Bull. Astr. Soc. India (2000) **28**, 529-538

Tidal effects on a satellite galaxy influenced by a massive perturber

P.M.S. Namboodiri[1], R. Cowsik[1,2] and D. Sugimoto[3]

[1]*Indian Institute of Astrophysics, Bangalore 560 034, India*
[2]*Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India*
[3]*Department of Earth Science and Astronomy, University of Tokyo, Tokyo 153, Japan*

Received 20 September 1999; accepted 24 March 2000

Abstract. The tidal influence on a satellite galaxy by a massive perturber is studied by numerical simulations. The satellite is modelled as a non-rotating spherical cluster of uniform density. The perturber is a galaxy described as a Plummer model. The satellite undergoes penetrating collisions on hyperbolic, parabolic, elliptic and circular orbits. The disruption of the satellite, in parabolic and elliptic encounters, is estimated in terms of the density ratio ρ/ρ_R where ρ is the mean density of the satellite and ρ_R a critical density, the Roche density. In these models the satellite suffers disruption when $\rho < \rho_R$ and survives the tidal encounter otherwise. The survival of the satellite strongly depends on the distance of closest approach. The direction of the orbital angular momentum after the encounter is aligned with that of the initial orbital angular momentum of the pair.

Our results also suggests that disruption of the satellite occurs for values of ρ/ρ_R < 3 in circular orbit encounters. In hyperbolic encounters the satellite galaxy is seen to suffer considerable damage only in the case of near head-on collision.

Key Words : stellar dynamics - galaxies: interactions - methods: numerical.

1. Introduction

Tidal disruption and merging are two important processes in the dynamical evolution of a binary stellar system. The times of disruption and merging for a pair of spherical galaxies moving in circular orbit is given by

$$\frac{\tau_d}{\tau_m} \approx \frac{6}{(5-n)} \frac{a}{R} \frac{M}{M_l} \tag{1}$$

where τ_d and τ_m are the disruption and merging times, M and M_1 are the masses of the galaxies, a is the orbital radius, R is the radius of M and n is the polytropic index describing the density distribution of M (Alladin & Parthasarathy, 1978). It can be seen that if the galaxies are centrally concentrated and have similar masses, merging occurs more rapidly than disruption.

On the other hand, if the masses are appreciably different the interaction between them is likely to cause considerable disruption of the less massive galaxy. In this case the disruption time could be shorter than the merging time.

Most of the earlier simulations dealt with collisions of galaxies of comparable mass (e.g., White 1978; Gerhard 1981; Barnes 1988; see White 1982 for review). Collisions of galaxies of unequal mass were considered by Dekel, Lecar & Shaham (1980), Villumsen (1982), Aguilar & White (1985), Mc Glynn (1990), Namboodiri & Kochhar (1991). Dekel et. al considered slow hyperbolic encounters and obtained total changes in the energy of a satellite galaxy. Villumsen (1982) considered the merger of galaxies having mass ratio 3:1. Aguilar & White (1985) considered hyperbolic encounters and compared their results of energy change and mass loss with those computed using impulse approximation. Mc Glynn studied collisions of galaxies having mass ratio in the range $10^2 - 10^6$ and compared the density profiles with a sample of elliptical galaxies.

Namboodiri & Kochhar (1991) have studied a model consisting of a compact cluster and a point-mass perturber undergoing non-penetrating collisions. The assumption that the perturber is a point-mass object is valid in the case of distant collisions. They estimated the stability of a compact cluster in terms of the density ratio ρ/ρ_R where ρ is the mean density of the satellite and ρ_R, a critical density called the Roche density. The compact satellite suffered considerable disruption if $\rho/\rho_R < 1/2$ and survived the tidal encounter if $\rho/\rho_R > 1/2$. Evidently it is of great interest to extend this work in the case of galaxies having different density and undergoing penetrating collisions. The present work considers a pair of galaxies having different masses and densities and the collision is a penetrating one. Moreover both the galaxies are modelled as self-consistent N-body systems. The disruption of the less massive galaxy is investigated in terms of the changes in its internal energy. We derive a criterion for the disruption of a galaxy due to the influence of a massive perturber. The behaviour of the transfer of orbital angular momentum is also investigated. Our model is described in section 2. The results are presented in section 3. The conclusions are given in section 4.

