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On the formation of bridges and tails in interacting galaxies. II

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Abstract. The formation of bridges and tails in a galaxy tidally perturbed by another galaxy moving in a parabolic orbit is studied by numerical experiments based on restricted-three-body approach. It is shown that the structure of a tidally interacting galaxy is determined by the dimensionless parameter $\nu^2 = \frac{\Delta V^2(R)}{V_c^2(R)}$, where $\Delta V(R)$ is the magnitude of the typical velocity increment and $V_c(R)$ is the circular velocity at the periphery of the test galaxy of radius R. ν scales in a simple way with the parameters of the collision. Bridges and tails form in the range $0.1 \leqslant \nu \leqslant 0.7$. For $\nu < 0.1$, there is very little change in the structure, whereas for $\nu > 0.7$, there is appreciable disruption.

Key words : interacting galaxies—bridges and tails

1. Introduction

Extensive numerical computations have shown that brief but violent tidal forces are responsible for the formation of bridges and tails in interacting galaxies (Toomre & Toomre 1972, see review by Alladin & Narasimhan 1982).

We have discussed the effect of mass ratio of the interacting galaxies on the formation of bridges and tails (Namboodiri & Kochhar 1985 = Paper 1). Here we introduce the parameter ν — the ratio of the velocity increment to the circular velocity at the periphery of the galaxy—and study numerically how the structure of an interacting galaxy depends upon it.

2. Dependence of on collision parameters

Let $S(x, y, z)$ be a star in a test galaxy, mass M, radius R, perturbed by a galaxy of mass M_1 moving in a conic section of eccentricity $e \leqslant 1$. The components of the velocity perturbations of S, ΔV_x, ΔV_y, ΔV_z, under the impulsive approximation (Alladin & Narasimhan 1982) are

$$\Delta V_x = \frac{\pi GM_1 x}{(1+e) p^2 V_p}, \quad \ldots(1)$$

$$\Delta V_y = \frac{\pi GM_1 y}{(1+e) p^2 V_p}, \quad \ldots(2)$$

$$\Delta V_z = \frac{2\pi GM_1 z}{(1+e) p^2 V_p}, \quad \ldots(3)$$

where p is the distance of closest approach; $V_p = \left[\frac{G(M+M_1)}{p}(1+e)\right]^{1/2}$ is the speed at closest approach; and G is the gravitational constant. We shall consider a disc galaxy in which stars are moving in the X-Y plane, so that $\Delta V_z = 0$. If we consider a point at the periphery of the disc galaxy and let $R^2 = x^2 + y^2$ where R is the radius of the galaxy, then the typical velocity increment $\Delta V(R)$ and circular velocity $V_c(R)$ are given by

$$\Delta V^2(R) = \Delta V_x^2 + \Delta V_y^2$$

$$= \frac{\pi^2 G^2 M_1^2 R^2}{(1+e)^2 p^4 V_p^2} \quad \ldots(4)$$

and

$$V_c^2(R) = \frac{GM}{R}. \quad \ldots(5)$$

We now define a dimensionless parameter ν :

$$\nu^2 \equiv \frac{\Delta V^2(R)}{V_c^2(R)} = \frac{\pi^2}{(1+e)^3} \frac{M_1^2}{M(M+M_1)} \left(\frac{R}{p}\right)^3. \quad \ldots(6)$$

It can be seen from equation (6) that the important parameters in a galaxy-galaxy collision are p/R, M_1/M and e. The impulsive approximation suggests that if ν is kept constant, the peripheral morphological effects would be similar. We test this numerically.

3. Numerical results

As in paper 1, we study the structure of the tidally perturbed test galaxy using the restricted-three-body approach. We assume that the test galaxy is a point mass surrounded by 150 non-interacting particles and that the mass-point perturber moves in a parabolic orbit in the same sense as the stars revolve in the test galaxy. Time is measured in units of $(R^3/GM) \simeq 1.3 \times 10^8$ yr. We set $G = M = R = 1$. Lengths are measured in units of 20 kpc and mass in units of 10^{11} $M_\odot$ except in case 4b where the corresponding units are 200 pc and $10^5 M_\odot$.

We discuss five cases for different values of ν, ranging from 0.05 to 0.9. Each value of ν is arrived at by two different sets of values of p/R and $\mu = M_1/M$. See table 1.

Table 1.

