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Remnants of closely interacting galaxies

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Merging and non-merging collisions of galaxies have been performed by numerical simulations. The galaxies are modelled as equal mass spherical systems and the density distribution closely follows the Plummer model. The simulations use a set values for the distance of closest approach in the range $0 < \frac{p}{R_h} < 10$ (p being the distance of closest approach and R_h the half-mass radius) and the orbit is assumed to be parabolic. Merging takes place when ever the galaxies overlap significantly at closest approach. In the *fundamental plane*, the merger remnants lie on a line to the right of normal ellipticals with slope ∼ -2. Remnants conserve fairly well mass and energy. In distant encounters, the galaxies retain their initial structure.

1. Introduction

The influence of environment in shaping the structure of a galaxy has been recognized for several years. Many numerical simulations convincingly demonstrated the existence of galaxies with various appendages. Galaxies with close companions are expected to merge in a few galactic crossing times. Collisions of galaxies of comparable mass that are moving on a marginally bound orbit result in mergers. Giant luminous galaxies at the cores of dense clusters are supposed to have formed by the merger of smaller neighbours.

Merging and disruption are two important processes in the dynamical evolution of a binary stellar system. The ratio of the times of disruption and merging is given by the approximate relation

$$\frac{t_d}{t_m} \simeq \frac{6}{(5-n)} \frac{a}{R} \frac{M}{M_1} \tag{1}$$

where t_d is the disruption time, t_m is time for merging, a is the orbital radius, R the radius of the galaxy, M and M_1 are masses of the stellar systems and n is the polytropic index describing the density distribution of the stellar system [1]. It is clear that merging is more likely to occur if both the galaxies are centrally condensed (i.e., $n \sim 4$) and have similar masses ($M = M_1$). The process of merging is enhanced for systems which significantly overlap (i.e., the distance of closest approach $p < R$) each other and has a smaller relative velocity V_p at closest approach than the escape velocity V_e.

Pairs of elliptical galaxies comprise about 10 % of any remarkably complete sample of binary galaxies. They are almost gas free systems so that the effect of gas dynamics can be neglected. Bound elliptical pairs tend to have similar mass and their separation and velocity difference are smaller compared to other types of pairs [2]. Hence they are well posed for numerical simulations.

Previous work in this field considered several initial conditions for the merging to take place in a galactic encounter [3-21]. Most of the above simulations mainly considered collisions of galaxies in which the components ultimately become strongly bound or coalesced. The analytical formula for merging to take place by [22] is valid in the case of fast and distant encounters. Slow inter penetrating collisions involve highly non - linear processes and can be studied by numerical simulations only. The present work considers two equal mass galaxies undergoing collision with various impact parameters. The initial relative velocity of the galaxy is parabolic. If the galaxies do not merge in a close encounter, they are expected to suffer significant disruption. Both merging and non merging cases are investigated so that one can study the transition region between these two processes.

Our numerical simulations are described in Section 2. The results are presented and discussed in Section 3. The conclusions are given in Section 4.

Table I
Model parameters and results

Model	p/R_h	V_p/V_e	$\Delta U/\mid U\mid$	$\Delta M/M$	$(\Delta M/M)_E$	M/M_0	E/E_0	R/R_0	t_m/t_{cr}
P1	0	0	0.984	0.153	0.068	1.864	2.113	2.275	4
P2	0.5	0.62	0.999	0.159	0.042	1.916	2.025	2.233	10
P3	1.0	0.73	0.988	0.157	0.042	1.916	2.029	2.144	13
P4	1.5	0.79	0.869	0.220	0.033	1.935	2.077	2.134	20
P5	2.0	0.95	1.176	0.216	0.057	1.886	2.077	4.230	29
P6	2.5	0.97	1.092	0.197	0.054	1.893	2.035	3.976	34
P7	3.0	1.00	0.242	0.055	-	-	-	-	-
P8	4.0	1.01	0.073	0.025	-	-	-	-	-
P9	5.0	1.03	0.033	0.013	-	-	-	-	-
P10	7.5	1.06	0.020	0.004	-	-	-	-	-
P11	10.0	1.09	0.026	0.003	-	-	-	-	-

2. The simulations

2.1 Initial conditions

For the simulations of this work a galaxy is modelled as a spherical non-rotating cluster of 1024 identical particles. The positions and velocities of the particles are generated using random numbers so that the resulting density distribution closely follows the Plummer model. The initial cluster is evolved for about ten crossing times to produce a dynamically stable galaxy. Barnes *treecode* is used for computation of orbits [23]. The parameters used are N=1024, θ = 0.7 and ϵ = 0.2. We use a system of units so that G=M=1, where G is the gravitational constant and M, the total mass of the galaxy. After the initial evolution, 50 per cent of the mass is enclosed within R_h = 0.91 and 90 per

