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# Rotation curve bifurcations as indicators of close recent galaxy encounters

S. Pedrosa[1,2], P. B. Tissera[1,2], I. Fuentes-Carrera[3], and C. Mendes de Oliveira[4]

[1] Consejo Nacional de Investigaciones Científicas y Técnicas, CONICET, Argentina
e-mail: supe@iafe.uba.ar
[2] Instituto de Astronomía y Física del Espacio, Casilla de Correos 67, Suc. 28, 1428 Buenos Aires, Argentina
e-mail: patricia@iafe.uba.ar
[3] GEPI, Observatoire de Paris, CNRS, Université Paris Diderot, Place Jules Janssen, 92190 Meudon, France
e-mail: isaura.fuentes@obspm.fr
[4] Universidade de São Paulo, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Departamento de Astronomia, Rua do Matão 1226, Cidade Universitária 05508-900 São Paulo SP, Brazil
e-mail: oliveira@astro.iag.usp.br

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**ABSTRACT**

*Context.* Rotation curves of interacting galaxies often show that velocities are either rising or falling in the direction of the companion galaxy.
*Aims.* We seek to reproduce and analyse these features in the rotation curves of simulated equal-mass galaxies suffering a one-to-one encounter as possible indicators of close encounters.
*Methods.* Using simulations of major mergers in 3D, we study the time evolution of these asymmetries in a pair of galaxies during the first passage.
*Results.* Our main results are: (a) the rotation curve asymmetries appear right at pericentre of the first passage, (b) the significant disturbed rotation velocities occur within a small time interval, of ~0.5 Gyr $h^{-1}$, and, therefore, the presence of bifurcation in the velocity curve could be used as an indicator of the pericentre occurrence. These results are in qualitative agreement with previous findings for minor mergers and flybys.

**Key words.** galaxies: interactions – galaxy: kinematics and dynamics – galaxies: spiral

## 1. Introduction

Rotation curves of interacting and merging galaxies are often highly disturbed. First observations of Rubin et al. (1991) showed several cases of sinusoidal rotation curves and asymmetries for a large fraction of compact group galaxies obtained from long-slit spectroscopy. Although Mendes de Oliveira et al. (2003) have shown that many of these peculiarities are smoothed over when rotation curves (hereafter RC) are derived from 2D velocity maps, some disturbances still remain, indicating their true nature as a global feature of the galaxy. For interacting galaxies, features on the RCs are related not only to the structure of the disk itself, but also to the external perturbations due to the companion (e.g. Rubin & Ford 1983; Elmegreen & Elmegreen 1990; Chengalur et al. 1994; Salo & Laurikainen 2000; Marquez et al. 2002; Hernandez Toledo et al. 2003; Fuentes Carrera et al. 2004; Garrido et al. 2005). One noticeable perturbation in a rotation curve occurs when the velocity on one side decreases considerably, while the other side remains fairly constant. Commonly these features, so-called bifurcations, happen when there is a close companion galaxy. An example of this behaviour can be seen in Fig. 1, obtained by Fuentes Carrera et al. (2004), where the RC of a galaxy, in a pair of galaxies of similar sizes and masses, is displayed.

The natural question to ask here is how these velocity disturbances relate to the passage of the companion galaxy and if they can be used as a timer of the stage of evolution of an interaction.

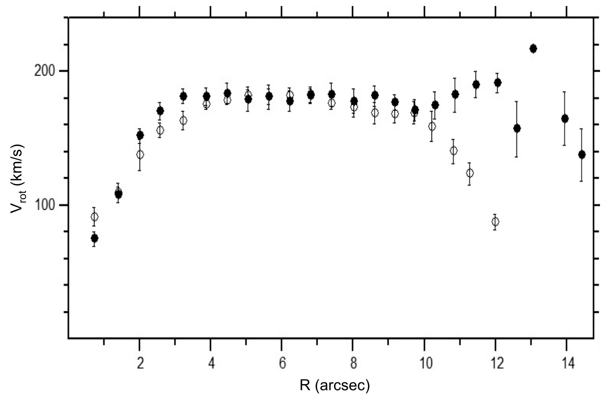


**Fig. 1.** Rotation curve of the spiral galaxy NGC 5953 in the interacting galaxy pair KPG 468 (Hernandez Toledo et al. 2003) within the inner 15″, derived from a full 2D velocity map. A velocity bifurcation between the approaching side (full circles) and receding one (empty circles) can be seen at 9″. The companion NGC 5954 is a galaxy of similar size and morphological type.

