Keplerian Rotation of Our Galaxy?

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Abstract

It is common to attribute a flat rotation curve to our Galaxy. However, in a recent paper, Galazutdinov et al. obtained a Keplerian rotation curve for interstellar clouds in the outer parts of the Galaxy. They calculated the distances from equivalent widths of interstellar CaII lines. The radial velocity was also measured on the interstellar CaII absorption line. We verify the results of Galazutdinov et al. based on observations of old open clusters. We propose that the observations of flat and Keplerian rotation curve may be caused by the assumption of circular orbits. The application of formulas derived with the assumption of circular orbits to elliptical ones may mimic the flat rotation curve. The interstellar clouds with cross-sections larger than stars may have almost circular orbits, and the derived rotation curve will be Keplerian.

Key words: Galaxy: kinematics and dynamics – (cosmology:) dark matter

1. Introduction

Our Galaxy usually is thought to have a flat rotation curve. The flat rotation curves of galaxies are usually explained assuming existence of dark matter. The M0dified Newtonian Dynamics (MOND) models are less popular. However, some galaxies have Keplerian rotation curves which fall as \( \sim 1/\sqrt{r} \) in the outer parts of the galaxies. In a sample of 45 galaxies analyzed by Honma & Sofue (1997), 11 have a Keplerian rotation curve.

Sofue et al. (2009) made a compilation of the rotation velocities observed in our Galaxy. They transformed the rotational velocities from various sources to common parameters \( R_\odot = 8 \text{ kpc} \) and \( v_\odot = 200 \text{ km s}^{-1} \). In this paper, we adopt the recently obtained solar velocity, \( v_\odot = 240 \text{ km s}^{-1} \) (Honma et al. 2012, 2015; Sofue 2016). The rotation curves and rotational velocities of individual objects were recalculated using \( v_\odot = 240 \text{ km s}^{-1} \). Rotation velocities from Sofue et al. (2009), derived with tangent point method or from radial velocity, are shown on Figure 2(a).

The absence of dark matter in the solar neighborhood was postulated by Moni Bidin et al. (2012). Their result is based on stellar kinematics in direction perpendicular to the Galactic plane. However, their calculation leads to a flat rotation curve.

The recent paper by Galazutdinov et al. (2015) shows a Keplerian rotation curve of our Galaxy. They have based on distances and radial velocities derived from interstellar CaII absorption lines. The aim of this paper is to reconcile the flat rotation curve from Sofue et al. (2009) and the Keplerian rotation derived by Galazutdinov et al. (2015).

2. Old Open Clusters

To verify the result by Galazutdinov et al. (2015), we analyzed the rotation velocity of old open clusters (older than \( 10^9 \) years) located in the outer part of the Galaxy \( l \in (90^\circ, 270^\circ) \). All analyzed open clusters are located close to the Galactic plane \( |b| < 20^\circ \).

The rotational velocity was calculated from the observed radial velocity. The heliocentric radial velocity \( v_h \) was first transformed to the local standard of rest (LSR),

\[
v_{\text{LSR}} = v_h + U_\odot \cos b \cos l + V_\odot \cos b \sin l + W_\odot \sin b, \tag{1}
\]

using the Sun velocity \((U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25) \text{ km s}^{-1}\) from Schönrich et al. (2010). The rotational velocity was calculated using a formula derived for circular orbits (e.g., Bhattacharjee et al. 2014):

\[
v(r) = \frac{r}{R_\odot} \left( \frac{v_{\text{LSR}}}{\sin l \cos b} + v_\odot \right). \tag{2}
\]

In this formula, \( r \) is the projection of galactocentric distance on the Galactic plane:

\[
r = \sqrt{R_\odot^2 + d^2 \cos^2 b - 2R_\odot d \cos b \cos l}. \tag{3}
\]

The clusters with Galactic longitude \( l = 180^\circ \pm 20^\circ \) were excluded from our sample because the \( \sin l \) in the denominator of formula 2 leads to unphysical (i.e., negative) rotation velocities.

At least some old open clusters have nearly circular orbits. The five old open clusters analyzed by Carraro & Chiosi (1994) have eccentricities less than 0.14, with two clusters having eccentricities as low as \( e = 0.03 \). We collected open clusters data from the literature (see Table 1), and determined the rotation velocity using Equations (1) and (2). The open cluster’s linear velocity, as well as the angular velocity, is presented on Figure 1. The advantage of the angular velocity is...
that its error does not depend from the distance to cluster, which is known with little accuracy.