2. Initial conditions

Our model consists of two galaxies the primary and the secondary whose mass distributions are chosen in such a way that they represent extreme cases of high central concentration and uniform mass distribution respectively. It is convenient in the present case to designate the more massive galaxy as the primary (perturber) and the less massive one as the secondary (satellite). The primary has disruptive effects on the secondary whereas the effect of secondary on primary is negligible. The secondary is a spherical galaxy of uniform density containing N=512 particles. It has a half-mass radius equal to 1.5 units. The total mass M_2 of the secondary is set equal to unity as is the gravitational constant G. The units of mass, distance and time for a typical simulation are respectively 10^{11} $M_\odot$, 1 kpc and 1.5 Myr. The primary galaxy whose mass is denoted as M_1, is a spherical cluster whose density distribution closely follows the Plummer model (n=5 polytrope). Since the radius of a Plummer model galaxy is infinite, we choose a cut off radius, viz. $R_1 = 10$ within which lies more than 98 percent of the mass of the galaxy. The radius of the secondary $R_2 = 2$. We use mass ratios $\mu = 5$, 10, 20 and 50 where $\mu = \frac{M_1}{M_2}$.

The individual particles in both the galaxies have equal mass and the number of particles in the primary for different simulations are given in table 1. Both the model galaxies have been evolved in isolation for a few crossing times and found to be in equilibrium.

One of the most important parameter in a galaxy collision is the velocity of collision. High speed collisions in which the perturber moves in a hyperbolic orbit may not produce much changes in the galaxies. Slow collisions in which the galaxies move in bound orbits is expected to result in the merger of the galaxies within a Hubble time. Intermediate type of collisions on parabolic orbits may cause considerable damage to the less massive companion. We have, therefore, concentrated mainly on collisions in which the relative orbit of the pair is parabolic. Additionally we have a few simulations in which the relative orbit is elliptic, circular and hyperbolic. The eccentricities in the elliptic and hyperbolic orbit encounters are respectively e = 0.5 and e = 2.0. The various models are denoted by the letters H, P, E and C followed by a number. The letters H, P, E and C identifies the type of relative orbit, viz., hyperbolic, parabolic, elliptic and circular respectively of the pair in a particular model. The orbital plane is the X-Y plane. The initial separation between the galaxies is 20 units in parabolic models and 15 units in hyperbolic models. In the elliptic orbit models the satellite is placed at the apocentre initially. The distance of closest approach p is chosen in the range $4 \leq p \leq 8$ except in H models. This choice of p ensures that mergers are avoided. The collision parameters and the results for various models are given in table 1. The evolution of the combined system is followed till either the satellite disrupts or shows tendency to recede from the primary.

3. Results and discussion

3.1 General features

The satellite galaxy remains almost intact until it crosses the perigalactic point. There is considerable rearrangement of energy and angular momentum taking place during the second half of the encounter. Consequently many particles in the satellite gain enough energy and become unbound from the system. For smaller values of p, the satellite shows tendency for disruption and loses more than 40 per cent of its initial mass in P, E and C models. In disrupting cases the satellite leaves a spray of particles connecting the primary in the form of a tail (Toomre & Toomre, 1972). The encounter does not have any profound effect in the primary galaxy. The mass loss is essentially absent and there is very little change in its internal energy. The overall size increases as a result of which it shows slight expansion. The expansion occurs in the outer region whereas the inner half-mass region remains intact. Of the 18 simulations we carried out, the satellite in ten cases disrupted and in the rest of them it survived the encounter.