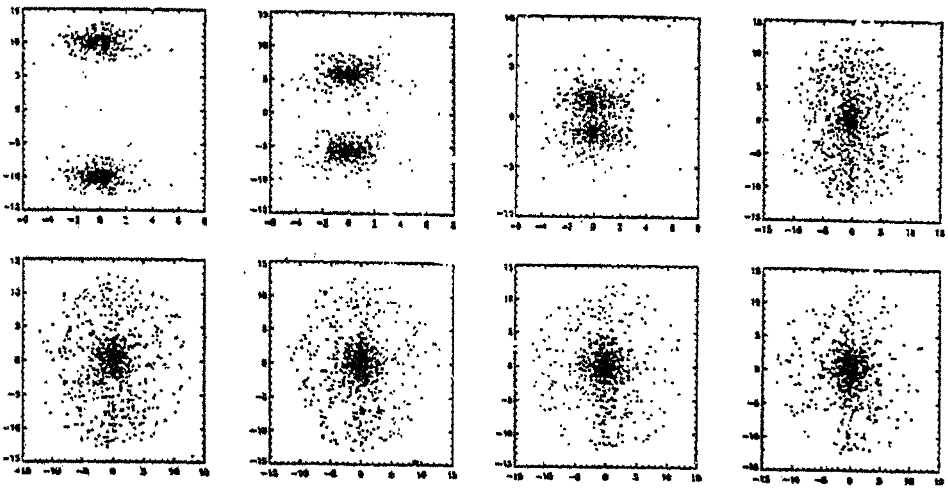

Figure 1: Snapshot of particles for model P1 at times t= 0, 6, 10, 16, 18, 20, 23, and 25.

cent within less than $3R_h$. The galaxy extends to about $10R_h$ so that it is a highly centrally concentrated galaxy. The crossing time $t_{cr} = 2R_h/\langle\overline{v}^2\rangle^{1/2}$, ($\langle\overline{v}^2\rangle$ being the internal mean square velocity) is equal to 2.8 units. The times are expressed in terms of the crossing time. The evolved galaxy is very close to virial equilibrium, almost spherical in size and possesses no net angular momentum.

2.2. Collision parameters

The important parameters in galaxy-galaxy collision are the impact parameter, the relative velocity of collision at maximum separation (or at infinity) and the mass ratio of the galaxies. The dynamically significant quantity corresponding to the impact parameter is the distance of closest approach p. We have considered collisions of equal mass galaxies. The merging of galaxies is rather rare or even impossible for high velocity distant encounters. Galaxies that are bound to each other are expected to merge in a few orbital periods. The interaction is expected to be strong when the galaxies undergo collision on a marginally bound or parabolic orbit. Consequently the initial relative orbit is assumed to be parabolic.

Two identical galaxies are placed in a relative parabolic orbit at an initial separation D=20 units. At this separation, the tidal forces are much less than the internal gravitational force in a system. We use different values for the distance of closest approach such that $\frac{p}{R_h}$ = 0, 0.5, 1, 1.5, 2, 2.5, 3, 4, 5, 7.5 and 10 and these models are respectively denoted by P1, P2,........,P11. The initial position and velocity of the centre of mass of the galaxies are determined by assuming the galaxies to be point mass objects. The X-Y plane is the orbital plane. The computations have been performed till merging is complete in models P1 - P6. In other models, the computations are stopped when the two systems showed tendency to recede from each other. The collision parameters and some of the main results are given in table 1. The properties of the merger remnants are also given in this table.

