Volume Title
*ASP Conference Series, Vol. **Volume Number***
Author
© ***Copyright Year** Astronomical Society of the Pacific*

Errors in rotation curves and kinematic distances

Gilberto C. Gómez

Centro de Radioastronomía y Astrofísica,
Universidad Nacional Autónoma de México,
Apartado Postal 3-72 (Xangari), Morelia, Michoacán, 58089, México

Abstract. We have explored the consequences of ignoring non-circular motions in galactic orbits by performing synthetic observations of a simulated disk galaxy. We have obtained a synthetic rotation curve and estimated the errors in measured kinematic distances. The *measured* rotation curve had been found to have features similar to the one measured for the Milky Way Galaxy, and differs from the *real* rotation, i.e., the one obtained from the background potential imposed in the simulation. When the *measured* rotation is used to estimate distances, the error is ¡ 0.5kpc for most of the disk and larger at the locations of the spiral arms, therefore selectively affecting objects related to the spiral structure. The distance errors were actually larger when we used the *real* rotation curve. If we use kinematic distances under the assumption of circular orbits in order to reconstruct the structure of the model galaxy from the synthetic l-v map, we obtain a quite distorted picture of the galaxy. If we, instead, assume a non-circular velocity model and use it to determine distances, most of density structure in the numerical model is recovered.

1. INTRODUCTION

Since the classic work by Oort et al. (1958), there have been many attempts to use the kinematic properties of the diffuse gas to determine the large scale spiral structure of the Milky Way. Very early in the study of the Galaxy, it was determined that the orbits of the disk components of the Galaxy were not very different from circular, with an orbital frequency that decreases monotonically as a function of galactocentric radius. These facts allow the use of the kinematic distance method as a first approximation to map the gaseous component of the galactic disk. Nevertheless, it was soon realized that the deviations from circular orbits, however small in absolute value, might have a strong impact on how we see the Galaxy. The main goal if this work is to further explore the effects of non-circular motions in the image one would obtain of the Galaxy when we rely on the kinematic method for distances. An observer is imagined inside the numerical model of a galaxy, which is assumed similar to the Milky Way, and the analysis that this observer would perform is reproduced.

2. THE SIMULATION

The initial setup consisted of a gaseous disk with an exponential density profile in the radial direction. The equation of state for the gas was isothermal with $T = 10^4\,^\circ$K. This disk was threaded by a magnetic field, with an intensity of $5.89\,\mu$G at $R_\odot = 8\,$kpc.

