GRAVITATIONAL INTERACTIONS BETWEEN GALAXIES

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INTRODUCTION :

We may distinguish three stages in the history of the development of Dynamical Astronomy on the basis of Newtonian Mechanics. Soon after the Newton's law of gravitation was discovered, it was applied to solve the problems of the motions of the bodies in the solar system. Eminent mathematicians like Laplace, Lagrange, Euler, Gauss, and Tisserand developed the subject of celestial mechanics. Until the beginning of the twentieth century, celestial mechanics, or the dynamics of the solar system, attracted most of the attention in dynamical astronomy.

The second stage was the application of the principles of dynamics to the motions of stars in a stellar system. Stellar dynamics orginated in the early years of the twentieth century. In 1904, Kapteyn discovered the famous " star streams " and thereby showed that the velocity vectors of the stars, though lying in all directions, were not isotropically distributed as had previously been supposed. This led to the study of an isolated stellar system characterized by ellipsoidal law of distribution of velocities. The subject of stellar dynamics was then developed by Schwarzschild, Eddington, Jeans, Lindblad, Oort, Chandrasekhar, Ambartsumian, Spitzer, Lin, and others.

Until about 1950, however, galaxies were treated as though they were isolated stellar systems. Even as late as 1957, Kurth (1957) remarked : " The problems which arise from the interaction of stellar systems have hardly been considered up to the present time. " After 1950, particularly in the present decade, much interest arose in the subject of gravitational attraction between galaxies. We may regard this development as the third stage in the application of Newton's law of gravitation to the motions of celestial bodies. Much of the stimulus for research in this field was due to the discovery of galaxies with peculiar features. A survey of the photographs of interacting galaxies (Vorontsov-Velyaminov 1959; Arp 1966; Toomre 1974) provides many examples of double and multiple galaxies with strange appendages. Sometimes pairs of galaxies are found to be connected by luminous bridges ; sometimes luminous tails stream out behind them.

There had been two schools of thought as regards theoretical interpretation of the phenomena of bridges and tails in galaxies. One group of astronomers favoured the gravitational interpretation of the phenomena. The other group favoured interpretation on the basis of non-gravitational forces. Before discussing this controversial issue, let us see why the dynamics of galactic encounters should be different from the dynamics of stellar encounters.

THE DYNAMICS OF GALACTIC ENCOUNTERS :

There are two reasons why the dynamics of a galaxy-galaxy encounter is different from the dynamics of a star-star encounter:

1. **Departure of Intergalactic Gravitational Force from Inverse Square Law** :—In stellar dynamics, the force between two stars is inverse square force to a good degree of accuracy. This is because the stars are generally spherically symmetric and are separated from each other by enormous distances. Even in a star cluster like the Pleiades, the characteristic ratio defined as the mean distance between neighbouring stars to the mean radius of a star is of the order of 10^7. On the other hand, most galaxies are not spherically symmetric and the relevant characteristic ratio is quite small. In the Coma cluster of galaxies, for example, the ratio of the mean distance between neighbouring galaxies to the mean radius of a galaxy is only about twenty. Hence close collisions, in which galaxies interpenetrate each other, also occur. Hence, in an accurate study of the dynamics of galaxies, the extended nature of the galaxies, and hence the departure of the intergalactic force from inverse square, has to be taken into account. Particularly, if two galaxies interpenetrate each other during the encounter, the departure from the inverse square force could be considerable.

The potential energy Ω due to the gravitational attraction of a pair of galaxies may be written as

$$\Omega = - GM_1 M_2 \Psi / r, \tag{1}$$

where the factor Ψ takes into account the departure from inverse square force. Ψ would be a function of the separation, r, of the two galaxies and the density distribution in the two galaxies. The function Ψ has been obtained numerically by Alladin (1965) for spherically symmetric galaxies of equal radii, and by Potdar and Ballabh (1974) for spherically symmetric galaxies of unequal radii. Ballabh (1973) has obtained Ψ for disk galaxies.