Case	p/R	$\mu = M_1/M$	ν
1a	6.27	1.0	0.05
1b	36.56	10^2	0.05
2a	4.0	1.0	0.1
2b	10.0	10	0.1
3a	1.57	1.0	0.4
3b	9.14	10^2	0.4
4a	2.5	10	0.7
4b	125	10^6	0.7
5a	2.40	10	0.9
5b	5.32	10^2	0.9

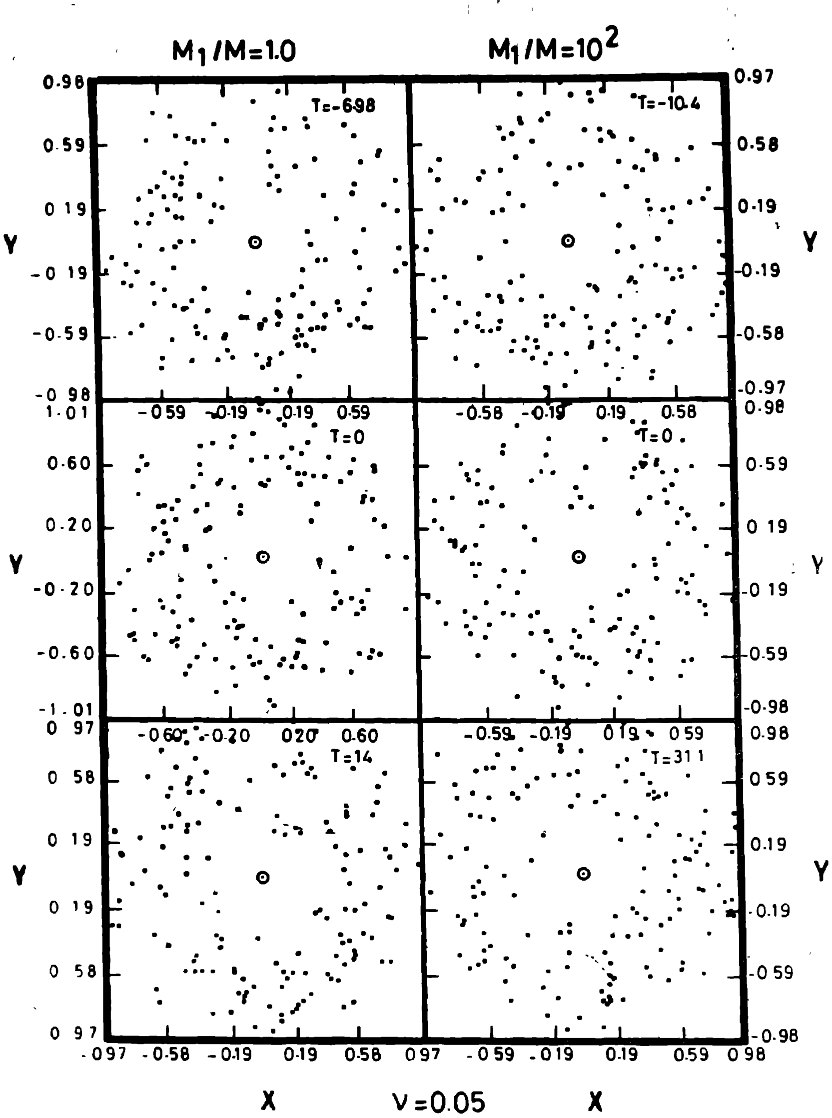

Figure 1. The configuration of the test galaxy at different times for $\nu = 0.05$. One time unit corresponds to 1.3×10^8 yr. The centre of the test galaxy is the origin of the co-ordinate system. Figures 1a & b correspond to $p/R = 6.27$ and 36.56 respectively.

The galaxy structure for $\nu = 0.05$ shows no trace of bridge or tail (figures 1a, b). As we increase the value of the parameter ν, tendency for the formation of the tail emerges (figures 2a, b). Note that although M_1/M and p/R are different in the two cases a and b, the structure determined by $\nu = 0.1$ is the same in both the cases.

Figures 3a and b show intermediate cases ($\nu = 0.4$) in which the bridges and tails are developed. Both the figures are more or less identical in structure, although they correspond to different individual values of p/R and M_1/M. The tails get developed after the perigalactic passage of the perturber. We also observe an expansion in both the systems at the end of the computations.

