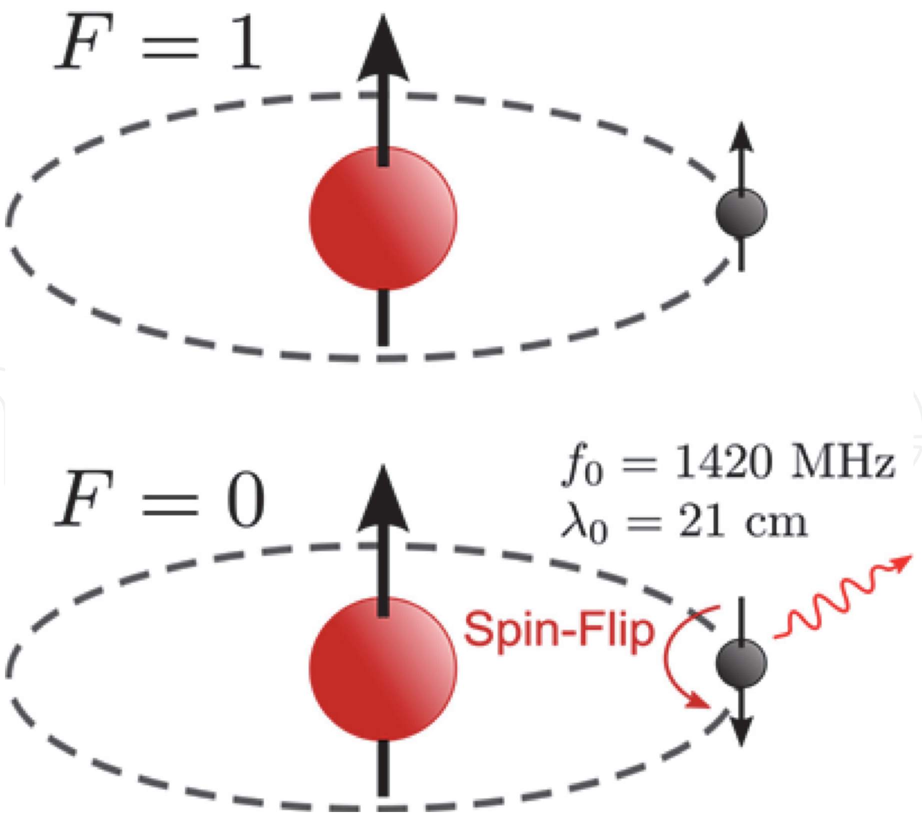

Figure 6.
Hydrogen 21-cm emission line.

The hydrogen atoms that we study are moving relatively to us so the signal coming from them is a subject to the same phenomenon as for the ambulance's siren applies. That is the change in frequency that enables us to calculate the radial velocity of such hydrogen cloud along the line of sight (which is defined by galactic longitude).

To find the speed of the hydrogen cloud, a simple fact is used, that is the radial velocity results in difference between the projection of ours (Sun's) velocity on the line of sight and the hydrogen cloud's velocity on the line of sight (see **Figure** 7). The line of sight is determined along the galactic longitude (see **Figure 8**) on which we set the radio telescope.

This results in the following equation for velocity of observed hydrogen cloud:

$$V_r = V\frac{R_0}{R}\,sin\,(l) - V_0\,sin\,(l) \tag{8}$$

Among the objects observed along the given line of sight, the one with the smallest distance will have the biggest velocity. The smallest possible distance between us and the source is when it lies in the tangent point; hence simple trigonometry allows us to determine the distance:

$$R = R_0\,sin\,(l) \tag{9}$$

which simplifies Eq. (8) to

$$V = V_r + V_0\,\sin\,(l). \tag{10}$$

Eqs. (8) and (9) provide all required information to plot a rotational curve of the galaxy. This method works for objects in I and IV Quadrants of galactic longitude, that is for $0° < l < 90°$ *and* $270° < l < 360°$ and inside the galactocentric radius of the Sun.

