ON THE ROTATION SPEED OF THE MILKY WAY DETERMINED FROM H I EMISSION

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Received 2016 July 20; accepted 2016 August 8; published 2016 November 30

ABSTRACT

The circular rotation speed of the Milky Way at the solar radius, \( \Theta_0 \), has been estimated to be 220 km s\(^{-1}\) by fitting the maximum velocity of H I emission as a function of Galactic longitude. This result is in tension with a recent estimate of \( \Theta_0 \approx 240 \) km s\(^{-1}\), based on Very Long Baseline Interferometry (VLBI) parallaxes and proper motions from the BeSSeL and VERA surveys for large numbers of high-mass star-forming regions across the Milky Way. We find that the rotation curve best fitted to the VLBI data is slightly curved, and that this curvature results in a biased estimate of \( \Theta_0 \) from the H I data when a flat rotation curve is assumed. This relieves the tension between the methods and favors \( \Theta_0 \approx 240 \) km s\(^{-1}\).

Key words: Galaxy: kinematics and dynamics – Galaxy: fundamental parameters – Galaxy: structure – ISM: atoms

1. INTRODUCTION

The rotation speed of the Milky Way, \( \Theta_0 \), at the distance of the Sun from its center, \( R_0 \), is a fundamental parameter for both Galactic and Local Group dynamics. The value of \( \Theta_0 \) is needed to convert velocities from the observed heliocentric frame to a Galactocentric frame, and it is key to estimating the mass of the Milky Way. One can find estimates of \( \Theta_0 \) ranging from about 170–270 km s\(^{-1}\) in the literature over the past few decades. In 1985, the IAU recommended \( \Theta_0 = 220 \) km s\(^{-1}\) (Kerr & Lynden-Bell 1986), in part based on a particularly compelling analysis by Gunn et al. (1979, hereafter GKT) of the maximum observed velocity of H I emission as a function of Galactic longitude measured in the inner Milky Way.\(^1\)

Recent measurements of large numbers of trigonometric parallaxes for masers associated with high-mass star-forming regions with Very Long Baseline Interferometry (VLBI) have provided full three-dimensional velocities along with “gold standard” distances to sources across large portions of the Milky Way (Honma et al. 2012; Reid et al. 2014). Modeling the most recent data suggests a value of \( \Theta_0 \) of 240 ± 8 km s\(^{-1}\) (Reid et al. 2014), significantly greater than the IAU recommendation. Independently, the apparent motion of Sgr A*, assumed to be the reflex of the solar orbit about the Galactic center, yields a similar value for \( \Theta_0 \) provided \( R_0 \approx 8.3 \) kpc (Ghez et al. 2008; Gillessen et al. 2009; Do et al. 2013; Reid et al. 2014).

Of course, other estimates of \( \Theta_0 \) can be found in the recent literature. In particular, Bovy et al. (2012) argue for \( \Theta_0 \approx 220 \) km s\(^{-1}\), coupled with a very large value of the Sun’s peculiar motion in the direction of Galactic rotation of \( V_o = 26 \) km s\(^{-1}\). (\( V_o = 15 \) km s\(^{-1}\) is used to define local standard of rest (LSR) velocities.) However, adopting a larger value for \( V_o \) would not relieve the tension between the H I estimate of \( \Theta_0 \approx 220 \) km s\(^{-1}\) and the VLBI parallax and proper motion estimate of \( \Theta_0 \approx 240 \) km s\(^{-1}\), since it would lower both estimates.

In this paper, we explore the method of estimating \( \Theta_0 \) from H I emission spectra in order to resolve this tension.

2. H I TANGENT-POINT EMISSION

In Figure 1, we reproduce the plot of the maximum LSR velocity of H I emission as a function of the sine of the Galactic longitude, \( l \), from GKT. For any given longitude, the maximum positive velocity in the first quadrant (and maximum negative velocity in the fourth quadrant) should occur at the tangent point.Along a ray from the Sun at any longitude, the tangent point is the closest point to the Galactic center, and at this point the observed LSR velocity is given by

\[
V_p = \Theta(R_{\odot}) - \Theta_0 \sin l,
\]

where \( \Theta(R_{\odot}) \) is the circular rotation speed at the tangent point radius from the Galactic center, \( R_{\odot} = R_0 \sin l \). GKT show traces of the magnitude of the maximum H I velocity, \( V_\star \), in the first and fourth Galactic quadrants. They fitted a straight line to the first quadrant trace over the range 0.5 < \( \sin l \) < 1.0, yielding \( V_\star = 28 + 220(1 - \sin l) \). Note that at the tangent point for \( \sin l < 0.5 \), radii are \( > 4.2 \) kpc and one expects significant non-circular motions for gas in the vicinity of the Galactic bar.