The distances to open clusters analyzed by Carraro et al. (2007) were determined by fitting a isochrone to the CMD (color–magnitude diagram). The largest error of distance in their sample of five open clusters is 21%. The distance to Saurer 1 was also determined by fitting a isochrone to the CMD. For the open cluster Berkeley 31, we were unable to track down the method used to determine distances. The distance of 8.3 kpc to Berkeley 31 was cited by Carraro et al. (2007), but other distances can be found in the literature: the distance 3.68 kpc was cited by Janes & Phelps (1994), and 5.2 ± 0.5 kpc was determined by fitting isochrones to the CMD (Guetter 1993). Distances to other clusters were determined using the synthetic CMD method (Tosi et al. 1991), but the errors of distances were not given. The authors state that the synthetic CMD method is more accurate than the isochrone fitting to CMD. Therefore, we adopted the

| Cluster  | Radial Velocity [km s⁻¹] | Stars | Ref. | l [°] | b [°] | Dist. [pc] | Age [log yr] | Ref. | r [kpc] | ω(r) [km/(s·kpc)] | v(r) [km s⁻¹] |
|---------|-------------------------|-------|------|------|------|-----------|-------------|------|--------|----------------|-------------|
| Berkeley 20 | 75.51 ± 4.85 | 9     | a    | 203.483 | −17.573 | 8710 | 9.763 | a | 16.0 ± 1.7 | 10.6 ± 1.6 | 169.5 ± 43.6 |
| Berkeley 25 | 134.30 ± 1.62 | 4     | e    | 226.612 | −9.700 | 11400 | 9.699 | e | 17.7 ± 2.2 | 9.6 ± 0.3 | 170.4 ± 26.4 |
| Berkeley 31 | 55.80 ± 1.13 | 2     | o    | 206.254 | 5.120 | 8300 | 9.301 | e | 15.8 ± 1.7 | 18.3 ± 0.3 | 290.4 ± 36.1 |
| Berkeley 32 | 105.00 ± 1.40 | 9     | m    | 207.950 | 4.400 | 3162 | 9.720 | n | 10.9 ± 0.6 | 5.9 ± 0.4 | 64.3 ± 7.8  |
| Berkeley 66 | −50.65 ± 0.07 | 2     | a    | 139.434 | 0.218 | 4570 | 9.580 | a | 11.9 ± 0.9 | 20.2 ± 0.0 | 239.1 ± 17.6 |
| Berkeley 73 | 95.70 ± 0.57 | 2     | e    | 215.278 | −9.424 | 9800 | 9.176 | e | 16.8 ± 2.0 | 12.8 ± 0.1 | 214.9 ± 27.0 |
| Berkeley 75 | 94.60 ± 0.35 | 1     | e    | 234.307 | −11.188 | 9100 | 9.602 | e | 15.1 ± 1.7 | 17.9 ± 0.1 | 269.8 ± 31.1 |
| Cr 110    | 40.00 ± 1.00 | d     | d    | 209.650 | −1.980 | 1950 | 9.230 | d | 9.7 ± 0.4 | 23.9 ± 0.3 | 233.0 ± 11.4 |
| King 11   | −35.00 ± 1.60 | l     | l    | 117.160 | 6.480 | 2198 | 9.615 | n | 9.2 ± 0.3 | 26.0 ± 2.3 | 239.2 ± 28.4 |
| NGC 2243  | 61.00 ± 1.00 | i     | i    | 239.480 | −18.010 | 3532 | 9.681 | c, i | 10.1 ± 0.5 | 23.4 ± 0.2 | 236.8 ± 13.6 |
| NGC 2506  | 83.70 ± 1.40 | f     | f    | 230.560 | 9.940 | 3311 | 9.230 | j, f | 10.4 ± 0.6 | 18.7 ± 0.2 | 194.3 ± 12.7 |
| NGC 6093  | −18.98 ± 0.19 | 26    | k    | 95.990 | 12.300 | 1820 | 9.114 | b | 8.4 ± 0.1 | 29.1 ± 0.0 | 244.0 ± 3.6  |
| Pismis 2  | 49.20 ± 7.80 | 9     | h    | 258.850 | −3.340 | 3467 | 9.041 | g | 9.3 ± 0.4 | 25.6 ± 1.0 | 238.2 ± 19.3 |
| Saurer 1  | 104.60 ± 0.30 | 2     | p    | 214.689 | 7.386 | 13200 | 9.699 | e | 20.2 ± 2.7 | 10.2 ± 0.1 | 205.2 ± 28.6 |
| Tombaugh 2| 120.51 ± 2.19 | 37    | a    | 232.832 | −6.880 | 7950 | 9.204 | a | 14.2 ± 1.5 | 13.7 ± 0.3 | 194.7 ± 25.2 |

Note. If the error of radial velocity was not given, we assumed 1 km s⁻¹.

