

THE SLINGSHOT EJECTIONS IN MERGING GALAXIES

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Received 1988 November 28; accepted 1989 July 8

ABSTRACT

A merger of two galaxies, each containing a central black hole, produces a semistable black hole binary. In successive mergers, three black hole and four black hole interactions take place, and thus the multiple merger process may lead to escapes of black holes from the galaxy, as was originally suggested by Saslaw *et al.* in connection with the so-called slingshot process. We have carried out new three- and four-body experiments in which the energy losses to gravitational radiation have been incorporated via a simple collision algorithm. The results demonstrate that the inclusion of the collisions of black holes and the effect of the galactic potential give a model in which the symmetry aspects of the escaping black holes are consistent with data on double radio sources. We study in greater detail a particular galaxy merger process with a continuous distribution of the black hole masses. Masses are drawn at random from this distribution, and the relevant dynamical processes are calculated. Nearly all escapes fall in one of two categories: (a) nearly symmetric escapes, and (b) one-sided escapes. Symmetric escapes dominate at low velocities, and one-sided escapes dominate at high velocities. Therefore, symmetric black hole pairs are found in or near the merged galaxy, and singly escaping black holes are typically found at a much larger distance from the galaxy. When we combine these results with previous studies of the radiative strength of black hole trails as a function of escape speed, as well as with results which show the dependence of the radiative power on the mass of the black hole, we expect that the one-sided escape trails would emit only about 0.1% of the power of the symmetric escape trails. An exception to this rule is made by those one-sided escape trails where the escape speed is low; the number of such trails is only about 10% of the number of symmetric escape trails. In the present form of the slingshot model, the degree of symmetry of the black hole separations from the center of the galaxy is very close to the degree of symmetry by which the lobes of the 3C double radio sources are placed relative to the center of the radio galaxy. Other radio source samples which, unlike 3C, are not flux-limited, should show quite different symmetry properties. Definite predictions are made of what these “true” radio samples should look like.

Subject headings: black holes — galaxies: interactions — galaxies: internal motions — galaxies: nuclei — radio sources: galaxies

I. INTRODUCTION

As early as in 1954, Baade and Minkowski proposed that radio galaxies result from mergers of galaxies. For decades the idea was unpopular, but recent investigations have revived this idea again (Heckman, Carty, and Bothun 1985; Heckman *et al.* 1986). The new popularity is based on strong correlations between the presence, number, and size of companions, and the occurrence of a strong radio source in an elliptical galaxy.

A similar correlation has been suggested in case of Seyfert galaxies (Dahari 1984). In Seyferts, it is possible to explain the connection between the activity and the companions as a result of tidal interaction (Byrd *et al.* 1986; Byrd, Sundelius, and Valtonen 1987). The Seyferts are primarily disk systems in which spiral density waves are excited by the presence of companions, and this wave feeds material to the center of the galaxy. If a supermassive black hole is situated in the center of the galaxy, then the inflow of matter may show up as non-thermal emission or some other activity arising in the neighborhood of the black hole.

Elliptical galaxies are a different case. There is no disk gas to be perturbed into the nucleus. Moreover, a companion can cause little gravitational influence on the central region of the galaxy. It is therefore more reasonable to assume that the activity is a result of a past merger with a companion galaxy (Roos 1981*b*; Gaskell 1985). The companions which are seen in

the neighborhood of the radio galaxy are not directly causing the present active phase, but will perhaps one day contribute to the radio emission by plunging into the dominant galaxy.

Mergers of galaxies in an expanding universe have been studied by several authors; e.g., Aarseth and Fall (1980) and Roos (1981*a, b*). In those simulations, groups of galaxies are formed which subsequently decay through mergers. Sometimes only one large galaxy is left in place of the group (Navarro, Mosconi, and Garcia Lambas 1987). Even when the galaxies are initially equal in mass, a mass distribution is gradually built up which is not dissimilar to the observed luminosity function of galaxies. The rate of mergers was found to be about one per 10^9 yr. This is not inconsistent with the number of companions around strong radio sources (Heckman, Carty, and Bothun 1985): typically about four to eight companions, each about 10% of the mass of the primary, are found at about 25–40 kpc projected separation from the primary. Their expected merger times fall into the range of 10^9 – 10^{10} yr (Borne 1984). In particular, ellipticals with a large number (16–32) of companions appear to be strong radio sources.