3.2 Transfer of orbital energy

Orbital energy and angular momentum are transferred to the internal energy and spin of both the galaxies. The values of $\left[\frac{\Delta E}{|E|}\right]_P$, $\left[\frac{\Delta E}{|E|}\right]_S$, $\left[\frac{L_S}{L_{orb_i}}\right]_P$ and $\left[\frac{L_S}{L_{orb_i}}\right]_S$ are given in table 1. Here E is the unperturbed self energy of a galaxy and ΔE its change during an encounter, L_S is the magnitude of the spin angular momentum which was initially zero and L_{orb_i} is the initial orbital angular momentum. The suffixes P and S respectively refer to quantities corresponding to the primary and secondary galaxy. The gain in the internal energy of the primary galaxy in P models is negligible as can be seen from table 1. This energy change is maximum in elliptic orbit model

E1. The secondary galaxy acquires most of the energy during the encounter. A galaxy is considered disrupted if it loses more than 40 per cent of its initial mass and in such cases the value of $\Delta E/|E|$ is found to be greater than two. $\Delta E/|E| = 1$ does not necessarily imply the total disruption of the satellite galaxy, as a significant fraction of the mass may still remain bound in this case; e.g., in model C2 even though $\Delta E/|E| = 1.162$ more than 60 per cent of the mass is bound to the galaxy and consequently the secondary is not considered as disrupted. The criterion for disruption, $\Delta E/|E| > 2$, is in agreement with that of Miller (1986) and also that of Namboodiri & Kochhar (1990).

The mean density ρ of the satellite of mass M_2 within radius R_2 is

$$\rho = \frac{3M_2}{4\pi R_2^3} \tag{2}$$

We define a critical density ρ_R, called the Roche density as

$$\rho_R = 2\rho_1 = \frac{3M_1}{2\pi p^3} \tag{3}$$

The values of ρ/ρ_R for various models are given in table 1. In figure 1 we plot the fractional change in energy of the satellite in P and E models, against the density ratio ρ/ρ_R. It is evident

Table 1. Collision parameters and results.

Model	μ	p	N	$\left[\frac{\Delta E}{\|E\|}\right]_P$	$\left[\frac{\Delta E}{\|E\|}\right]_S$	$\left[\frac{L_S}{L_{orbi}}\right]_P$	$\left[\frac{L_S}{L_{orbi}}\right]_S$	$\frac{\Delta M}{M}$	$\frac{\rho}{\rho_R}$
H1	10	0.5	5120	0.191	2.45	6.30E-2	7.22E-2	0.59	0.0008
H2	10	1	5120	0.204	0.39	5.81E-2	4.25E-2	0.20	0.006
P1	5	4	2560	1.50E-2	2.42	6.79E-2	0.612	0.48	0.80
P2	5	5	2560	1.05E-2	1.40	3.46E-2	0.451	0.25	1.56
P3	5	6	2560	7.17E-3	0.51	4.48E-2	0.145	0.02	2.70
P4	10	4	5120	2.10E-3	4.02	3.94E-2	0.856	0.81	0.40
P5	10	5	5120	1.69E-3	3.13	2.37E-2	0.820	0.60	0.78
P6	10	6	5120	3.06E-4	1.92	2.76E-2	0.405	0.31	1.35
P7	20	6	10240	1.26E-3	4.22	3.19E-2	0.833	0.56	0.68
P8	20	7	10240	2.06E-3	1.85	3.54E-2	0.444	0.33	1.07
P9	20	8	10240	1.02E-3	1.72	1.02E-2	0.256	0.26	1.60
P10	50	6	25600	1.58E-2	8.90	6.78E-2	0.930	0.91	0.27
P11	50	7	25600	1.69E-2	8.94	5.50E-2	0.885	0.89	0.43
P12	50	8	25600	1.71E-2	5.88	4.35E-2	0.709	0.57	0.64
E1	10	5	5120	0.916	2.15	0.178	0.507	0.57	0.78
E2	10	6.5	5120	0.392	0.08	4.09E-2	0.632	0.26	1.72
C1	10	7	5120	0.403	2.41	0.187	0.606	0.42	2.14
C2	10	8	5120	0.388	1.16	0.149	0.902	0.34	3.20

Note : Column 1, model identification; column 2, mass ratio; column 3, distance of closest approach; column 4, number of particles in the primary; columns 5 & 6, fractional change in energy of primary and secondary; columns 7 & 8, ratio of orbital angular momentum after the encounter to the initial orbital angular momentum; column 9, mass loss of secondary; column 10, density ratio.

