Bull. Astr. Soc. India (2000) **28**, 385-388

Classification of colliding galaxies - II

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Abstract. In our Paper I we had classified galaxies in increasing order of the intensity of tidal effects on the basis of transfer of energy from the motion of galaxies to the internal motions. This work has been refined by presenting the classification on the basis of the velocity of collision, which is an observable parameter. Analytic expressions are obtained for V_{dis}, the maximum velocity required for the disruption of one of the galaxies and V_{cap}, the maximum velocity required for mutual capture of the galaxies, in terms of collision parameters. Examples of some observed pairs of galaxies for the classification types are given.

1. Introduction

A classification of colliding galaxies in increasing order of intensity of tidal effects was made on the basis of the fractional energy changes $\frac{\Delta U}{|U|}$ and $\frac{\Delta E}{|E|}$ where U and E are the internal energy and external energy of the galaxies respectively (Narasimhan et al. Paper I). Narasimhan had the opportunity of discussing this classification with Professor. L. Spitzer at Princeton in 1996 who gave the valuable suggestion that it would be better to present the results in terms of the velocity of galactic encounter which is an observable parameter. The present paper aims to do this.

2. Critical velocity

Spitzer (1987) has obtained a simple expression for the critical velocity V_c in an encounter between a binary star with a single star such that if the initial velocity of encounter V is less than V_c the star cannot disrupt the binary without getting captured, and if V exceeds V_c the binary cannot capture the star. The corresponding velocity V_c in the case of a pair of colliding galaxies of masses M_1 and M_2 can be obtained by setting

$$|U_1|+U_2| = M_1 M_2 V_c^2/2(M_1 + M_2) \quad (1)$$

whence

$$V_c^2 = [(M_1 + M_2)/M_2] (V_{rms})^2_1 + [(M_1 + M_2)/M_1] (V_{rms})^2_2 \quad (2)$$

For identical galaxies, $V_c = 2 V_{rms}$. This holds for any distance of closest approach, p. If $V < V_c$ disruption of the galaxies without capture cannot occur. If $V > V_c$ tidal capture of the two galaxies cannot take place. Stringent conditions for a given p will now be obtained.

3. Disruption and capture velocities in non-interpenetrating galactic collisions

Since $\Delta U/|U|$ varies and $1/V^2$ and $|\Delta E|/E$ varies and $1/V^4$, we define disruption and capture velocities of a pair of colliding galaxies as those velocities for which $\Delta U/|U| = (V_{dis}/V)^2 = 1$ and $|\Delta E|/E = (V_{cap}/V)^4 = 1$ respectively. We have $V^2_{rms} = GM/2R$, where R is the dynamical radius, we assume $R = R_{rms}$. Using the formulae given in Paper I, we obtain for a non-penetrating collision for e>1 (results for e<1 can be got by similar process).

$$V^4_{cap} = \langle e_i^2\rangle[(e + 1)^2/(e - 1)] G^2(M_1 + M_2) (M_1R_2^2+M_2R_1^2)/p^4 \quad (3)$$

$$= 4\langle e_i^2\rangle [(e + 1)^2/(e - 1)] (1 + M_{12}) (M_{12} + R_{12}^2) (R_2/p)^4 V^4_{rms2} \quad (4)$$

where $M_{12} = M_1/M_2$ and $R_{12} = R_1/R_2$

$$(V_{dis})_2^2 = 2 \langle e_i^2\rangle (e + 1) G M_1^2 R_2^3/M_2p^4 \quad (5)$$

$$= 4\langle e_i^2\rangle (e + 1) M_{12}^2 (R_2/p)^4 V^2_{rms2} \quad (6)$$

For identical galaxies these give :

$$V_{cap} = 2[\langle e_i^2 \rangle (e + 1)^2/(e - 1)]^{1/4} (R/p) V_{rms};\ e>1 \text{ and} \quad (7)$$

$$= 2.6 (R/p) V_{rms}, \text{ for a rectilinear orbit } (e \to\infty) \quad (8)$$

$$V_{dis} = 2[\langle e_i^2\rangle (e + 1)]^{1/2} (R/p)^2 V_{rms};\ e > 1 \text{ and} \quad (9)$$

$$= 3.3 (R/p)^2 V_{rms} \text{ for } e\to\infty \quad (10)$$

$\langle e_i^2 \rangle$ is a complicated function of e. It varies from 2.5 to 0.5 as we go from e = 1 to e = 5 and for $e = \infty$, $\langle e_i^2 \rangle = 0$ (Narasimhan and Alladin 1983). Spitzer's treatment for rectilinear orbits gives the same results.

4. Disruption and capture velocities in penetrating galactic collisions

For galaxies of equal dimensions, the analysis of Narasimha Rao and Narasimhan (1992) yields for penetrating collisions :

$$(V_{dis})^2_2 = (3GM_1^2/M_2R) e^{-p/R} \text{ and } V^4_{cap} = [3G^2(M_1 + M_2)^2/2R^2]e^{-p/R} \quad (11)$$

which for identical galaxies reduce to

$$V_{dis} = 2.4\ e^{-p/2R}\ V_{rms} \text{ and } V_{cap} = 2.2\ e^{-p/4R}\ V_{rms} \tag{12}$$

For $p = 0$, $V_{dis} = 2.4\ V_{rms}$ and $V_{cap} = 2.2\ V_{rms}$. These compare well with $V_c = 2\ V_{rms}$ given in Section 2.