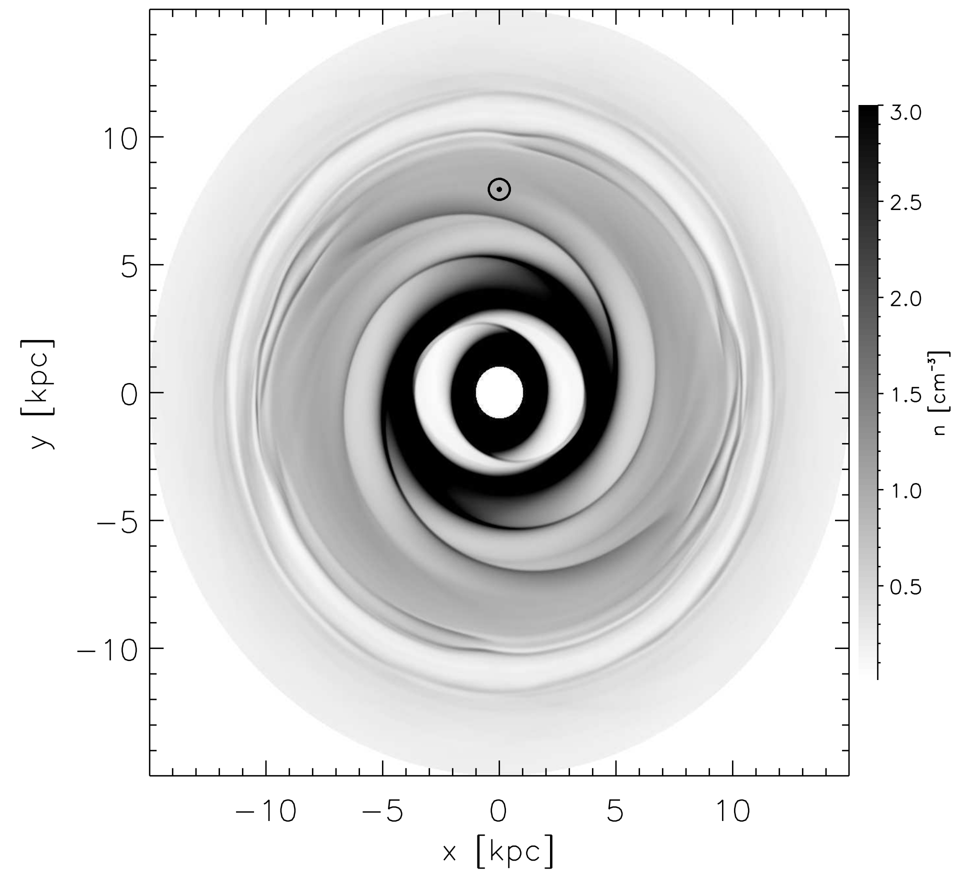

Figure 1. Density distribution of the simulation after 1 Gyr of evolution. The Sun symbol shows the position chosen for the imaginary observer. It is noticeable that, although the perturbation has only two arms, the gas response shows four arms.

The gas initially follows circular orbits, with a velocity given by the equilibrium between the background gravitational potential (Dehnen & Binney 1998, model 2), the thermal and magnetic pressures, and the magnetic tension. The equilibrium was then perturbed by a two-armed spiral potential (Pichardo et al. 2003). The perturbation rotates with an angular speed $\Omega_P = 20\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ (Martos et al. 2004a,b). It is worth mentioning that the perturbing potential does not have the usual sinusoidal profile, and that its parameters (total mass in the arms, pitch angle, pattern speed, etc.) were constrained so that the pattern is self-consistent in the stellar orbits sense.

Figure 1 shows the simulation after 1 Gyr of evolution. It is noticeable that, although the perturbation consists of two spiral arms, the gas forms four arms (two pairs with pitch angles of 9^{o} and 13^{o} each, as opposed to the perturbation with a pitch angle of 15.5^{o}).

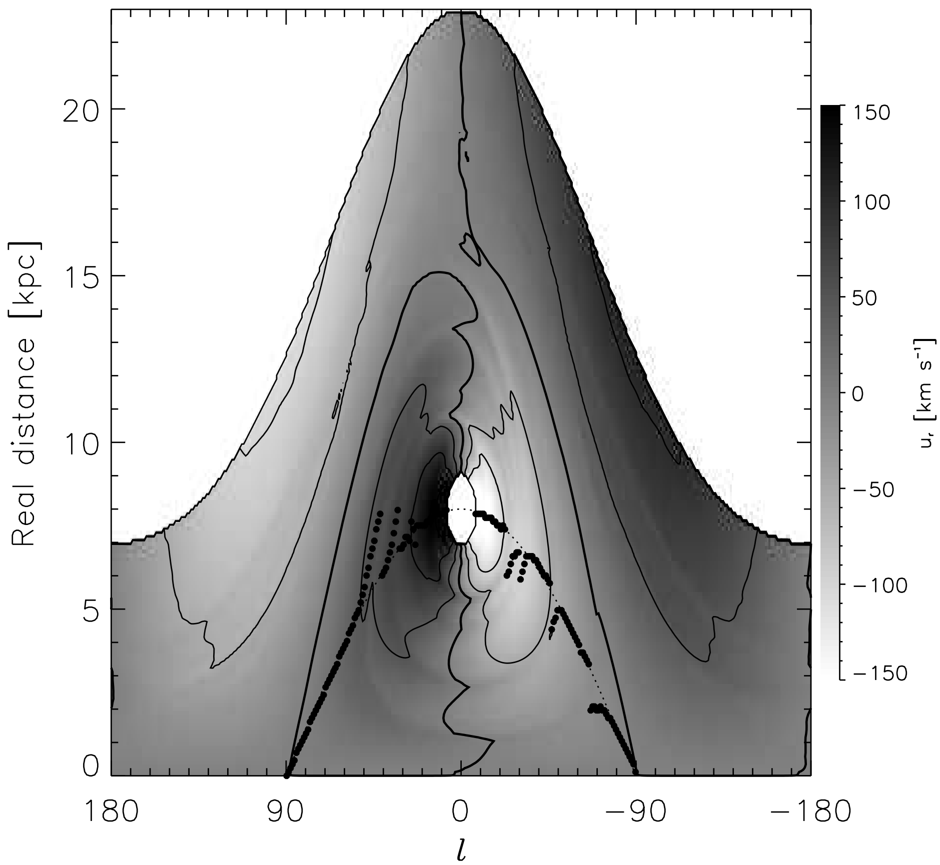

Figure 2. Line-of-sight component of the velocity field as a function of galactic longitude and (real) distance to the observer, with contours every 50 km s^{-1} (the thicker contour marks the $u_r = 0$ km s^{-1} level). The dotted line shows the locus of the tangent points, while the circles show the positions at which the terminal velocity is reached.

