Milky Way Rotation Models from Neutral Hydrogen and Molecular Clouds: Galactic Constants, Common Details and Differences

Igor' I. Nikiforov

Sobolev Astronomical Institute, St. Petersburg University, Bibliotechnaya pl. 2, 198904 St. Petersburg, Russia

1. Introduction

Kinematic data from neutral hydrogen observations provide information to solve the interdependent problems of the determination of the main Galactic constants (the Solar-Galactic center distance \( R_0 \), the Oort constant \( A \) and others) and the Galactic rotation curve (Nikiforov & Petrovskaya 1994, hereafter NP94, and references therein). However, in the standard method for finding \( R_0 \) by comparing the rotations of \( \text{H} \text{I} \) clouds and some other objects (typically \( \text{H} \Pi \) regions/CO clouds), the kinematic model, constructed typically solely from \( \text{H} \text{I} \) data, is considered to be the same for both galactic subsystems (e.g. Merrifield 1992). In practice a discrepancy between their rotation curves can produce strongly erroneous results (Merrifield 1992, NP94). Establishing the common rotation law from \( \text{H} \text{I} \) plus \( \text{H} \Pi /\text{CO} \) data in NP94 is only a part of attacking the problem.

In this paper, techniques for the evaluation of \( R_0 \) which account for most of the effect of a difference between the rotation laws of CO clouds and \( \text{H} \text{I} \) is suggested. We derive the main Galactic constants, construct the rotation models, and discuss the difference between \( \text{H} \text{I} \) and CO rotations.

2. Data

For this study the \( \text{H} \text{I} \) tangent points and five independent \( \text{H} \text{I} \) data sets from the whole 21-cm line profile (see NP94) were taken. These latter contain Camm’s function values \( \Omega \equiv R_0 (\omega - \omega_{\text{LSR}}) \) in relation to \( x \equiv R/R_0 \), where \( R \) is the distance to the galactic axis, \( \omega \) and \( \omega_{\text{LSR}} \) are the angular velocities of \( \text{H} \text{I} \) at the distance \( R \) and at the Local Standard of Rest, respectively.

Two catalogues of CO clouds (COCs) from Brand & Blitz’s (1993) list were used here. In the first one (“BFS2”) CO radial velocities relative to the LSR \( V_r \), heliocentric distances \( r \), and galactic coordinates \( l, b \) were collected for 107 COCs associated with \( \text{H} \Pi \) regions. For addition of data on southern COCs associated with \( \text{H} \Pi \) regions or reflection nebulae (BBW sample), the second “BFS2/BBW-catalogue” (in all 209 objects) covers a greater longitude range, but it is less uniform in the object type. For more details, see Nikiforov (1999b).
3. Method

Two fitting procedures are used in this study, both consisting of two steps.

The first step, referred to as "W(CO+HI) fitting", is the same for both procedures. It presents the way of using the HI and CO data to find the rotation model, common to these gaseous subsystems, with a given \( R_0 \).

Let us consider the function \( W(x) = \Omega(x) = R[\omega(x) - \omega_{\text{LSR}}] \), for which values can be calculated for every HI and CO data point. The following polynomial was selected as a model for the function \( W(x) \):

\[
W_n(x) = \sum_{i=0}^{n} w_i (x - 1)^i. \tag{1}
\]

The obvious relations hold for coefficients in (1):

\[
w_0 = -\Delta \theta_{\text{LSR}}, \quad w_1 = -2AR_0 - \Delta \theta_{\text{LSR}}, \tag{2}
\]

where \( \Delta \theta_{\text{LSR}} = \theta_{\text{LSR}} - \theta_0 \), \( \theta_{\text{LSR}} \) and \( \theta_0 \) are the linear rotation velocities of the LSR and gaseous subsystems (average for HI and CO) at \( R_0 \), respectively. Using (2) the condition equations for observed values of \( W(x) \) can be written

\[
W(x) = -\Delta \theta_{\text{LSR}}x - 2AR_0(x - 1) + \sum_{i=2}^{n} w_i (x - 1)^i. \tag{3}
\]

