Astro 540 Term Paper

The Mass of the Milky Way

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ABSTRACT

Mass is one of the most essential properties of the Milky Way. Mass is measured with the combination of observed dynamics and theoretical structures. In paper, I introduced the major techniques to measure the rotation curve of the Milky Way and other observational constrains of the mass of the Milky Way. I gave a brief overview of the mass models of the galaxy. And finally I discussed about the limitation of the measurement and potential improvements.

1. Introduction

Mass is one of the most fundamental properties of the Milky Way. Since the Milky Way is a system that is bond by gravity, its mass is a major driver of the Milky Way's dynamic evolution. On the other hand, the mass distribution of the Milky Way provided us a most direct view of the structure of the Milky Way. Also, comparing the mass measured from kinematic with the matter that we can see in the Milky Way, we can obtain the mass to light ratio in the Milky Way, which tells us whether there is dark matter in the Milky Way.

The essentiality of mass in our understanding of the Milky Way calls for a precise measurement. In most of the cases, to measure the mass of the Milky Way is to measure the gravity it generates. Thus the most straight forward scale of mass is the rotation curve, because in the first order, the gravity's role is control the matter to orbit in the galaxy. Many techniques are developed to measure the rotation curve at different galactocentric radii. Except for rotation curves, more complicated effects of gravity such as tidal effect could also provide us with observational constrains of the mass.

However, dynamic measurement itself cannot provide us with the mass. Galaxies with different mass could possibly provide the same rotation curve if they have different mass distribution. Therefore, we need mass models. Mass models represent our abstract recognition of the galaxy, describe the construction of the Milky Way and the profiles of different component. To connect theoretical model with observational measurement, we can define the free parameters in the models, including the most important one, mass.

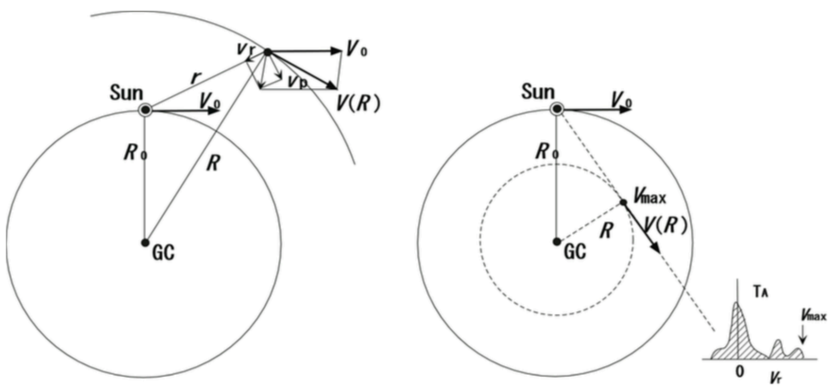

Fig. 1.— Rotation curve measurement and tangential point diagram Sofue (2013)

2. Rotation Curves

The principle of mass measurement with rotation curves is simple.

$$vc^2 = -\nabla_r \Phi \tag{1}$$

Equation 1 is also easy to be decomposed with different components. The geometry of Rotation curve measurement is also as straight forward. As shown in figure 1, if the distance r and radial velocity $v_r$of a specific object with galactic longitude l are known, and if we assume that we know the position (R_0)and the motion (v_0)of sun in the Milky Way, we can easily calculate the velocity $v(R)$ and orbit radius R of it with equation 2 Sofue (2013). However the measurement of distance and velocity could be difficult.

$$\begin{aligned} R &= \sqrt{r^2 + R_0^2 - 2rR_0 \cos l} \\ v(R) &= \frac{R}{R_0}\left(\frac{v_r}{\sin l} + v_0\right) \end{aligned} \tag{2}$$

2.1. Rotation curve inside of the solar circle

For the region that is inside of the solar circle, tangential point provide us with a shortcut of rotation curve measurement. For this region, the rotation curve is often measured with H I 21 cm line or CO lines. If we observe H I 21 cm line with a specific galactic longitude l, the maximum radial velocity $v_{r,\mathrm{max}}$will fall on the tangential point as shown in the right panel of figure 1. Thus equation 2 can be simplified as,

$$\begin{aligned} v(R) &= v_{r,\mathrm{max}} + v_0 \sin l \\ R &= R_0 \sin l \end{aligned} \tag{3}$$

which means we do not need to worry about distance measurement.

As an example, Malhotra (1994, 1995) used H I 21 cm line to measure the rotation curves. In this measurement, the velocity dispersion is smaller than 9 km s^{-1}. circle. $V_{\mathrm{T}} = v(R) - v_0 \sin l$

2.2. Rotation curve outside of solar circle

The tangential point disappears in the outer region of the Milky Way. Therefore the distance measurement becomes important in this circumstances.

Brand and Blitz (1993) used H II region and reflection nebulae to measure the rotation curves. The distance of the region was measured by photometric and spectroscopic fitting. The expand the boundary of rotation curves to around $2R_0$.

Pont et al. (1997) gived the radial velocities and photometry for Cepheids in the outer disk. For Cepheids stars, the distance could be calculated with the period-luminosity relation.

There were other methods being proposed to measure the rotation curves in outer disk, e.g. using the H I 21 cm lines. However, there are still large uncertainties and biases for the distance measurement.

2.3. Result

Combine several measurements together, a rotation curve within $2R_0$ could be obtained (figure 2). The most prominent feature on the rotation curve is its flatness in large radii, which is contradict with the disk model of the galaxy.

