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Determination of the Rotation Curve of the Milky Way Using the 21 cm Hi Emission Line

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Abstract
In this paper, the rotation curve of the Milky Way galaxy has been determined using the observed HI emission line at a wavelength of 21 cm. Particularly, the Tangent Point Method was used in order to measure the rotational velocity and the distance to the center of the Milky Way. The measured rotation curve showed that the rotational velocity remains approximately constant at large distances from the center of the Galaxy. This is actually an evidence for the existence of dark matter in the halo of the Milky Way. If all the matter in the Milky Way is visible, then the behavior of the rotation curve of the galaxy should experience a Keplerian decline. The mass of the Milky Way within a radius of 15 kpc was also estimated to be ~ 1.65×10^{11} $M_{\odot}$ which represents the mass of luminous matter in the Galaxy. However, if one assumes that the dark matter halo extends to 50 kpc, then the mass of the Galaxy should be ~ 5.615×10^{11} $M_{\odot}$. The results indicate that the mass of dark matter in the Milky way within a radius of 50 kpc is ~ 3.96×10^{11} $M_{\odot}$.

Keywords: Dark matter, Galaxies, Rotation curves, HI emission line.

حساب منحني الدوران لمجرة درب التبانة باستخدام خط انبعاث الهيدروجين المتعادل ذي الطول الموجي 21 سم

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الخلاصة
في هذا البحث تم حساب منحني الدوران لمجرة درب التبانة باستخدام خط انبعاث الهيدروجين المتعادل ذي الطول الموجي 21 سم. وعلى وجه التحديد، تم استخدام طريقة النقطة المماسية لحساب السرعة الدورانية والمسافة لمركز مجرة درب التبانة. المنحني المحسوب اثبت بأن السرعة الدورانية تبقى تقريباً ثابتة لمسافات بعيدة من مركز المجرة. وهذا دليل على وجود المادة المعتمة في الهالة المجرية لمجرة درب التبانة. حيث لو ان كل المادة في مجرة درب التبانة هي مضيئة فأن سلوك منحني الدوران يجب ان يعاني نقصان في السرعة الدورانية والذي عادة ما يدعى نقصان كبلر. كذلك تم اجراء حسابات تقريبية لكتلة مجرة درب التبانة ضمن مدار نصف قطره 15 فرسخ فلكي ووجدت بانها تساوي تقريباً 1.65×10^{11} $M_{\odot}$ وهي تمثل كتلة المادة المضيئة في المجرة. اذا افترضنا بأن الهالة المجرية تمتد لمسافة 50 فرسخ فلكي فأن كتلة المجرة تساوي

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5.615×10^{11} M$_\odot$. اوضحت النتائج بأن كتلة المادة المعتمة في مجرتنا ضمن مدار نصف قطره 50 فرسخ فلكي هي بحدود 3.96×10^{11} M$_\odot$.

INTRODUCTION

The fraction of visible matter in the Universe is only ~ 5 % of the total mass and the rest is in the form of dark matter (27%) and dark energy (68%). Therefore, it is very important to study the observational evidences of the existence of dark matter. The fraction of each component in the Universe according to PLANCK 2015 constraints [1] is shown in Figure- 1. There are many evidences for the existence of dark matter in the Universe.

The first evidence of the existence of dark matter was published by Zwicky in the 1930s [2, 3]. He estimated the velocity dispersion of galaxies in Coma cluster and found that the velocity dispersion is higher than expected from the visible matter only. Gravitational lensing provides another evidence for the presence of dark matter in bullet clusters such as 1E0657-558. These systems comprise of two colliding clusters of galaxies and as a result of the collision, the smaller cluster passes through the main cluster. Gravitational lensing analyses show that the peak of mass distribution is offset from that obtained from x-ray analyses which represent the peak of the visible mass distribution. This also proves that the dark matter in these clusters is collisionless [4- 6].

In addition, the flatness of the rotation curves of spiral galaxies at large radial distance is an evidence for the existence of dark matter in those galaxies [7- 9]. According to the Newtonian mechanics, there should be a balance between the centrifugal force and the gravitational force [10]:

$$\frac{mV_C^2}{R} = \frac{GmM}{R^2} \quad \text{.......(1)}$$

Where m is the mass of an object within the galaxy, V_C is the rotational velocity, R is the distance to the center, G is the gravitational constant, and M is the mass within the radius R. Therefore, if all the mass in spirals is luminous, then the circular velocity should decline according to the following formula:

$$V_C = \sqrt{\frac{GM}{R}} \quad \text{.......(2)}$$

This paper aims to prove the existence of dark matter in the Milky Way by measuring its rotation curve from HI profile.

