The mass distribution and the rotation curve of the Milky Way Galaxy using NARIT 4.5 m small radio telescope and the 2.3 m Onsala radio telescope

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Abstract. This study was aimed to make the neutral hydrogen (HI) mapping and rotation curve of the Milky Way at galactic longitude 0° to 90° in the galactic plane by using the 4.5 m Small Radio Telescope (SRT) of National Astronomical Research Institute of Thailand (NARIT) and the 2.3 m Onsala radio telescope. The HI spectra at wavelength of 21 cm can be used to analyze the dynamical properties of the Milky Way with Gaussian fitting software, which was developed by using Python programming language. SalsaJ is another free astronomical software which was also used in this study by analyzing the Gaussian spectra of the Onsala radio telescope. For making sure the performance of developed software, therefore, it will be tested between their observation spectra of NARIT 4.5 m SRT and the Onsala radio telescope together with the public international archive. The results showed that the positions of HI are distributed in a spiral - arms shape and the rotation curve is constant at the galactic distance (R) > 3 kpc. The spherical mass distribution (in terms of the surface mass density) was approximated by directly using rotation curve. Our results are in good agreement with the standard values.

1. Introduction

A neutral hydrogen (HI) atom emits a radio line at a wavelength 21 cm (or a frequency 1420 MHz). It is the most abundant gas in the Galaxy. The spectral line is produced by hyperfine splitting between proton’s spin and electron’s spin in hydrogen atom. This 21 cm radiation can be used to study the dynamical properties of the Milky Way Galaxy. Previously, the Milky Way mapping by detection the HI using the small radio telescope (SRT) was made by Tarif Rashid Santo and Syed Ashraf Uddin [1]. In the same year, Yoshiaki Sofue [2] determined the mass distribution in the Galaxy by applying the results obtained from rotation curves of galaxies. In 2017, the first observation of HI using NARIT 4.5 m SRT and the data analysis were performed by Attasit Phakam [3]. They aimed to make the rotation curve and to map the Milky Way.

Therefore, we aimed to compare the dynamical properties of the HI clouds in the Milky Way by using the observational data from NARIT 4.5 m SRT and the 2.3 m Onsala radio telescope, Sweden. Their dynamical properties can be studied through the rotation curve, mapping of HI clouds and the spherical mass distribution (in terms of the surface mass density).
2. Theory

2.1. Neutral Hydrogen

Neutral Hydrogen (HI) atoms are plentifully in the low-density regions of the interstellar medium (ISM) and can be easily observed in galaxies. A neutral hydrogen atom consists of one proton and one electron. If it is excited, electron spin can be flipped and has parallel direction compared with proton spin afterwards. It can also be flipped again and has anti-parallel direction. Therefore, changing the energy states of HI from the excited state to ground state can be emitted the radio emission in the wavelength 21 cm line (or ~ 1420 MHz) [1]. The frequency is

\[ f = \frac{\Delta E}{h} = 1420.4057517667 \pm 0.0009 \text{ MHz}, \]

where the energy gap (\( \Delta E \)) is \( \frac{4\pi^2\hbar^4}{3m_p m_e^2 c^2 a^4} \approx 5.83 \times 10^{-6} \text{ eV} \), \( h \) is reduced Planck constant, \( m_p \) and \( m_e \) are mass of proton, electron, respectively. \( a \) is the Bohr radius.

2.2. The Doppler effect

Doppler effect is the change in wavelength by the relative motion of the source and the observer (in this case the source is hydrogen gas in Milky Way). The Doppler effect was defined by Christian Johann Doppler and can be defined by equation (2):

\[ \frac{\Delta f}{f_0} = -\frac{v_r}{c}, \]

where \( \Delta f \) is the frequency shift, \( f_0 \) is the rest frequency of the line, \( v_r \) is the radial velocity and \( c \) is the speed of light in vacuum. This equation is used in the case for non-relativistic system.

2.3. Galactic geometry

The Geometry observation of the Milky Way is simplified in figure 1 [1].

![Figure 1](image.png)

**Figure 1.** The schematic diagram shows the top view of two objects which assumed to orbit perfectly around the galactic center (C). \( V_0 \) and \( V \) vectors show the rotational velocity of the Sun and the HI clouds, respectively.

In the figure, C is galactic center. \( V_0 \) and \( V \) vectors show the rotational velocity of the Sun and the HI clouds which are moving around the galactic center, respectively. Geometry observation of the Milky Way can be used to calculate the radial velocity of HI and the distance between C and M at the different longitudes in galactic plane. Then we can rewrite,
\[ R = \frac{R_o V_o \sin l}{V_o \sin l + v_r} \]  
(3)

as illustrated on figure 1. At the tangential point (T), we have:
\[ V = v_{rot} = v_{r, max} + V_o \sin l, \]  
(4)

Where, \( R_o \) is the distance between C and S (assuming \( R_o = 8.05 \) kpc and \( V_o = 238 \) km s\(^{-1} \) [4]) and \( v_{r, max} \) is the maximum radial velocity which being observed at different Galactic longitude (\( l \)). By applying the law of cosines, we have
\[ R^2 = R_o^2 + r^2 - 2R_o r \cos l, \]  
(5)

where \( r \) is the distance M from S. The position of HI in Milky Way Galaxy was calculated by using the equations in the forms of cartesian and polar coordinates as shown in equations (6) and (7);
\[ x = r \cos(q), \]  
(6)
\[ y = r \sin(q), \]  
(7)

where \( q = l - 90^\circ \).

