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On the formation of tails and bridges in interacting galaxies

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Abstract. Interacting galaxies produce peculiar features like tails, bridges, and counterarms of various sizes and shapes. Numerical experiments have been performed to investigate as to how the formation of tails and bridges depends on mass ratio of the two interacting galaxies. Results indicate that tail formation is favoured when the mass ratio μ is close to unity. When $\mu \ll 1$, tail appears to be shorter and thinner than in the case when μ is about unity. As a result of the encounter, a sharp decrease in the density of the main galaxy at the tidal radius is numerically observed.

Key words : interacting galaxies—tails and bridges

1. Introduction

It is well known that interacting galaxies show peculiar features like bridges, counterarms and tails of various sizes and shapes. It is natural to conclude that these peculiar features are the results of tidal interaction (*e.g.* Alladin & Narasimhan 1982). From a study of 500 interacting galaxies, Vorontsov-Velyaminov (1958) concluded that these features could not be produced by means of gravitational tides and rotation. Zwicky (1959) considered these peculiar features to be jets of stars ejected from galaxies during close encounters. Following Pfleiderer & Siedentopf (1961) many numerical experiments were performed to explain the mechanism of the formation of bridges and tails in interacting galaxies, see, *e.g.*, Pfleiderer (1963), Tashpulatov (1970a, 1970b), Yabushita (1971), Toomre & Toomre (1972), Wright (1972) and Clutton-Brock (1972). All these authors used restricted-three-body approach, except Tashpulatov who used hydrodynamical calculations. Miller & Smith (1980) used N-body technique and showed that collisions from unbound initial states of two galaxies can produce bridges and tails between them.

Stockton (1974a) observationally verified the existence of a long narrow tail in the peculiar double galaxy NGC 4676, and showed (Stockton 1974b) that the radial velocity and the mass ratio of the interacting system Arp 295 agree well with the tidal model proposed by Toomre & Toomre (1972). Schweizer (1978) also invoked tidal theory to describe the tail of NGC 4038/9.

The computer experiments show that gravitational interaction between galaxies can really produce the peculiar features seen in them. According to Toomre & Toomre (1972), to produce good bridges and tails, the collision must be slow; the galaxies must penetrate each other, but not too deeply; and the sense of motion of the perturber and galactic rotation should roughly be the same. They also noted that the formation of bridge is favoured if the perturber's mass is smaller and of the tail if it is larger or equal. The present investigation attempts to study the effect of the mass ratio of the galaxies on the formation of bridges and tails over a bigger range of the mass ratio.

2. Numerical technique and initial conditions

The method and the initial conditions used are the same as those of Wright (1972). We assume the main galaxy to be a point mass which is fixed at the origin. It is surrounded by noninteracting particles distributed in a thin disc containing the main galaxy. The secondary galaxy, or the perturber, also assumed to be a point mass, approaches the main galaxy along a parabolic orbit. In these computations, only parabolic encounters with the main galaxy are considered. This simple assumption enables one to analytically evaluate the position of the secondary galaxy at any time, and the problem reduces to a restricted-three-body problem for each star.

The initial positions of the stars are determined using pseudorandom number generator in such a way that the density of the stars in the disc decreases inversely as their distance from the centre. No stars were placed at a distance of less than 0.3 units (see below) (*i.e.* about 6.6 kpc) since these stars are assumed to be unaffected during the encounter. This is different from Toomre & Toomre's (1972) model in which rings of stars surround the nucleus of the main galaxy. Time was reckoned from negative to positive values with zero being the time of perigalactic passage. The initial positions and velocities are given by

$$x = a \cos \theta; \quad y = a \sin \theta; \quad V_x = a^{-1/2} \sin \theta; \quad V_y = -a^{-1/2} \cos \theta;$$

where a is the initial distance of the star (in units of 20 kpc) from the centre and