METHODOLOGY

The rotation curve of spiral galaxies is defined as the variation in the rotational velocity of objects such as stars and gas clouds at different radial distances of spirals. A MATLAB code was written in order to show the behavior of different types of rotation curves and the results are shown in Figure- 2. The circular velocity of a solid body increases linearly with the distance from the center of the object see Figure- 2(a). Figure- 2(b) shows that because the enclosed mass decreases, the rotational velocity decreases with the radial distance according to the Keplerian rotation. A flat rotation Figure- 2(c) indicates that the mass increases with the distance from the center. The expected behavior of the rotation curve of spiral galaxies is shown in Figure 2d. The rotational velocity of a spiral galaxy should increase with the distance near the center of the galaxy because the enclosed mass increases so fast with the radial distance. Based on the Newtonian mechanics, the rotation curve then should experience a Keplerian decline at large radial distances (see equation 2). However, the observed rotation curve is completely different as shown in Figure 2e. We notice that the rotational velocity remains approximately constant at large radial distances. This implies that the enclosed mass still increase with the radial distances and this in turn indicates that there is matter that is not in the form of visible matter (i.e. dark matter), see e.g. [10].

One of the most powerful techniques of measuring the rotation curve of the Galaxy is from the Doppler shift of clouds of HI emission line. This neutral hydrogen radio line at a wavelength of 21 cm is useful because it is not strongly scattered or absorbed by interstellar dust. The location and velocity of an HI cloud cannot be determined directly. However, the so-called tangent point method is used to measure the Galactic rotation curve. A gas cloud that is located along the line of sight closest to the Galactic center has the maximum radial velocity. Figure- 3 shows a schematic diagram of the 21 cm HI emission line profile.

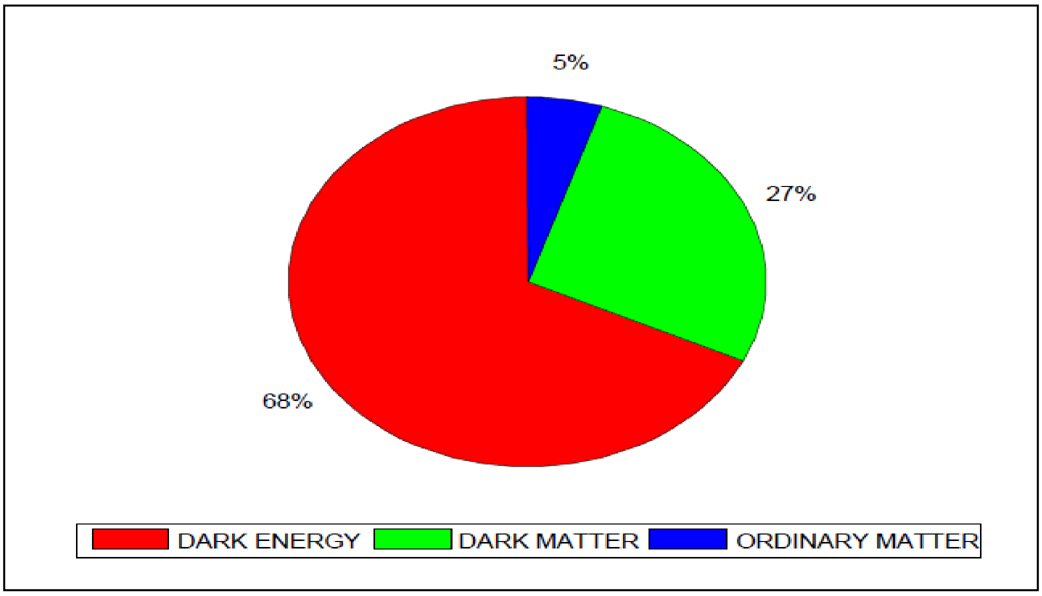

Figure 1-The components of the universe based on the recent PLANCK data [1].