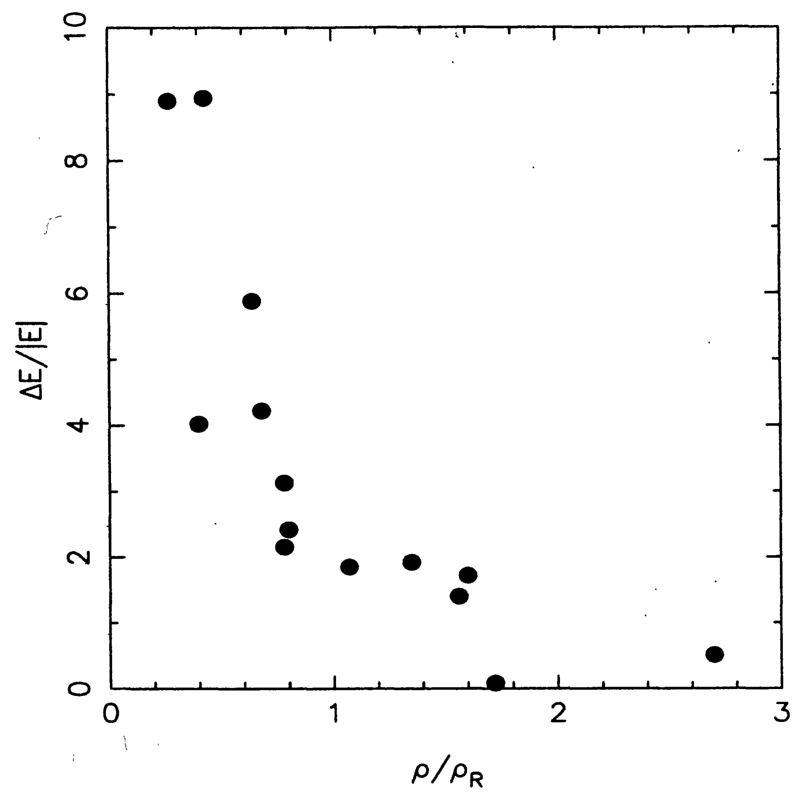

Figure 1. Plot of relative change in energy $\Delta E/|E|$ against density ratio ρ/ρ_R for P and E models.

from this figure that tidal effects as measured by $\Delta E/|E|$ fall off steeply upto $\rho/\rho_R = 1$ but decreases more slowly beyond this. It can be seen that in these models disruption of the satellite occurs for values of $\rho/\rho_R < 1$. This is different from the results of Namboodiri & Kochhar (1991) in which it was shown that disruption occurs near $\rho/\rho_R < 1/2$. This difference is due to the fact that their satellite galaxy was much more centrally concentrated than that in the present case. Moreover the perturber was a point mass object and the collision was along a distant circular orbit. Alladin, Ramamani & Meinya Singh (1985) have performed analytic calculations under the assumption of adiabatic approximation and have shown that there would be a sudden decrease in the disruption rate near $\rho_h = \rho_R$ where ρ_h is the density of the satellite at half-mass radius. Our results, however, show that one should use, in the case of a secondary that is much less centrally concentrated, the full radius instead of the half-mass radius to obtain the condition for disruption. We thus see that for parabolic and elliptic orbit encounters tidal disruption can fairly well be determined by estimating the density ratio ρ/ρ_R. If $\rho/\rho_R < 1$, the satellite suffers considerable disruption whereas for $\rho/\rho_R \geq 1$ the satellite is expected to survive an encounter. We also note that as p increases, the tidal effects decrease whereas an increase in the mass ratio results in an increase in the tidal effects as expected on general grounds. The ratio ρ/ρ_R is equivalent to the ratio F_I/F_T where F_T is the magnitude of the tidal force at perigalactic point and F_I is the internal gravitational force and the condition for disruption becomes $F_I/F_T < 1$ (Miller 1986). It can be seen from figure 1 and table 1 that

