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Head-on collision of spherical galaxies

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Abstract. N-body simulations of head-on collision of a pair of identical spherical galaxies have been performed with a set of initial conditions covering both merging and non-merging types of collisions. The merging of the galaxies takes place when the relative velocity of collision V is less than about four times the internal velocity dispersion σ, i.e., $V < 4.1\sigma$. The transition between merging and non-merging of galaxies occurs in a narrow range in collision velocity. The energy change, the mass-loss, the half-mass radius, the central concentration etc. reach maximum value when $V = 4.1\sigma$. Mass transfer dominates when the collision velocity is small and consequently the merger remnants show negligible mass-loss. There is evidence for the formation of a tighter core and more extended envelope than that of the initial model. The estimates of energy transfer using impulse approximation show large discrepancy with numerical results in merging cases. In non-merging cases, the analytic formula overestimates the energy change by more than a factor of two.

Key words: stellar dynamics—numerical methods—galaxies—interactions—structure

1. Introduction

Several workers have long suggested that galaxy collisions are inevitable in clusters of galaxies. Nearly all the early type galaxies from the field or belonging to small groups have undergone at least one merger with a companion (Prieur 1990). Pairs of galaxies involved in interpenetrating collisions are expected to merge into a single system. Observations of colliding galaxy NGC 7252 by Schweizer (1982) provide evidence for a merged galaxy. In a head-on collision, the short range tidal force produces maximum disturbance during the overlap of the two galaxies. Head-on collisions in which the collision velocity is several times the internal velocity dispersion, leave the galaxies more or less unaffected. A pair of similar galaxies undergoing close encounter is expected to merge if the collision velocity is comparable to the internal velocity dispersion.

van Albada & van Gorkom (1977) considered the collision of two galaxies whose density distribution was similar to that of an $n = 3$ polytrope and showed that merging of galaxies occurred for relative velocity at infinity $V_\infty = 3\sigma$, where σ is the internal velocity dispersion. Roos & Norman (1979) investigated the effects of collisions in clusters of galaxies. They used very few particles to represent a galaxy and noted that head-on collisions resulted in a merger if the relative velocity of collision is about 3.2σ. Navarro & Mosconi (1989) performed computations in which a stellar system was represented by $N = 250$ particles. They used a pericentric velocity V_p in the range $2.7\sigma_p \leq V_p \leq 17\ \sigma_p$ where σ_p is the velocity dispersion at closest approach. Their numerical results showed discrepancy with estimates of impulse approximation. Fully self-consistent simulation of collisions between identical galaxies shows that in head-on collisions, capture occurs if $V_\infty^2 < 2.6 < v^2 >$ (see White 1982).

The most important encounters for the merger of galaxies to take place are precisely those in which the galaxies overlap significantly at closest approach and the relative velocity of collision is small. N-body studies of slow galaxy collisions of elliptical galaxies are surprisingly rare and have been neglected by observers for lack of morphological signatures. In this paper we study the effect of changing collision velocity on the dynamics of two identical spherical galaxies undergoing head-on collision. We use a large range in collision velocity i.e., $0 \leq V/\sigma \leq 7.5$. The present work essentially extends those of Roos & Norman and that of Navarro & Mosconi and uses a large number of particles ($N \sim 10^3$). The simulations cover both merging and non-merging collisions. The use of a wide range in collision velocity enables one to identify the transition zone from merging to non-merging type of collisions. The numerical results are compared with estimates obtained under impulse approximation.

The numerical model of our simulations is described in Section 2. The results are presented and discussed in Section 3. The conclusions are given in Section 4.