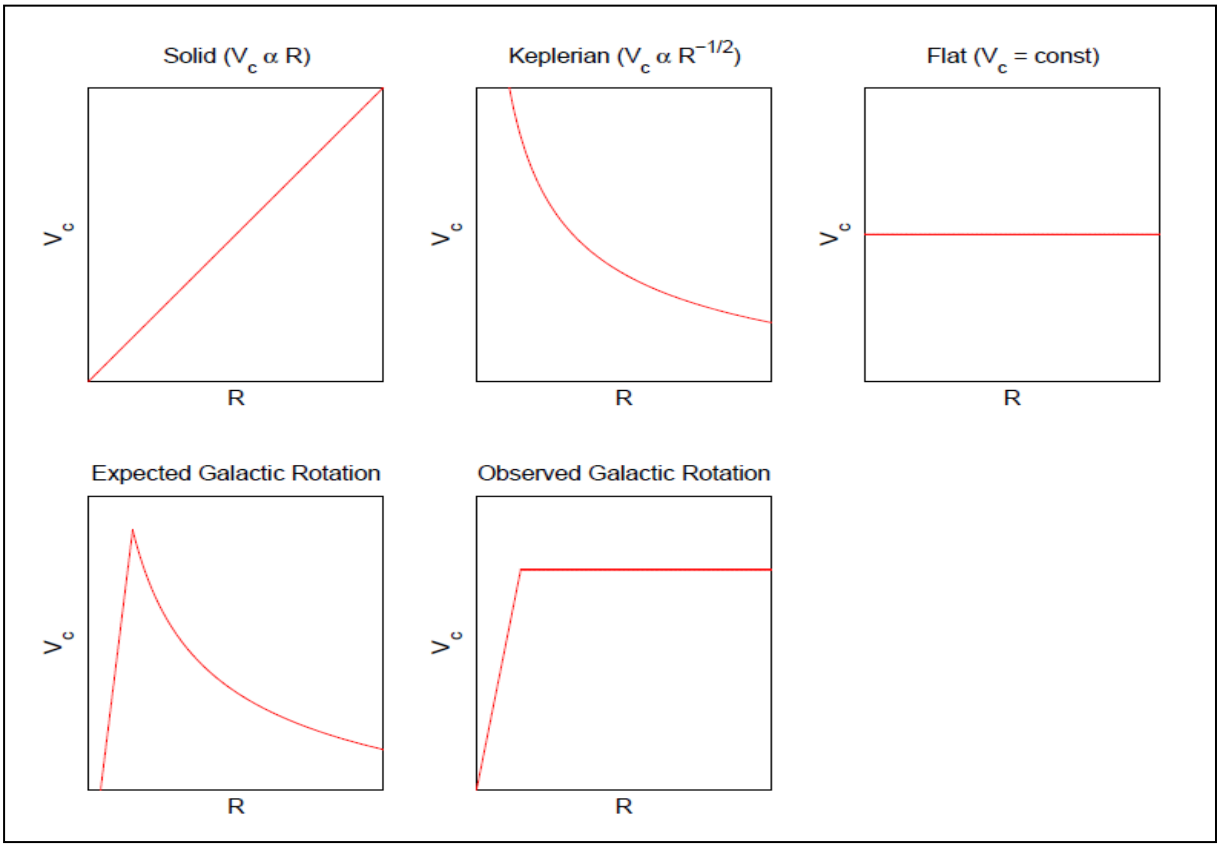

Figure 2- A schematic diagram of different types of rotations including the expected and observed rotation curve of a spiral galaxy (d and e).