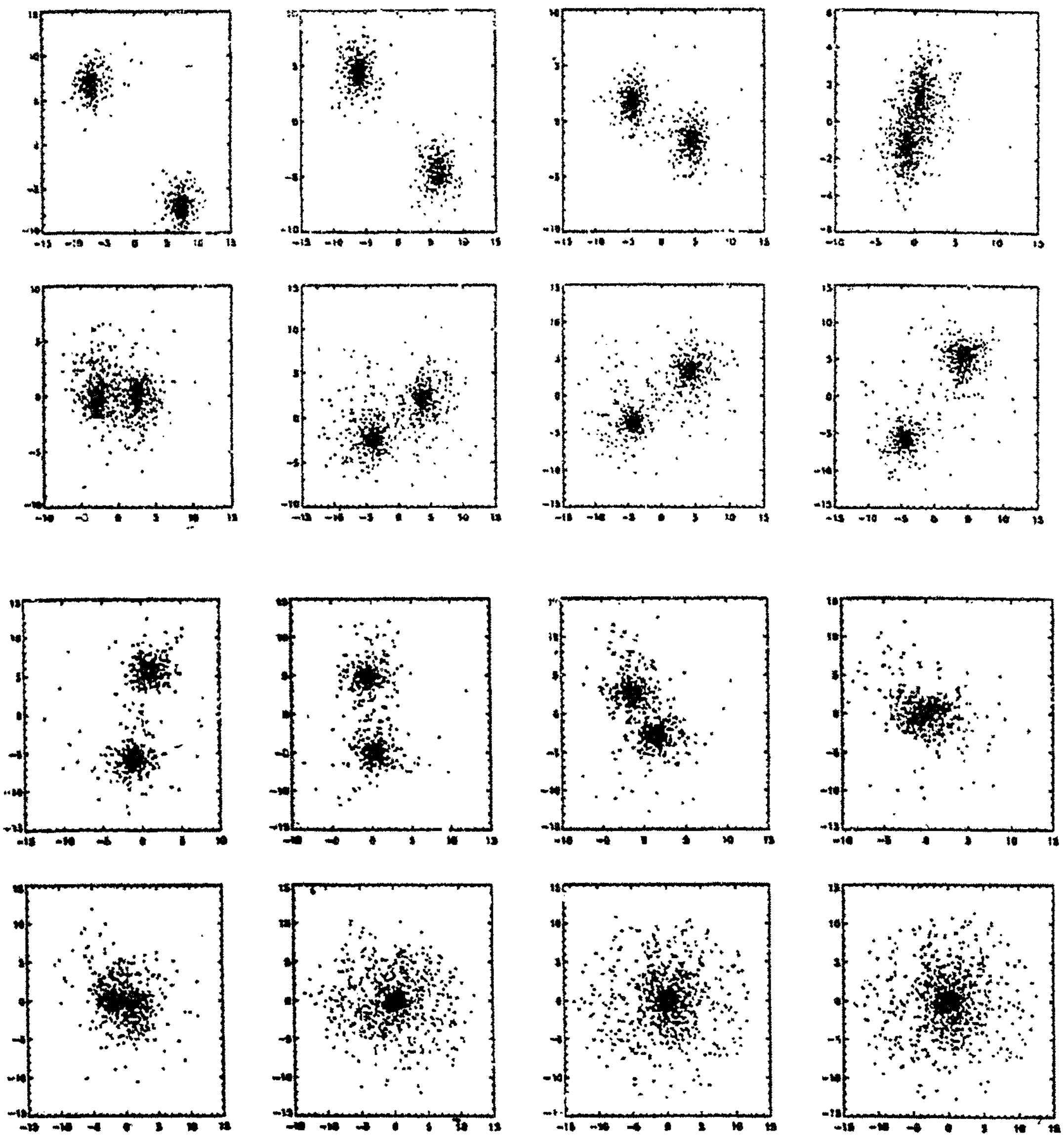

Figure 2: Snapshot of particles for model P6 at times t = 0, 4, 8, 12, 15, 18, 20, 25, 29, 34, 38, 41, 43, 46, 49 and 50.