To get some idea of the effects of the departure from the inverse square force in interpenetrating galaxies, consider two similar spherically symmetric galaxies, each of 10^{11} solar masses and radius 10 kiloparsecs, and having density distribution that of a polytrope of index n=4. It has been indicated by Rood (1965) that this polytropic model is a good approximation to the density distribution of a globular galaxy. In a polytrope of index n=4, roughly 90 per cent of the mass lies within 0.3 R, about 75 per cent within 0.2 R and 30 per cent within 0.1 R, where R is the radius (Limber 1961). We know from classical dynamics that the angle of deflection Φ in a two body encounter is given by

$$\tan \Phi/2 = (e^2 - 1)^{-\frac{1}{2}} \quad (2)$$

where e is the eccentricity of the orbit. If $e=\infty$, $\Phi=0°$ and we have a rectilinear orbit; and if $e=1$, $\Phi = 180°$ and we have a parabolic orbit. Thus, if two stars approach each other from infinite separation with infinitesimal velocity, the angle of deflection Φ would be 180° irrespective of the distance of closest approach of the two stars. In the case of interpenetrating globular galaxies described above, the angle of deflection will depend on the distance, p, of closest approach as shown in Table 1.

Table 1

Angle of deflection as a function of distance of closest approach for collisions between two globular galaxies approaching each other from infinite separation with infinitesimal velocity

p/R	>	0.5	0.3	0.2	0.1	0.0
Φ	~	180°	160°	130°	80°	0°

2. **Inelastic Nature of Galactic Collisions** :- The second reason why the dynamics of galactic ecounters is different from the dynamics of stellar encounters is that while in a star-star encounter the total energy of the orbital motion of the stars is conserved, in a galaxy-galaxy encounter the total energy of the orbital motion of the galaxies decreases since a part of it is used up in accelerating the constituent stars in the two galaxies. In order to see this point, consider a galaxy of mass M_1 approaching a galaxy of mass M_2 from a large distance. Suppose v_i and v_f are the velocities of a star of mass m in M_2 before and after the collision. Let Δv be the change in velocity of the star during the encounter. Then

$$v_f = v_i + \Delta v, \quad (3)$$

and the change in kinetic energy of the star of mass m is :

$$\tfrac{1}{2} m (v_f^2 - v_i^2) = \tfrac{1}{2} m \left\{ 2 v_i \Delta v + (\Delta v)^2 \right\}. \quad (4)$$

When we consider a large number of stars, we may set statistically $\sum v_i \cdot \Delta v = 0$, so that the change in the kinetic energy of the whole galaxy is

$$\Delta T = \sum \tfrac{1}{2} m \ (\Delta v)^2, \quad (5)$$

where the summation is over all the stars in the galaxy. The tidal effects are generally of impulsive nature so that we may assume for simplicity, without much loss of accuracy, that the change in the potential energy of the galaxy during the encounter is negligible. Hence, the total internal energy U of the galaxy, due to the distribution and motion of its stars, increases by an amount $\Delta U = \Delta T$ as a result of the encounter at the expense of the external energy due to the relative orbital motion of the two galaxies. The ratio $\Delta U / |U|$ is a convenient order of magnitude discriminant of the disruptive effects of tidal forces. If $\Delta U / |U| > 1$, the galaxy of mass M_2 will have positive energy after the collision and will therefore disrupt.

Spitzer and Baade (1951) were the first to make numerical estimates for the change in internal energy of galaxies due to tidal effects of collisions. Making a very rough estimate for the fact that the galaxies are not mass points, they concluded that in the Coma cluster of galaxies, $\frac{\Delta U}{|U|}$ per collision would be 2×10^{-4} if we take the relative velocities of the galaxies as 2400 km/sec, so that the effects of even one hundred collisions on the size and shape of a galaxy would be negligible. Therefore, as far as the stars are concerned, galactic collisions would be an absolutely harmless affair. On the other hand, Zwicky (1957) was of the opinion that on close encounters, galaxies can disrupt each other and populate the intergalactic space not only with gas and dust but also with stars.

Alladin (1965) studied the tidal effects of collisions between two spherically symmetric galaxies by representing their density distributions by those of polytropes, using the analysis of spherically symmetric matter by Limber (1961). It was assumed for simplicity that in so far as the determination of $\frac{\Delta U}{|U|}$ is concerned, the motions of the stars in the galaxies may be neglected. This is the so called " impulsive approximation " earlier used by Spitzer (1958) in deriving the disruptive effects of a passing interstellar cloud on a galactic cluster. $\frac{\Delta U}{|U|}$ was obtained by selecting a number of stars as representative of the test galaxy and calculating from the polytrope theory the tidal forces exerted on them by the field galaxy during the encounter. The tidal forces integrated over all time, yield the changes in velocity of the representative stars during the collision from which the change in energy of the entire galaxy during the collision is inferred. If M_1 and M_2 represent the masses of the field and test galaxies, R_1 and R_2 their radii, and n_1 and n_2 the polytropic indices representing their density distributions, then

