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On the tidal disruption of a spherical galaxy

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SUMMARY
The disruption of a satellite galaxy as it undergoes collision with a massive perturber is investigated by numerical simulations. Our models are restricted by a constant pericentric distance. The disruption of the satellite is estimated in terms of the density ratio ρ/ρ_R where ρ is the initial density of the satellite and ρ_R a critical density, the Roche density. The satellite suffers considerable disruption if $\rho/\rho_R < 1/2$ and it survives the tidal encounter when $\rho/\rho_R > 1/2$. For the same initial conditions, the circular orbit models show larger tidal effects than the other models.

1 INTRODUCTION

Tidal interaction between galaxies results in exchange and redistribution of energy, mass and angular momentum. Close encounters in which the galaxies have comparable mass and are initially almost bound lead to mergers. The merging becomes robust for systems which significantly overlap each other and have a smaller relative velocity at closest approach than escape velocity. The collision affects both galaxies in the unequal mass pair but it has a more profound effect on the less massive of the two. An important consequence of collisions of galaxies of unequal mass is the disruption of the smaller galaxy by the larger one. A satellite galaxy is considered disrupted if it gains energy comparable to its initial energy. This could happen if the satellite galaxy is weaker in mass, density and central concentration than the perturbing galaxy.

Most of the earlier simulations dealt mainly 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) and McGlynn (1990). Villumsen (1982) concentrated on mergers while Dekel *et al.* (1980) considered slow hyperbolic encounters and obtained total changes in the energy. Aguilar & White (1985) compared their *N*-body results of energy change and mass loss with impulse approximation estimates. They found reasonable agreement between the two. They (Aguilar & White 1986) also showed that the final shape of the density profiles of galaxies that have undergone a tidal encounter followed the de Vaucouleurs profile characterized by an extended tail. McGlynn (1990) performed *N*-body calculations of King models shocked in a variety of fashions and compared the density profiles of the remnants with a sample of elliptical galaxies. It is evidently of great interest to extend these results to encounters of galaxies of widely differing mass that are undergoing collisions on bound and parabolic orbits.

In the present work, we investigate the conditions under which a satellite galaxy disrupts as it undergoes collision with a massive perturber. For systems widely differing in mass, the disruption of the less massive one is chiefly determined by the density ratio whereas the disruption of the larger is determined by the mass ratio of the two galaxies. In the cases studied here the mass ratio ranges from 2 to 10^3. Our analysis suggests that in order that a given cluster be stable, its density must be larger than a critical density, the Roche density. We describe the initial conditions of the models in Section 2. The results are presented and discussed in Section 3 and the conclusions are given in Section 4.

2 INITIAL CONDITIONS

Our model consists of two galaxies: the primary (the perturber) has mass $M_1 > M$, the mass of the test galaxy (the satellite). The test galaxy is a spherical cluster of $N=250$ equal mass particles subject to a softened potential. The half-mass radius R_h of the test galaxy is $R_h = 6.55$. A total of 90 per cent of the mass is contained within about $3R_h$ and 100 per cent, within about $6R_h$. The point-mass perturber can choose from a number of orbits all at fixed pericentric distance $p=100$. The models are designated as P, E or C according as the relative orbit of the perturber is parabolic, elliptic or circular. The orbital plane coincides with the x–y plane with the x axis pointing in the direction of closest approach. In the elliptic case, the eccentricity of the initial relative orbit $e=0.5$. Aarseth's N-BODY2 code is used to integrate the equations of motion (see Namboodiri & Kochhar 1990, hereafter Paper I).

