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CHANGES IN ELLIPTICALS DUE TO COLLISIONS WITH SPIRALS AND THEIR CONSEQUENCES

T.K.CHATTERJEE[1], V.B.MAGALINSKY[1,2]

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A study of collisions between spiral and elliptical galaxies (approximated as composite spherical masses) is made to assess the changes undergone by the elliptical. Results indicate that unless the spiral is extremely massive compared to the elliptical, the elliptical is almost unaffected, while the spiral is strongly affected. For the frequent type of collision between equally massive spiral and elliptical galaxies, the elliptical is negligibly affected, while disruptive effects set in the spiral. However, the stellar pattern of the elliptical is changed and the stars are found to crowd in faint shells after the collision. The consequences of these results are explored in the context of the morphology-density relationship and the elliptical companions of ring galaxies.

1. *Introduction*. The kinetic description of gravitating systems has acquired a vital importance (see, e.g., [1,2]). The disruptive effects of collisions on disk-like systems is well known (see e.g., [3]); but an analysis of its implications in the context of the morphology-density relationship [4] is relevant. The mechanisms of ring formation (in the spiral) and shell formation (in the elliptical) during spiral-elliptical collisions has been well studied ever since the observations of these galaxies (see, e.g., [5-10]); but the shells studied are prominent ones observed in giant ellipticals which are due to the disruption and phase wrapping of a spiral galaxy, of relatively insignificant mass compared to the elliptical, that has fallen into the elliptical. An analysis of faint shell structures in ellipticals during collisions with a massive spiral (leading to the formation of a prominent ring galaxy) is important in the context of the companions of ring galaxies (see, e.g., [11]).

To analyze these problems we study the relative energy changes during head-on and on-axies disk-sphere collisions and overall largescale structural changes undergone by the spherical galaxy.

2. *Theory*. We model the elliptical galaxy as a superposition of polytropes ($n=0$, 3, 4 with the mass equally distributed amongst the components) of mass M_s, and the spiral galaxy by a thickened exponential model disk (of mass M_d) and a polytropic bulge (of mass M_b), containing a third of the mass of the galaxy (identically modeled as the spherical galaxy) is superposed on it; (see, e.g., [12,13]); $M_D = M_d + M_b$ being its total mass.

The theory is essentially a modification of that of [8]. We consider head-on, on-axis collisions between a disk galaxy and a spherical galaxy of equal radius R; varying the other collision parameters. But due to the high central concentration of the spherical galaxy, almost all of its mass is concentrated within 1/3 of its radius. The spherical galaxy moves along the Z-axis and penetrates the disk normal to its plane. We integrate numerically the equations of motion for both the galaxies (from $Z = -3R$ to $Z = 3R$) in small steps, determining the changes in internal energies for both the galaxies taking into account the dynamical friction; (see, e.g., [14] and references therein). The use of the impulsive approximation gives good estimates for the changes in energy for relative velocities higher than the escape velocity between the colliding pair and escape velocity for galaxy pairs deducted from it agree with N-body calculations (see, e.g., [15]).

For a collision in the vicinity of the escape velocity we adopt the restricted three-body approach to make a crude study of the changes in the positions of the stars (see, e.g. [16,17]). We consider the tidal effects of the perturbing disk galaxy on the spherical (test) galaxy, assuming that initially all the stars move in circular orbits and their directions of motion have circular symmetry. Representative stars are chosen in radial zones at distances at intervals of 0.1 R, starting from 0.1 R; each zone being of width 0.1 R. We consider a velocity slightly above the escape velocity (to prevent a merger) and a disk galaxy twice as massive as the spherical galaxy so that substantial effects are produced in the spherical galaxy. We choose the dimensionless system of units $M = 1$, $R = 1$ and $G = 4.50 \times 10^{-4}$; such that a translation to physical units for the specific collision, $M_s = M_D = 2 \times 10^{11}$ solar masses, $R = 20$ kpc, gives the unit of velocity as 1.0×10^3 km/s.