$$0.3 < a \leqslant 1; \quad 0 \leqslant \theta \leqslant 2\pi.$$

The equations of motion of a particular star can be written as

$$\frac{d^2\mathbf{R}_0}{dt^2} = -\frac{GM_0}{R_0^3}\mathbf{R}_0 - \frac{GM_1}{R_1^3}\mathbf{R}_1 - \frac{GM_1}{R^3}\mathbf{R}, \qquad \ldots(1)$$

where $\mathbf{R}_0 = (x_0, y_0)$ is the position vector of the star; $\mathbf{R} = (X, Y)$ is the position vector of the perturbing galaxy; $\mathbf{R}_1$ is the position vector of the perturbing galaxy with respect to the star; M_0 is the mass of the main galaxy; M_1 is the mass of the perturber; and t is the time. The unit of mass used is M_0 ($10^{11} M_\odot$), the unit of distance is the perigalactic distance of the perturbing galaxy (20 kpc). Time is measured in the units of $[Q^3/G(M_0 + M_1)]^{1/2}$ where Q is perigalactic distance; the unit corresponds to 10^8 yr when $M_0 = M_1$.

The equations of motion (1) are numerically integrated for each star, using Adam-Moulton's predictor-corrector method. The formulae used are

$$x^{p}_{n+1} = x_n + \frac{\Delta t}{24} (55\dot{x}_n - 59\dot{x}_{n-1} + 37\dot{x}_{n-2} - 9\dot{x}_{n-3}), \qquad ...(2)$$

$$x^{c}_{n+1} = x_n + \frac{\Delta t}{24} (9\dot{x}^{p}_{n+1} + 19\dot{x}_n - 5\dot{x}_{n-1} + \dot{x}_{n-2}), \qquad ...(3)$$

where $\dot{x}_n$ is the component of the velocity in the x-direction at time $t = t_n$ and similarly for the y-coordinate. To start the integration, one should know the positions and velocities at three time steps and this is obtained by using the fourth order Runge-Kutta method. The step-size for each star was determined in such a way that two iterations produced an error in its position less than 1%. We used 150 stars in all our computations. The integrations started at $t = -2$ and proceeded up to $t = 5$ units.

3. Results and discussion

We have performed a series of computations with the mass ratio $\mu = M_1/M_0$ ranging from 10 to 0.001. In all cases, stars were rotating in a clockwise direction which is also the direction of motion of the perturber; and consequently, tails are observed to be formed in a direction opposite to the motion of the perturber. The initial configuration of the main galaxy is shown in figure 1.

In the cases where $\mu = 0.001$ and 0.01, no bridge or tail-like structure is observed and all the stars essentially remain bound to the main galaxy. Even though the positions of the stars are disturbed, the overall structure of the main galaxy remains the same. The results of computations for $\mu = 0.001$, 0.01 and 0.1 are shown in figure 2.

A series of 10 computations were performed in the mass ratio range 0.1 to 1. In each case, tail appeared to form shortly after the perturber has passed the perigalactic point. When $\mu = 0.1$ the tail is short and thin and does not extend to the outer parts of the main galaxy. A bridge connects the main galaxy and the perturber at $t = 2$ but it does not exist at $t = 5$. Nearly 68% of the stars remain bound to the system, 25% form tail, and the remaining stars have escaped by the end of the computation.

When $\mu = 0.5$, the formation of tail and bridge is observed at $t = 2$. The tail gets developed at $t = 5$ whereas the bridge has almost disappeared at $t = 5$. The fraction of the stars forming tail is less than that in the case when $\mu = 1$. Further the length of the tail and its thickness also get reduced. The percentage of stars remaining bound to the system is 34 and the percentage forming tail is 45.

When $\mu = 1$, the tail is well developed at $t = 2$. (The unit of t is 10^8 yr.) It persists at $t = 5$ but extends to double the distance as compared to $t = 2$. At the end of the computation (*i.e.* at $t = 5$), 21% of the stars are bound to the system, 48% of the stars form the tail, and 31% have escaped from the system. The configuration of the system for $\mu = 0.5$ and 1 is shown in figure 3.