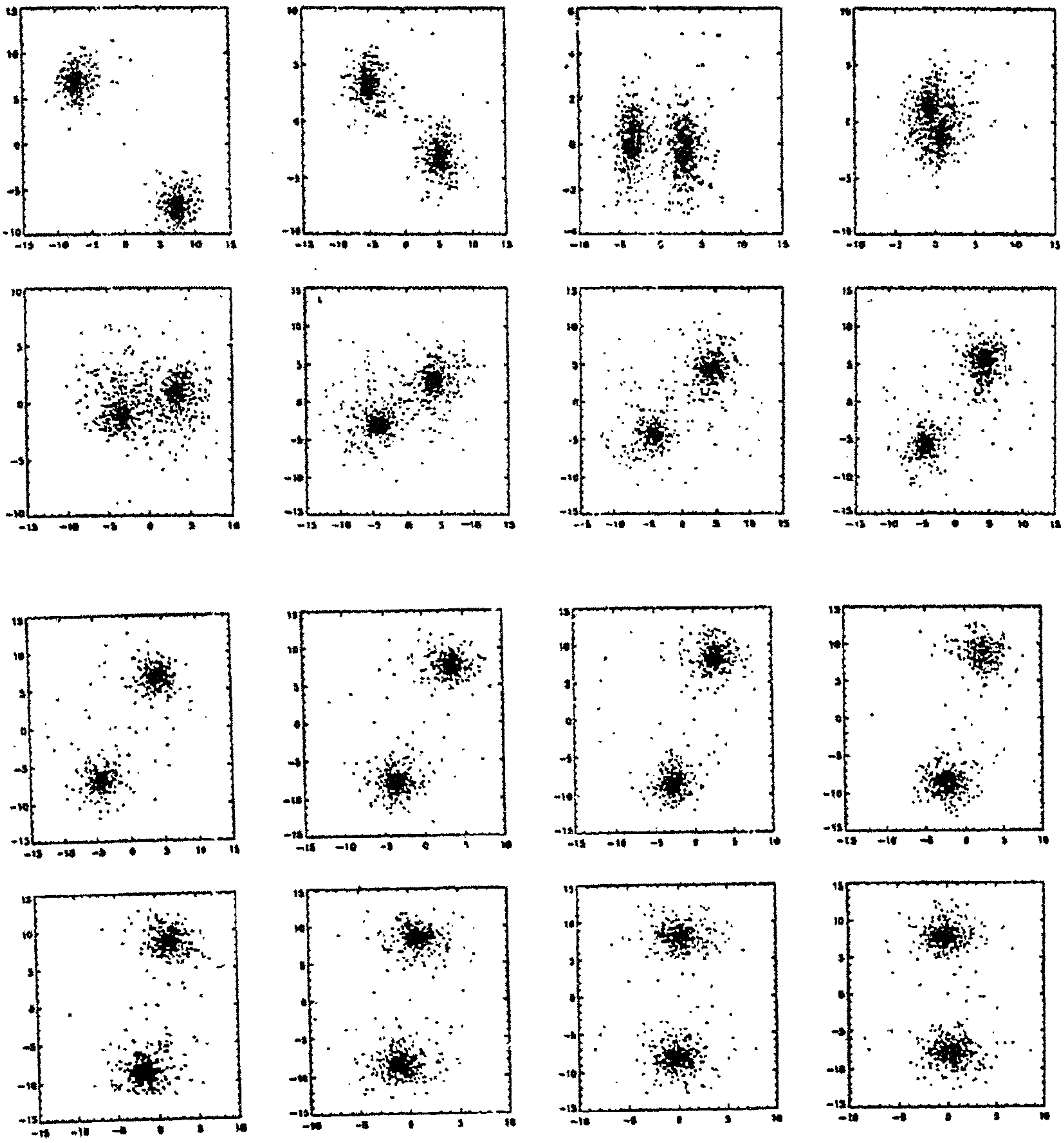

Figure 3: Snapshot of particles for model P7 at times t = 0, 6, 10, 13, 16, 19, 22, 25, 28, 32, 36, 39, 42, 45, 48 and 50.

3.Results and discussion

3.1. General features

Figs. 1 - 3 show the projection of particles on to the X-Y plane at a series of times during the encounter. Fig.1 shows the evolution of the galaxies in a head-on collision (Model P1). The merging is complete by t=16 and the merger remnant remains stable afterwards. Fig.2 shows the evolution of Model P6 ($p/R_h = 2.5$) through out the simulation. In this model the galaxies come close together at t=12 and move apart after this close encounter. The second encounter results in their merger at t=41 and remain as a single system till the end of the computation. In models P1 - P6 merging does not take place during the first close contact. However after this, their orbits become less and less eccentric and finally merge into a single system. This occurs in less than 50 crossing times. It is to be noted that the extent of the galaxy remnants in merging cases are significantly larger than those of the initial systems. Fig.3 shows the evolution of Model P7. In this model both the galaxies survive the encounter. The merging does not take place in 50 crossing times. Models P8 - P11 are also non - merging simulations.

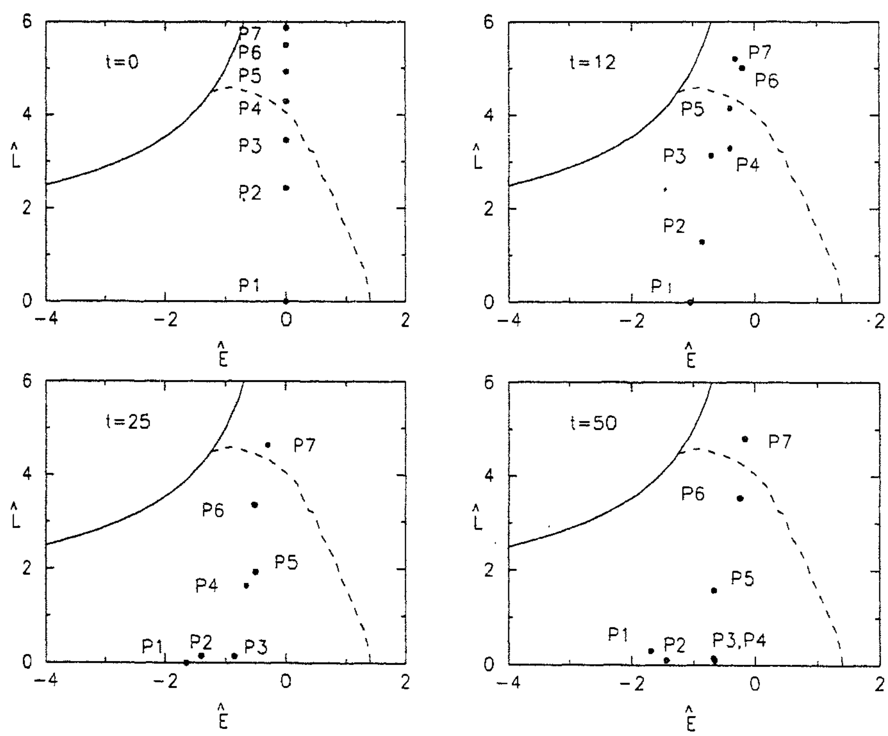

Figure 4: The merger criterion for the models at selected times.