Recently, Kronberger et al. (2006, hereafter Kron 06) have investigated disturbed RCs in simulated interacting galaxies. Using simulations, those authors reproduced the observations of intermediate redshift galaxies ($z$ ~ 0.5) by putting a virtual slit along the major axis of each investigated system (see also, Barton et al. 1999). They also found that the features associated with the perturbations in the RCs strongly depend on the viewing angles, particularly for the derived asymmetry parameters (Dale et al. 2001), which presented quite a large dispersion for minor mergers and flybys. For major mergers, no similar detailed study of the temporal behaviour of these asymmetries has been made. This motivated us to revisit Kronberger's study focussing on the analysis of the time evolution of the asymmetries for *major mergers*. Furthermore, we chose to peform our analysis in 3D to uncover the real level of disturbance of the systems. For this purpose, we used *N*-body/hydrodynamic simulations with cooling, star formation, and supernova feedback.

## 2. The numerical experiments

We ran pre-prepared initial conditions of major mergers involving Milky Way-type galaxies. We used the procedure developed by Springel et al. (2005) to construct near-equilibrium galaxies, each one consisting of a dark matter halo, a disk of gas and stars, and a bulge with a virial velocity of 160 km s$^{-1}$. The gaseous and stellar disks have exponential surface densities with a scale-length, $h_\mathrm{d}$, of 2.5 kpc $h^{-1}$ and a scale-height of 0.2 $h_\mathrm{d}$. The bulge component follows a Hernquist profile (Hernquist 1990) with a scale-length of 0.2 $h_\mathrm{d}$. The dark matter halo is consistent with a Hernquist profile scaled to match the inner density distribution of dark matter haloes found in cosmological simulations (Navarro et al. 1996) with a concentration parameter $c = 9$. We use 20 000, 10 000, 50 000, and 30 000 particles to represent the stellar disk, the stellar bulge, the gas, and the dark matter components, respectively, of a given galaxy. Baryonic masses range from $1.9 \times 10^5 h^{-1}$ $M_\odot$ for particles on the disk to $1.3 \times 10^5$ $h^{-1}$ $M_\odot$ in the bulge component, while the dark matter particles have $3 \times 10^8$ $h^{-1}$ $M_\odot$. We assume a 10% fraction of baryons initially in the form of gas. We also ran a higher resolution simulation with 600 000 total particles to discard resolution effects.

The two identical galaxies were given an initial relative velocity of 200 km s$^{-1}$. The minimum separation, $r_\mathrm{p}$, achieved after 1.3 Gyr $h^{-1}$, during the first passage is 30 kpc $h^{-1}$. Galaxies are set on parabolic orbits and will merge due to dynamical friction. We investigated four possible configurations for the encounter. We ordered the experiments using the orbital parameters of Toomre & Toomre (1972) as $i_1 = 0$ and $i_2 = 0$ for A; $i_1 = 0$ and $i_2 = 180$ for B ; $i_1 = 45$, $i_2 = -45$ and $\omega_2 = 90$ for C; $i_1 = -45$, $i_2 = 45$ and $\omega_2 = 270$ for D. We chose these initial configurations to study the kinematical behaviour of the galaxies between the extreme cases of a parallel encounter versus a perpendicular one. For experiment A, we also ran two simulations changing the minimum separation at pericentre: A1 and A2 with $r_\mathrm{p}$=15 kpc $h^{-1}$ and $r_\mathrm{p}$=50 kpc $h^{-1}$, respectively.