Structural changes produced for $\nu = 0.7$ are shows in figures 4a and b. It can be seen that the bridges and tails are developed in both cases. In case 4b, even though the perturber is much more massive than the test galaxy compared to

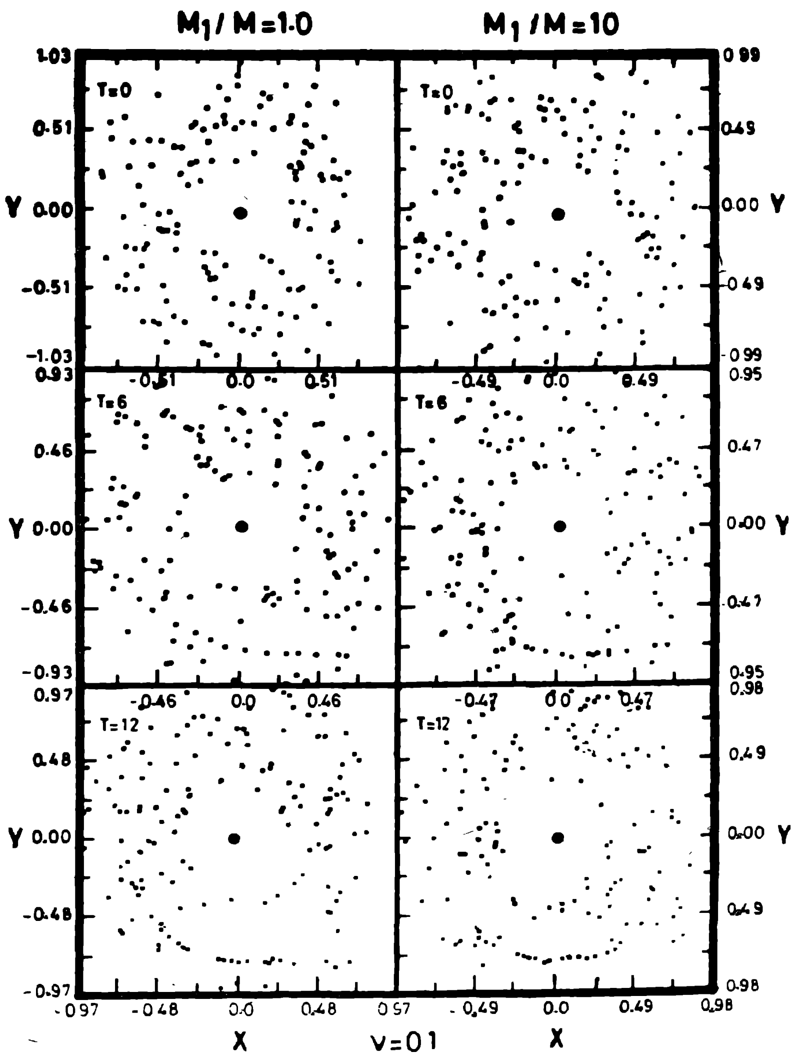

Figure 2. Same as figure 1, but for $\nu = 0.1$ Figures 2a & b correspond to $p/R = 4.0$ and 10.0 respectively.