When $\mu = 2$, very few stars remain bound to the system. Increasing the mass of the perturber leads to greater disruption of the main galaxy. When $\mu = 10$, most of the stars escape and few of them are captured by the perturber. There is evidence for the formation of a prominent bridge when the perturber is much more massive than the main galaxy. The computational results for the case $\mu = 2$ and 10 are shown in figure 4. The scales for different times are indicated in each of them.

Wright (1972) has considered three cases for the mass ratio : $\mu = 1, \frac{1}{4}$ and 1/10. Toomre & Toomre have considered mass ratios $\frac{1}{4}$, 1 and 4. The present work takes into account a good range of mass ratios. Therefore, we are able to study the effect of mass ratio on the formation of tails in interacting galaxies. Figure 5 is a histogram showing the fraction of the stars that remains bound to the system, at the end of computation, as a function of μ. This figure clearly shows that as mass ratio increases, the fraction of the stars remaining bound to the system decreases. In the mass ratio range considered, the variation appears to be smooth.

Figure 6 shows the fraction of the stars forming tail as a function of mass ratio at the end of computation. The number of stars forming tail increases as the mass ratio increases and remains almost constant in the range $0.5 \leqslant \mu \leqslant 1$. When $\mu < 0.5$, the tail appears to be thinner and shorter than in the case when μ is about unity, indicating that tail formation is favoured when the mass ratio is close to unity.

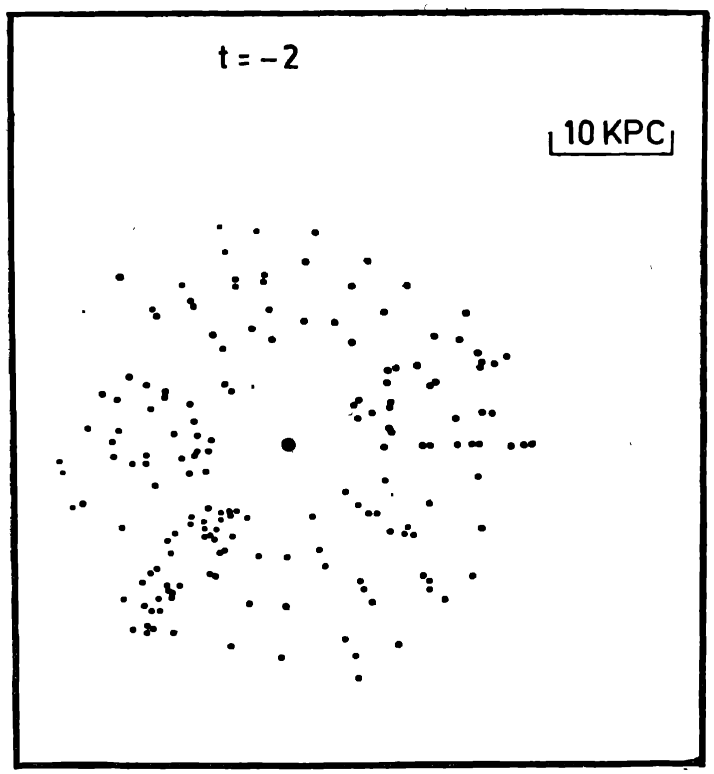

Figure 1. Initial configuration of the main galaxy at $t = -2$.