2. The model

2.1 *Initial conditions*

The model consists of a pair of spherical galaxies each containing $N = 1024$ particles of equal mass. A different random number generating seed is used to determine the positions and velocities of particles in each model. The initial location and velocity of the particles were determined so as to be consistent with the Plummer model. The deviation from virial equilibrium is about $1/\sqrt{N} = 0.03$. The units are chosen such that the gravitational constant G, as well as the mass M of the galaxy is set equal to unity. The initial radius of the galaxy is about 1.3 units. The half-mass radius R_h is close to unity and the energy, $U = -0.25$. The crossing time, given by $\tau = [G^2 M^5 / 2|U|^3]^{1/2}$, is equal to $2\sqrt{2}$. The velocity dispersion is nearly 0.24 and the ratio of radial to tangential velocity is 0.66. Initially the kinetic energy in radial motion is about 30 per cent of the total kinetic energy indicating that the orbits of the particles are predominantly tangential. The evolution of the two stellar systems is followed using Barnes' treecode (see Barnes & Hut 1986; Hernquist 1987). For the integrations, only the monopolar terms of tidal interactions have been considered. The accuracy parameter θ is set equal to unity and the softening parameter used is $\epsilon = 0.025$.

2.2 *Collision parameters*

To reliably follow the evolution of the stellar systems, they should be placed at large initial separation where the tidal effects are negligible. A crude estimate for the tidal effects can be obtained from the ratio of the magnitude of tidal force F_T to the internal gravitational force F_I assuming that the entire mass in each stellar system is concentrated at its respective centre. This gives rise to

$$\frac{F_T}{F_I} \sim 2 \left(\frac{R}{D}\right)^3 \tag{1}$$

where R is the radius of the stellar system and D, the initial separation between them. We take the value of $D = 16$ units so that $F_T/F_I < 10^{-3}$. It has been pointed out by Ostriker (1977) that in clusters, collision between galaxies will generally be hyperbolic regardless of the impact parameter and deviations from rectilinear motion of the galaxy centres will be small. Further, pairs of interacting elliptical galaxies are found with a large range, between 0–1200 km s^{-1}, of relative radial velocities (Quintana 1990). Consequently in our simulations the galaxies are set to move on nearly straight line orbits resulting in head-on collisions. The computations are performed with respect to the centre-of-mass of both the systems. The collision velocity is a crucial parameter in galaxy collisions. High velocity collisions that are common in clusters of galaxies do not produce mergers and have little effect on the inner parts of galaxies. The effect of such collisions can be approximately evaluated by the impulse approximation. Galaxy collisions in which the relative velocity of collision is small are the ones that affect the structure of the galaxy significantly. We consider various models in which the initial relative velocity of collision, V, is in the range $0 \leq V/\sigma \leq 7.5$. The various models are denoted by M1, M2, ..., M7. The X-Y plane is taken as the orbital plane and the galaxies are initially placed on the Y-axis on either side of the origin. The galaxies move along the direction of Y-axis and the head-on collision is expected to take place at the origin. The collision parameters and some of the important results are given in table 1.

3. Numerical results

3.1 *General features*

Head-on collision effects are different from that of eccentric ones because during the overlap, the additional mass exerts maximum force which causes them to collapse. This occurs generally during the time when the galaxies have minimum separation. In addition to this effect, if the relative velocity of collision happens to be small, the collision can result in the merger of the two systems. The general features of the galaxies at different times in the course of collision are shown in Figs 1-4. Fig. 1 shows the projection of particles on to the X-Y plane at various times during a collision for $V/\sigma = 5.83$ (Model M2). The first close contact occurs at $t = 10$ and by $t = 25$ they separate into two non-overlapping systems. Both the galaxies survive the collision and develop more or less identical structures. Fig. 2 shows the structure of the galaxies undergoing collision with $V/\sigma = 4.1$ (Model M3). The merging takes place at $t = 14$ and at $t = 30$, they recede from each other and can be clearly identified as two separate systems. The collision in this case produces more damage than that in the previous case. Few particles gain energies close to zero and escape from the system. The effect of a head-on collision when $V/\sigma = 3.3$ (Model M4) is shown in Fig. 3. The first close contact occurs at $t = 16$. At $t = 24$, they separate into two systems. In this model the galaxies are on a merging course. When a pair of galaxies are on a merging course they experience a series of close encounters. The merging becomes complete after the second close encounter at $t = 32$. After that the centres of the systems are nearly coincident. The interaction is stronger after the pericentric passage and produces maximum tidal effects. The configuration of the galaxies for $V/\sigma = 2.5$ (Model M5) is shown in Fig. 4. The merging is delayed till $t = 34$, and the coalesced configuration is roughly maintained till $t = 48$. In models M5, M6 and M7 the mass-loss is less than 11 per cent indicating that most of the mass is bound to the merged remnant.