The slope of the fitted line gives a direct estimate of \( \Theta_0 \), provided the rotation curve of the Milky Way is flat between \( R_0/2 \) and \( R_0 \). GKT give a formal error on the slope of 3 km s\(^{-1}\), but add that a realistic uncertainty is 10 km s\(^{-1}\), reflecting the possibility of a slight slope in the rotation curve. In particular, for a power-law form of the rotation curve, they rule out the possibility of \( \Theta_0 = 240 \) km s\(^{-1}\), as it would require a rising rotation curve with an unrealistically large \( \Theta(3R_0) = 280 \) km s\(^{-1}\).

Over the years there has been discussion in the literature of the methods used to estimate \( V_\star \) from H I spectra. GKT define \( V_\star \) as the extreme velocity of emission brighter than 1.0 K, and treat the non-zero intercept (28 km s\(^{-1}\)) as due to turbulent broadening. Of course, this value is sensitive to the method of estimating \( V_\star \), McClure-Griffiths & Dickey (2007) point out that H I absorption against continuum emission from H II regions can affect estimates of \( V_\star \), favoring interferometric spectra with high angular resolution, which allow editing of

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\(^1\) The same authors (Knapp et al. 1978) also estimated \( \Theta_0 \) by modeling the most extreme H I velocities in the outer Galaxy, but subsequent work (e.g., Jackson 1985) demonstrated that the extreme velocities differed between the first and fourth quadrants, as did the radial scale length of H I in the outer Galaxy, a key input parameter in this analysis. Knapp et al. (1988) ultimately concluded that the outer Galaxy data alone only constrain \( \Theta_0 \) to a fairly broad range from 210 to 250 km s\(^{-1}\).
absorbed spectra. Also, instead of using a simple brightness threshold, they fit multiple components to the spectra to estimate \( V_x \). However, while these improvements suggest a slightly rising rotation curve, their estimates of \( \Theta_0 \) still fall well below 240 km s\(^{-1}\), whether using the \( V_x \) method (see their Figure 7) or re-scaling the forms of the well-cited rotation curves of Burton & Gordon (1978) or Brand & Blitz (1993) (see their Figure 8).

3. THE “UNIVERSAL” ROTATION CURVE

VLBI parallaxes and proper motions, from the Bar and Spiral Structure Legacy (BeSSeL) Survey and the VLBI Exploration of Radio Astrometry (VERA) observations of molecular masers associated with high-mass star-forming regions, should be excellent tracers of Galactic dynamics. Eighty sources from the combined surveys were modeled with various forms for the rotation curve by Reid et al. (2014). The best-fitting model, shown in Figure 2, used a “universal” rotation curve of Persic et al. (1996). This formulation is well motivated by observations of large numbers of spiral galaxies. (Specifically, the curve is for an L\(_{\odot}\) galaxy (\( \beta = 0.72\)), with \( V(R_{\odot}) = 241 \text{ km s}^{-1} \), \( R_{\odot} = 8.34 \text{ kpc} \). Note that the fitted universal rotation curve is nearly flat between about 5.5 and 8.0 kpc, but curves downward inside of 5.5 kpc. At 4.2 kpc (\( \approx R_{\odot}/2 \)) the rotation speed is 228 km s\(^{-1}\), it peaks at 241 km s\(^{-1}\) at 7.2 kpc, and it declines very slightly to 240 km s\(^{-1}\) just past \( R_{\odot} \) (assumed to be 8.34 kpc).

As Figure 3 shows, \( V_x \) predicted by the universal rotation curve matches the highest velocity of H\(_{\text{I}}\) emission very well over most of the inner Milky Way, and at \( \sin l < 0.5 \) it provides a much better fit than for flat rotation curves with \( \Theta_0 \) of 220 or 240 km s\(^{-1}\). However, note that over the longitude range fitted by GKT (0.5 < \( \sin l < 1.0 \)), the universal curve is roughly linear in \( V_x \) and can be approximated by a flat curve of 220 km s\(^{-1}\). This holds even though the universal rotation
curve has a circular velocity of 240 km s\(^{-1}\) at the solar radius and an average velocity of 238 km s\(^{-1}\) over the fitted range.

To further demonstrate this point, in Figure 4 we fit \(V_T\) predicted by the universal curve with a straight line over the GKT range of sin\(l\) and find a slope of 224 km s\(^{-1}\), consistent with the GKT result. Alternatively, simply defining a straight line by the rotation curve values at the endpoints of their fitting range yields a similar value of 220 km s\(^{-1}\).

We conclude that a rotation curve that rises from 228 km s\(^{-1}\) at 4.2 kpc to 241 km s\(^{-1}\) at 7.2 kpc and then flattens, as does the universal rotation curve fitted to the VLBI data, gives a biased estimate of \(\Theta_0\) that is low by about 20 km s\(^{-1}\), when fitting a straight line to tangent-point velocities between radii of \(R_0/2\) and \(R_0\). This resolves the apparent tension between the two methods of estimating \(\Theta_0\) and favors a value of 240 km s\(^{-1}\).

Facilities: VLBA, VERA, EVN.

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