3. ***Results***. In Table 1 we give the internal energy changes for a collision between equally massive elliptical and spiral galaxies (for the bulge to disk mass ratios $M_b/M_d = 1/10$, 1/2, 3/4, which mimic spirals of Sc, Sb and Sa types respectively), for different collision velocities; for the collision parameters $M_s = M_D = 2 \times 10^{11}$ solar masses, $R = 20$ kpc and $V = 1000$ km/s. Notice that the gain

Table 1

INTERNAL ENERGY CHANGES AS A FUNCTION OF RELATIVE VELOCITY
(COLLISION PARAMETERS: $M_D = M_S = 2 \times 10^{11}\ M_\odot$, $R = 20$ kpc, $V = 1000$ km/s)

V/V_E	$(\Delta U/\lvert U\rvert)_S$	$(\Delta U/\lvert U\rvert)_D$ $M_b/M_d = 1/10$	$(\Delta U/\lvert U\rvert)_D$ $M_b/M_d = 1/2$	$(\Delta U/\lvert U\rvert)_D$ $M_b/M_d = 3/4$
1.2	0.0908	1.40	1.13	1.12
1.5	0.0581	0.899	0.726	0.715
2.0	0.0328	0.508	0.410	0.404
2.5	0.0209	0.327	0.261	0.257
3.0	0.0145	0.225	0.182	0.179
4.0	0.00817	0.126	0.102	0.101

in internal energy of the elliptical is negligible, but the internal energy for the spiral has increased to ~1.5 times its initial value even for a collision velocity of twice the escape velocity. Only for a velocity of the order of four times the escape velocity, the internal energy changes in the spiral becomes negligible.

In Table 2 we give the internal energy changes for different mass ratios, M_D/M_s, of the elliptical to the spiral for the collision parameters $M_s = 2 \times 10^{11}$ solar masses, $R = 20$ kpc and $V = 1000$ km/s. The relative velocity is adjusted to be $V = 1.1\,V_E$; so that the pair just manages to escape. It is evident from the Table that for the case of the frequent collision between an elliptical and a spiral of equal mass, the fractional change in internal energy of the elliptical is insignificant (~1/10) as compared to the spiral (~1.5). Thus the elliptical is hardly affected; but the spiral is strongly affected and disruption sets in (see,

Table 2

INTERNAL ENERGY CHANGES FOR DIFFERENT MASS RATIOS NEAR ESCAPE VELOCITY ($V = 1.1\,V_E$)
(COLLISION PARAMETERS: $M_S = 2 \times 10^{11}\,M_O$, $R = 20$ kpc, $V = 1000$ km/s)

M_D/M_S	$(\Delta U/\lvert U\rvert)_S$	$(\Delta U/\lvert U\rvert)_D$ $M_b/M_d = 1/10$	$(\Delta U/\lvert U\rvert)_D$ $M_b/M_d = 1/2$	$(\Delta U/\lvert U\rvert)_D$ $M_b/M_d = 3/4$
1/2	0.0390	4.43	3.58	3.52
1	0.115	1.78	1.44	1.41
2	0.273	0.555	0.449	0.441
3	0.468	0.271	0.213	0.372
4	0.661	0.164	0.132	0.130
5	0.720	0.100	0.0807	0.0795
6	0.861	0.056	0.046	0.044

[10]). The elliptical begins to feel the effect of the collision only when the spiral is at least 2 times as massive; in which case the fractional increase its internal energy is ~1/3, while for the spirals (of various bulges) it is ~1/2. When the spiral becomes 3 times as massive as the elliptical the fractional change in internal energy of the elliptical exceeds that of the spiral. Only when the spiral is 6 times as massive as the elliptical the internal energy of the elliptical is of the same order as its initial internal energy and disruption sets in.

As the internal energy changes in the elliptical become substantial only when the spiral is twice as massive as the elliptical, we study the changes in the positions of the stars for a collision in which $M_D/M_s = 2$ and $V = 1.1\,V_E$, so that the galaxies just manage to escape. We reckon time from the instant $Z = -3$ and study the collision up to $Z = +3$; $Z = 0$ corresponds to the closest approach between the pair. In the Table 3 we give the positions of the stars in various zones in terms of their mean radial distance, $\langle l \rangle$; before the collision ($Z = -3$), shortly after the closest approach ($Z = 0.5$) and at the end of the collision ($Z = 3$). It is noticeable from the Table 3 that shortly after closest approach, at $Z = 0.5$, the elliptical contracts