The density ρ of M within a sphere of radius R is

$$\rho = \frac{M}{4\pi R^3/3}. \tag{1}$$

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

$$\rho_R = 2\rho_1 = 2\left(\frac{M_1}{4\pi p^3/3}\right). \tag{2}$$

We have performed computations for values of $\rho/\rho_R = 1/16$, 1/8, 1/4, 1/2, 1 and 4. The initial separation of the perturber in the parabolic case is twice the distance of closest approach and the integration was terminated when the perturber's distance is much larger than the initial separation. The perturber is placed at apocentre in the bound orbit cases and the integration is followed for one complete orbit. At each time interval the centre of mass of N particles (excluding the perturber) is computed and particles with positive energy with respect to this centre of mass are identified as escapers. The centre of mass of the remaining particles is again evaluated and escapers relative to this new centre of mass are identified next. This iteration is continued until convergence is reached. The particles remaining in the system at the end of this iteration are identified as bound particles. The relevant quantities are computed with reference to this iteratively obtained centre of mass. Details of the simulations are given in Paper I.

3 RESULTS AND DISCUSSION

Table 1 lists the results for various models. The first column of this table identifies the model. Column 2 gives the mass ratio and column 3 the initial density ratio. The ratio of the half-mass radius of the final bound system to that of initial system is given in column 4. The ratio of the central density (containing the innermost 10 per cent of the mass of the final bound system) to that of the initial system is given in column 5. Columns 6 and 7 respectively show the fractional change is energy of the total system and the fractional mass loss after an encounter.

In all models, the half-mass radius of the system nearly remains constant whereas the region containing 90–100 per cent of the mass shows considerable expansion. Because of the tidal effects, the system as a whole expands in the orbital plane and contracts in a direction perpendicular to the orbital plane. An examination of the values in column 7 of Table 1 shows that in general the central density of the satellite increases as a result of the encounter.

The fractional change in the energy $\Delta U/|U|$, where U is the unperturbed initial energy of the test galaxy and ΔU its increase is a reasonably good measure of tidal disruption. A galaxy is considered disrupted if it loses more than 30–40 per cent of its initial mass (Miller 1986) and in such cases the numerical value of $\Delta U/|U|$ is observed to be greater than two (Paper I). This result does not agree with that of McGlynn (1990) wherein the encounter can produce a mass loss as high as 50 per cent and still the system can survive. This is due to the fact that our models are less centrally concentrated than his King models. The parabolic encounters in our models leave a well-defined remnant except in model P4.

Models E4 and E5 show considerable disruption and no remnant is noticed in model C6. In cases where $\Delta U/|U| \sim 1$ (e.g., in models E6 and C7) slight enhancement in the energy is observed when the perturber makes a second close contact (see Paper I). Energy change in a single collision only affects stars in the outer parts rather weakly but repeated collisions

Table 1. Collision parameters and results of tidal encounter.

1	2	3	4	5	6	7
Model	$\frac{M_1}{M}$	$\frac{\rho}{\rho_R}$	$\frac{R_{hf}}{R_h}$	$\frac{\rho_{cf}}{\rho_c}$	$\frac{\Delta U}{\lvert U\rvert}$	$\frac{\Delta M}{M}$
P4	166.6	0.063	0.87	2.07	2.297	0.272
P5	83.3	0.125	1.06	1.36	0.970	0.124
P6	41.7	0.250	1.11	1.14	0.449	0.068
P7	20.8	0.500	1.05	1.26	0.066	0.024
P8	10.4	1.000	1.14	1.26	0.051	0.008
P10	2.6	4.000	0.98	1.59	0.003	0.000
E4	166.6	0.063	0.76	2.25	8.711	0.396
E5	83.3	0.125	0.82	1.16	3.774	0.236
E6	41.7	0.250	0.90	1.75	1.035	0.140
E7	20.8	0.500	1.02	0.50	0.396	0.076
E8	10.4	1.000	0.93	0.85	0.167	0.044
E10	2.6	4.000	1.07	0.97	0.026	0.016
C6	41.7	0.250			11.470	1.000
C7	20.8	0.500	0.95	2.30	1.610	0.172
C8	10.4	1.000	0.88	2.09	0.553	0.084
C10	2.6	4.000	0.99	1.23	0.032	0.016

(1) Model; (2) Mass ratio; (3) Initial density ratio; (4) Ratio of half-mass radii of final and initial system; (5) Ratio of central densities of final and initial system; (6) Fractional change in energy; (7) Fractional mass loss. No remnant left in model C6.