3.2. Merging criterion

It has been shown by several workers that close collision of the two galaxies results in the merger of them if the collision velocity is comparable to the root mean square internal velocity of the galaxies. [24] have shown that the fate of a collision can be determined by two quantities $\hat{E}$ and $\hat{L}$ of the initial model where $\hat{E} = E_{orb}/0.5\langle v^2\rangle$ and $\hat{L} = L_{orb}/R_h\langle v^2\rangle^{1/2}$ and E_{orb} and L_{orb} are the energy and angular momentum per unit mass respectively. In Fig.4 we plot these values for a few times during the collision. In this figure, the dashed line represents the boundary between merging and non-merging collisions. Galaxies with $(\hat{E}, \hat{L})$ values lying below the dashed curve are expected to merge in less than a Hubble time. Initially all the models lie on a line corresponding to the parabolic orbit $\hat{E} = 0$ and only three are within the merging region. By the time of closest approach i.e., at t = 12, two more models move to the merging region. At t = 25 models P1 - P6 lie in the merging region and they merge in less than 35 time units. Model P7 does not merge in spite of following it up to t = 50. This suggests that its merging time scale is larger than a Hubble time. Our experiment shows that the dashed line shown in [24] should be pushed upward to include all galaxies that merge in less than a Hubble time.

In our numerical experiments models P1 - P6 merge or become tightly bound in less than 25 crossing time. Models P7 - P11 do not merge in 50 crossing time. Earlier numerical simulations have shown that in a head-on collision merging occurs when the collision velocity at minimum separation $V_p < 1.16V_e$ [25]. This velocity should be still lower for distant collisions. [4] showed that merging can occur when galaxies overlap significantly such that $p < 2.5R_h$. Our work, how ever, shows that when ever the galaxies overlap such that $p < R_h$ merging occurs if the collision velocity at minimum separation is less than the escape velocity there i.e., $V_p < V_e$. It can be seen from table 1 that for models P1 - P6, $V_p/V_e < 1$ and consequently merging takes place in these models. This implies that a knowledge of the value of p/R_h together with V_p/V_e, in principle, should enable one to determine the fate of a galaxy collision. The merging process is seen to depend strongly first on the impact parameter and then on the velocity of collision.

3.3.Features of merger remnants

Two galaxies first become closely bound during the first close contact and then proceed to merge into a single system. In table 1 we give properties of the merger remnants. The merger time is defined as the time elapsed between the time of first close contact and that at which both the galaxies become bound to each other with a separation less than a tenth of its original radius. It can be seen from this table that the merging time increases with p/R_h.

[26] have compared the merging times of colliding galaxies obtained using impulsive approximation with that computed by [9] using multiple three body algorithm, in the case of circular orbit encounters. They found reasonable agreement between the two estimates. The merging time for a general conic orbit derived using impulsive approximation can be written as [26]

$$t_m = \frac{a^{3.5}(1-e^2)^3(M_1+M_2)^{1/2}}{2\pi G^{1/2}M_2R_h^2}. \tag{2}$$

Here a is the semi-major axis and e, the eccentricity of the orbit. For equal mass galaxies moving on parabolic orbit, this becomes

$$t_m = \frac{2\sqrt{(2)}}{\pi}(\frac{p}{R_h})^3 t_{cr}. \tag{3}$$

The present work shows that for parabolic orbits, the merging time goes linearly with the impact parameter, i.e.,

$$t_m = c(p/R_h)t_{cr} \tag{4}$$

where C is a constant. A comparison of equations (3) and (4) shows that the dependence of the impact parameter on the merging time is not as strong as demonstrated by analytical work. The merging time computed using the analytical formula generally over estimates it as its derivation neglects the motion of the stars in comparison with the orbital motion of the galaxies.

