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Classification of colliding galaxies

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Abstract. We propose a classification scheme for colliding galaxies based on the fractional changes in their binding energy and the orbital energy. We give examples of actual observed pairs of interacting galaxies for the various types of collisions proposed in the scheme.

1. Introduction

Though originally thought to be exciting but rare phenomenon, galaxy-galaxy collisions have, over the years, been considered to play an important role in the formation and evolution of galaxies. In these collisions translational energy, E, of galaxies is generally transferred to the energy, U, of the constituent stars. In this paper we propose a classification scheme for colliding galaxies based on this energy transfer and give examples of the various types from observed pairs of interacting galaxies.

2. Earlier work

Zwicky (1959) proposed a classification of temporary multiple galaxies based on the increasing order of the intensity of tidal effects resulting from galactic encounters, as follows : (i) Galaxies which may encounter each other without any significant effect on each other, with only insignificant rearrangement within them; (ii) galaxies which may encounter each other at very close range resulting in the loss of energy from the orbital motion (Translational energy) of the galaxies and correspoinding gain in the internal degrees of freedom and (iii) galaxies which may collide with each other head-on or nearly head-on resulting in considerable disruption of the galaxies or even tidal capture leading to merger.

Heggie (1975) has classified encounters between binary stars and a single star. He has summarized the results of the encounters in a classification scheme based on changes in energy, which in our notation is as follows :

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Case (i) : $\frac{\Delta U}{|U|} < 0$: De-excitation of the binary

Case (ii) : $0 < \frac{\Delta U}{|U|} < 1; \frac{|\Delta E|}{E} < 0$: Excitation of the binary

Case (iii) : $0 < \frac{\Delta U}{|U|} < 1; \frac{|\Delta E|}{E} \geq 1$: Resonance, Single star captured

Case (iv) : $\frac{\Delta U}{|U|} \geq 1; \frac{|\Delta E|}{E} < 1$: Ionisation, binary disrupts

Case (v) : $\frac{\Delta U}{|U|} \geq 1; \frac{|\Delta E|}{E} \geq 1$: Exchange

Here $\frac{\Delta U}{|U|}$ and $\frac{|\Delta E|}{E}$ are fractional changes in the binding energy of the binary and the total translational energy of the system.

A quantitative classification based of Zwicky's qualitative classification was given by Sastry and Alladin (1977, 1979) who classified galaxy collisions according to increasing intensity of tidal effects into types A, B, C and D as follows :

Type A : Change in size and mass of the galaxy both negligible
$\frac{\Delta R}{R} < 0.1; \frac{\Delta M}{M} < 0.01; \frac{\Delta U}{|U|} < 1$

Type B : Significant change in size or in mass or in both
$\frac{\Delta R}{R} \geq 0.1$ and / or $\frac{\Delta M}{M} \geq 0.01; \frac{\Delta U}{|U|} < 1$

Type C : Test galaxy captured by the field galaxy
$\frac{|\Delta E|}{E} \geq 1$

Type D : Test galaxy disrupted by the field galaxy
$\frac{\Delta U}{|U|} \geq 1$

Sastry and Alladin's classification was used by Miller (1983) in his study of galaxy clusters.

3. Present classification scheme

In this paper we present a classification scheme of galaxy collisions based entirely on energy changes which analogous to that proposed by Heggie for stellar encounters but with minor modification. Case (i) rarely happens in galactic encounters. It occurs under very special conditions (Byrd *et al.* 1986). We modify Cases (i) and (ii) in Heggie classification to

Case (i) : $\frac{\Delta U}{|U|} < 0.1; \frac{|\Delta E|}{E} < 1$: A Type collision : Tidal effects small

Case (ii) : $0.1 < \frac{\Delta U}{|U|} < 1; \frac{|\Delta E|}{E} < 1$: B Type collision : Tidal effects moderate

Many interesting features such as bridges, tails and rings are formed in B type collsions. Cases (iii), (iv) and (v) remain the same as in Heggie. These correspond to capture without disruption (C type), disruption without capture (D type) and disruption with capture (CD type) in the case of two galaxies.

This classification scheme is simpler than that earlier proposed by Sastry & Alladin (1977). The changes in mass and dimension are simply related to ΔU as indicated by Dekel *et al.* (1980). Hence it is not necessary to include them as additional parameters.

4. Equations for energy changes

We give the basic equations used in the present classification scheme, for estimating energy changes. These equations have been derived under implusive approximation (Spitzer 1958) using polytropic or Plummer model for galaxies. Impulsive approximation gives reasonable estimates even for low velocity, highly penetrating collisions (Aguilar & White 1985).