For given \( n \) and \( R_0 \) the system (3) is solved for \( \Delta \theta_{\text{LSR}}, A R_0 \), and \( w_i, \; i = 2, n \). The best-fit solution is the one that minimizes the sum \( \sum_j p_j [W(x) - W_n(x)]^2 \) over all HI and CO data points. Values of \( x \) and \( \Omega \) for COCs and of weights \( p_j \) were calculated in much the same way as NP94, but with some parameters revised and with the overall weight of CO data equated to the weight of HI data (see Nikiforov 1999c).

Second step. To determine \( R_0 \) correctly one should take account of a possible difference between the rotation laws of HI and CO. If we assume a constant differential asymmetric drift between HI and CO subsystems we may consider the model parameters \( A R_0 \) and \( w_i, \; i = 2, n \), found at the first step, as known functions of \( R_0 \). Two variants of the second step are suggested here:

(i) \( W(\text{CO}) \) fitting. The system of equations (3) can be solved for only \( R_0 \) and \( \Delta \theta_{\text{LSR}} \) from the CO data alone.

(ii) \( W/\nu_r \) fitting. Under assumption of purely circular motions, the radial velocity field of COCs can be described by the following equation:

\[
V_r = \left[ -2AR_0(x - 1) + \sum_{i=2}^{n} w_i (x - 1)^i \right] x^{-1} \sin \nu \cos \theta - \Delta \theta_{\text{LSR}} \sin \nu \cos \theta - \Pi_{\text{LSR}} \cos \nu \cos \theta. \tag{4}
\]

System (4) is solved for \( R_0, \Delta \theta_{\text{LSR}}, \) and \( \Pi_{\text{LSR}} \) (the LSR radial motion in the direction \( \nu = 0^\circ \)) by minimizing the sum of residual velocities squared. A difference between the \( \Delta \theta_{\text{LSR}} \) values obtained at the second and first steps represents a mean drift between the rotation curve for COCs and the average one over both subsystems.
Figure 1. The neutral hydrogen and CO data on the Galaxy rotation and rotation models constructed in this paper.

"Acceptable" degrees $n$, for which polynomial $W_n(x)$ represents well all the reliable structure in the data, were determined in the manner suggested by Nikiforov (1999a,b). Objects with large residuals have been excluded.

4. Results and discussion

The obtained $R_0$ estimates are summarized in Table 1. Column (4) gives the result derived by an analysis of the $V_r$ field of COCs without using HI data (Nikiforov 1999b). Column (5) gives the weighted average of values in columns (2)–(4). The average of all six $R_0$ values in the latter columns was taken as the final estimation from COC distances: $R_0 = 8.2 \pm 0.7$ kpc (here the scatter of results was added in quadrature). Values obtained via mere $W$(CO+HI) fitting, as in NP94, are listed in the last column; in this case $R_0$ is underestimated.

Table 1. $R_0$ from CO clouds with and without using HI data.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$W$(CO) fitting</th>
<th>$W/V_r$ fitting</th>
<th>$V_r$ fitting</th>
<th>Average</th>
<th>$W$(CO+HI) fitting</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFS2</td>
<td>8.52 $^{+0.27}_{-0.34}$</td>
<td>7.59 $^{+0.28}_{-0.34}$</td>
<td>8.26 $^{+0.28}_{-0.37}$</td>
<td>8.03 $\pm 0.57$</td>
<td>7.12 $^{+0.31}_{-0.33}$</td>
</tr>
<tr>
<td>BFS2/BBW</td>
<td>8.56 $^{+0.34}_{-0.36}$</td>
<td>7.92 $^{+0.35}_{-0.34}$</td>
<td>8.87 $^{+0.35}_{-0.37}$</td>
<td>8.34 $\pm 0.39$</td>
<td>7.93 $^{+0.37}_{-0.39}$</td>
</tr>
<tr>
<td>Average</td>
<td>8.55 $^{+0.42}_{-0.44}$</td>
<td>7.81 $^{+0.40}_{-0.44}$</td>
<td>8.67 $^{+0.44}_{-0.44}$</td>
<td>8.24 $^{+0.46}_{-0.46}$</td>
<td>7.48 $^{+0.33}_{-0.30}$</td>
</tr>
</tbody>
</table>