3. THE ROTATION CURVE

Local maxima in column density vs. galactic longitude plots for the diffuse gas are usually interpreted as the directions at which the line-of-sight is tangent to spiral arms. By moving the observer around the solar circle, at 8 kpc in the numerical model, the number and positions of the local maxima can be fitted to the observed values for the diffuse gas. In this work, the chosen directions were those tangent to the locus of the spiral arms proposed by Taylor & Cordes (1993).

Once a position for the observer is chosen, the next step toward calculating the kinematic distances is to adopt a rotation curve for the simulated galaxy. For the inner galaxy ($r < R_\odot$), the standard procedure consists in searching for the terminal velocity of the gas. If one assumes that the gas orbits are circular, the terminal velocity arises

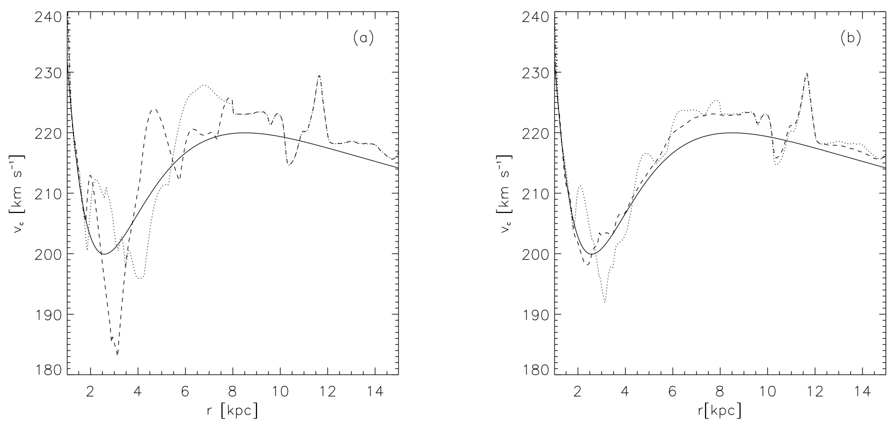

Figure 3. a) The rotation curve given by the background potential (solid line), compared with the measured rotation curve. For the inner galaxy, both the rotation measured for positive (dotted line) and negative longitudes (dashed line) are presented. The rotation curve corresponding to the outer galaxy is also shown (dashed-dotted line). b) The rotation curve given by the background potential (solid line), compared with the average of the north and south rotation curves (dotted line) and the mean azimuthal velocity of the gas in the simulation (dashed line). Notice that both the mean velocity and the mean rotation curve are above the background rotation curve for most of the radial domain.

from the point at which the line-of-sight is tangent to the orbit, and so, the galactocentric radius of the emitting gas is known.

Figure 2 shows the line-of-sight component of the velocity field. The figure also shows the actual positions at which the terminal velocity is reached for a given galactic longitude, *l*. Although the distance between those terminal-velocity points and the tangent points is typically small, the non-circular motions and spiral shocks generate kpc-scale deviations and discontinuities in the terminal-velocity locus. Since those deviations happen at the positions of the spiral arms, they will generate larger errors at the vicinity of the arms, and will strongly affect the observer's view of the spiral structure of the model galaxy.

For the outer galaxy ($r > R_\odot$), the usual procedure to determine the rotation curve involves looking for sources with independently known distance and measuring their line-of-sight velocity (Brand & Blitz 1993, for example). This procedure was simulated by assuming that the observer finds such a source at each point of the numerical grid outside the solar circle. It is assumed that the distances to such sources are less reliable the farther they are from the observer. So, the circular velocity for the outer galaxy was taken to be the weighted average of the de-projected line-of-sight velocities for all the points in the numerical grid.

Figure 3(a) shows the so obtained rotation curves, together with the rotation consistent with the background gravitational potential. The northern rotation curve is lower than the southern rotation at $3.5\,\mathrm{kpc} < r < 5.5\,\mathrm{kpc}$, while the opposite is true up to $r = R_\odot$, in agreement with the rotation curve reported by Blitz & Spergel (1991).