Table 3

POSITIONS OF THE STARS AT VARIOUS TIMES DURING THE COLLISION ($M_D = 2M_S$, $V = 1.1V_E$)

Zone No	Mean radial distance of the stars in a zone at various times $\langle r \rangle$		
	$Z = -3$	$Z = 0.5$	$Z = 3$
1	0.10	0.85	0.10
2	0.20	0.23	0.35
3	0.30	0.29	0.43
4	0.40	0.42	0.41
5	0.50	0.43	0.36
6	0.60	0.58	0.44
7	0.70	0.68	0.82
8	0.80	0.70	0.98
9	0.90	0.79	1.25

(to about 90% of its size). This contraction is due to the fact that the central gravitational force increases at closest approach when the centers of the two galaxies coincide and the velocity dispersion of stars is no longer able to support the galaxy against self-gravitation; the contraction obviously causes the self-potential energy of the galaxy to increase. Stars at zone numbers 3, 4 and 5 crowd at an average radial distance of 0.38; while stars beyond the radial distance 0.6 shift inwards, which results in the contraction of the passage of the perturber (at $Z = 0$) followed by a decrease of the same, which causes stellar orbital radial dependence of dynamical timescales to drift out of phase, resulting in radial bunching of orbits. After the galaxies have receded sufficiently from each other, at $Z = 3$, it is noticeable that the elliptical expands (to about 1.4 times its size). This is due to the reduction of the central gravitational force after the closest approach and the transfer of orbital energy of the galaxies to their internal energies. From the Table 3 it is evident that there is a marked crowding of stars from zone numbers 2, 3, 4, 5 and 6 at an average radial distance of 0.4; at the same time the radial space between 0.1 to 0.3 is evacuated. Such that the stars crowd in a shell of inner radius 0.35 and outer radius 0.45, of thickness 0.1. Stars beyond the radial distance 0.6 shift outwards, which results in the expansion of the galaxy.

4. *Conclusions*. As we have seen, during spiral-elliptical collisions the elliptical is hardly affected unless the spiral is very massive compared to the elliptical. However, collisions between equally massive galaxies are the most frequent ones (see, e.g., [3,15]). For such a collision it is evident that the effect on the elliptical is negligible, but even when the spiral galaxy has a 3/4 of its mass in the bulge its total internal energy has increased to almost 2.5 times its original value. Results of [8] show that part of the spiral is disrupted and a ring galaxy without a nucleus (RE type) is formed for collision velocities in the vicinity of the escape velocity; for higher velocities ring galaxies with nucleus (RE type)

are formed (provided the collision trajectory is suitable). The ring galaxy VII Zw 466 has two companions, an elliptical and a spiral. Appleton et. al. [11] find that the spiral companion shows considerable activity in the mid-infrared and radio continuum, while the elliptical is only marginally detected; and postulate the spiral to be the intruder responsible for the collisional ring formation. But this ring galaxy is of the RE type and to knock out the nucleus requires a violent collision, characterized by an elliptical, rather than a spiral, intruder. Our results indicate that the elliptical will be negligibly affected by the collision. Only the stellar pattern will change, giving rise to shell structures. However these shell structures are very faint and are likely to be detected only photometrically; unlike the prominent shell structures observed in giant ellipticals (see, e.g., [9]) which are due to the disruption and phase wrapping of a spiral galaxy, of relatively insignificant mass compared to the elliptical, that has fallen into the elliptical (see, e.g., [10]). Hence it is more conceivable that the elliptical is the intruder responsible for the ring formation in VII Zw 466.