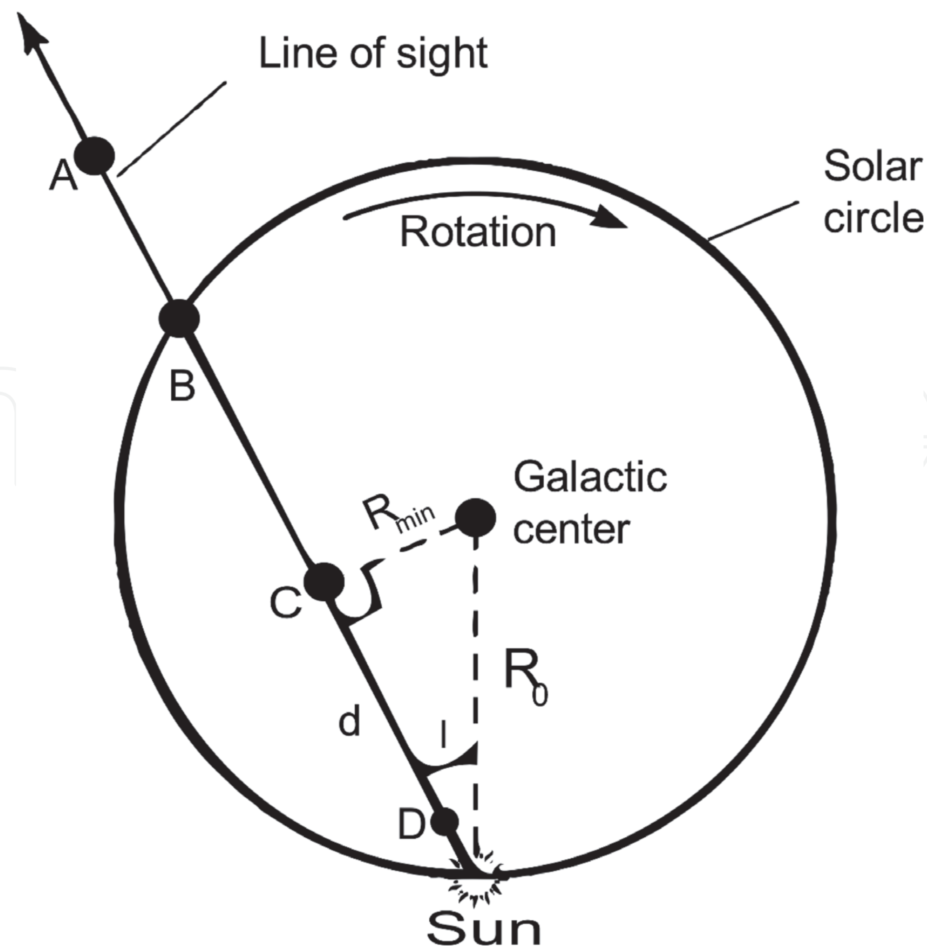

Figure 7.
Figure presenting two objects (A, B) along the line of sight. Hence object B lies in tangent point, i.e., its distance from the center of the galaxy is smaller, and its velocity is greater than the velocity of object A.

5.2 Results

Twenty-nine objects with galactic longitude $0° < l < 90°$ have been studied. Their positions on the map of the Milky Way are presented in **Figure 9**. Tangent point method applied to the data results in rotational curve presented in **Figure 10**.

Our rotational curve plot, **Figure 10**, is comparable to the plot obtained from data from LAB survey [24] and consistent with the ones that can be found in literature [23, 25]. We follow [25] in their choice of function to fit the data, namely

$$\frac{V}{V_0} = a\left(\frac{R}{R_0}\right)^b + c \tag{11}$$

where we put $V_0 = 220\,\frac{km}{s}$ and $R_0 = 8.5$ kpc and find the coefficients to be $a = -5.495e - 06$, $b = -21.28$, and $c = 0.9808$.

We conclude that the rotational curve reveals the existence of dark matter within the Milky Way. Taking (nonrelativistic) law of gravity, that is, the force of gravity is proportional to inverse squared distance, one would expect that the farther away the hydrogen clouds (constituting the distribution of matter) are from the massive center of the galaxy, the lower their velocities will be. As one see from the rotational curve, **Figure 10**, this is not the case; the velocities seem to be constant over a distance of roughly 3 kpc. Which means there is nonluminous matter distributed in such a way just to “keep up” with the increasing distance from