Table 1. Collision parameters and results.

1	2	3	4	5	6	7	8	9	10	11	12
Model	$\frac{V}{\sigma}$	T_D	$\frac{\Delta U}{\|U\|}$	$\left(\frac{\Delta U}{\|U\|}\right)_{IA}$	$\frac{\Delta M}{M}$	Q	R_h	R_{20}	R_{80}	σ	β
M1	7.50	7	0.421 0.412	1.03	0.042 0.048	0.52 0.51	1.49 1.47	0.88 0.98	2.94 2.93	0.23 0.21	0.89 0.93
M2	5.83	10	0.705 0.691	1.37	0.172 0.154	0.64 0.63	1.58 1.92	0.94 1.24	5.98 5.29	0.24 0.23	1.12 1.05
M3	4.10	14	0.889 0.876	2.20	0.196 0.023	0.69 0.75	2.29 2.42	2.21 2.26	6.87 6.94	0.24 0.23	1.04 1.08
M4	3.33	16	0.036	2.54	0.110	0.54	1.92	1.05	6.63	0.32	1.02
M5	2.50	20	0.026	3.70	0.084	0.52	1.64	0.84	6.49	0.33	0.97
M6	1.67	24	0.021	4.77	0.065	0.52	1.45	0.75	5.21	0.36	0.90
M7	0.00	50	0.014		0.042	0.50	1.46	0.72	3.80	0.36	0.87

Note (1) Model identification; (2) Initial collision velocity in terms of internal velocity dispersion; (3) Merging time from the start of simulation; (4) Fractional change in energy; (5) Fractional change in energy using impulse approximation; (6) Fractional mass-loss; (7) Virial coefficient $Q = T/|W|$, T and W being total kinetic and potential energy; (8) Half-mass radius; (8) & (9) Radii containing 20 and 80 per cent of mass normalized with respect to their initial values; (11) velocity dispersion; (12) Velocity anisotropy parameter $\beta = V_r/V_t$, V_r & V_t being the radial and tangential velocity dispersion. The quantities in columns 4, 6, 7, 8, 9, 10, 11 and 12 for models M1, M2 and M3 represent those corresponding to each galaxy in the pair.

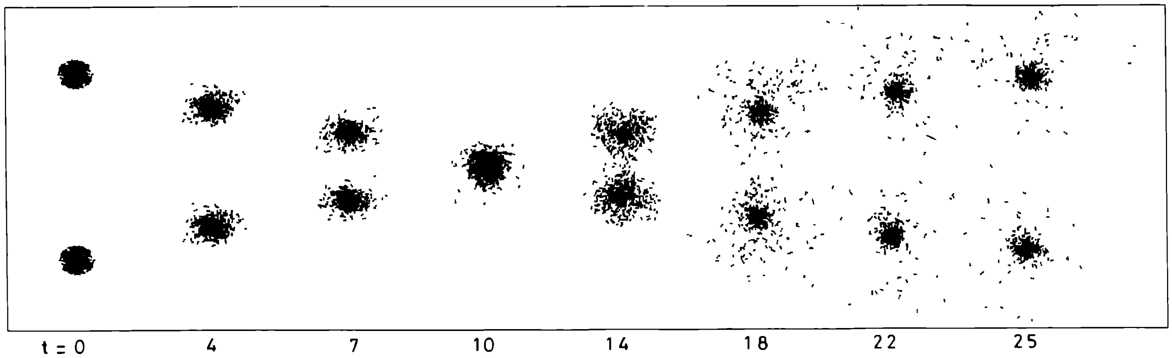

Figure 1. Projection of particles onto the orbital plane for model M2. The numbers indicate the time after the start of the simulation.