$$\frac{\Delta U}{|U|} = \frac{5-n_2}{3} \frac{G M_1^2}{V_p^2 M_2 R_2} \cdot J\left(\frac{R_1}{R_2}, \frac{p}{R_2}, n_1, n_2\right), \quad (6)$$

where p and V_p are the distance and speed at closest approach of the two galaxies. The factor J is obtained from the polytrope theory by performing certain numerical integrations. For $M_1 = M_2 = 10^{11}$ solar masses, $R_1 = R_2 = 10$ kpc, $n_1 = n_2 = 4$, and $V_p = 1{,}000$ km/sec, the results given in Table 2 were obtained (Alladin 1965; Sastry and Alladin 1970). $\frac{\Delta U}{|U|}$ for other masses and relative velocities may be obtained from this Table by simple scaling from equation 6.

Table 2

$\frac{\Delta U}{|U|}$ as a function of the distance of closest approach for $V_p = 1000$ km/sec

p/R	0.0	0.2	0.6	1.0	2.0	5.0	10.0
$\frac{\Delta U}{|U|}$	8.6×10^{-1}	2.2×10^{-1}	1.3×10^{-2}	1.6×10^{-3}	8.8×10^{-5}	2.2×10^{-6}	1.4×10^{-7}

It will be seen from the results that for close encounters, the increase in internal energy of a galaxy due to an encounter with a second galaxy can easily be of the same order as its initial internal energy. Thus galaxies would undergo considerable change in structure in close collisions if the relative velocity of the two galaxies is sufficiently small. Thus, Limber (1965) indicated that the properties of the strange double systems VV 117 (= Arp 143) and VV 123 (= Arp 141) are explicable as the results of very recent collisions between elliptical and spiral galaxies in which the spirals undergo considerable change in structure due to tidal effects.

It can also be inferred from the results that very close encounters, in spite of their low frequency of occurrence, contribute most to $\frac{\Delta U}{|U|}$ in the life of a typical galaxy, since $\frac{\Delta U}{|U|}$ decreases rapidly as p increases.

GALACTIC BRIDGES AND TAILS :

Whether galactic bridges and tails are tidal relics of close encounters has been a controversial issue. In the 1950's, when large numbers of galaxies with strange appendages were first discovered, it was immediately proposed that these morphological anomalies were the after effects of gravitational forces exerted during near collisions between galaxies. Zwicky (1957) regarded bridges and tails to be jets of stars ejected from the galaxies during collisions. In the 1960's, this idea fell into disrepute, although no alternative theory won general acceptance. Gold and Hoyle (1959) felt that a tidal perturbation of a galaxy could alter its shape, but could not draw out a long narrow filament. Pikelner (1968) was of the opinion that the bridges and tails of interacting galaxies could hardly exist without a regular magnetic field.

Vorontsov-Velyaminov (1961) asserted that tails and bridges have nothing to do with tidal phenomena. He argued that the tails are much more frequent than the bridges. The tails and bridges are often so thin and so long that no tidal forces could produce them. Further, the frequency of occurrence of bridges and tails in clusters of galaxies is not higher than that in the general field. If bridges and tails were due to tidal effects, one should expect them to occur more often in clusters where collisions are more frequent. Vorontsov-Velyaminov also doubted the magnetic nature of the interaction owing to the fact that the bridges and the tails were also observed among the elliptical galaxies which are short of gas and consist of old stars.

Numerical computations of the motions of the stars in a galaxy during a collision with another galaxy on the basis of Newtonian mechanics were first performed by Pfleiderer and Seidentopf (1961) and Pfleiderer (1963). The equations of motion of the restricted three body problem were used. Pfleiderer showed that the tail-like filaments could be formed under a variety of conditions during a close approach of the two galaxies. Pfleiderer's work however did not attract much attention, chiefly due to the fact that he was trying to answer the question, whether the formation of the spiral structure, in general, could be due to interactions with passing field galaxies (a question which Pfleiderer finally answered in the negative on the grounds that the probability of two galaxies meeting under favourable conditions to form spiral structure was small).

Contopoulos and Bozis (1964) studied the problem of escape of stars during a collision of two galaxies. Their numerical results indicated that if the relative speed of the two galaxies is 2000 km/sec, the escaping stars do not form a bridge or link between the two galaxies. They however mentioned that much slower collisions might explain the formation of bridges.