The amount of energy transferred from the orbit to the internal energy gives an idea of the strength of interaction. The ratio $\Delta U/\mid U \mid$, where U is the unperturbed energy of the initial galaxy and ΔU is its change during the encounter provide a convenient order of magnitude estimate of this process. In table 1, the values $\Delta U/\mid U \mid$ and $\Delta M/M$ represent the typical relative change in the energy and mass of a single galaxy during the encounter. It can be seen from this table that maximum energy transfer occurs in model P5 and P6. In all other models $\Delta U/\mid U \mid< 1$ and the mass loss is less than 22 per cent. It should be noted that some particles leaving one galaxy is captured by the other galaxy and so the effective mass loss $(\Delta M/M)_E$ is less than 6 per cent. Distant encounters do not produce much disruption as demonstrated by models P7 - P11 where $\Delta U/\mid U \mid$ is much smaller and $\Delta M/M$ negligible. How ever in close collisions as in models P1 - P6, disruption effects are quite considerable as $\Delta U/\mid U \mid\geq 1$. In these models, merging takes place with considerable disruption.

If E_0, M_0, R_0 represent the values of the binding energy, mass and virial radius of the initial galaxy and E, M, R are that of the remnant after the merging is complete, then the ratios E/E_0, M/M_0, R/R_0 give the condition for hierarchical merging. Fig.5 shows the parameters $M/M_0, E/E_0$ and R/R_0 as a function of p/R_h for all the models. These ratios slightly increase with p/R_h and reach a maximum around $p/R_h = 2$ and then drop drastically and remains almost constant after $p/R_h = 2.5$. This sudden decrease clearly shows the transition from merging to non-merging simulations. When $p/R_h < 2$, these ratios satisfy the relation

$$M/M_0 \sim E/E_0 \sim R/R_0 \sim 2 \tag{5}$$

that is characteristic of hierarchical merging.

All the merger remnants and survivors tend toward a single density profile which in our case closely resembles that given by de Vaucouleurs. Fig.6 shows the surface density profiles for a few models. The solid line represents the fit for de Vaucouleurs' $r^{1/4}$ law. The fit is remarkably good in the inner parts of the merger remnants but shows deviations in the outer parts. This phenomenon of tidal distension has been noticed by earlier workers in the case of tidally disturbed galaxies. Galaxies with close companions have such density profiles. The density profiles of non-merging systems do not exhibit this feature.

Elliptical galaxies can be described in terms of the effective radii, the mean surface density and the velocity dispersion. The relation involving such quantities is called the *fundamental plane* which indicates the processes of formation and evolution of elliptical galaxies. The projection of this plane reduces to the more familiar relationship in the $r_e - \mu_e$ plane [27]. [28] has shown that there exists good correlation between r_e and μ_e where r_e is the radius that contains half the mass and μ_e, logarithm of the surface brightness at that point. This correlation is expressed in the form

$$\mu_e = -1.31 log r_e + constant. \tag{6}$$

In fig.7 we show this correlation for our simulations. The solid line passing through the initial galaxy represents the fit for the relation given by [28]. The survivors of the collision lie close to this line as is the case for normal ellipticals. The merger remnants fall on a line with slope $\sim$ -2. The merger remnants are larger and fainter than the progenitors. [10] has noted that remnants of parabolic collision would lie to the right of the relation shown by [28]. This is consistent with our results. The fact that the remnants lie along a line of slope $\sim$ -2 without much scatter suggests that the mass

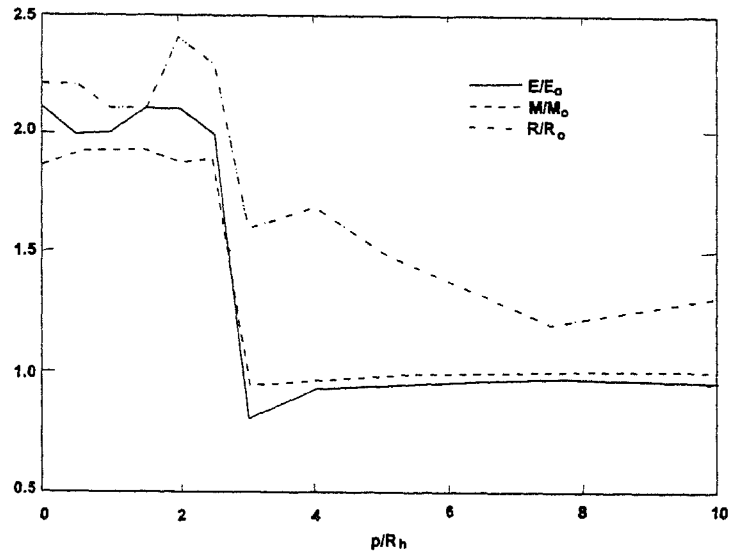

Figure 5: Plot of M/M$_0$, E/E$_0$ and R/R$_0$ as a function of p/R$_h$.