The simulations were run by using the Tree-SPH Gadget-2 code (Springel 2005). The cold gas can form new stars following the Kennicutt law, according to a stochastic algorithm (Scannapieco et al. 2005). However, since the initial gas component is a small fraction of the total mass, the impact of new stars is not important for this analysis.The systems experienced a number of close encounters until they finally merged. We focus only on the perturbation arising during the first close passage.

## 3. Simulated rotation curves

In a disk structure supported by rotation and in equilibrium within its potential well, the only velocity component should be a tangential velocity ($v_\phi$) on the plane perpendicular to the angular momentum of the system. In practice, this is not necessarily the case. Motions of stars and gas in the disk can be modified by the presence of structures in the disk or by external perturbations. In this case, particular features on the RCs, such as bifurcations, may appear.

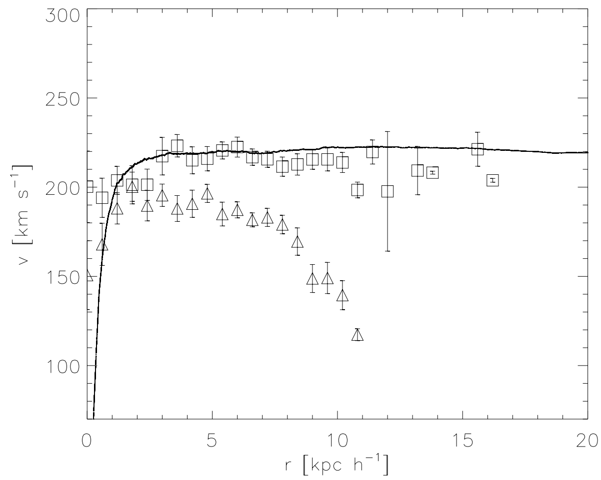


**Fig. 2.** Circular (continuous line) and tangential velocities (triangles and squares) in experiment A show clear bifurcation. Triangles and squares denote opposite orientations along a given direction used to measure the curves. The side that shows a declining tangential velocity is the one closest to the companion galaxy. Error bars correspond to the standard deviations of the mean values computed within each bin.

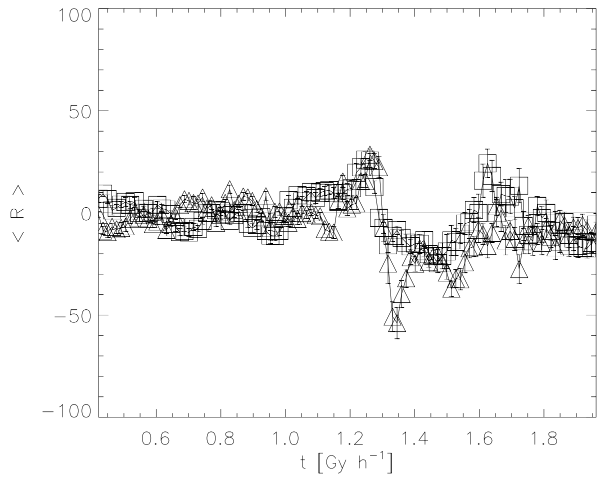


**Fig. 3.** Velocity residuals as a function of time estimated for baryons within $\alpha$ (squares) and $\beta$ (triangles) angles for experiment A.

At a given time during the interaction, the simulated RCs are constructed by calculating $v_\phi$ on the rotation plane (defined as the plane perpendicular to the total angular momentum of the system) as a function of the distance to the mass centre of the galaxy ($r$). For the purposes of analysing possible asymmetries in the RCs, we considered $v_\phi$ within four cones of a solid angle of 60 degrees along two orthonormal directions on the disk plane: $\alpha$–$\beta$, $\delta$–$\gamma$. We note that results are insensitive to variations of these angles. In fact, we have varied these angles between 10 and 60 degrees, finding no significant changes in the trends. By analysing the velocities and angular momentum of the mass within these angles, we can study the effects of interactions in different regions of the disks and look for loss of symmetry in the velocity patterns.