3. Other Constrains

Other observational constrains are brought in to improve the accuracy of the milky way mass measurement.

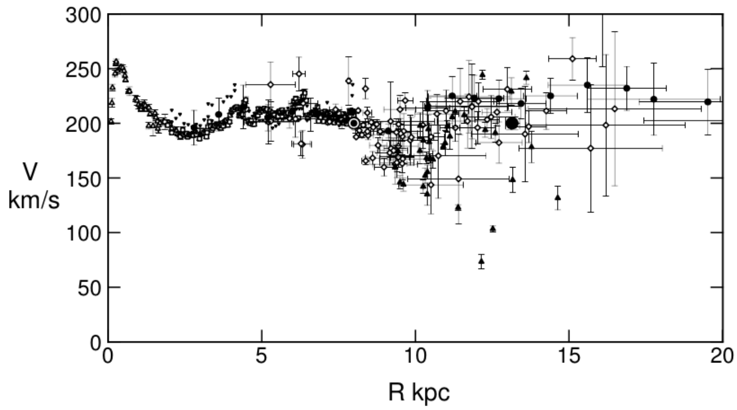

Fig. 2.— Observed circular velocities representing the rotation curve of the galaxy Sofue (2013).

3.1. Local constrains

For all the rotation curve measurements listed above, the rotation velocities and orbit radii are all based on sun's motion. However, solar motion and position are not well constrained as expected. For example, Reid et al. (2009) reported VLBI measurements of trigonometric parallaxes and proper motions for 18 masers located in several of the Galaxys spiral arms. These measurements yielded the circular rotation speed at the position of the Sun for $v_{r,0} = 254 \pm 16$kms1, which is 15% higher than the standard IAU 220kms[1]. Several other measurement did not reduce the scatter of the measurement.

Local surface density also provide constrain on model fitting. However, this value is also not well measured Dehnen and Binney (1998).

Smith et al. (2007) dug local information in another point of view. They used a sample of high-velocity stars from the RAdial Velocity Experiment to calculate the local escape speed. Their result demonstrates that the local escape speed is significantly higher than $\sqrt{2}v_c$, which gives a hint of the dark matter halo.

3.2. Kinematic tracer at large radii

The rotation curves are roughly limited at the radius of 2 times of the solar orbit radius. However, observations indicate that this radius is still far from the edge of the galaxy, especially for the mysterious dark matter halo. Thus mass measurement at large radii is urgently needed.

Xue et al. (2008) used Blue Horizontal Branch (BHB) stars to push the edge of the galaxy mass measurement to 60 kpc. BHB stars are not only very bright, but have small scatter in luminosity. Therefore they would provide a very good photometric distance measurement at large distance. With BHB stars observation, they derived a rotation curve by comparing their data with mock observations of simulated galaxies at such large radius.

As satellite galaxies gradually becomes well-known, they are also used as a mass tracer. Watkins et al. (2010) took a sample consisting of 26 satellite galaxies with line-of-sight velocities to estimate the mass of the Milky Way within a radius of 300 kpc.

4. Mass Models

Mass models are the prior assumption of the mass distribution of the Milky Way. Generally, mass models always have three components, the bulge, disk and dark matter halo. Mass Modeling is possible because the gas particles and stars are sensitive to the full potential contributed by both baryon and dark matter. If we decompose the total circular velocity,

$$v_c \sim \sqrt{v_{\rm gas}^2 + v_{\rm star}^2 + v_{\rm halo}^2} \tag{4}$$

Gas and star component could come from the observation of luminous matter. Halo components on the other hand comes from the total circular velocity subtracted the star and halo part. Each component has different mass distribution profile, ending up with different format of gravity potential.

Bulge is studied with the observation in the galactic center. Proper motion studies in the near infrared have revealed individual orbits of stars within the central 0.1 pc Sofue (2013). Outside the very nuclear region, radial velocity of OH and SiO maser lines from IR stars in the galactic center region are used to study the kinematics. From these study, the bulge is revealed to have a near-prolate, triaxial rotating profile. However in the modeling, axisymmetric approximation is often applied McMillan (2011).

From the observation luminous matter, e.g. star number density, the Milky Way's disk is usually considered to have two components, the thin disk and the thick disk. The two disk are always modeled with exponential profile with different scale height and scale length.

The flatness of rotation curve at large radii implies there is huge mass in the Milky Way that we don't see. These mass is modeled with dark matter halo. On observational side, the only trace of dark matter is the dynamics at large radii. On theoretical side, simulations provide the profile of the dark matter halo. In the mass Model, NFW profile is often used.

In the model, several parameters related to mass, including local disk surface density, local dark matter density, bulge density. These parameter are fixed by fitting the observation rotation curve to the model. Then the mass could be calculated.

5. Discussion

In recent studies, the results of mass measurement fall in the range around $10^{12} M_{\odot}$. However, the scatter is considerable. Several improvement could be made for the precision of the mass measurement.

The rotation curve at outer disk could be the first consideration. GAIA is starting a new era of parallax measurement, and is going to provide with more accurate distance at larger radius.

The mass estimators on the edge of the galaxy need to be further studied, Since they are the best constrain of the dark matter halo. Except for the contribution in mass measurement, these study could disclose more information of the property of the halo and dark matter itself.

The limitations of the mass models also need to be overcome. The most thorny issue of mass modeling is the intrinsic degeneracy of the model solution due to strong covariances between the disk and halo model parameters. To break the degeneracy, we need more observation constrains.

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