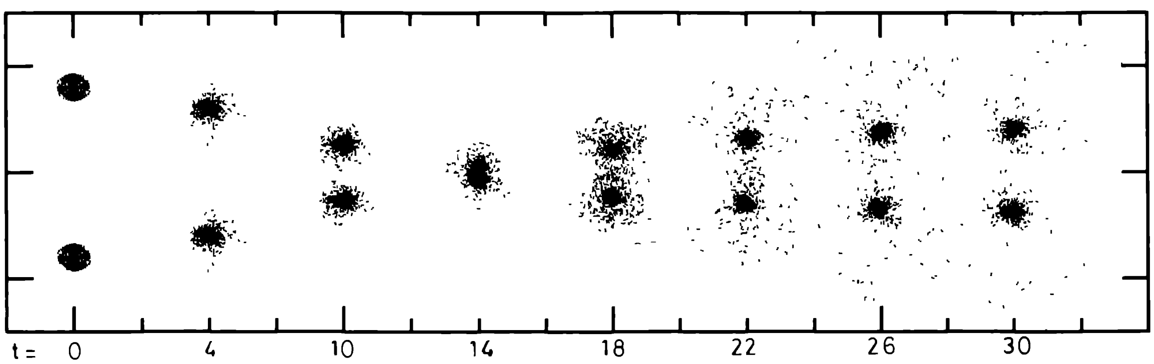

Figure 2. Same as fig.1 but for model M3.

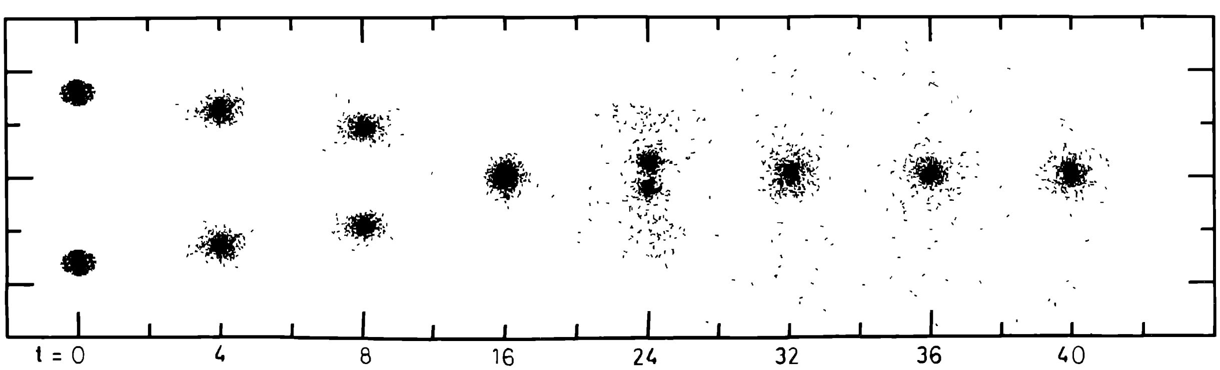

Figure 3. Same as fig.1 but for model M4.

