Energy loss due to gravitational radiation in galaxy mergers

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Abstract. Energy loss by gravitational radiation for binary galaxies in the process of merger is of the order of about 10^{31} erg s^{-1}. A simple relationship is obtained between the average energy loss by gravitational radiation, $[\langle dE/dt \rangle]_{GR}$, and the average energy loss in tidal interaction $[\langle dE/dt \rangle]_{TI}$ for merging galaxies, namely,

$$\left[\left\langle \frac{dE}{dt} \right\rangle \right]_{GR} \simeq \frac{40G}{c^5} \left[\left\langle \frac{dE}{dt} \right\rangle^2 \right]_{TI}.$$

Key words :   galaxy mergers—gravitational radiation

Introduction

In this note we estimate the power radiated by binary galaxies in the process of merger. We also compare the energy loss by gravitational radiation with that due to transfer of energy from orbital motion of the galaxies to their internal motions by tidal interaction in galaxy mergers.

The average rate of energy loss due to gravitational radiation from a binary system moving in a conic orbit is given by (Zeldovich & Novikov 1978):

$$\left[\left\langle \frac{dE}{dt} \right\rangle \right] = \frac{32G^4}{5\,c^5} \frac{M_1^2 M_2^2 \, (M_1 + M_2)}{a^5 \, (1 - e^2)^{3.5}} \left[1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right], \qquad \cdots (1)$$

where M_1 and M_2 are the masses; a and e the semi major axis and the eccentricity of the motion of the relative orbit. This leads to the time scale for the merger time given by

$$(t_m)_{GR} = \frac{5}{64} \frac{c^5 a^4 \, (1 - e^2)^{3.5}}{G^3 M_1 M_2 (M_1 + M_2) \left[1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right]}. \qquad \cdots (2)$$

The average rate of energy transfer from orbital motion of the pair of galaxies to the motion of the constituent stars is given by (Alladin & Narasimham 1982) :

$$\left[\left\langle \frac{dE}{dt} \right\rangle \right]_{TI} = \frac{\pi}{2} G^{1.5} \frac{M_1 M_2 \{ M_1 R_2^2 + M_2 R_1^2 \}}{a^{4.5} (1 - e^2)^3 (M_1 + M_2)^{0.5}}. \qquad \cdots (3)$$

Here R_1 and R_2 are the root mean square radii of the two galaxies. The time scale for merger by this process is given by

$$(t_m)_{TI} = \frac{a^{3 \cdot 5} (1 - e^2)^3 (M_1 + M_2)^{0 \cdot 5}}{\pi \, G^{0 \cdot 5} [M_1 R_2^2 + M_2 R_1^2]}. \qquad ...(4)$$

Equations (3) and (4) have been derived on the assumption that the galaxies do not interpenetrate. However we shall use these equations for overlapping binaries since we are concerned with making only order of magnitude estimates.

It may be noted from these equations that the dependences of the energy loss on a and e are not too different in the two processes. But the dependence on mass is much stronger in the case of gravitational radiation. In both cases for a fixed value of the closest approach, the effect is maximum for a circular orbit.

A simple relationship between the two energy losses can be obtained for the circular orbit for identical galaxies. For galaxies in the process of merger, it is reasonable to put $a = R_1 + R_2 \equiv 2R$. Equation (3) then reduces to

$$\left[\left\langle \frac{dE}{dt} \right\rangle \right]_{TI} = \frac{\pi}{4\sqrt{2}} \frac{G^{1 \cdot 5} M^{2 \cdot 5}}{a^{2 \cdot 5}}. \qquad ...(5)$$

For identical galaxies moving in a circular orbit equation (1) gives

$$\left[\left\langle \frac{dE}{dt} \right\rangle \right]_{GR} = \frac{65}{5} \frac{G^4}{c^5} \frac{M^5}{a^5}. \qquad ...(6)$$

It follows from equations (5) and (6) that

$$\left[\left\langle \frac{dE}{dt} \right\rangle \right]_{GR} = \frac{40G}{c^5} \left[\left\langle \frac{dE}{dt} \right\rangle^2 \right]_{TI}$$

$$= 4 \times 10^{-59} \left[\left\langle \frac{dE}{dt} \right\rangle^2 \right]_{TI} \qquad \text{C.G.S. units} \qquad ...(7)$$

For two galaxies of masses $10^{12} \, M_\odot$ and separation of centres 10 kpc spiralling into each other in a nearby circular orbit, we obtain from equations (5) and (6)

$$\left[\left\langle \frac{dE}{dt} \right\rangle \right]_{TI} \cong 10^{45} \text{ ergs s}^{-1} \text{ and } \left[\left\langle \frac{dE}{dt} \right\rangle \right]_{GR} \cong 4 \times 10^{31} \text{ erg s}^{-1}.$$

It is interesting to note that the value of the energy loss due to the gravitational radiation from merging galaxies is comparable with that obtained for massive close binary stars, 10^{29}–10^{31} erg s^{-1} (Zeldovich & Novikov (1978).

The numerical estimates also show that the energy loss from gravitational radiation is less than that due to tidal interaction by many orders of magnitude. Even if the binary was composed of the most massive galaxies such as M 87, for which the mass is as high as $10^{14} \, M_\odot$ (Fabricant & Gorenstein 1983), the order of magnitude estimates would not be altered appreciably since the increase in dimension and the reduction in orbital velocity of the galaxies due to penetration effects will offset the effect of increased mass. Equations (5) and (6) show that the energy losses depend on the ratio M/a. The time scale for merger due to gravitational radiation therefore remains far greater than the time scale for merger due to tidal interaction even in the case of massive merging galaxies. In order that the effects

of gravitational radiation may be significant we require that at least $(M/M_\odot) \times (a/kpc)^{-1} \approx 10^{15}$. The galaxies observed at present do not satisfy this requirement but this may be relevant in earlier epochs when the protogalaxies were denser and closer.

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References

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