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

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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 H I clouds and some other objects (typically H II regions/CO clouds), the kinematic model, constructed typically solely from H 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 H I plus H II/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 H I is suggested. We derive the main Galactic constants, construct the rotation models, and discuss the difference between H I and CO rotations.

2. Data

For this study the H I tangent points and five independent H I data sets from the whole 21-cm line profile (see NP94) were taken. These latter contain Camm's function values $\Omega \equiv R_0(\omega - \omega_{\mathrm{LSR}})$ in relation to $x \equiv R/R_0$, where R is the distance to the galactic axis, ω and ω_{LSR} are the angular velocities of H 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 H II regions. For addition of data on southern COCs associated with H II 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*, refered to as "W(CO+H I) fitting", is the same for both procedures. It presents the way of using the H I and CO data to find the rotation model, common to these gaseous subsystems, with a given R_0.

Let us consider the function $W(x) \equiv x\Omega(x) = R[\omega(x) - \omega_{\rm LSR}]$, for which values can be calculated for every H I 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):

$$w_0 = -\Delta\theta_{\rm LSR}, \quad w_1 = -2AR_0 - \Delta\theta_{\rm LSR}, \tag{2}$$

where $\Delta\theta_{\rm LSR} = \theta_{\rm LSR} - \theta_0$, $\theta_{\rm LSR}$ and θ_0 are the linear rotation velocities of the LSR and gaseous subsystems (average for H I and CO) at R_0, respectively. Using (2) the condition equations for observed values of $W(x)$ can be written

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

For given n and R_0 the system (3) is solved for $\Delta\theta_{\rm LSR}$, AR_0, and w_i, $i = 2, n$. The best-fit solution is the one that minimizes the sum $\sum_j p_j \left[W(x) - W_n(x)\right]_j^2$ over all H I and CO data points. Values of x and Ω 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 H I data (see Nikiforov 1999c).

Second step. To determine R_0 correctly one should take account of a possible difference between the rotation laws of H I and CO. If we assume a constant differencial asymmetric drift between H I and CO subsystems we may consider the model parameters AR_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(CO) fitting. The system of equations (3) can be solved for only R_0 and $\Delta\theta_{\rm LSR}$ from the CO data alone.

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

$$\begin{aligned} V_r \; = \; & \left[-2AR_0(x-1) + \sum_{i=2}^{n} w_i (x-1)^i\right] x^{-1} \sin l \cos b - \\ & -\Delta\theta_{\rm LSR} \sin l \cos b - \Pi_{\rm LSR} \cos l \cos b. \end{aligned} \tag{4}$$

System (4) is solved for R_0, $\Delta\theta_{\rm LSR}$, and $\Pi_{\rm LSR}$ (the LSR radial motion in the direction $l = 0°$) by minimizing the sum of residual velocities squared. A difference between the $\Delta\theta_{\rm LSR}$ 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.

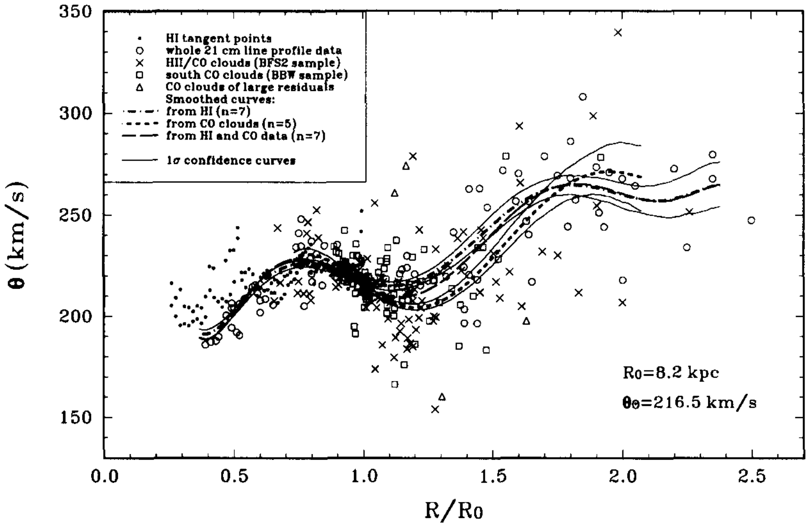

Figure 1. The neutral hydrogen and CO data on the Galaxy rotation and rotation models constructed in this paper.