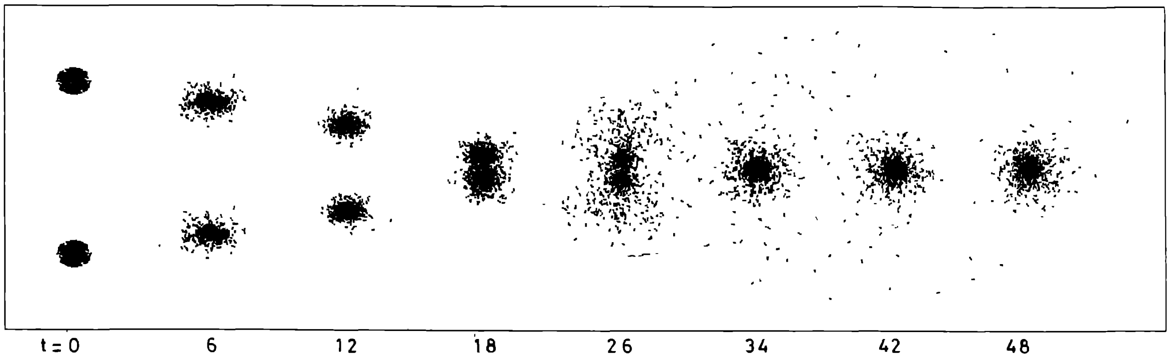

Figure 4. Same as fig.1 but for model M5.

In models M4, M5, M6 and M7 the merger remnants are elongated along the line of orbit and flattened towards the orbital plane. The elongation is maximum for model M4 (70%) and minimum for model M7 (35%). For the sake of convenience we denote the core radius by $R_{20}$and the outer radius by R_{80}. Here R_{20} and R_{80} respectively denote the radii containing 20 and 80 per cent of the mass and they are normalised with respect to the corresponding initial values. Most of the particles beyond R_{80} have energies close to zero and hence R_{80} can be taken as the radius of the bound system. The core radii of the merger remnants slightly decrease from their initial values. However the outer radii show considerable expansion. This expansion is approximately seven times its initial value for model M4. The extent of the outer envelope decreases as the collision velocity decreases as can be seen from table 1. The merger remnants are characterised by a contracted core and an extended outer envelope. A similar phenomenon has been observed by White (1978) for galaxies undergoing off-centre collisions.

3.2 *Change in energy and mass*

During the collision of two galaxies, the orbital energy is transferred to the internal energy of the galaxies. Consequently some of the stars in each galaxy gain enough energy to escape from the system. An estimate of the energy change and the mass loss is expected to provide information regarding the structure of the galaxies. If the change in the internal energy is larger than its initial energy, the galaxy would suffer considerable disruption during the course of a collision. It has been shown that if $\Delta U/|U|>2$, tidal disruption of the galaxy occurs and if $\Delta U/|U|\leq 2$, the disruption is considered negligible (Namboodiri & Kochhar 1990). Here U is the unperturbed total energy of the galaxy and ΔU, its change during a collision.

The gain in galalxy energy increases with decreasing collision velocity. In models M1, M2 and M3, where the relative velocity of collision is high, $\Delta U/|U|<<1$ and the galaxies survive the collision. In models M4, M5, M6 and M7 the collision results in the merger of the two galaxies. $\Delta U/|U|$ takes a sharp turn around V = 4.1s and further reduction of the collision velocity produces a steep descend in $\Delta U/|U|$. Fig. 5 shows the variation of $\Delta U/|U|$ with V/σ. Maximum tidal effects are observed when $V = 4.1\sigma$. The quantities like the half-mass radius R_h, the central concentration given by R_{20} and the radius of the bound system denoted by R_{80} also reach maximum for this model. The anisotropy parameter β, i.e. the ratio of radial to tangential velocity, is given in column 12 of table 1. An examination of these values indicates that the merger remnants tend to approach more and more isotropic.