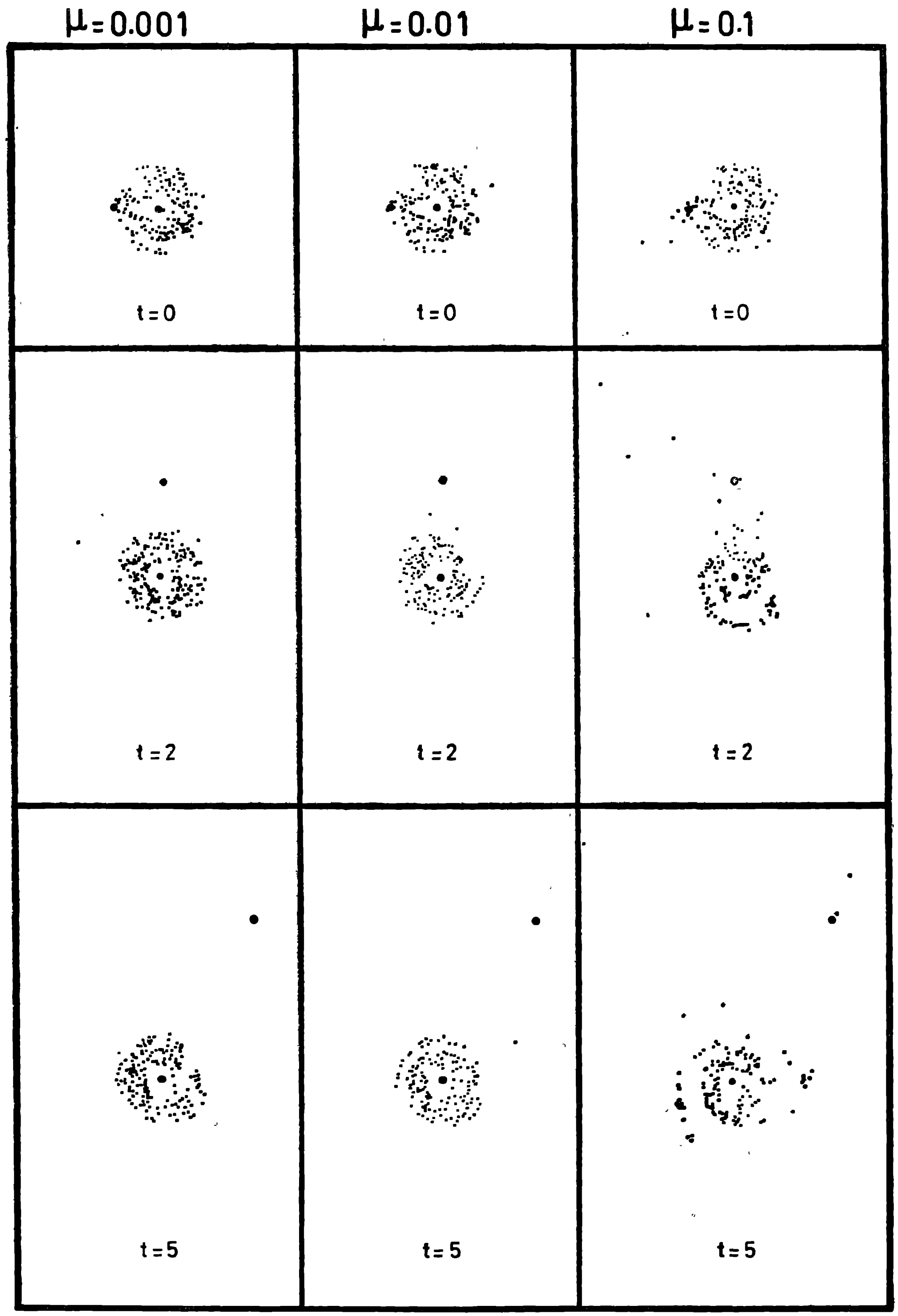

Figure 2. The configuration of the system for $\mu = 0.001$, 0.01 and 0.1. Under each case, the structure of the system for different times are shown.