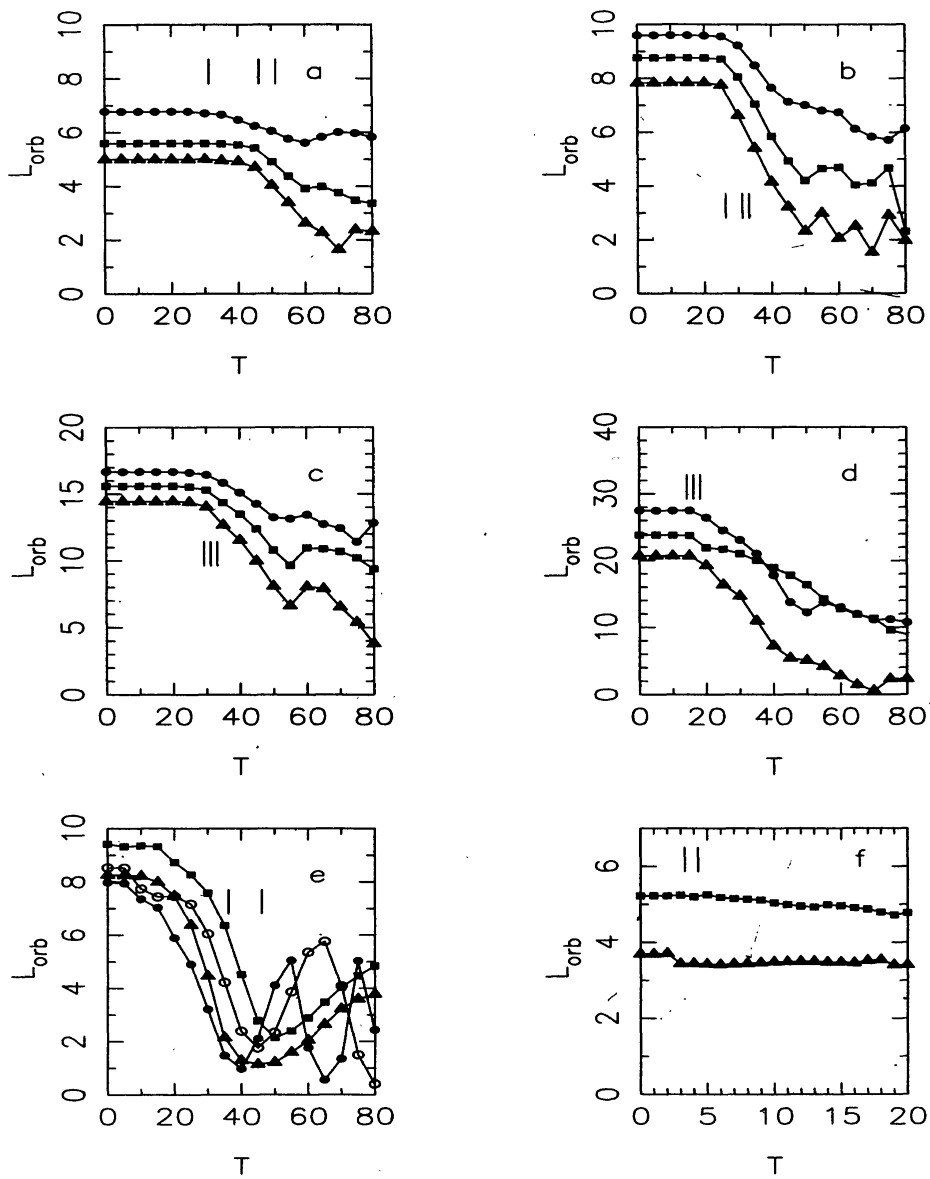

Figure 2. Variation of orbital angular momentum with time. a) μ = 5, b) μ = 10, c) μ = 20 of P models, d) μ = 50, e) μ = 10 for E and C models, f) μ = 10 for H models. Symbols filled triangle, filled square and filled circle respectively represent models P1, P2, P3 in (a) P4, P5, P6 in (b) P7, P8, P9 in (c) and P10, P11, P12 in (d). Filled triangle, filled square, filled circle and open circle represent models E1, E2, C1 and C2 in (e). Filled triangle and filled square represent models H1 and H2 in (f). The symbol I marks the time of perigalactic passage in H, P and E models in ascending order of p.