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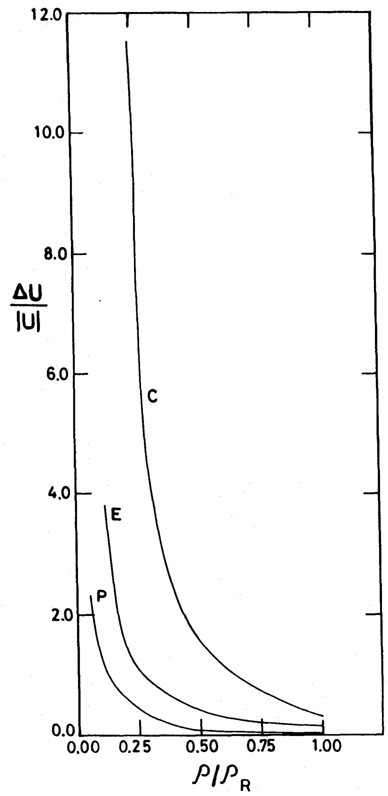

Figure 1. Variation of $\Delta U/|U|$ with ρ/ρ_R for various models: P for parabolic model; E for elliptic model; C for circular model.

may have significant effect at considerably smaller radii. The satellite orbit decay process is insensitive in P models. There is slight shrinkage of the orbit of the satellite in models E and C when the masses of the galaxies are comparable. It can be seen that in general an increase in the density ratio by a factor of two decreases the tidal effects approximately by the same factor. The tidal effects decrease with increasing density ratio $\rho/\rho_{\rm R}$ for a constant pericentric distance.

Fig. 1 shows the variation of $\Delta U/|U|$ as a function of $\rho/\rho_{\rm R}$ for all models. It is evident from this figure that the tidal effects as measured by $\Delta U/|U|$, decrease more drastically in the circular case than in other cases. In circular model, transition from disruption to non-disruption occurs near $\rho/\rho_{\rm R}=1/2$ whereas in other models this happens at still lower values of the density ratio. It can, therefore, be inferred that the survival of a satellite in circular orbit is guaranteed if its initial density is greater than one half the Roche density. Alladin, Ramamani & Meinya Singh (1985) have performed analytic calculations under the assumption of adiabatic approximation and have concluded that there would be a sudden decrease in the disruption rate near $\rho_{\rm h}=\rho_{\rm R}$ where $\rho_{\rm h}$ is the density of the satellite at half-mass radius. Our results, however, show that for circular encounters one must use the full radius and not the half-mass radius to obtain the condition for stability.

4 CONCLUSIONS

We have performed a variety of simulations to study the effects of a massive perturber on a less massive spherical stellar system. Our simulations use a small number of particles to represent a galaxy and the results are applicable for encounters of constant pericentric distance. Tidal disruption is determined in terms of fractional change in energy and mass loss. As already shown a satellite galaxy is considered disrupted if it loses more than 30–40 per cent of its initial mass and in such cases the numerical value of the fractional change in energy is estimated to be greater than two. For the same initial conditions the circular model shows larger tidal effects than the other models. The tidal disruption can fairly well be determined by estimating the density ratio $\rho/\rho_{\rm R}$, when the stellar systems are influenced by tidal forces. If $\rho/\rho_{\rm R}<1/2$, the satellite may suffer considerable disruption especially in a circular encounter whereas for $\rho/\rho_{\rm R}>1/2$, the satellite is guaranteed to survive a tidal encounter. A compact cluster can survive an encounter whereas a loose cluster can be stable only if it is sufficiently distant from the perturbing galaxy.

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