 Adopting the value for $R_0$ found above we obtain values of $AR_0 = 141.0 \pm 4.0$ km s$^{-1}$, $A = 17.20 \pm 0.48$ km s$^{-1}$ kpc$^{-1}$ from all HI and CO data, the LSR
Figure 2. Differences between the smoothed rotation curve for H\textsc{i} and the ones found for all CO clouds (solid line), clouds with 0° ≤ l < 180° (short dashed line) and clouds with 180° ≤ l < 360° (long dashed line). Bars show the result of errors in smoothed values of $\theta_{\text{HI}}$ and $\theta_{\text{CO}}$.

motion relative to the COCs of $\Delta\theta_{\text{LSR}} = 2.6 \pm 1.3$ km s$^{-1}$, $\Pi_{\text{LSR}} = -2.8 \pm 1.2$ km s$^{-1}$, Galactic gas's linear rotation velocity at the sun of $\theta_0 = 215 \pm 24$ km s$^{-1}$ and $\theta_{\text{LSR}} = 216.5 \pm 24$ km s$^{-1}$ (with the Kerr & Lynden-Bell (1986) value of $\omega_0 = 26.4 \pm 1.9$ km s$^{-1}$ kpc$^{-1}$).

The H\textsc{i} and CO rotation curves and their 1-σ confidence limits, found by Monte Carlo simulations, are shown in Figure 1. The linear rotation velocity ($\theta$) of COCs is found to be, in average, $4.9 \pm 2.2$ km s$^{-1}$ less than the H\textsc{i} value. However the difference ($\theta_{\text{HI}} - \theta_{\text{CO}}$) turns out not to be constant (see Figure 2): it is significant at the 3-σ level only for $1.09^{+0.04}_{-0.08} \leq x \leq 1.46 \pm 0.02$.

Hence the suggested techniques account for only the net effect of the radius-average H\textsc{i}-CO difference on $R_0$. However with a modelling this difference in detail, the comparision with H\textsc{i} rotation becomes meaningless.

The smoothed rotation curve for H\textsc{i} is hardly affected by streaming motions because the whole 21-cm line profile data represent all galactocentric azimuths, in contrast to COCs, and owing to a direct correction (Malahova & Petrovskaya 1992). Therefore the $l$-dependent H\textsc{i}-CO difference (cf. the north and southern CO-curves in Figure 2) may be considered as an effect of a spiral wave, namely the Perseus arm, on the COCs. This allows us to estimate directly the pitch...
angle of the arm as $22^\circ \pm 3^\circ$, which coincides with Blitz’s (1983) result from HI kinematics for $x > 1$ and supports the four-arm picture for the spiral structure of our Galaxy.

The drop in $\theta$, found by NP94, of $\sim 20$ km s$^{-1}$ at $0.75 < x < 1.15$ on average, is confirmed and traced from both HI and CO data individually (Figure 1). This feature may be a “signature” of a dip in disk density (Nikiforov et al. 1999), which can be responsible for the existence of warps seen in the outer regions of the Galaxy. Both HI and CO data show a rise in $\theta$ at $1.1-1.2 < x < 1.7-1.8$.

Acknowledgments. This work is supported by the Russian Foundation for Basic Research (grant no. 96-02-19636) and by the State Integrated Research and Development Program “Astronomiya” of Russia (problem no. 1.2.3.2).

References

Nikiforov, I. I. 1999a, Astrofizika, 42, 399
Nikiforov, I. I. 1999b, Astronomy Reports, 43, 345
Nikiforov, I. I. 1999c, submitted to Kinematika i Fizika Nebesnykh Tel
Nikiforov, I. I., Petrovskaya, I. V. and Ninković, S. 1999, these proceedings