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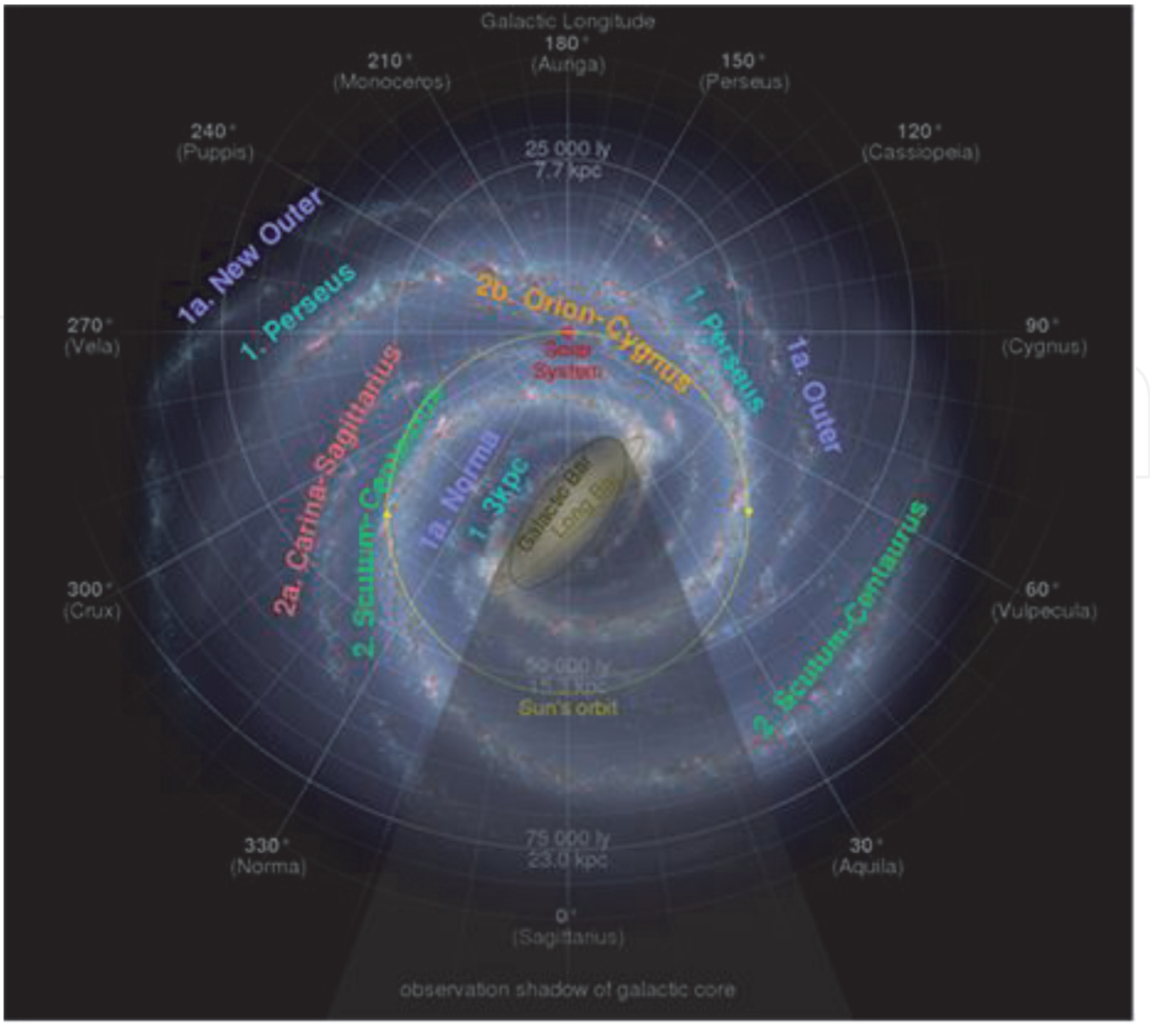

Figure 8.
Figure presenting galactic longitude. L = 0° is direction from the solar system to the center of galaxy. Credit: *File: Artist's_impression_of_the_Milky_Way.Jpg: NASA/JPL-Caltech/ESO/R.hurt.*