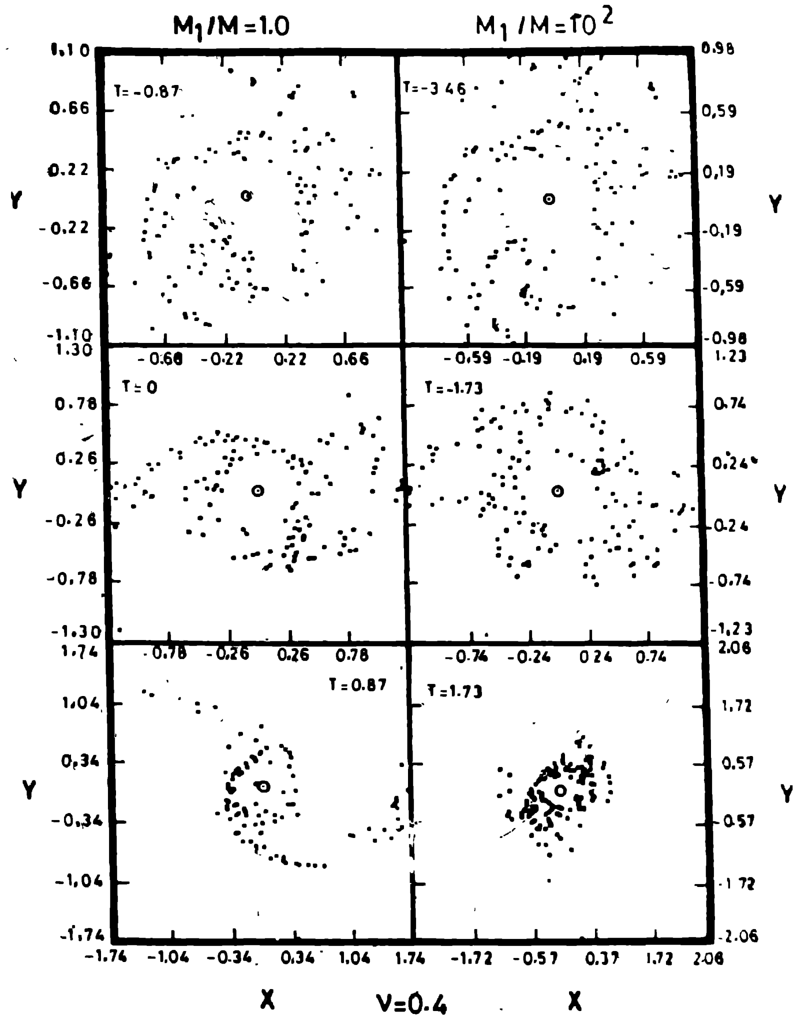

Figure 3. Same as figure 1, but for $\nu = 0.4$. Figures 3a & b correspond to $p/R = 1.57$ and 9.14 respectively.

case 4a, the changes produced in the test galaxy are almost the same in the two cases. In both cases, the test galaxy is expanded in size at the end of computation.

Figures 5a, b show the cases for $\nu = 0.9$ of table 1. In these cases tails and bridges form, but do not last long. The test galaxy gets appreciably disrupted at the end of computation. A considerable number of stars escape in both cases. The structures of the test system in both cases are more or less comparable.

We note that figure 2 ($\mu = 0.1$) and figure 3 ($\mu = 1.0$) of paper 1 are respectively similar to figures 2 and 4 here, because they correspond to the same values of the parameter.

4. Conclusions

It can be noted from our simple model that the formation of similar bridges and tails in interacting galaxies can be fairly well achieved by simple scaling of masses and distances. The formation of bridges and tails depends on ν. It is easy to see

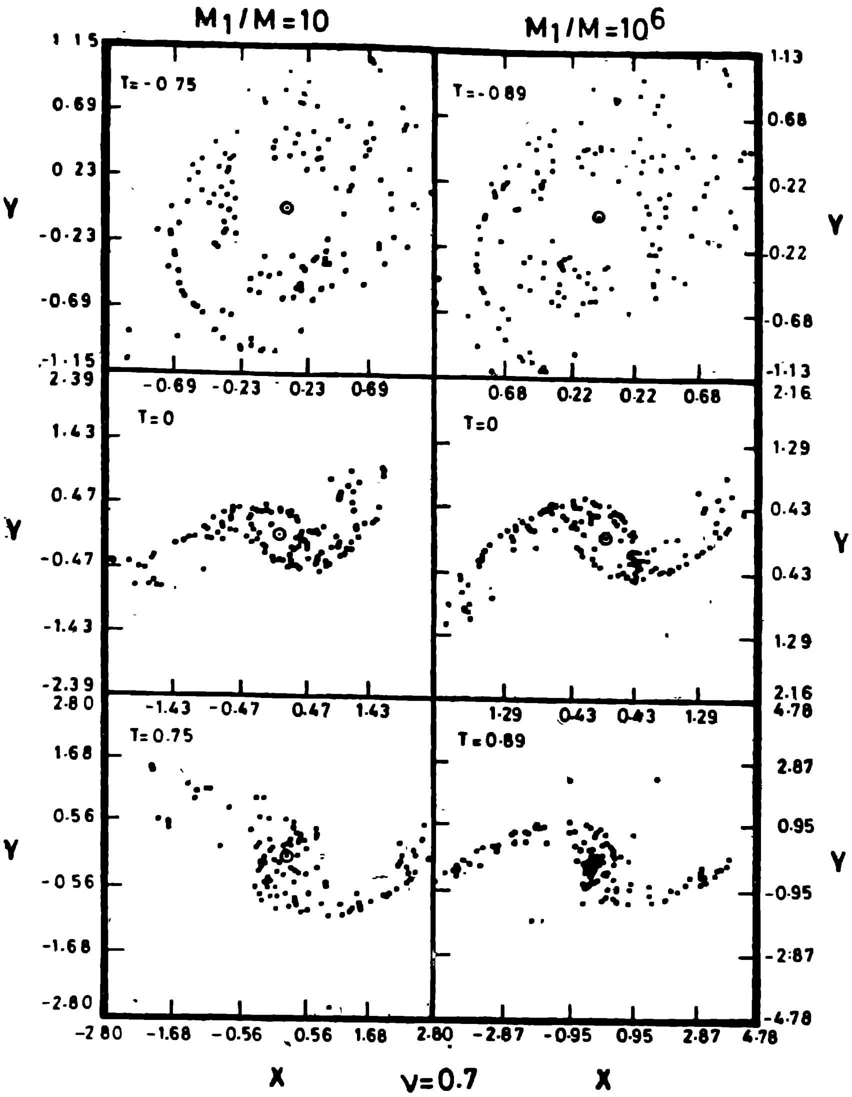

Figure 4. Same as figure 1 but for $\nu = 0.7$. Figures 4a & b correspond to $p/R = 2.5$ and 125 respectively.