In this paper, we study what happens to the central black holes of the merging galaxies during multiple mergers. According to present ideas, supermassive black holes are responsible for the manifestations of activity, and their presence shows up as radio emission. We assume that central black holes are

common; i.e., that each of the galaxies joined in the merger possesses its own supermassive black hole (or black holes). This assumption is supported to some extent by the high frequency of Seyfert-like characteristics in the nuclei of even relatively faint galaxies (Filippenko and Sargent 1986), and by evidence for black holes even in common galaxies (Tonry 1987; Dressler and Richstone 1988).

In Paper I (Valtaoja, Valtonen, and Byrd 1989), the details of the merger process and the formation of binary black hole systems were studied. It was found that the black hole binaries formed in this way are generally stable, unless they are perturbed by additional black holes from successive mergers. Roos (1988) considered a process where the companion slowly approaches the nucleus of the primary in a nearly circular orbit and claimed that in such a situation, the interaction of the companion and the primary may lead to the coalescence of the binary owing to gravitational radiation before the merger is complete. However, this is a rather hypothetical situation, because calculations in Paper I show that the orbit of the companion is typically far from circular, even up to the point at which the companion is completely broken up. Therefore, the merger proceeds rapidly, and the black hole of the companion interacts with the binary at the center of the primary before much evolution has taken place in the semimajor axis of the binary orbit. The time scale for the energy loss as a result of gravitational radiation is generally much greater than the corresponding dynamical time scale. The expected mass distributions in the binary systems were also derived in Paper I. We use these data as a starting point in the present study of three or four black hole interactions.

II. PREVIOUS WORK

The three-body problem, where a binary and a third black hole interact strongly, has been studied extensively by Saslaw, Valtonen, and Aarseth (1974). In that work, the ordinary Newtonian inverse square law of gravity was used. If any two black holes approached each other closer than a given distance, the system was left out of consideration because the general-relativistic corrections could not be calculated. It is expected that gravitational radiation modifies the dynamics considerably at close range.

Later Valtonen (1976) included the gravitational radiation in the three-body calculations. It was shown that the statistical distributions do not change drastically when the radiation term is included. However, it was demonstrated that, in this case, new types of dynamical phenomena arise which are not expected in purely Newtonian calculations. It was found that mergers of black holes, caused by gravitational radiation, take place so promptly that one might as well carry out Newtonian calculations until the separation between any two bodies becomes smaller than a critical value, and thereafter one may simply assume that an instantaneous merger between those two bodies has taken place.

This property has led to the study of the few-body problem with mergers by Mikkola, Saarinen, and Valtonen (1984), who considered equal-mass planar systems. The basic model was a hierarchically fragmenting gas cloud (a "spinar"), but the results may be equally well applied to black hole dynamics.

In Mikkola, Saarinen, and Valtonen (1984), two binaries were initially either in circular (case 1) or nearly parabolic (case 2) relative orbit. The latter type of experiments are more relevant to the merging galaxies, according to the orbit calcu-

lations in Paper I. The end results of the dynamical evolution were classified in the system of Mikkola (1983):

1. Two binaries in a hyperbolic relative orbit;
2. One escaper and a hierarchical three-body system;
3. One binary and two escapers;
4. Total disruption into four single bodies.

The four-body calculations of Mikkola, Saarinen, and Valtonen (1984) were carried out either without mergers, as in the ordinary Newtonian problem, or by including mergers at close approaches. In the Newtonian problem of case 2 experiments, about 70% of systems ended up in class 1, about 23% ended up in class 2, and 7% ended up in class 3. Class 4 was energetically impossible. It is expected that under the conditions in galactic nuclei, class 2 will later develop into class 3. On the other hand, Mikkola, Saarinen, and Valtonen (1984) found that when mergers are taken into account, almost all (97%) systems which did not completely collapse ended up in class 1.