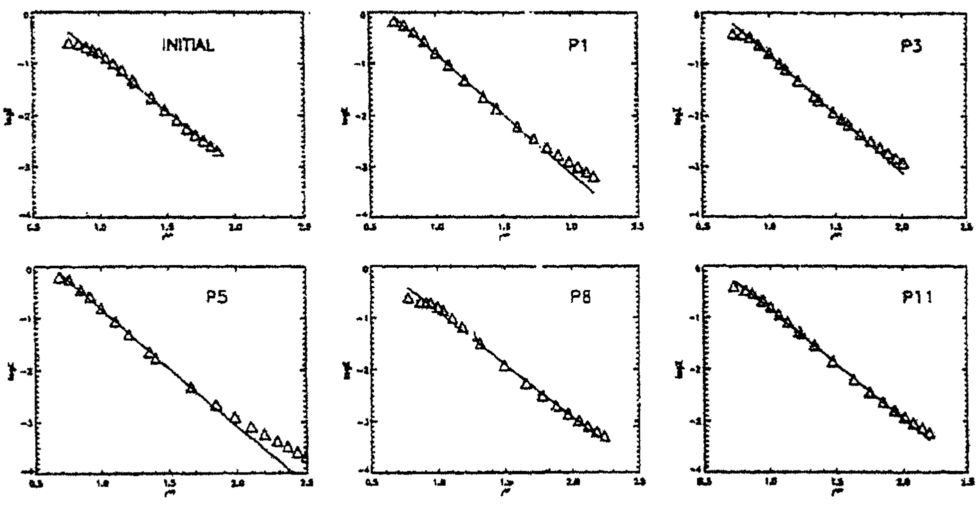

Figure 6: Plot of density vs $r^{1/4}$ for certain models.

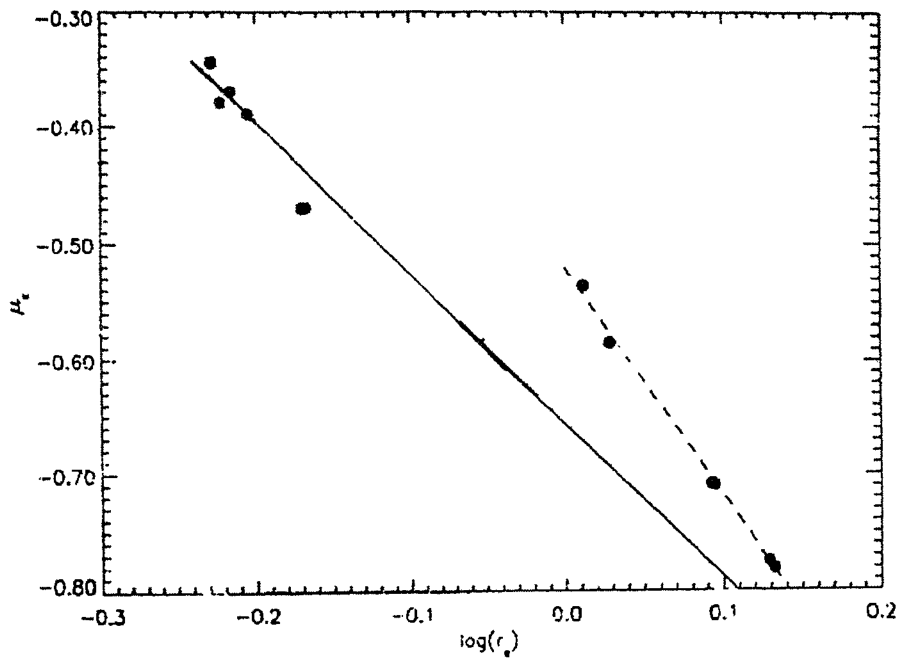

Figure 7: Plot of μ_e vs $\log(r_e)$ for the models before and after the collision.

loss is negligible during collision.

3.4. Comparison with previous work

[4] performed N-body simulations of pairs of spherical galaxies. His model D is similar to our model P5. Models E and F are also comparable with P3 and P1 respectively. Model E merges in about 10 crossing time. The merging time agrees with our estimates. However White did not follow model D till the merger is completed. We have quantified these results more accurately by considering both merging and non-merging collisions. Consequently it is possible to ascertain whether a collision with a set of collision parameters will result in a merger or not. According to our criterion model D will merge had it been followed for a few more crossing times.

[7] carried out numerical simulations of merging pairs and showed that equal mass mergers are more flattened than unequal mass mergers. He attributed the flattening observed in the remnants as partly due to rotation. He also cautioned that it is dangerous to extrapolate from the results of equal mass merging to unequal mass merging. The results for equal mass mergers agree well with our estimates. We also note that the acquired spin of the merger is not sufficient to support the relatively fast rotation observed in these systems. Further these remnants are elongated in a direction parallel to the direction of collision axis and at the same time compressed in a direction perpendicular to the orbital plane. A direct comparison becomes difficult as he used a different method for the integration of the orbits. However the over all macroscopic results agree well in both

cases.