The morphology-density relation [4] indicates that the population of early type galaxies increases and that of spirals decreases with increasing local density. But a more fundamental relationship seems to be the morphology-clustercentric radius relation [18], where a comparison of galaxy population within the same normalized (by a characteristic cluster radius) clustercentric radius indicates that the morphological fractions are almost unaffected by local properties in the clusters. Results indicate that the elliptical population in the outer regions of the clusters is relatively constant (~10%) for all types of clusters, but rises rapidly near the center of the cluster (within about 0.5 Mpc of the center) reaching values ~70%; while the spiral fraction falls rapidly near the center. Sc galaxies have a steeper fall in density gradient as compared to Sa galaxies, as we go away from the cluster center; and the region of exclusion near the cluster center is much larger for Sc galaxies as compared to Sa galaxies. For clusters with high X-ray luminosity the density of spirals falls off more rapidly as the center is approached. The richest clusters are found to have the highest fraction of gaseous mass (see, e.g., [19,20]). However in the field the distribution of early type galaxies and spirals is essentially the same (see, e.g., [21,22]). This indicates that there are destructive collisional mechanisms in high density regions which are not conductive for spirals. From our results it is to be noticed that the frequent type of collisions between equally massive spiral-elliptical pairs lead to substantial disruption of the spiral for collisions in the vicinity of the escape velocity and to substantial increase in internal energy even for higher velocities, but the elliptical is unaffected. This suggests that spirals are being destroyed by ellipticals by the collisional process in dense environments. Spectral evolution studies of ellipticals indicate a behavior consistent with a passive luminosity evolution model in which the main star formation episode occurs at a high redshift $z_f > 2$ and the assembly of the galaxies is almost complete by $z \sim 1$ (see, e.g., [23,24]). Recent studies of spectral energy distribution evolution of ellipticals by Broadhurst and Bouwens [25], using optical-infrared images of Hubble deep fields, indicate that the mean spectral energy distribution evolves passively (toward a mid-F star dominated spectrum) up to $z \sim 2$. Spirals are likely to have formed afterwards, as indicated by the estimates of Larson [26]. The disks of protospirals, in the process of formation are likely to be destroyed by collisions with ellipticals in dense environments. A dynamical timescale of interest is the collapse timescale $\sim 1.43/(G\rho)^{0.5}$, [27], ρ being the mean mass density of the region at the present epoch. Postman and Geller [28] find from their observational data that this timescale is $\sim 10^{10}$ years for field densities (less than ~5 galaxies/Mpc^3), $\sim 10^9$ years for regions of intermediate densities (~600 galaxies/Mpc^3) and $\sim 10^8$ years for dense regions (greater than ~3000 galaxies/Mpc^3) like cluster cores. Notice that in the field regions, where morphological fractions are almost constant indicating that the collision process is not effective, the dynamical timescale is of the order of the Hubble time. Here proto-spirals can form their disks in a quiescent atmosphere, as the disk formation timescale, of the order of several billion years (see, e.g., [29]), is less than the dynamical timescale. On the other hand in dense regions, where the collision process dominates and the ellipticals outnumber the spirals, the dynamical timescale is of the order of typical collision timescale between galaxies (see, e.g., [16,30]). Thus the collisional process between ellipticals and proto-spirals will impede disk formation. In the regions of intermediate densities the dynamical timescale is an order of magnitude lower than the Hubble timescale but an order of magnitude higher than typical collisional timescale; hence collisions will occur, but with a very much reduced frequency. Here the proto-spirals will be able to form their disks but the disks are expected to be truncated. It is notable that S0 galaxies dominate this region.

[1] Faculty of Science, FCC, Puebla A. University, Mexico
[2] Derartment of Theoretical Physics, University of the Friendship of Peoples, Moscow, Russia

ИЗМЕНЕНИЯ В ЭЛЛИПТИЧЕСКИХ ГАЛАКТИКАХ В РЕЗУЛЬТАТЕ СТОЛКНОВЕНИЯ СО СПИРАЛЬНЫМИ И ИХ ПОСЛЕДСТВИЯ

Т.К.ЧАТЕРДЖИ[1], В.Б.МАГАЛИНСКИЙ[1,2]

Проведено исследование столкновений между спиральной и эллиптической галактиками (принятыми как составные сферические массы) с целью выявления происходящих изменений в эллиптической галактике. Результаты

показывают, что в случае, если спиральная галактика не является по сравнению с эллиптической очень массивной, то эллиптическая галактика почти не подвергается воздействию, между тем спираль подвергается сильному воздействию. При часто встречающемся типе столкновения между спиральной и эллиптической галактиками равной массы, эллиптическая изменяется незначительно, а структура спирали почти полностью разрушается. Однако звездный узор эллиптической галактики меняется, и после столкновения звезды скапливаются в слабых оболочках. Последствия этих результатов исследуются в контексте связи морфология - плотность, а также эллиптических компаньонов кольцевых галактик.

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