in models P2, P3, P6, P8, P9 and E2 the ratio $\rho/\rho_R > 1$ and $\Delta E/|E| < 2$ and consequently the satellite survives the encounter. The above results are not valid for circular and hyperbolic orbit encounters. An examination of table 1 reveals that disruption occurs in C models for $\rho/\rho_R <$ 3. In the case of H models it is very difficult to get the less massive companion disrupted unless it is on a near head-on collision with large eccentricity as in the case of model H1. The condition for disruption in H models can not be inferred from these simulations.

3.3 Transfer of Orbital Angular Momentum

The variation of orbital angular momentum L_{orb} with time is shown in figure 2. L_{orb} is the orbital angular momentum computed with respect to the centre of mass of the combined system. The orbital angular momentum remains almost constant till the satellite reaches the perigalactic point. This time is marked by the symbol I for P, E and H models. A dramatic change in its behaviour occurs after this instant. At various times, the internal spin L_S (L_P) is computed with respect to the centre of mass of the satellite (perturber). As in the case of energy transfer, the primary galaxy gains very little spin due to the encounter. This can be seen from table 1. The maximum gain in spin is less than 7 per cent in P and H models. In E and C models this is about 18 per cent. A large fraction of the transferred angular momentum is absorbed by the escaping particles in the satellite galaxy. In disrupting cases, more than 60 per cent of L_{orb_i} is transferred to the satellite. The variation of L_{orb} shows oscillatory behaviour in E and C models as can be seen from figure 2(e). This is due to the fact that in these models, the galaxies are moving in closed orbits as a result of which the direction of tidal acceleration gets partially