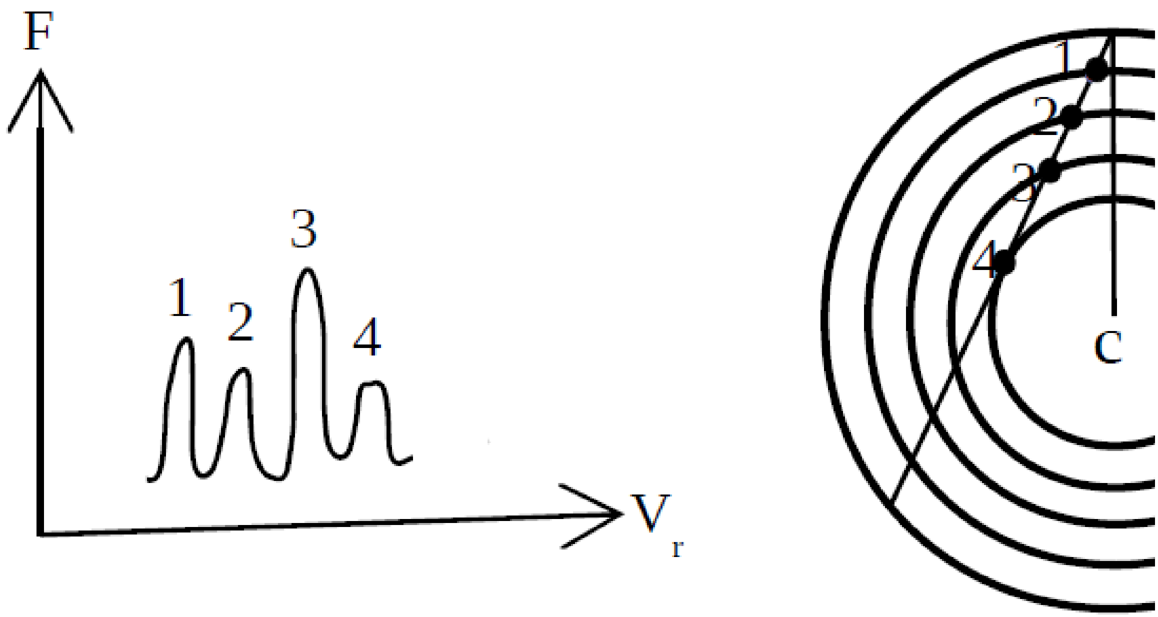

Figure 3- A schematic diagram of HI profile. The HI cloud 4 is located at a tangent point, so it has the maximum radial velocity.

The maximum radial velocity (Vr,max) is used to determine the location of the gas cloud from the Galactic centre (*R*) and the circular velocity of the gas cloud Vc at the tangent point from (see for example [11]):

$$R = R_o \sin l \qquad (3)$$

$$V_C = V_{r,\max} + V_o \sin l \qquad (4)$$

where l is the Galactic longitude, Ro is the distance of the sun from the Galactic center and Vo is the rotational velocity of the sun. This means that if the maximum radial velocity is known, one can easily determine the rotation curve of the Galaxy.

RESULTS AND DISCUSSION

In this work, the data of HI profile at b = 0 and $0 \leq l \leq 90$ have been collected from Leiden Argentine Bonn (LAB) Survey (See also [12, 13]).

In Figure- 4, we show the HI profiles at b = 0 and different values of Galactic longitudes. The maximum radial velocity has been obtained from these profiles and then equations 3 and 4 are used to determine the rotation curve of the Galaxy. The measured rotation curve is shown in Figure- 5. The figure also illustrates the rotation curve that was determined by [14]. This comparison clearly indicates that the rotation curve measured in this work is consistent with that measured by [14].

The flatness of the rotation curve at large radial distances basically indicates that there is extra matter that is not in the form of visible matter, namely, dark matter. If all the matter in the Galaxy is in the form of luminous matter, the rotational velocity should decline according to the Newtonian dynamics.

It was pointed out in the website of the Leiden Argentine Bonn (LAB) Survey that the velocities in the inner part of the Milky Way are very uncertain. Therefore, the rotation curve in this work has been determined for the outer part of the Milky Way ($l > 20^o$). However, this does not affect our results because the key goal here is to show that the rotation curve is flat in the outer part of the Galaxy.