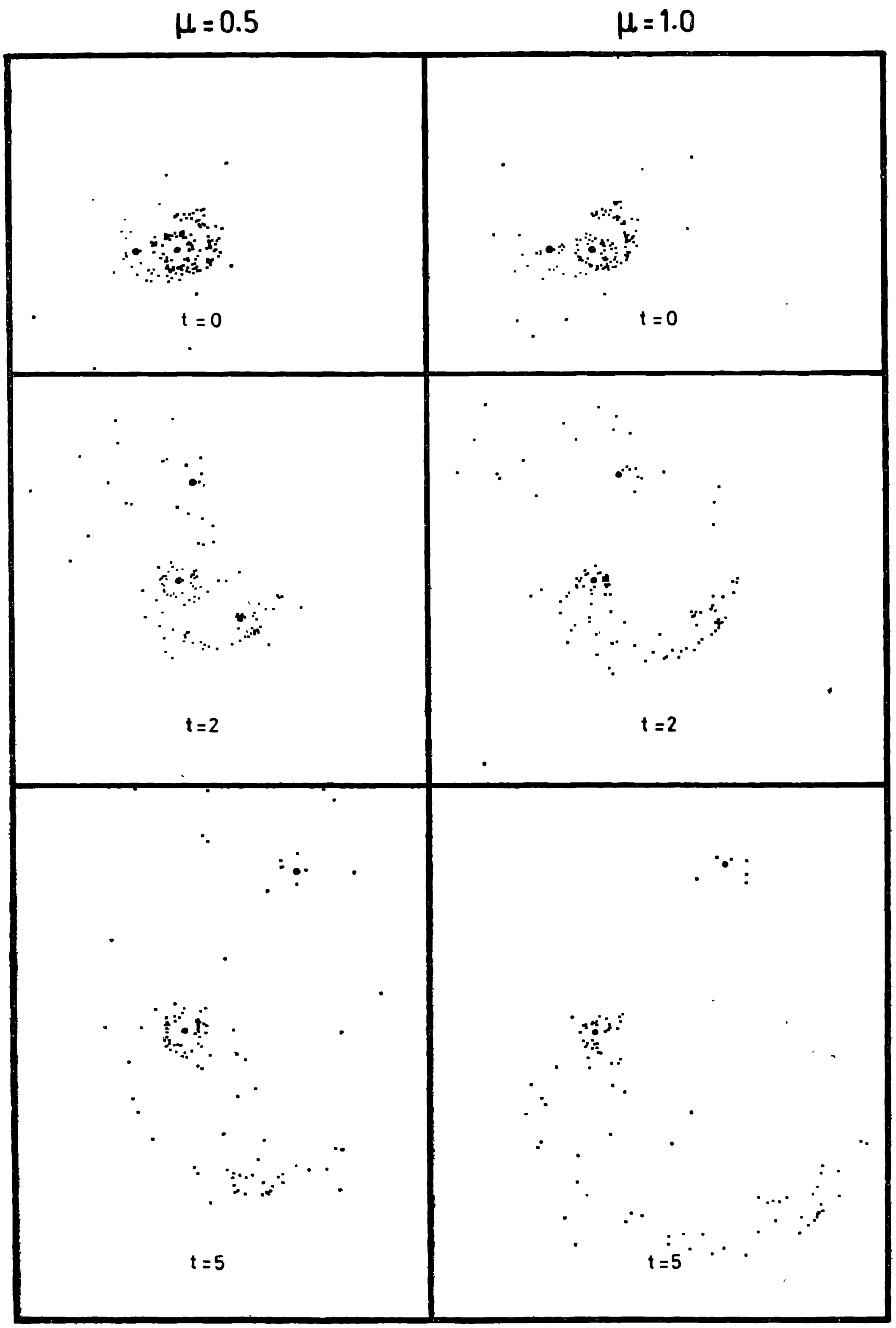

Figure 3. Same as figure 2 but for $\mu = 0.5$ and 1.