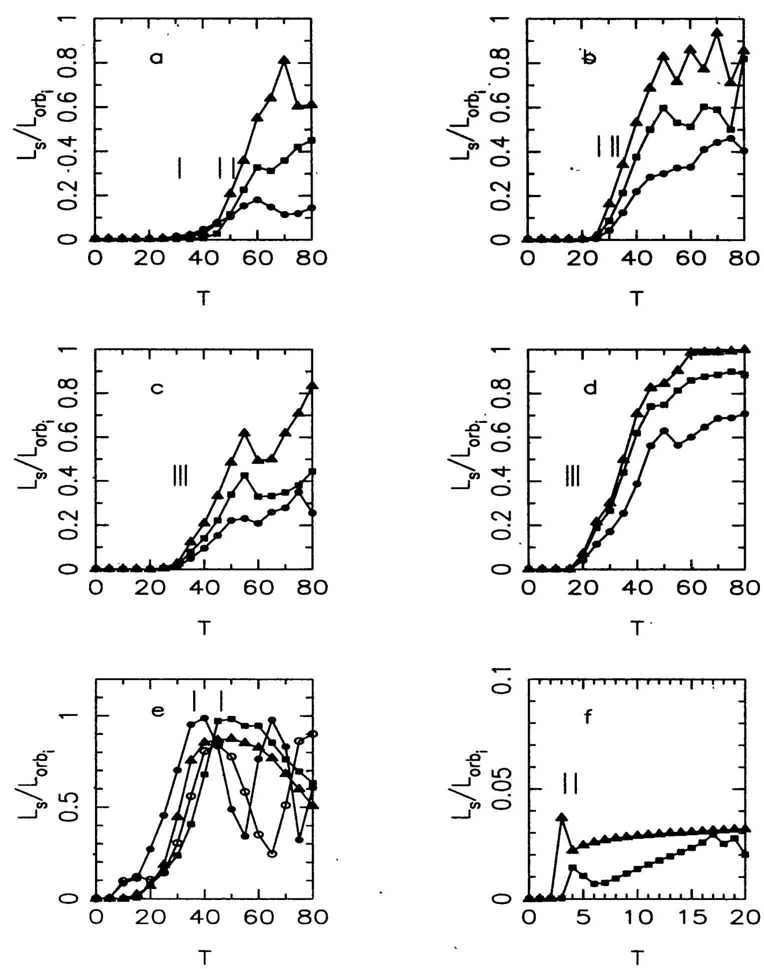

Figure 3. Variation of the ratio of internal spin of the satellite to the initial orbital angular momentum with time. The mass ratio μ and model symbols are same as those given in figure 2.

reversed. As expected the transfer of orbital angular momentum decreases as p increases. Figure 3 shows the fractional angular momentum content of the satellite galaxy. Among the models considered in the present work, P10 and P11 are the most disruptive ones. In both these models almost 90 per cent of the particles leave the system carrying away most of the orbital angular momentum. In model P10, 93 per cent of L_{orb_i} is transferred to the internal spin. Most of the transferred spin resides in loosely bound particles of the satellite. The internal angular momentum also shows oscillatory variation in E and C models. The gain in internal spin is negligible in H models.

Figure 4 shows the variation of the polar angle θ with time. Here θ is the angle in degrees between L_{orb} and the initial orbital angular momentum vector L_{orb_i}. It can be seen that in non-disrupting cases, L_{orb} is perfectly aligned with initial orbital angular momentum till T = 40 and shows deviation from the initial orbital angular momentum vector after passing the perigalactic point. The maximum deviation occurs in the disrupting case and it is less than 20 degrees in all but model E1. In model E1 this deviation is less than 35 degrees. Large deviations as depicted in figure 4(b), (d) and (e) are due to the large number of escaping particles which form loosely bound clumps in a direction opposite to the direction of collision. In non-disrupting cases the initial and final orbital angular momentum vectors are aligned within statistical fluctuations.

4. Conclusion

We have performed simulations of collisions of galaxies of unequal mass and density. The simulations cover mass ratios in the range $4 \leq \mu \leq 50$. Our main results are applicable to the case of parabolic and elliptic orbit encounters. A satellite galaxy is considered disrupted if it loses more than 40 per cent of its initial mass and in such cases the fractional change in the self energy of the galaxy is found to be greater than two. For P and E type encounters, the tidal disruption can be described in terms of the parameter ρ/ρ_R. When the satellite galaxy has uniform density distribution, disruption occurs if $\rho/\rho_R < 1$. The satellite is expected to survive the encounter if $\rho/\rho_R > 1$. For the circular case with mass ratio 10, disruption occurs for $\rho/\rho_R < 3$ whereas in hyperbolic case the uniform density satellite survives the encounter for as small a value as ρ/ρ_R = 5.0E-3. The tidal effects as measured by $\Delta E/|E|$ decrease as the distance of closest approach increases. In disrupting cases, more than 60 per cent of the orbital angular momentum is carried away by the escaping particles. This is as high as 90 per cent in totally disrupting encounters. The direction of orbital angular momentum, after the encounter, is aligned with the direction of the initial orbital angular momentum of the pair in non-disrupting simulations. The survival of the loose cluster strongly depends on the distance of closest approach. A loose cluster could remain stable only if it is sufficiently away from the perturbing galaxy.