Computer experiments performed in the 1970's, such as by Toomre and Toomre (1972), Wright (1972), Clutton-Brock (1972), Tashpulatov (1969, 1970), Yabushita (1971), Alladin et. al. (1972) have begun to reaffirm that gravitation may in fact be responsible for the appearance of some of the peculiar features of the interacting galaxies.

It has been found that the following conditions must be satisfied in order to obtain good bridges and tails (Toomre 1972, 1973): (i) The collisions must be slow. The galaxies must approach in parabolic orbits or in slower elliptical orbits. (ii) The galaxies must penetrate each other during the encounter, but not too deeply. (iii) The approach of the perturbing galaxy, M_1, must be roughly in the same direction as that in which the test galaxy, M_2, rotates.

The formation of a bridge is favoured if $M_1 < M_2$. On the other hand, if $M_1 \gg M_2$, the formation of a tail is favoured. To obtain really long tails, the masses of the two galaxies must be nearly the same. If $M_1 \gg M_2$, a galaxy having the shape of an integral sign will result after the encounter (Clutton-Brock 1972). Cases of exceptional thinness of either the bridges or the tails may simply be accidents of viewing these three dimensionally curving ribbons or surfaces of tidal debris from especially favourable directions (Toomre and Toomre 1972).

Striking bridges and tails are underabundant in dense clusters of galaxies because the encounters between galaxies generally take place there with high relative velocities and such velocities are not conducive for the formation of bridges and tails. Furthermore, any long period double galaxy in a cluster of galaxies will be in greatest danger of dissolution by the transit of a third galaxy.

FORMATION OF DOUBLE GALAXIES BY TIDAL CAPTURE :

It is known from classical dynamics that an encounter between two mass points, subject only to their mutual gravitational interaction, cannot lead to the formation of a close binary system, without the aid of a third body. An encounter between two galaxies, however, is an inelastic collision and may lead to the formation of a double galaxy by tidal capture, if the energy of the orbital motion of the two galaxies is reduced by the tidal forces to such an extent that it becomes negative after the encounter. It also follows, as a consequence of the tidal friction experienced by the galaxies in their relative motion, that double galaxies, however formed, will revolve around each other with mean separations that will continually decrease in time and may ultimately give rise to a single loose system.

Cox and Toomre have studied the case of a head-on collision between two equal and approximately spherical galaxies presumed to have started from rest at infinity. Their results indicate that the tidal friction is so considerable that at least 80 per cent of the total mass soon tumbles into a single heap (Toomre 1974).

Sastry (1972) made estimates for $\frac{\Delta U}{|U|}$ for various density distributions of spherically symmetric galaxies. His work indicates that in a head-on collision with relative velocity of about 500 km/sec, the two galaxies will form a double system if they are centrally concentrated (density distribution that of polytrope of index $n=4$), they will pass through each other without tidal disruption if they are homogeneous ; in case one of them is homogeneous and the other centrally concentrated, the homogeneous galaxy will be disrupted by the tidal forces, while the structure of the centrally concentrated galaxy will hardly be affected.

In a compact spherical cluster of galaxies, of radius one megaparsec, containing 1000 galaxies with velocity dispersion of 500 km/sec (this is the velocity required by the virial theorem for stability), there will be about 2000 interpenetrating collisions in 10^{10} years and about 20 of these will result in the formation of double galaxies by tidal capture (Potdar 1974).

FURTHER WORK :

It would be of interest to study the tidal effects of galactic collisions between two disk galaxies taking into account more accurately the gravitational potential energy of the two galaxies due to their mutul interaction. In most of the studies made so far, the perturbing galaxy is assumed to be a mass-point and the tidal effects are estimated by studying the stars lying in the outer parts of the test galaxy. Ballabh's (1973) work on potential energy of gravitationally interacting disk galaxies would be useful for this purpose.

It is also of much interest to study the dynamical evolution of a pair of galaxies. We would like to know how long it would take for a pair of galaxies to become merged into one due to the effects of tidal friction. Studies in this direction are being made by Toomre (1974).

The problem of the formation of double galaxies by tidal capture in clusters of galaxies is a fascinating one. It would be of interest to study how the double galaxy, once formed in a cluster, would evolve and how it would influence the other galaxies in the cluster.

Another problem of interest is that of escape of stars from galaxies into the intergalactic space in clusters of galaxies. Preliminary studies have been made by Gallagher and Ostriker (1972) and by Potdar (1974). Gallagher and Ostriker have suggested that the large amount of tidally dispersed debris may constitute the centrally located galaxies designated cD systems which often dominate the very dense clusters. A more detailed study of the problem is desirable.

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