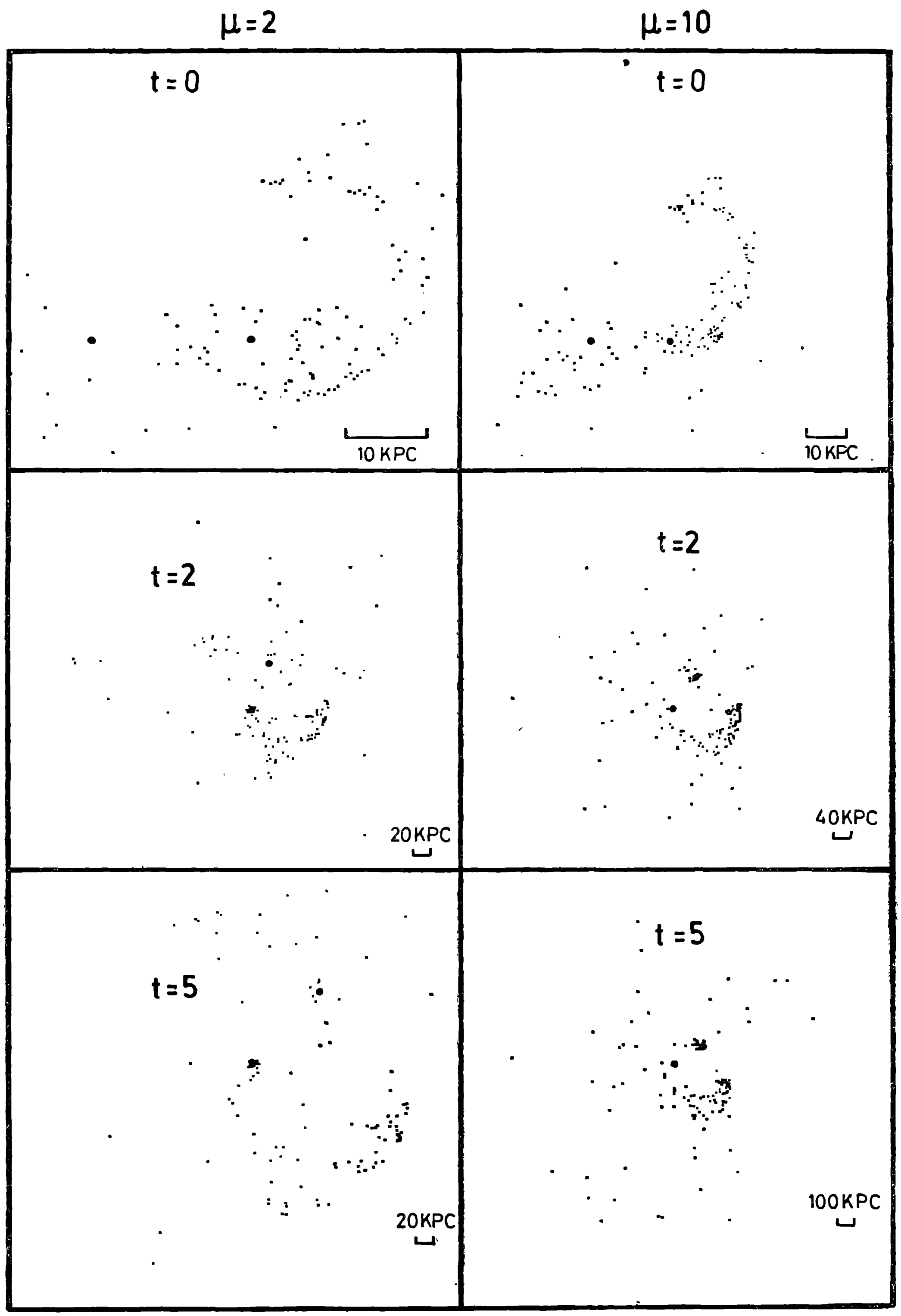

Figure 4. Same as figure 2 but for $\mu = 2$ and 10. Note that scales are different at different times.