We calculated the mean tangential velocity, $\langle v_\phi \rangle$, estimated in equally-spaced radial bins of size 1.5 kpc $h^{-1}$. We also

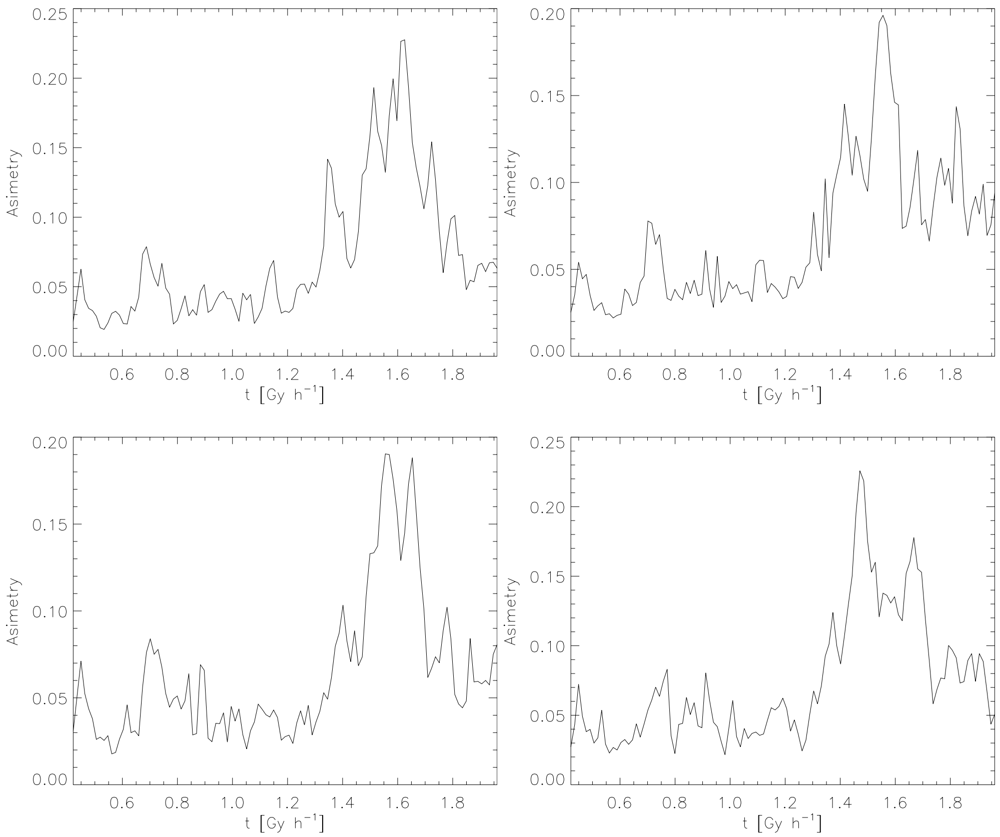


**Fig. 4.** Asymmetry parameter as a function of time for our four experiments (A, B, C, D) along the $\alpha$–$\beta$ directions (see Sect. 2 for experiment description).

estimated the velocity that particles on circular orbits within a potential well dominated by dark matter should statistically have as $V_{\rm cir}(r) = (\frac{GM_{\rm tot}(<r)}{r})^{0.5}$, where $M_{\rm tot}(<r)$ is the total mass (baryons plus dark matter) within $r$. For systems in rotational equilibrium within such a potential well, we should find that $\langle v_\phi \rangle \sim V_{\rm cir}$. Important departures from this relation will be assumed to be indicative of a loss or a gain of angular momentum by the action of an external force. Before the galaxies start interacting, the disks are in rotational equilibrium within their potential wells, regardless of the angular sector chosen to measure $\langle v_\phi \rangle$.