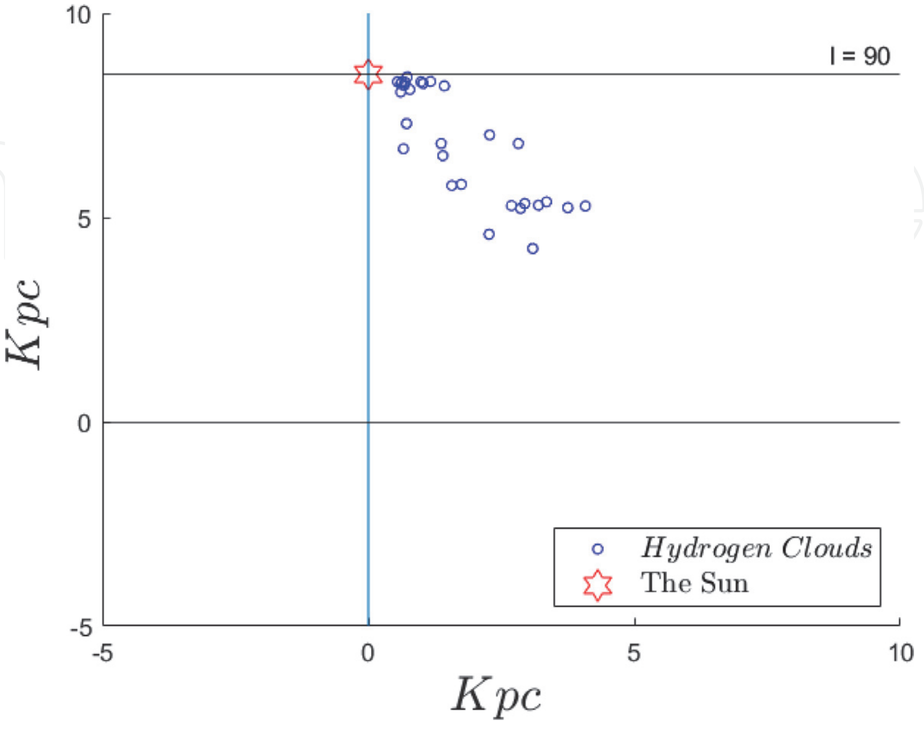

Figure 9.
Map of the hydrogen clouds used to determine the rotational curve of the Milky Way.

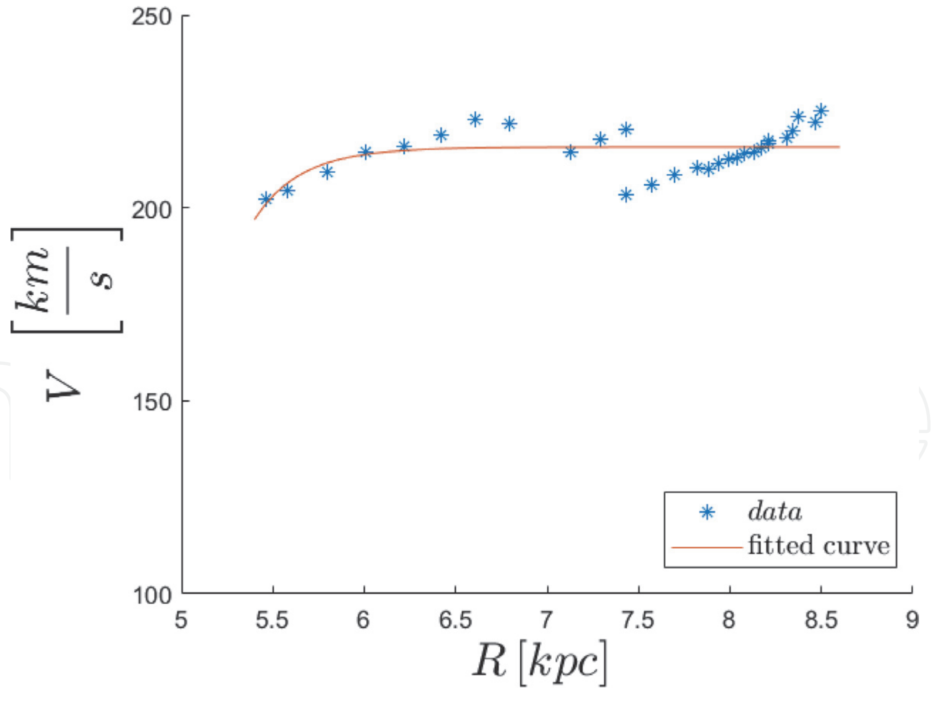

Figure 10.
Rotational curve obtained from 21-cm line observations of the Milky Way. Note that the velocity of the studied objects appears to be constant over roughly 3 kpc distance.

the center of galaxy and make it so that the velocities of hydrogen atoms are almost constant as the distance increases.

6. Conclusions

The problem of missing matter discovered by Fritz Zwicky in 1933 appears to be still an open question. The most important premise of existence of the dark matter is the shape of rotational curves of galaxies, introduced as a tool for studying galaxy rotation by Vera Rubin. With our current understanding of the Universe, the dark matter, still a mysterious substance, makes up 86% of all the matter in the Universe. Throughout the years various attempts have been made to explain its nature. Some of the ideas have been proven unlikely (MACHOs). Some of them contradict each other (DAMA/LIBRA, the COSINE-100 collaboration). Yet even simple Milky Way's observations as presented in Section 5 lead to the conclusion that the dark matter is present in the halo of our galaxy.

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