In these calculations, we have assumed that the inner parts of the main galaxy, *i.e.* mass within about 6.6 kpc, are unaffected during the encounter. Further we

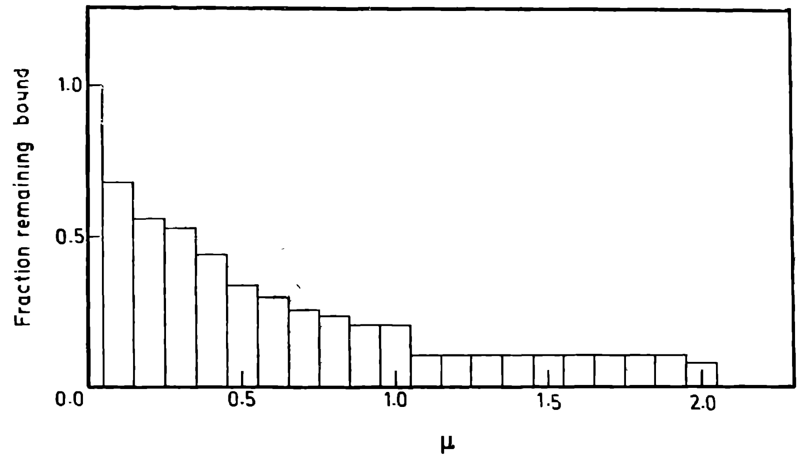

Figure 5. Histogram of the fraction of the stars remaining bound to the galaxy at $t = 5$.

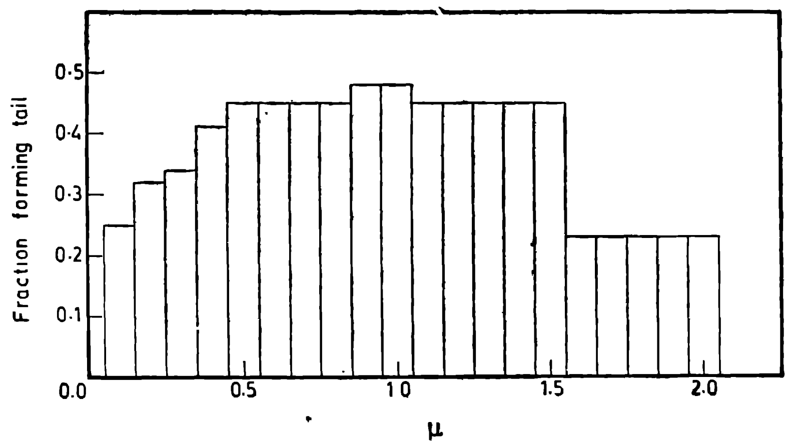

Figure 6. Histogram of the fraction of the stars forming tail at $t = 5$.

observe a change in density of the main galaxy at the tidal radius as predicted by Alladin *et al.* (1985). The reduction in density is more pronounced in the case where the mass of perturber is the same as that of the main galaxy.

4. Conclusions

Our simple model assumes the systems to be coplanar and shows the structure of the main galaxy as the perturber passes along a parabolic orbit. Our results agree well with those of Wright (1972) and Toomre & Toomre (1972). Further we infer that tail formation is favoured when mass ratio is close to unity. The tail is broad and long when μ is close to unity, and becomes thinner and shorter as the mass ratio decreases. In other words, the central concentration of stars increases as the mass ratio decreases. The main galaxy essentially remains unaffected by the passage of the perturber when $\mu \ll 1$. Increase in the mass of the perturber leads to greater disruption of the main galaxy.

The present numerical experiment does not consider retrograde motion of the perturbing galaxy. In this case, it has been shown by Wright (1972) that even though retrograde motion causes escape of stars, there is no evidence of formation of tail or bridge-like structure. Many factors that should effect the situation have been neglected in our simple model computations. It would be desirable to use *N*-body simulations to treat all possible consequences of interacting stellar systems in a selfconsistent way. The results are consistent in the sense that the formation of bridges and tails can be explained on the basis of gravitational interaction. Further one may be able to obtain some idea about the mass ratios of the galaxies by looking at the shapes and sizes of the peculiar features observed in interacting galaxies.

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