In order to assess the effects of the interaction on the rotation curves, we analysed the departures of $\langle v_\phi \rangle$ from $V_{\rm cir}$, within each adopted angle as a function of time, for the four experiments performed. Figure 2 shows an example of a disturbed RC in the $\alpha$–$\beta$ direction for experiment A. A very asymmetric response of the disk can be seen. For this RC, the velocity on the left side of the galaxy ($\beta$ direction) decreases considerably, while the velocity on the right side of the galaxy ($\alpha$ direction) remains fairly constant, producing a bifurcation similar to those reported by observations (Fig. 1).

In order to study the presence of these bifurcations in the RCs along the interaction event, we defined the residual velocities between the RC and the circular velocity as: $R = \langle v_\phi \rangle - V_{\rm cir}$. By estimating $R$ as a function of radius, we can quantify the difference – and its amplitude – between the measured tangential velocity on one side of the galaxy and the tangential velocity on the opposite side.

Since we are interested in the evolution of these differences with time, we defined a mean residual velocity $\langle R \rangle$ at each given time, averaging out the corresponding residuals (the central regions of the galaxies are excluded to avoid an artificial weakening of the signal originated by the disk structure). Figure 3 shows the mean residuals calculated for experiment A, as a function of time, in the $\alpha$–$\beta$ direction. From this figure, we can observe that, in general, significant residuals are present, starting at $t \approx 1.25$ Gyr $h^{-1}$, which corresponds to the time of peripassage. We note that the largest bifurcations appear when the RC is measured within the angular sector closer to the companion galaxy. This can be seen in Fig. 3 where the $\beta$ direction, which is the one closest to the companion, shows the largest mean residuals. A detailed analysis of the angular momentum content of the simulated galaxies shows that these residuals can be directly linked to the variation of angular momentum on orthogonal directions.

## 4. Can bifurcations be used as a timer for recent interactions?

In order to quantify if bifurcations in the RCs can be used as a timer of the stage in the interaction, we analyse the evolution with time of the global RC asymmetry as defined by Dale et al. (2001). This asymmetry parameter (hereafter $AP$) is calculated as the area between the approaching and receding halves of the RC, normalised by the average area under the curve. Figure 4 shows that when the simulated galaxies have galaxy-galaxy distances of approximately $r = 30$ kpc $h^{-1}$, significant signal of asymmetry appears. Similar levels of $AP$ are detected in our four experiments, although the details of the features vary from one to the other.

Hence, according to the trends shown in Figs. 3 and 4, two galaxies need to be very close to start experiencing a significant, internal re-distribution of angular momentum and mass, but when this has occurred, the RCs remain perturbed for an extended period until they reach equilibrium again, after almost 1 Gyr $h^{-1}$ of the pericentre, when the centres of masses are separated by more than 200 kpc $h^{-1}$, in agreement with previous findings for minor mergers and flybys (e.g., Kron 06).

A detailed analysis of the evolution of the *AP* displayed in Fig. 4 shows that before the peripassage, the *AP* for the four experiments remains approximately at a value of 5%. From the peripassage, a noticeable increase is detected with values up ≈20% and greater than 10%, and with a mean *AP* that, at least, doubles the level registered up to peripassage. After 0.5 Gyr $h^{-1}$ from peripassage, it starts decreasing. A similar analysis for A1 and A2 shows that *AP* anticorrelates with $r_p$. We find no *AP* greater than 10% for $r_p$ larger than ≈50 kpc $h^{-1}$ in this merger configuration.