"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 H I 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+H I) 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 H I data.

Sample	W(CO) fitting	W/V_r fitting	V_r fitting	Average	W(CO+H I) fitting
BFS2	$8.52^{+0.67}_{-0.54}$	$7.59^{+0.50}_{-0.46}$	$8.26^{+0.82}_{-0.77}$	8.03 ± 0.57	$7.12^{+0.31}_{-0.25}$
BFS2/BBW	$8.56^{+0.36}_{-0.34}$	$7.92^{+0.35}_{-0.34}$	$8.87^{+0.57}_{-0.54}$	8.34 ± 0.39	$7.93^{+0.33}_{-0.30}$
Average	8.55 ± 0.42	7.81 ± 0.40	8.67 ± 0.64	$\mathbf{8.24 \pm 0.46}$	7.48 ± 0.30

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 H I and CO data, the LSR

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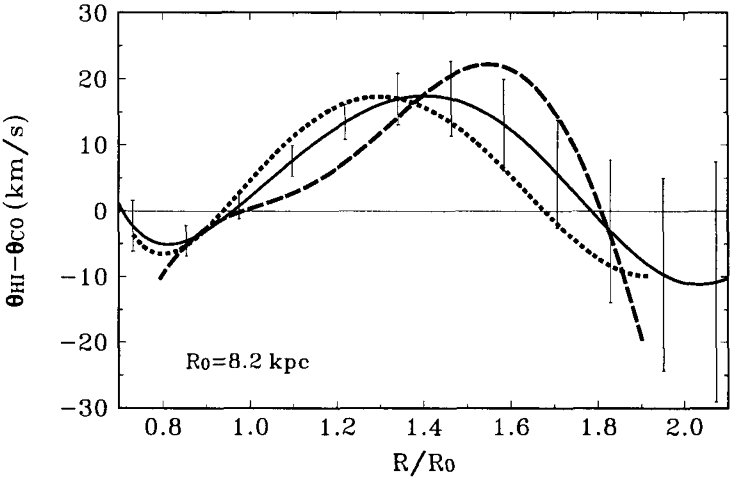

Figure 2. Differences between the smoothed rotation curve for H I and the ones found for all CO clouds (solid line), clouds with $0° \leq l < 180°$ (short dashed line) and clouds with $180° \leq l < 360°$ (long dashed line). Bars show the result of errors in smoothed values of $\theta_{\mathrm{H\,I}}$ and θ_{CO}.

motion relative to the COCs of $\Delta\theta_{\mathrm{LSR}} = 2.6 \pm 1.3$ km s^{-1}, $\Pi_{\mathrm{LSR}} = -2.8 \pm 1.2$ km s^{-1}, Galactic gas's linear rotation velocity at the sun of $\theta_0 = 215 \pm 24$ km s^{-1} and $\theta_{\mathrm{LSR}} = 216.5 \pm 24$ 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 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 (θ) of COCs is found to be, in average, 4.9 ± 2.2 km s^{-1} less than the H I value. However the difference $\langle\theta_{\mathrm{H\,I}} - \theta_{\mathrm{CO}}\rangle$ 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 I-CO difference on R_0. However with a modelling this difference in detail, the comparision with H I rotation becomes meaningless.

The smoothed rotation curve for H 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 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 H I kinematics for $x > 1$ and supports the four-arm picture for the spiral structure of our Galaxy.

The drop in θ, found by NP94, of $\sim$20 km s^{-1} at $0.75 < x < 1.15$ on average, is confirmed and traced from both H I 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 H I and CO data show a rise in θ at 1.1–1.2 $< x <$ 1.7–1.8.

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