from our computations that if $0.1 \leqslant \nu \leqslant 0.7$ bridges and tails are formed. Toomre & Toomre (1972) have used mass ratios $\frac{1}{4}$, 1 and 4. They were able to produce bridges and tails for $0.1 \leqslant \nu \leqslant 0.5$. This is consistent with our work. If $\nu < 0.1$, practically no damage is done to the test galaxy during the encounter. If $\nu > 0.7$, the test galaxy suffers appreciable disruption in the course of the encounter.

Since a massive galaxy will also generally be large in size, in all cases we have considered p is of the order $R_1 + R_2$ where R_1 and R_2 are the radii of the galaxies. Hence to produce good bridges and tails, the galaxies must penetrate but not too deeply (Toomre & Toomre 1972). Grazing and slightly penetrating collisions are effective in producing bridges and tails. However, if the massive galaxy happens to be compact, distant collisions can also lead to the formation of

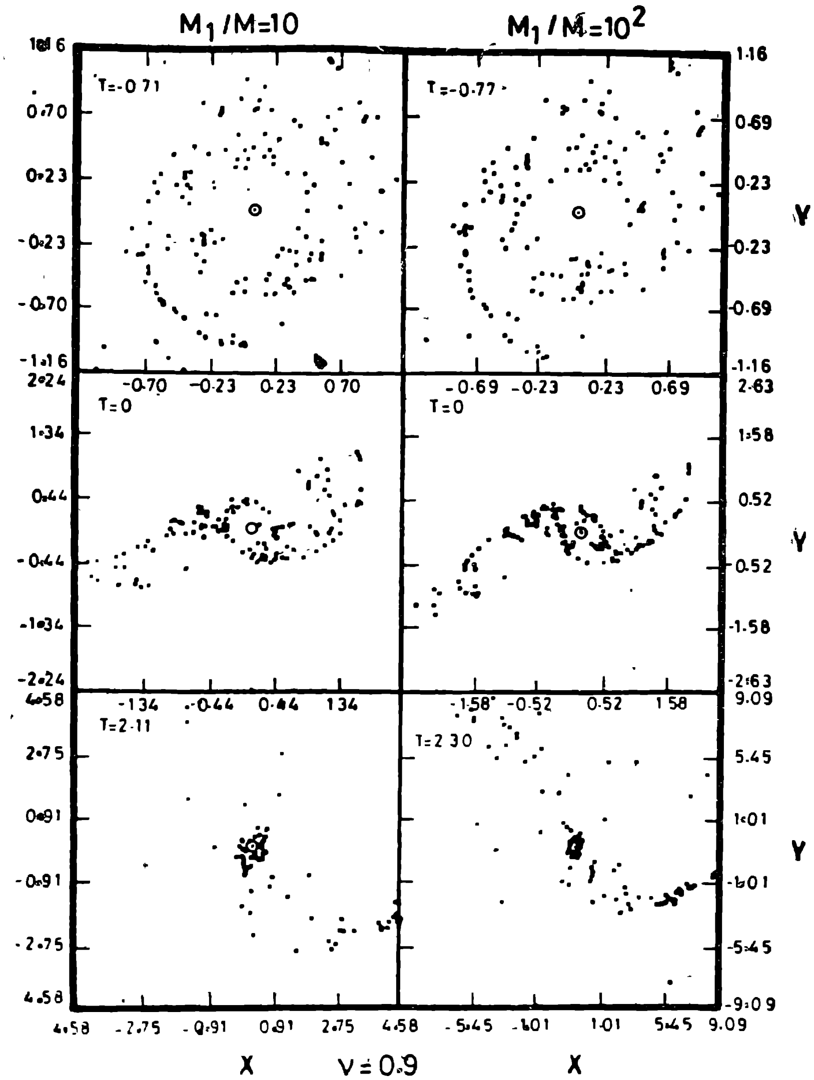

Figure 5. Same as figure 1, but for $\nu = 0.9$. Figures 5a & b correspond to $p/R = 2.4$ and 5.32 respectively.

these morphological features since in this case the separation would be much greater than the sum of the radii of the individual galaxies.

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