Fast head-on collisions of identical spherical galaxies generally produce negligible mass-loss. van Albada & van Gorkom's N-body simulation produced a mass-loss of one per cent. In off-centre collisions, Aguilar & White (1985) noted that 30 per cent of the mass lost by one galalxy was captured by the other when the collision velocity is smaller than the velocity dispersion. Roos & Norman have obtained a mass-loss of 25 per cent for head-on collisions of identical galaxies. White's simulations produced escapers of a few per cent. However he noted that more particles escaped from the parabolically colliding systems than from those which are initially on bound orbits. Navarro & Mosconi found that exchange of particles takes place between the galaxies and softer encounters are efficient in producing larger mass-loss. Our experiments show that non-merging simulations produce a mass-loss of less than 20 per cent. When the galaxies merge, the mass-loss does not exceed 11 per cent. We also find that some material escaping from one galaxy is captured by the other and vice versa. The velocity dispersion of the merger remnant increases by 30 to 50 per cent of the initial value. An examination of the values of $Q = T/|W|$ where T and W are respectively the kinetic and potential energy of the system shows that the merger remnant tends to evolve into a state of virialised situation. The values of $\Delta U/|U|$, $\Delta M/M$ and Q are given in table 1.

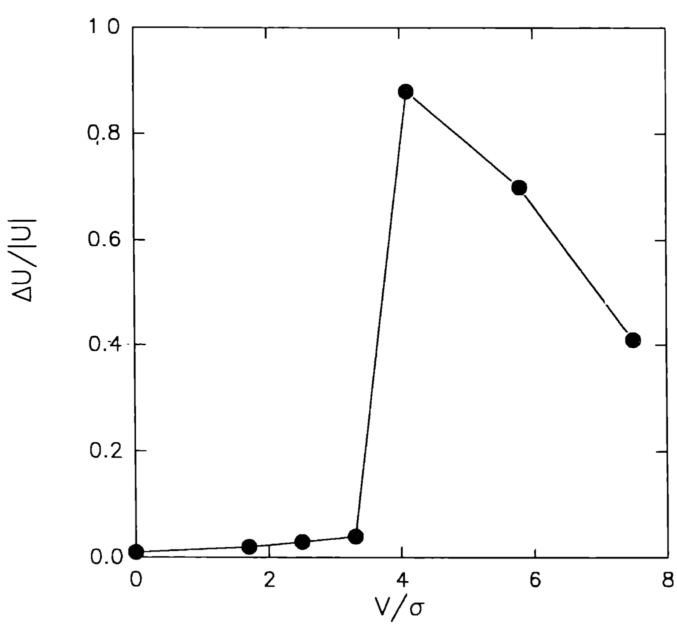

Figure 5. The variation of $\Delta U/|U|$ with V/σ.

3.3 *Merging criterion*

The criterion used to determine whether a pair of galaxies have merged is based on the relative separation between their centres-of-mass. The centre-of-mass of each system is determined by a method similar to that adopted in Namboodiri & Kochhar (1990). The galaxies are assumed to have merged if their separation never exceeds 3R after the pericentric passage. In Fig. 6 the separation is plotted as a function of time for all the models. It is interesting to see that there exists a bump in the cases for models M4, M5, M6 and M7. This indicates that the galaxies come close together more than once and the merging is complete only after the second close contact. The quantity T_D in table 1 measures the time of first minimum separation after the start of the simulation. T_D increases as the relative velocity of collision decreases. Figs 3 & 4 clearly show the process of merging for models M4 and M5.