We calculated the *AP* for the RCs of 3 galaxies in isolated pairs of galaxies of similar masses, studied by Fuentes-Carrera (2004) and 2 galaxies in Hickson Compact Groups observed by Mendes de Oliveira et al. (2003), which show bifurcations. We derived all RCs from full 2D velocity field maps by averaging large velocity cones around the major axes of the galaxies. Therefore, they are good representations of their kinematics as a whole. They have been corrected by inclination so that the comparison with simulations is as precise as possible. In the case of the pairs studied by Fuentes Carrera, the asymmetry values obtained are: 19% for NGC 5426, 13% NGC 5427, and 9% for NGC 5953. A similar behaviour is obtained for the galaxies in groups: 13% for HCG7c and 36% for HCG 96a. We have also calculated *AP* for non-bifurcated-RC galaxies (HCG 10d, HCG 88a, HCG 88c, HCG 88d, HCG 89a, HCG 91c1, HCG 96d) in compact groups. The obtained mean value was 7%, which is very similar, qualitatively, to the one found in the simulations, during the unperturbed phase (5%). It is interesting to note that the galaxies with bifurcated *RC* in compact groups are spiral galaxies with only one companion of similar mass (HCG 07a and HCG 96c, respectively), and several other considerably less massive companions (1/3 of the mass of the first ranked galaxy, at most). Hence, from the analysis of these high quality observed RCs we get similar results to those found in simulations for the asymmetry value of the bifurcated RCs.

## 5. Conclusions

We studied the RCs of two simulated Milky Way-type galaxies during their first encounter. We performed four simulations with different orientations of the angular momentum direction of the systems. The simulated RCs displayed bifurcations consistently with observational findings. The evolution of the features with time were investigated.

Our main conclusions are that the asymmetry parameter (defined by Dale et al. 2001) shows a clear increase at the peripassage, reaching values larger by a factor of two than the levels detected for RCs in equilibrium. After ≈0.5 Gyr $h^{-1}$, the asymmetry parameter begins to decrease again to lower values. We found that observed RCs corrected by inclination yield a similar behaviour. The most significant asymmetries are detected at peripassage when the systems are separated ≈30 kpc $h^{-1}$. In our experiments, we found that the perturbations in the RCs can be detected even after almost 1 Gyr $h^{-1}$ of the peripassage, in agreement with previous works for minor mergers and flybys (Kron 06). Therefore, the asymmetry parameter could be used to roughly estimate if the pericentre has occurred in the last ≈0.5 Gyr $h^{-1}$. The question of whether these features can always be seen in RCs of interacting galaxies might depend on the viewing angle (Kron 06). However, the good agreement of the observational and numerical results we obtained encourages us to carry out a more comprehensive comparison with observations in a future paper.

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## References

Barton, E. J., Bromley, B. C., & Geller, M. J. 1999, ApJ, 511, 25
Chengalur, J. N., Salpeter, E. E. & Terzian, Y. 1994, AJ, 107, 1984
Dale, D. A., Giovanelli, R., Haynes, M. P., et al. 2001, AJ, 121, 1886
Elmegreen, D., & Elmegreen, B. G. 1990, ApJ, 364, 412
Fuentes Carrera, I., Rosado, M., Amram, P., et al. 2004, A&A 415, 451
Garrido, O., Marcelin, M., Amram, P., et al. 2005, MNRAS, 362, 127
Kronberger, T., Kapferer, W., Schindler, S., et al. 2006, A&A, 458, 69
Hernandez, T. H., Fuentes Carrera, I., Rosado, M., et al. 2003, A&A, 412, 669
Hernquist, L. 1990, ApJ, 356, 359
Marquez, I., Masegosa, J., Moles, M., et al. 2002, A&A, 393, 389
Mendes de Oliveira, C., Amram, P., Plana, H., & Balkowski, C. 2003, AJ, 126, 2635
Navarro, J., Frenk, C. S., & White, S. 1996, ApJ, 462, 563
Rubin, V. C., & Ford, W. K. 1983, ApJ, 271, 556
Rubin, V. C., Hunter, D. A., & Ford, W. K. 1991, ApJS, 76, 153
Scannapieco, C., Tissera, P. B., White, S. D. M., & Springel, V. 2005, MNRAS, 364, 552
Salo, H., & Laurikainen, E. 2000, MNRAS, 319, 377
Scannapieco, C., Tissera, P. B., White, S. D. M., & Springel, V. 2006, MNRAS, 371, 1125
Springel, V. 2005, MNRAS, 364, 1105
Springel, V., Di Matteo, T., & Hernquist, L. 2005, MNRAS, 361, 776
Toomre, A., & Toomre, J. 1972, ApJ, 178, 623