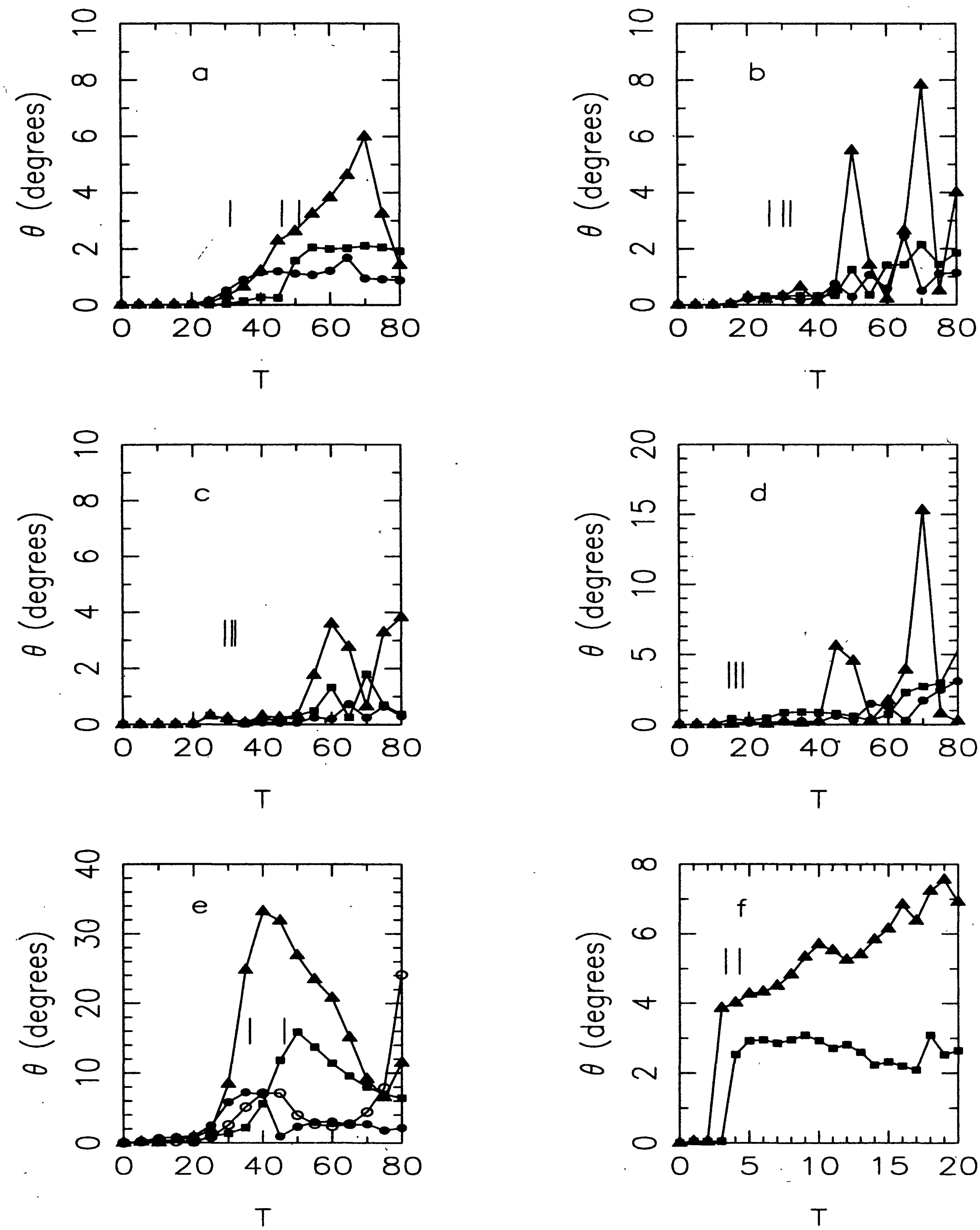

Figure 4. Variation of polar angle θ with time. The mass ratio μ and model symbols are same as those in figure 2.

The above conclusions apply exclusively to a narrow range of parameters of collision. It remains to be seen how far these results can be extrapolated to values of the parameters beyond this narrow range.

Acknowledgement

We thank the referee for useful criticisms. This work was done under the India-Japan Cooperative Science Programme of the DST and JSPS in the field of Astronomy and Astrophysics. The computations were performed partly in the Department of Earth Science and Astronomy of the University of Tokyo, Tokyo and partly in Indian Institute of Astrophysics, Bangalore. The recently installed special purpose processor GRAPE-3A system was used for the numerical simulations.

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