References. a: Andreuzzi et al. 2011; b: Andreuzzi et al. 2004; c: Bonifazi et al. 1990; d: Bragaglia & Tosi 2006 and references therein; e: Carraro et al. 2007 and references therein; f: Carretta et al. 2004; g: Di Fabrizio et al. 2001; h: Friel et al. 2002; i: Gratton & Contarini 1994; j: Marconi et al. 1997; k: Milone 1994; l: Scott et al. 1995; m: Sestito et al. 2006; n: Tosi et al. 2007; o: Yong et al. 2005; p: Carraro et al. 2004.
relative error of distances equal to 21% for all analyzed open clusters.

The distances to open clusters are known with better accuracy than the distances to HII regions, which were used by Sofue et al. (2009) to construct his rotation curve. The distances to HII regions were determined using optical spectrophotometric methods (Fich et al. 1989). The maximal relative error of their distances is 40% and the average error is 25%.

Figure 1 presents rotational velocity of old open clusters. The same data is presented as angular velocity because angular velocity error does not depend on distance error. Therefore, we checked the agreement between open clusters velocity and flat/Keplerian rotation curves with the angular velocity data. Because errors of the angular velocity are negligible as compared with distance errors, we analyzed the data as a $r(\omega)$ function. We computed

$$\chi^2 = \sum_i \left( \frac{r_i - r(\omega_i)}{\sigma_i} \right)^2.$$

For Keplerian rotation curve, we got $\chi^2 = 30.4$, while for the flat rotation we have $\chi^2 = 377.9$. The angular velocity of analyzed open clusters agrees with the Keplerian rotation curve at the significance level $\alpha = 0.005$. The open cluster Berkeley 32 was excluded from this analysis.

### 3. Non-circular Orbits

The source of discrepancy in the rotation curve determinations may be the assumption of circular orbits. We assumed elliptical orbits as the simplest model of non-circular orbits. We checked if the assumption of stars on elliptical orbits is consistent with observed radial velocities. We analyzed the radial velocities of K and M giants in the Galactic anticenter from the CORAVEL spectrograph by Famaey et al. (2005). Stars in binary systems were removed from the analyzed sample. Regardless of the size of square centered on the Galactic anticenter, the standard deviations of radial velocities cannot be explained assuming circular orbits (Table 2). We obtained standard deviation of radial velocities similar to observed ones, assuming elliptical orbits with eccentricities uniformly distributed in the range 0–0.6 in the outer parts of our Galaxy. Therefore, the assumption of non-circular orbits is consistent with observed radial velocities.

We made a Monte Carlo simulation of stars on elliptical orbits beyond the Sun—Galactic center ($R_\odot$) distance. The semimajor axis ($a$), eccentricity ($e$), true anomaly ($\nu$), and argument of pericenter ($\omega$) were randomly chosen with uniform distribution. All orbits were located in the Galactic plane. The mass inside the solar orbit was set to $1.07 \cdot 10^3 M_\odot$, which corresponds to solar velocity $v_\odot = 240$ km s$^{-1}$.

| Square Side [°] | Observed Std. Dev. of $v_r$ [km s$^{-1}$] | Circular Orbits [km s$^{-1}$] | Elliptical Orbits $0 \leq e \leq 0.6$ [km s$^{-1}$] |
|----------------|-----------------------------------------|-----------------------------|---------------------------------------------|
| 6              | 38.0                                    | 3.1—6.2                     | 31.4—51.6                                   |
| 8              | 43.7                                    | 4.1—7.1                     | 28.7—56.7                                   |
| 10             | 40.7                                    | 7.1—9.5                     | 29.3—56.7                                   |
| 12             | 39.6                                    | 8.0—11.8                    | 34.0—50.8                                   |
| 14             | 40.6                                    | 11.1—14.4                   | 20.9—61.2                                   |
| 16             | 39.0                                    | 12.1—15.2                   | 36.8—48.5                                   |
| 18             | 37.6                                    | 12.7—17.8                   | 32.3—57.4                                   |
| 20             | 37.6                                    | 15.4—18.6                   | 35.6—53.9                                   |

Note. The Square in Which We Analyze the Radial Velocities is Centered on the Galactic Anticenter. The Minimum and Maximum Standard Deviation of Radial Velocity is Calculated from 10 Monte Carlo Simulations.