The accuracy values of Rotation curve can be performed by following Sofue [5, 6]. The error estimation can be calculated by using equations (8) to (11):
\[ \Delta V_{rot}^{v_r} = \sqrt{dV_{v_r}^2 + dV_T^2}, \]  
(8)

where,
\[ dV_{v_r} = \frac{\partial V}{\partial v_r} dv_r, \quad dV_T = \frac{\partial V}{\partial r} dr, \]  
(9)
\[ dR = \frac{s}{R} dr, \]  
(10)

Further, we can estimate the error of mapping HI in \( r \) term by using equations (12) and (13).
\[ dx = r(\cos(l + \Delta l) - \cos l) + \cos l(\Delta r), \]  
(12)
\[ dy = r(\sin(l + \Delta l) - \sin l) + \sin l(\Delta r), \]  
(13)

where \( dv_r \) is the error of radial velocity from gaussian fitting, \( \Delta l \) is the error of beam width of SRT.

2.4. The spherical mass distribution
We estimate the simplified mass distribution of our Galaxy as suggested in Sofue [6]. We assume that the HI clouds are in spherical shape and are purely inside.
The spherical mass distribution (in terms of the surface mass density at the distance \( R (\sum_S(R)): SMD \)) was approximated by using rotation curve. It can be determined from equation (14),

\[
\sum_S(R) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{1}{r \sqrt{r^2 - R^2}} \frac{dM(r)}{dr} dr,
\]

where \( M(r) \) is mass depends on the radius (or distance) in our Galaxy and \( r \) is the distance of the sun and the HI clouds.

3. Methodology and Data Analysis

Two softwares were used for analysing and comparing the radial velocity of peak in the observational data i.e. SalsaJ program and our own developed software. The first software is a free software with its java application and another one was made from Python programming language. To fit the data, the Gaussian technique was applied. We recorded the voltages at each frequency from different longitudes in galactic plane and then transformed its frequency to the radial velocity by applying the Doppler shift effect. The developed software is used to estimate the radial velocity from the full width at half maximum (FWHM) of the peak. An example of analyzed data by using the developed software is shown in figure 2.

![Figure 2](image.png)

**Figure 2.** Peaks of Gaussian fitting from the developed software are labelled in colours and the blue line shows the raw data of NARIT 4.5 m SRT which was observed at the galactic position (0°, 72°).

The radial velocity at FWHM of the spectrum peaks can be used to calculate the values of \( R \) and \( V \) at different longitudes by using the equations (3) and (4), respectively. We calculated the position of the HI clouds in the cartesian and polar coordinates from equations (6) and (7). The spherical mass distribution (in terms of the surface mass density) was approximated by using the rotation curve from equation (14).

4. Analysis Result

4.1. Rotation Curve of Milky Way Galaxy

The rotation curve of our Galaxy is illustrated in figure 3. It represents the relationship between the HI distances (in kpc) and their rotational velocities (km s\(^{-1}\)). Due to the limitation of NARIT 4.5 m SRT,
the data around the center of our galaxy (-3 < l < 3 degrees) cannot be measured directly because the observation was done during the time that the galactic center of the Milky Way Galaxy overlap the position of the sun which made more noises than normal signals. Moreover, the galactic center consists of intensively HI clouds and the NARIT 4.5 m SRT has low angular resolution ~3-4 degrees, therefore, it cannot separate the HI clouds as the gaussian components. We therefore present the data from the galactic distance at 1.67 kpc to the Sun position (i.e. within 8.05 kpc). Our results are in consistent with previous work from Sofue [6].

Figure 3. The rotation curve of Milky Way from HI clouds. Triangles and crosses are observed by 2.3 m and 4.5 m radio telescope, respectively. Circles are taken from Sofue [6].

4.2. Mapping of HI clouds in the Milky Way Galaxy
The mapping of HI clouds was made by illustrating in the cartesian coordinate system as shown in figure 4. We compared the data of 2.3 m and 4.5 m radio telescope together with Hossain [7]. We found that the distributions of HI positions are shown in the spiral arm shapes and are consistent with previous work. All error estimations were calculated by using the equations in section 2.3.

Figure 4. The distribution of the HI clouds in the first quadrant of our Galaxy by showing in the cartesian coordinate. A big dot is marked as the center of the Sun and small circles are taken from Hossain [7].
4.3. The surface mass density in Milky Way Galaxy

The surface mass density in spherical assumption can be used to approximate the mass of HI form in the Milky Way Galaxy at the galactic distance (R) as shown in figure 5. Our results show that the surface mass density of our Galaxy is increasing at the galactic center ($10^3$ M$_{\odot}$/pc$^2$) and decreasing at the galactic distance. However, this value is a bit lower than previous work but it presents consistency.

![SMD distribution in the Milky Way](image)

Figure 5. Semi-logarithmic presentation of surface mass density (SMD) calculated by using the observed rotation curve in spherical assumption.

5. Conclusions

Spectral line of HI from observation using NARIT 4.5 m SRT and 2.3 m radio telescope can be used to create the rotation curve, the distribution map of HI clouds and approximate the SMD in Milky Way Galaxy. The distribution map of HI clouds shows the spiral – arms shape. The rotation curve is nearly constant at the galactic distance (R) > 3 kpc. The SMD result obtained from the direct method by using the rotation curve showed that it is strongly concentrated toward the galactic center. It might be suggested that the dynamical SMD is dominated by the disk’s stellar mass. There is also a supermassive object at the center of our Galaxy. Therefore, other observation techniques might be needed to improve this work.

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