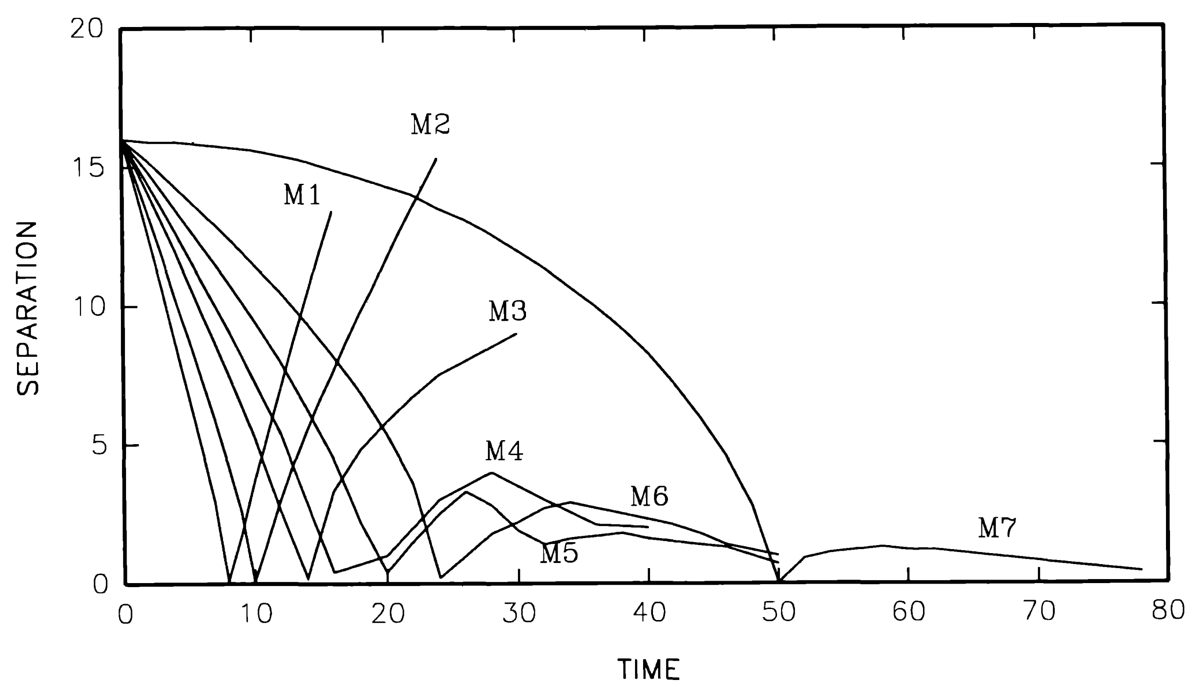

Figure 6. The separation between the galaxies is shown as function of time for all models.

Tremaine (1981), using impulse approximation, has derived analytic formula for the merging of spherical galaxies. According to this formula, the galaxies will merge if the relative velocity of collision V satisfies the relation,

$$V < \left[\frac{32\,G^2}{3M} \int_0^\infty \left[\frac{M(p)}{p} \right]^3 dp \right]^{1/4} \tag{2}$$

where M(p) is the projected galaxy mass within cylindrical radius p. For a Plummer model galaxy this turns out to be

$$V < 1.16 \left(\frac{3\pi GM}{4\alpha} \right)^{1/2} = 1.16\, V_{esc} \tag{3}$$

where V_{esc} is the escape velocity (see Alladin & Narasimhan 1982 and equation 7 below). Our numerical simulation shows that two identical galaxies merge if $V < 4.1\sigma$. This compares favourably with the result in equation (3). However the transition from merging to non-merging occurs in a narrow range in collision velocity, i.e., $3.3 < V/\sigma < 4.1$.

3.4 *Comparison with previous work*

The transfer of orbital energy and angular momentum to the internal energy and spin of the galaxies takes place during a collision. This increase in the binding energy results in their expansion. Approximate estimates of the magnitude of the energy transfer can be made by the *impulse approximation* (IA) method. The IA assumes that the collisions are so fast that the stellar motions can be neglected in comparison with the motion of galaxies. Under this assumption Alladin & Narasimhan (1982) have derived analytical expression for the relative change in the energy of a Plummer model spherical galaxy undergoing head-on collision. The change in the energy of a galaxy is the same as the change in its kinetic energy and it is given by

$$\Delta U = \Delta T = \frac{1}{2} \int V_\perp^2 dM = \frac{G^2 M^3}{3 V^2 \alpha^2} \tag{4}$$

where $V_\perp$ is the lateral speed of a test particle, M is the mass of the galaxy which moves with a constant large speed V and α is the scale length (see Toomre 1977). The self potential energy W of a Plummer model is

$$W = -\frac{3\pi GM^2}{32\,\alpha}. \tag{5}$$

Using the virial theorem one can write the relative change in energy as

$$\frac{\Delta U}{|U|} = \frac{64\,GM}{9\pi \alpha V^2}. \tag{6}$$

The escape velocity V_{esc} of the two-body problem is

$$V_{esc}^2 = \frac{3\pi GM}{4\alpha}. \tag{7}$$

Using (7) and (6) we have,

$$\frac{\Delta U}{|U|} = \frac{256}{27\pi^2} \left(\frac{V_{esc}}{V}\right)^2 \approx \left(\frac{V_{esc}}{V}\right)^2. \tag{8}$$