The rotation velocities were calculated using formulas that were derived assuming circular orbits. The rotation velocity was calculated from radial velocity ($v_r$) of star using

$$v(r) = \frac{r}{R_\odot} \left( \frac{v_r}{\sin \iota} + v_\odot \right).$$

where $r$ is the distance between the star and the Galactic center. We want to test the influence of formulas derived for circular orbits applied to stars on elliptical ones.

The semimajor axes in our simulation were distributed from 5 to 25 kpc to avoid truncation effects at $R_\odot = 8$ kpc. The stars with Galactic longitudes less then 20° from 0° or 180° were not shown, because the denominator in Equation (5) is too small. A small denominator in Equation (5) leads to unphysically large rotation velocities up to tens of thousands km per second.

The result of the Monte Carlo simulation for 200 objects is shown on Figure 2(b). Only objects with the distance 8–20 kpc from Galactic center are shown on the Monte Carlo simulations plots. The rotation velocities derived from radial velocities have large dispersion and look very similar to the observed rotation velocities from Sofue et al. (2009). The rotational velocities on Figure 2(b) are placed from below Keplerian rotation curve to above flat rotation curve. This is similar to the rotational velocities in Sofue et al. (2009) compilation.

The $\chi^2$ analysis was performed on the Monte Carlo simulated points in the same way as with open clusters. Although the simulated objects velocities were calculated assuming Keplerian rotation (on elliptical orbits $e = 0–0.5$), the $\chi^2 = 1268$ for the agreement with Keplerian rotation curve is almost eight times larger than $\chi^2_{0.005} = 13201$. The test of agreement with flat rotation curve $\chi^2 = 3201$ is almost 80 times larger.
than $\chi^2_{1-0.005}$. So the rotation velocity derived from observed radial velocity in the case of highly eccentric orbits cannot be used to distinguish between flat and Keplerian rotation curves.

## 4. Discussion

The main argument for the flat rotation curve of our Galaxy, given by Sofue et al. (2009), is the observation of Sharpless 269 star-forming region observed by VERA (VLBI Exploration of Radio Astrometry). Both radial and transverse velocities (Honma et al. 2007) lead to a rotation velocity of $\sim 200$ km s$^{-1}$. Also the VLBI measurements of parallaxes and proper motions of star-forming regions (SFR) published by Reid et al. (2014) leads to flat rotation curve. It seems that SFR (maybe all objects in spiral arms) have different rotation velocity than interstellar clouds.

The molecular clouds have the lowest velocity dispersion $\sigma_{z} = 5$ km s$^{-1}$ in the direction perpendicular to the Galactic plane as compared with stars or HII regions. Because of the large cross section, they may be better thermalized than stars. Therefore, the orbits of molecular clouds may have lower eccentricities than other objects. They match then very well the Keplerian rotation curve in our simulation, similar to velocities observed by Galazutdinov et al. (2015).

Eleven directions towards the Galactic anticenter were observed by Galazutdinov et al. (2015). The interstellar clouds are located in Galactic longitudes $184^\circ < l < 190^\circ$. The radial velocities towards these clouds have a standard deviation of 1.8 km s$^{-1}$. We cannot obtain such low dispersion in our simulations, even with circular orbits. The standard deviation of radial velocity for circular orbits in the mentioned longitude range is 3.5–7.2 km s$^{-1}$.

## 5. Conclusions

The rotation curve derived from observations of old open clusters seems to confirm the observations of Keplerian rotation curve for our Galaxy. The determination of flat rotation curve may be caused by applying the formula derived with the assumption of circular orbits to non-circular ones. The main results are:

- The observations of flat or Keplerian rotation curve of our Galaxy can be explained assuming Keplerian rotation, elliptical orbits of stars, and almost circular orbits of interstellar clouds.
- The Galactic rotation velocity derived from radial velocity in the case of elliptical orbits with high eccentricities cannot be used to distinguish between flat or Keplerian rotation curve.

The Keplerian rotation curve of the Galaxy will have a huge impact on the amount of dark matter in our Galaxy.

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![Figure 2. Comparison of the Galaxy rotation curves: (a) Points from Sofue et al. (2009) derived with tangent point method or from radial velocity. The Sofue et al. (2009) data were recalculated using $v_e = 240$ km s$^{-1}$. (b) Monte Carlo simulation of stars on elliptical orbits with eccentricities $e = 0-0.5$. The rotational velocities were calculated from radial velocities (Equation (5)). The lines show the model of flat rotation curve by Sofue et al. (2009) and the Keplerian rotation curve (both for $v_e = 240$ km s$^{-1}$).]
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