For a head-on collision between two Plummer model galaxies of masses M_1 and M_2 and scale lengths α_1 and α_2, we obtain from Ahmed (1979) :

$$V^4_{cap} = [2G^2(M_1 + M_2)\ (M_1\alpha_2^2 + M_2\alpha_1^2)/\alpha_1^2\alpha_2^2]\ B(\alpha_{12});\ \alpha_{12} = \alpha_1/\alpha_2 \tag{13}$$

$$\text{and } B(\alpha_{12}) = [2\alpha^2_{12}/(\alpha^2_{12} - 1)^2]\ [\{(\alpha^2_{12} + 1)/(\alpha^2_{12} - 1)\}\ \text{In}\ \alpha^2_{12} - 2];\ \alpha_1 \neq \alpha_2 \tag{14}$$

$$\text{For } \alpha_1 = \alpha_2,\ B(\alpha_{12}) = 1/3;\ \text{for } \alpha_1 >> \alpha_2,\ B(\alpha_{12}) = 1 \tag{15}$$

$$\text{Also } (V_{dis})^2_2 = (64/3\pi)(GM_1^2/M_2)\ (\alpha_2/\alpha_1^2)\ B(\alpha_{12}) \tag{16}$$

$$\text{Hence } V_{cap} = 2.2[B(\alpha_{12})\ (1 + M_{12})\ (M_{12} + \alpha^2_{12})/\alpha^2_{12}]^{0.25}\ V_{rms2} \tag{17}$$

$$\text{and } (V_{dis})_2 = 4.8\ (M_{12}/\alpha_{12})\ (B(\alpha_{12}))^{0.5}\ V_{rms2} \tag{18}$$

$$\text{where } V^2_{rms} = (3\pi/32)\ (GM/\alpha) \tag{19}$$

For a head-on collision between identical galaxies these reduce to

$$V_{cap} = 2.4\ V_{rms} \text{ and } V_{dis} = 2.8\ V_{rms} \tag{20}$$

Toomre's (1977) treatment for identical galaxies yields the same results. These may be compared with the accurate results $V_c = 2\ V_{rms}$ for identical galaxies obtained in Section 2. The disparity arises due to the simplifying assumption of constant velocity of collision made in the impulsive approximation.

It follows from Sections 3 and 4 that for identical galaxies V_{cap} and V_{dis} vary from 2 V_{rms} to less than V_{rms} as we go from a head-on collision to a grazing collision.

5. Classification in terms of velocities

Our earlier classification (Paper I) can now be expressed as follows

Type A : $V > 3\ V_{dis}$; $V \geq V_{cap}$: small tidal effects without capture

Type B : $3\ V_{dis} > V > V_{dis}$; $V \geq V_{cap}$: moderate tidal effects without capture

Type C : $V_{cap} > V > V_{dis}$: capture without disruption

Type D : $V_{cap} < V \leq V_{dis}$: disruption without capture

Type CD : $V \geq V_{dis}$; $V < V_{cap}$: both capture and disruption

6. Examples of some observed pairs

We illustrate the present classification scheme by giving two examples using the data given in Paper I.

a) NGC 1587 - 1588 (=K99) is a pair of elliptical galaxies. We take $M_1 = 1.95 \times 10^{11}\, M_\odot$, $M_2 = 0.65 \times 10^{11}\, M_\odot$, $R_{rms1} = 2.8$ kpc, $R_{rms2} = 1.6$ kpc, p = 20 kpc and V = 390 km/sec. These give e = 1.25, $\langle e^2_i \rangle = 1.8$, $V_{rms2} = 320$ km/ sec. $V_{dis2} = 25$ km/sec and $V_{cap} = 200$ km/sec. We note that $V > 3V_{dis}$ and $V > V_{cap}$, which means that the encounter is of type A.

b) Arp 141 (=VV 123) is an interacting pair of galaxies in which a spiral galaxy is disrupted by an elliptical galaxy in a close encounter. We take $M_1 = 3 \times 10^{12}\, M_\odot$, $R_{rms} = 10.3$ kpc, $M_2 = 8 \times 10^{10}\, M_\odot$, $R_{rms2} = 1.5$ kpc, p = 4.6 kpc and V = 3000 km/sec. These give e = 1.68, $\langle e^2_i \rangle = 1.3$, $V_{rms2} = 365$ km/sec, $V_{dis2} = 5440$ km/sec and $V_{cap} = 2450$ km/sec. We note that $V_{cap} < V < V_{dis}$. Hence the collision type is D.

Alternatively, if we treat the collision as nearly head-on as $p \ll R_1$ ($R_1 = 55$ kpc) and represent the galaxies by Plummer models with $\alpha_1 = 5.5$ kpc, $\alpha_2 = 0.9$ kpc, we get B ($\alpha_{12} = 6.1$) = 0.12. These give $V_{dis2} = 3740$ km/sec, $V_{cap} = 1390$ km/sec. We find $V_{cap} < V < V_{dis}$ implying that the collision type is D as before.

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