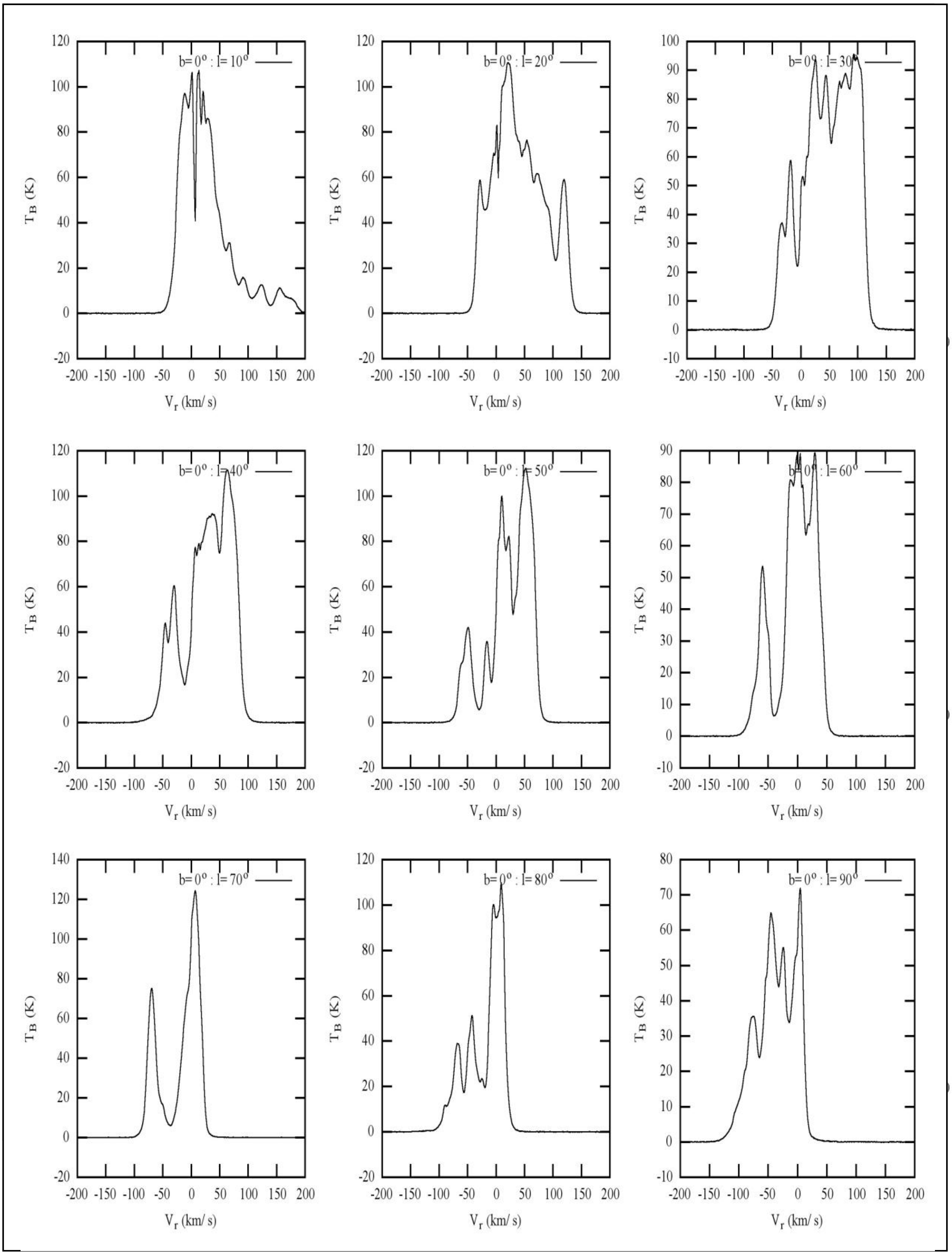

Figure 4- The HI profile at *b*=0° and 10 ≤ L ≤ 90°. The data were taken from Leiden Argentine Bonn (LAB) Survey.