For a perturber of mass M_1 moving in a relative orbit of eccentricity e, about a test galaxy of mass M_2, the changes in the internal energy ΔU_2, of the test galaxy is given by (Alladin & Narasimhan 1982; Narasimhan & Alladin 1983) :

$$\Delta U_2 \left[\frac{\pi}{1 + e}\right]^2 \frac{G^2 M_1^2 M_2}{p^4 V_p^2} (R_{rms2})^2; \; e \leq 1 \qquad (1)$$

and

$$\Delta U_2 = \frac{1}{2} \frac{GM_1^2 M_2}{p^3 (M_1 + M_2)} \langle e_i^2 \rangle (R_{rms2})^2; \; e > 1 \qquad (2)$$

$$\text{where } v_p = \frac{G (M_1 + M_2)}{p} (1 + e)$$

v_p being the velocity at the minimum separation p of the galaxies and R_{rms} is the root mean square radius of the galaxy. The fractional change in the binding energy, $\Delta U_2 / |U_2|$ is given by

$$\frac{\Delta U_2}{|U_2|} = \frac{2}{\beta_n} \frac{\pi^2}{(1+e)^3} \frac{M_{12}^2}{1+M_{12}} \left(\frac{R_{rms2}}{p}\right)^3; \; e \leq 1 \tag{3}$$

and

$$\frac{\Delta U_2}{|U_2|} = \frac{\langle e_i^2 \rangle}{\beta_n} \frac{M_{12}^2}{1+M_{12}} \left(\frac{R_{rms2}}{p}\right)^3; \; e > 1 \tag{4}$$

where β_n varies from 0.5 to 0.4 in a polytropic model as polytropic index n increases from 0 to 4 and $M_{12} = M_1 / M_2$. The Change in the orbital energy is obtained from

$$\Delta E = -(\Delta U_1 + \Delta U_2). \tag{5}$$

In a hyperbolic encounter, the criterion for capture is $\frac{|\Delta E|}{E} \geq 1$ or $E_f < 0$ where E_f, the final orbital enerrgy at the end of the encounter, has been obtained from :

$$E_f = \frac{1}{2} \frac{GM_1M_2}{M_1 + M_2} V_p^2 + \frac{GM_1M_2}{p} - \frac{(\Delta U_1 + \Delta U_2)}{2}. \tag{6}$$

For Plummer model galaxies of unequal mass, we have for a head-on collision (Ahmed 1979).

$$\frac{\Delta U_2}{|U_2|} = \frac{64}{3\pi} \frac{GM_1^2 \alpha_2}{M_2 V_p^2 \alpha_1^2} B(\alpha_{12}); \; \alpha_{12} = \alpha_1 / \alpha_2 \tag{7}$$

and

$$\frac{|\Delta E|}{E} = \frac{\alpha_{12}^2 + M_{12}}{2(1+M_{12})} \frac{B}{A_2} \left(\frac{Vesc}{Vp}\right)^4 \tag{8}$$

wher α is scale length and Vesc is the escape velocity of the galaxies. A and B are functions of α_{12}. Namboodiri *et al.* (1987) define a dimensionless parameter υ given by

$$\upsilon = \frac{\pi^2}{(1+e)^3} \frac{M_{12}^2}{1+M_{12}} \left(\frac{R_2}{p}\right)^3; \; e \leq 1, \; p \approx (R_1 + R_2) \tag{9}$$

They find that bridges and tails are formed in the disk galaxy when $0.1 \leq \upsilon \leq 0.7$

The fractional change in the binding energy of a disk galaxy (D) due to a head-on collision with a spherical galaxy (S) is given by (Chatterjee 1984)

$$\frac{\Delta U}{|U|} = \frac{GM_s^2 R_D}{V^2 M_D R_s^2} \beta_D \tag{10}$$

where β_D is a function of the galaxy models, the ratio of radii R_s / R_D and the inclination of the disk to the relative orbital motion of the galaxies. Chatterjee finds that ring galaxies are formed when $0.4 \leq \frac{\Delta U}{|U|} \leq 1.8$ and $\frac{\Delta U}{|U|} \geq 2$ implies complete disruption.

5. Classification of some observed pairs of galaxies

In this section we classify pairs of interacting galaxies according to the scheme given in Section 3 using the observed data and the equations given in Section 4.

(i) NGC 1587 – 1588 (= K99) is a pair of elliptical galaxies showing off-centering of inner versus outer isophotes (Bonfanti *et al.* 1995), U-shaped velocity dispersion between galaxies (Combes *et al.* 1995). All these are attributed to tidal interaction.

From the simulations of Borne (1988), we adopt $M_1 = 1.95 \times 10^{11}\ M_\odot$, $M_2 = 0.65 \times 10^{11}\ M_\odot$. We take $Vp \approx 390$ km/sec, allowing for projection effects, p = 20 kpc. Fish's law (Alladin *et al.* 1975) yields $R_1 = 14$ kpc, $R_2 = 8$ kpc, $Rrms_1 = 2.8$ kpc and $Rrms_2 = 1.6$ kpc. This gives e = 1.25 and $\frac{\Delta U_2}{|U_2|} = 0.03$ and $E_f > 0$ implying that the orbit remains hyperbolic after the collision. We designate this collision as of *Type A*.