The IA estimates for all models except for model M7 are given in table 1. There exists a large discrepancy between numerical results and IA estimates. The increase in the energy during the time of maximum overlap is distributed among the particles causing more particles to become unbound. The escape of particles is not taken into account when estimating the energy of the galaxy. The particles move appreciably when the collision velocity is small. In the derivation of IA formula the motion of the stars is neglected which helps in reducing the tidal effects. In models M1 and M2 where there is no merging, the IA overestimates the energy change by more than a factor of two.

Aguilar & White (1985) found good agreement between the results obtained from impulse approximation and N-body experiments. They simulated a series of fast and distant encounters and concluded that the agreement holds only for impact parameters larger than 10 effective radii. Moreover they modelled the initial galaxy having King and de Vaucouleurs surface density profiles which is more centrally concentrated than our model. However Navarro & Mosconi (1989) compared their N-body results of head-on collisions with those obtained from impulse approximation. They noted that for low relative velocities, i.e., $V_p < 5\sigma_p$, the impulse approximation is found to overestimate the energy and mass-loss. In our models, this condition is satisfied as a result of which our numerical results significantly differ from that obtained from impulse approximation. Miller & Smith (1980) had pointed out that IA cannot be used for velocities less than 1000 km s^{-1}. If the velocity dispersion in a galaxy is taken to be 150 km s^{-1}, the ratio V/σ turns out to be greater than five which is clearly the case in models M1 and M2. Consequently none of the collisions in the present experiment could be described by the IA.

Our results are in good agreement with those obtained by van Albada & van Gorkom (1977). A comparison of Fig. 5 with the corresponding one in Roos & Norman (1979 Fig. 1) shows discrepancy for low velocity collisions. A detailed comparison, however, becomes difficult since they used very few particles ($N = 94$) to represent a stellar system.

4. Conclusions

The simulations described above demonstrate the processes of merging when two identical non-rotating spherical galaxies collide in a head-on fashion. The simulations are idealized and cover only a limited range in initial conditions. The main conclusions are the following:

(1) When two identical spherical galaxies undergo a head-on collision, merging occurs if the relative velocity of collision is smaller than about four times the internal velocity dispersion, i.e., $V < 4.1\sigma$. The condition for merging predicted by IA appears to be valid for self-consistent numerical simulations.

(2) The galaxies experience mass transfer and consequently the mass-loss is generally negligible.

(3) The merger remnant has a larger value for the half-mass radius. It shows higher central concentration and a more extensive envelope than that of the initial model. Tidal effects increase with V until it reaches $V = 4.1\sigma$ and afterwards they decrease with V. Maximum tidal effect is observed when $V = 4.1\sigma$. The energy change shows sudden decrease below $V = 4.1\sigma$. The velocity distribution tends to be more and more isotropic for $V/\sigma < 4.1$. The velocity dispersion increases by about 30 — 50 per cent.

(4) Comparison of IA estimates with numerical results for the energy change shows large discrepancy. In non-merging cases, IA overestimates the energy change by more than a factor of two. IA estimates could not be used for the merging simulations.

We have used a modest number of particles to represent a galaxy so that the simulations can be performed with the available computational facilities. However our results are consistent with those of earlier workers who mainly considered off-centre collisions of different types of galaxies. Its extension to the case of self-consistent head-on collisions covering both merging and non-merging types of collisions of identical spherical galaxies appears to be new.

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