In order to try to recuperate the true (background) rotation, that should more closely trace the large scale mass distribution, the average both northern and south-

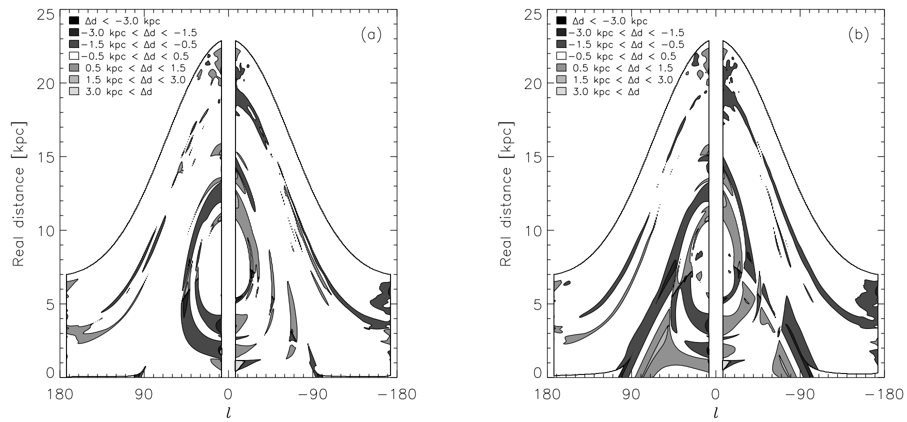

Figure 4. Error in the measured kinematic distance (Δd) obtained under the assumption of circular orbits following (a) the measured rotation curve, and (b) the rotation given by the background potential. Although the error in most of the galactic disk is of the order of 0.5 kpc, it is significantly larger at the positions of the spiral arms. The errors in measured kinematic distances are larger when the real (background) rotation curve is used.

ern rotation curves was taken [see fig. 3(b)]. Although the result is smoother and closer to the rotation consistent with the background potential, it is still systematically higher (in agreement with the results reported by Sinha 1978). Another approach is to take the full velocity field and average the azimuthal velocity of the gas (Brand & Blitz 1993). The result, also shown in Figure 3(b), is much closer to the background rotation, but it is still systematically larger.

4. ERRORS IN THE KINEMATIC DISTANCE

After adopting a rotation curve, and assuming that the gas follows circular orbits, the errors in the measured kinematic distances can be estimated by comparing the measured with the real distance in the simulation. Figure 4(a) shows such error for the model. It is noticeable that although the errors are of the order of 0.5 kpc in most of the galactic disk, they are significantly larger at the positions of the spiral arms. This fact has a special impact in studies of the spiral structure of the Galaxy that rely on kinematic distances, since it distorts the image the observer would generate (see §4.1).

There is another significant feature in Figure 4. Although the terminal velocity does not really arises from the tangent point, the circular orbits assumption assigns gas observed near terminal velocity to that point. This fact generates a feature in the errors that corresponds to the locus of the tangent points. Again, the error is significant at the position of the spiral arms and would generate large errors in the determination of distances to objects that trace the spiral structure.

The assumptions of circular orbits and different rotation curves for positive and negative longitudes are, of course, inconsistent. One solution is to fit a single rotation curve to both sides of the Galaxy. In order to test this method, the average of both rotation curves was taken and the equivalent of Figure 4(a) was calculated. The result

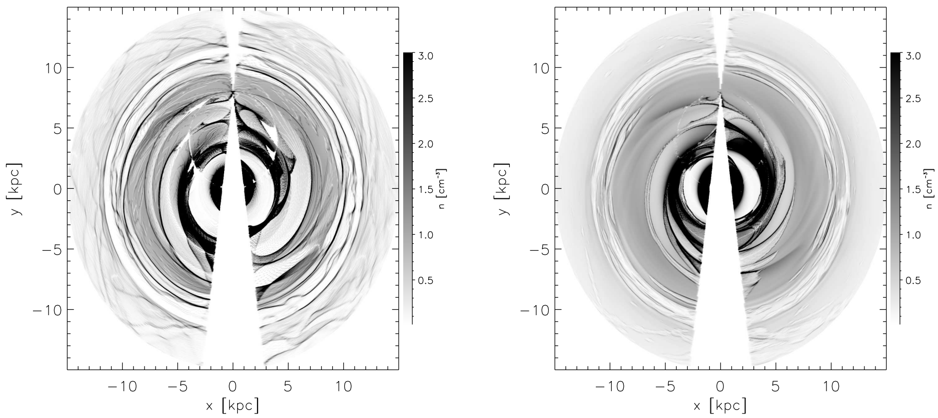

Figure 5. (*Left:*) Re-mapping of the gas distribution resulting from the kinematic distances using the measured rotation curves in Figure 3(a) and assuming circular gas orbits. Notice the regions near the tangent points and the corotation circle, where little or no gas is mapped to. (*Right:*) Re-mapping of the gas distribution, but using the full velocity field to recover the density distribution. Most of the characteristics of Figure 1 are recovered, although some spurious structure appears.

was that the magnitude of the error in the kinematic distances was approximately the same, but the area with error > 0.5 kpc spanned a larger fraction of the disk.