[9] results of merging times for non-circular collisions agree within statistical errors with our estimates. It should be noted that [9] has used a method called multiple three-body algorithm in which the self gravity of the stars is neglected.

[10] performed computations of colliding galaxies where the initial system was following King models. He noted that merger remnants fell on a line of slope -2 which was different from that of normal ellipticals. He how ever considered only merging simulations. Our results show that the remnants lie on line of slope -2 and the survivors align on the line of normal ellipticals. Even though our initial models are different the results are consistent with that of [10].

4. Conclusions

We have performed numerical simulation of both merging and non-merging collisions of non-rotating equal mass spherical galaxies to investigate the effect of changing the closest approach distance. Our simulations cover a range in closest approach distance; $0 \leq \frac{p}{R_h} \leq 10$ and the initial relative orbit of the galaxy is parabolic. The hierarchical merging takes place for $\frac{p}{R_h} < 3$ and $V_p < V_e$. Merging does not takes place during the first close contact of the galaxies but during subsequent close contact only. The separation diminishes during subsequent passage and finally the two systems coalesce. Both energy and mass are fairly well conserved during the merger. In the (r_e, μ_e) plane, the merger remnants lie along a line to the right of that of normal ellipticals and its slope is $\sim$ -2. Equal mass distant encounters do not produce much disruption in the stellar systems as indicated by the value of $\Delta U / \mid U \mid$. The most wide encounter ($\frac{p}{R_h} = 10$) retains the structure of the component galaxies as that of the initial systems. In close encounters, the disruption effects are quite considerable and the value of $\Delta U / \mid U \mid \geq 1$. In these models merger takes place with considerable disruption.

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References

1 Alladin S M, Parthasarathy M, *Mon. Not. Roy. Astron. Soc.*, 184 (1978), 871.
2 Charlton J C, Whitmore B C, Gilmore D M, *ASP Conference Series.* 70 (1995), 49.
3 van Albada T S, van Gorkom J H, *Astron. Astrophys.* **54** (1977), 121.
4 White S D M, *Mon. Not. Roy. Astron. Soc.*, 184 (1978), 185.
5 Roos N, Norman C A, *Astron. Astrophys.* 70 (1979), 75.
6 Aarseth S J, Fall S, *Astrophys. J.*, 236 (1980), 43.
7 Villumsen J V, *Mon. Not. Roy. Astron. Soc.* 199 (1982), 493.
8 Farouki R T, Shapiro S L, Duncan M, *Astrophys. J.*, 271 (1983), 22.
9 Borne K D, *Astrophys. J.*, 287 (1984), 503.
10 Navarro J F, *Mon. Not. Roy. Astron. Soc.* 239 (1989), 257.
11 Navarro J F, *Mon. Not. Roy. Astron. Soc.* 242 (1990), 311.
12 Mc Glynn T A, *Astrophys. J.* 348 (1990), 515.
13 Namboodiri P M S, Kochhar R K, *Mon. Not. Roy. Astron. Soc.* 243 (1990), 276.
14 Barnes J E, *Astrophys. J.*, 393 (1992), 484.
15 Hernquist L, *Astrophys. J.* 400 (1992), 460.
16 Makino J, Hut P, *Astrophys. J.* 481 (1977), 83.
17 Funato Y, Makino J, *Astrophys. J.* 511 (1999), 625.
18 Evstigneeva E A, Reshetnikov V P, Sotnikova N Y, 2002. *Astron. Astrophys.*, 381 (2002), 6.

19 Gonzalez-Gracia A C, van Albada T S, *Mon. Not. Roy. Astron. Soc.*, 342 (2003), L36.
20 Nipoti C, Londrillo P, Ciotti L, *Mon. Not. Roy. Astron. Soc.*, 342 (2003), 501.
21 Dantas C C, Capelato H V, Ribeiro A L B, de Carvalho R R, *Mon. Not. Roy. Astron. Soc.* 340 (2003), 398.
22 Tremaine S, In *The Structure and Evolution of Normal Galaxies*, eds., S M Fall & D Lynden-Bell, University of Cambridge, (1981), 67.
23 Barnes J E, Hut P, *Nature*, 324 (1986), 446.
24 Binney J, Tremaine S, In *Galactic Dynamics*, Princeton University Press, Princeton, New Jersey, (1987).
25 Dekel A, Lecar M, Shaham J, *Astrophys. J.* 241 (1980), 946.
26 Alladin S M, Narasimhan K S V S, Ballabh G M, In *IAU Colloq.* 96, ed. M.J.Valtonen, Kluwer Academic Publishers, (1988), 327.
27 Capelato H V, De Carvalho R R, Carlberg R G, *Astrophys. J.*, 451 (1995), 532.
28 Kormendy J, *Astrophys. J.* 218 (1977), 333.

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