(ii) NGC 2672 – 2673 (K 175 = Arp 167) is another with pair of isolated elliptical galaxies showing similar characteristics of interaction. We use the collision parameters as given in Balcells *et al.* (1989). We $M_1 = 4 \times 10^{11}\ M_\odot$, $M_2 = 4 \times 10^{10}\ M_\odot$, $R_1 = 20$ kpc, $R_2 = 6.3$ kpc, $Rrms_1 = 4$ kpc, $Rrms_2 = 1.26$ kpc, vp = 540 km/sec and p = 16 kpc, we obtain e = 1.1, $\frac{\Delta U_2}{|U_2|} = 0.01$ and $E_f > 0$. This is also a collision of *Type A*.

(iii) NGC 4782 - 4783 (3c 2780 is a lose pair of interacting galaxies. Madejsky and Bien (1993) have presented a high velocity and deeply penetrating hyperbolic encounter model which agrees with the observed data.

Following Borne *et al.* (1988), we chose $M_1 = 8.1 \times 10^{11}\ M_\odot$, $M_2 = 5.6 \times 10^{11}\ M_\odot$ and using Fish's law we obtain $Rrms_1 = 6$ kpc and $Rrms_2 = 5$ kpc. Taking Vp = 960 km/sec and p = 17 kpc as in Madejsky and Bien (1993), we get $\frac{\Delta U_2}{|U_2|} = 0.1$ indicating that the collision is of *Type B*.

(iv) NGC 5194 - 5195 (=M 51 = VV1) is the whirlpool nebula. From Toomre's (1972) model, we adopt $M_1 = 13.5 \times 10^{10}\ M_\odot$, $M_2 = 4.5 \times 10^{10}\ M_\odot$, p = 25 kpc and e = 0.8. Taking

R_1 = 15 kpc, R_2 = 10 kpc (typical values for radii), we find $\upsilon = 0.25$, $\frac{\Delta U_2}{|U_2|} = 0.15$. e = 0.8 implies that a capture has already taken place. The collision is of *Type C*.

(v) A0035 (= NGC 4650 A = AM 064 - 0741) : A0035 is known as Cartwheel galaxy. The collision parameters are given in Chatterjee (1984). He finds that $0.8 \leq \frac{\Delta U_2}{|U_2|} \leq 1.8$. We classify this collision as of *Type D*.

(vi) Arp 141 (= VV 123) pair : The peculiar nature of this interacting pair was attributed by Burbidge and Burbidge (1959) to the disruption of a spiral galaxy by an elliptical galaxy in a close encounter. Following Samdage (1963), we take R_2 = 8 kpc and p = 4.6 kpc. We assume for the elliptical galaxy a typical mass $M_1 = 3 \times 10^{12} M_\odot$. Fish's law then gives R_1 = 55 kpc, $M_2 = 8 \times 10^{10} M_\odot$. In the absence of information about the relative velocity of the pair, we assume crudely the differential velocity of 3000 km/sec of the system as Vp. these collision parameters give eee = 1.68 and $\frac{\Delta U_2}{|U_2|} \approx 3$. This means that the spiral is getting distrupted in a hyperbolic encounter with the elliptical. We classify the collision as of Type D. Alternatively, since $p << R_1$, we may regard the collision as nearly head-on and from the treatment given in Ahmed (1979) we get $\frac{\Delta U_2}{|U_2|} \approx 1.5$ and $\frac{|\Delta E|}{E} << 1$. Hence in this case also the collision is of Type D. We note also that Chatterjee's (1984) criterion for the formation of ring galaxies is satisfied. This may possibly explain the ring structure observed in the pair.

(vii) NGC 2444 - 2445 (=Arp 143 = VV 117) is an interacting pair of elliptical (E4) and spiral (Sc) galaxies. Following Narasimhan and Alladin (1985), we adopt $M_1 = 1.4 \times 10^{11} M_\odot$, $M_2 = 9 \times 10^{10} M_\odot$, e = 0.3, p = 12 kpc and representing the galaxies by polytropes of indices $n_1 = 4$ and $n_2 = 3$ respectively, we get $\frac{\Delta U_2}{|U_2|} = 1.6$ and $\frac{|\Delta E|}{E} = 1.8$. Thus $\frac{\Delta U}{|U|} > 1$, $\frac{|\Delta E|}{E} > 1$. We classify this collision as Type CD. The spiral will merge with the elliptical with considerable disruption.

6. Conclusion

We have classified galaxies in increasing order of tidal effects; A : small tidal effect; B : moderate tidal effect; C : capture without disruption; D : distruption without capture and CD : both capture and disruption. The tidal effects are estimated from energy changes. At least one example of each collision type is given.

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