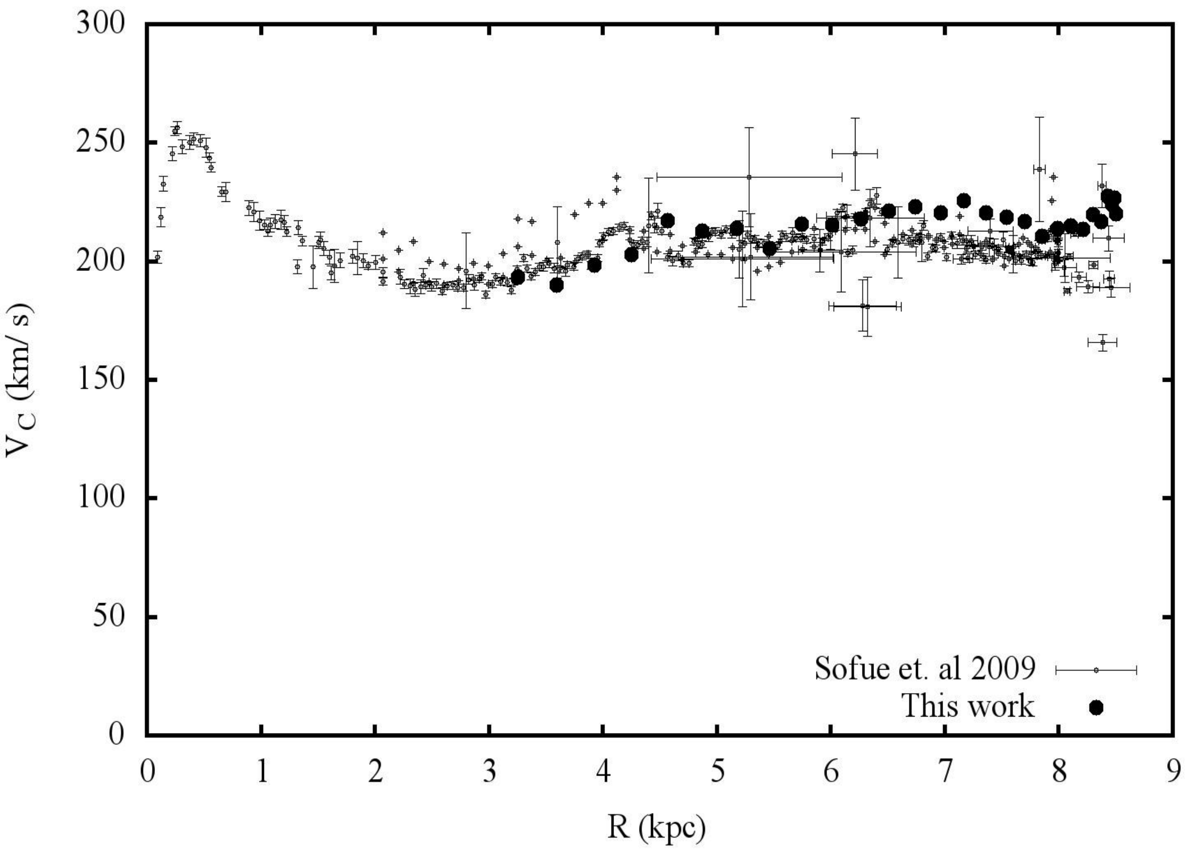

Figure 5- A comparison between the rotation curve of the Milky Way measured in this work and that measured by [14].

CONCLUSIONS

This work focuses on the determination of the Milky Way rotation curve using the observed neutral Hydrogen at a wavelength of 21 cm. We found that the rotation curve of the Milky Way measured in this work is consistent with that determined by [14]. The rotational velocity of the Galaxy remains almost constant in the outer part of the Galaxy. This indicates that the Milky Way contains a large fraction of matter that is in the form of dark matter. In addition to the Tangent Point Method that has been used in this work, several other techniques have been used to derive rotation curve of our own galaxy. For instance, the HI thickness method was used to measure the rotation curve of the Milky Way [15, 16]. The measurements of parallax and proper motions of H_2O maser sources are used to measure the rotation curve of the Galaxy [17]. The proper motions of red clump giant stars were also used to derive the rotation curve of the Galaxy [18]. Recently, observations of maser sources from VERA (VLBI Experiment for Radio Astrometry) are used to study the rotation curve of the Milky Way [19, 20]. We also estimated the mass of the Milky Way within a radius of R=50 kpc to be ~ 5.615×10^{11} $M_\odot$, whereas the mass of visible matter within a radius of R=15 kpc is found to be ~ 1.65×10^{11} $M_\odot$. This implies that the mass of dark matter in the Galaxy is ~ 3.96×10^{11} $M_\odot$ which is higher than that of the luminous matter. Our estimate of the mass of the Milky Way is obviously consistent with estimates from previously published works. For example, a sample of 2401 blue horizontal-branch halo stars from SDSS DR6 was used to estimate the mass of the Milky Way within a radius of 60 kpc and is found to be ~ $(4\pm0.7) \times 10^{11}$ $M_\odot$ [21]. The mass of the Galaxy was also estimated by [22] and is found to be ~ $(7.03\pm1.01) \times 10^{11}$ $M_\odot$.

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