Suppose now that the imaginary observer somehow manages to obtain the large scale distribution of stellar mass in the model galaxy. This would allow the determination of the real rotation curve from the background axisymmetric potential. If the observer now uses that real rotation to determine kinematic distances, even larger distance errors would be obtained, specially for the inner galaxy, as shown in Figure 4(b).

Although intrinsically inconsistent, the two different measured rotation curves were used in the remaining of this investigation since that procedure leads to smaller distance errors.

4.1. The Galaxy Distorted

Consider now that the imaginary observer tries to study the spiral structure of the galaxy he/she lives in. The procedure would consist of translating the longitude-velocity data into a spatial distribution using the kinematic distances that result from the assumption of circular orbits that follow the measured rotation curve. The resulting map is shown in the left panel of Figure 5. Notice that the features in Figure 1 all but disappear, while new fictitious features, like the structure in the outer Galaxy, are formed as a consequence of the oscillations in the outer rotation curve. Also significant are the regions where little or no gas is assigned by the mapping, namely the bands near the corotation circle and the quasi-triangular regions near the tangent point locus.

The imaginary observer would likely conclude that his/her home galaxy has 2 ill-defined spiral arms. If a logarithmic spiral model were forced, an $\sim 11^{\rm o}$ pitch angle and a density contrast much stronger than that in the model would be found.

Another possibility for determining the distance to a gas parcel consists in comparing the line-of-sight velocity of the parcel with the predicted velocity obtained from some model for the galactic structure. For the numerical model described in §2, given a galactic longitude, Figure 2 is searched for the required velocity, and the corresponding distance is read out. Notice that the non-circular motions introduce new distance ambiguities for certain longitude-velocity values (up to 11, although 3 is a more typical number). When these ambiguities appear, they happen close to each other, making their resolution difficult. So, when reconstructing the map of the galaxy, the gas density was equally split among these positions.

The result is shown in the right panel of Figure 5. The new distance ambiguities still introduce spurious structure, like the splitting of the spiral arms. Nevertheless, the number and position of the arms, the structure around the corotation radius and the lack of features in the outer galaxy are recovered. The imaginary observer would likely conclude that his/her home galaxy has 4 arms with 9^{o} and 12.5^{o} pitch angles, although he/she would also find non-existing bridges and spurs. On the other hand, it should be considered that the imaginary observer does not see thermal nor turbulent line broadening. When these are considered, some of the spurious structure might blend with the real structure and thus, in effect, dissapear.

5. DISCUSSION

The effect of the circular orbits assumption on our idea of the large scale structure of the Galaxy was explored. Since these errors might be quite large at the position of the spiral arms, the study of the spiral structure of the Galaxy and objects associated with it is particularly affected.

Even if the measured rotation curve includes deviations that do not reflect the true large scale mass distribution, Figure 4(a) shows that the errors in the distance are, in fact not very large for most of the galactic disk; in fact, the distance errors that arise from using the true rotation curve are larger. In both cases, however, the errors are quite large at the positions of the spiral arms. If we want to use this distance method for objects associated with the spiral structure, we need to consider non-circular motions. In this work, a numerical model was used to obtain the non-circular velocity field.

It has been shown that it is possible to recover most of the gaseous structure of the galactic disk using kinematic distances, as long as the full velocity field is considered. Nevertheless, applying these results to the Milky Way is a whole new issue, since obtaining the full velocity field is not trivial. For the procedure used here, how close the numerical simulation is to the real Galaxy remains the weak point of this approach.

References

Blitz, L., & Spergel, D. N. 1991, ApJ, 370, 205
Brand, J., & Blitz, L. 1993, A&Ap, 275, 67
Dehnen, W., & Binney, J. 1998, MNRAS, 294, 429
Martos, M., Hernández, X., Yáñez, M., Moreno, E., & Pichardo, B. 2004a, MNRAS, 250, L47
Martos, M., Yáñez, M., Hernández, X., Moreno, E., & Pichardo, B. 2004b, JKAS, 37, 199
Oort, J. H., Kerr, F. J., & Westerhout, G. 1958, MNRAS, 118, 379
Pichardo, B., Martos, M., Moreno, E., & Espresate, J. 2003, ApJ, 582, 230
Sinha, R. P. 1978, A&Ap, 69, 227
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674