Mikkola, Saarinen, and Valtonen (1984) also calculated how the dynamical system becomes more compact with time. As a result of a close two-body encounter, a new binary is formed whose semimajor axis is somewhat smaller than the pericenter distance of the encounter. In this way, systems which are initially not relativistic gradually obtain compact binaries with orbital speeds of the order of $10,000 \text{ km s}^{-1}$ or greater. When the binary orbital speed exceeds $30,000 \text{ km s}^{-1}$, its lifetime owing to gravitational radiation is so short that it may be considered a single body in subsequent calculations.

This compactification process is expected to take place in the few black hole systems. The energy loss to gravitational radiation is proportional to the inverse fourth power of the pericenter distance. As a result, the eccentricity e of the binary decays fast to values $e < 0.2$, while the pericenter distance changes little (Peters 1964). Thus, nearly circular binaries with semimajor axes somewhat below the original pericenter distance are formed.

It was shown in Paper I that binaries formed in merged galaxies have lifetimes owing to gravitational radiation which are of the order of the Hubble time. Few-body encounters lead usually to eccentric binaries, where the closest approach distance is typically an order of magnitude smaller than the original semimajor axis. Then, the loss of energy and angular momentum leads to typically four orders of magnitude reduction in lifetime owing to gravitational radiation. One more dynamical encounter brings us to the relativistic regime where the prompt merger approximation is valid.

In conclusion, we expect on the basis of previous simulations that three- and four-body interactions lead both to escapes of bodies (Saslaw, Valtonen, and Aarseth 1974) and to an increase in the compactness of the few-body system (Mikkola, Saarinen, and Valtonen 1984). The initial binary orbital speeds are of the order of 3000 km s^{-1} (Paper I). Therefore, escapes take place generally with speeds less than 1000 km s^{-1} (Saslaw, Valtonen, and Aarseth 1974), which means that escaped bodies return to the nucleus (Paper I). By the time the escaped body returns close to the binary, the binary system has orbital speeds of the order of $10,000 \text{ km s}^{-1}$, and escapes from the galaxy then become possible. Before total collapse or breakup of the system takes place, the binary orbital speeds may become as high as $50,000 \text{ km s}^{-1}$, and escape speeds may be several tens of thousands of km s^{-1} (Valtonen 1976).

To be more concrete, let us consider a few possible paths of dynamical evolution. These are not unique, because we are dealing with chaotic dynamical systems and the evolution is

known only in statistical sense. First, let us take a three-body encounter. It leads to close encounters between the three black holes. Because we are talking about nuclear scales where the influence of stars is not dynamically important, we may apply results from the general three-body problem (see, e.g., Valtonen 1988). Many types of dynamical evolution are possible: in *interplay* phase, all three bodies stay close to each other and have repeated close encounters between two of the bodies; in *ejection* phase, one of the three bodies goes to a large distance from the other two which form a temporary binary; in *revolution* phase, the system is divided semipermanently into a binary and a third body revolving around it; finally, in *escape* phase, one of the bodies leaves the binary permanently and the system acquires a stable configuration.

Initially, the three black hole system has the effective radius of about 0.1 pc, typical speeds are about 3000 km s^{-1} , and the crossing time is about 10^3 yr (Paper I). If the system goes into the interplay phase, it will have close two-body encounters about once every crossing time. The distribution of the pericenter distances of the encounters is approximately uniform between 0 and some upper limit, say 0.03 pc.

The gravitational radiation becomes important in the crossing time scale if the two-body encounter is closer than about 0.003 pc. Then, a binary of orbital speed around $15,000 \text{ km s}^{-1}$ is formed by the passing black holes, and it collapses in about 10^3 yr to form a single black hole. The probability of such a close encounter is about 10% in a single encounter, and if the interplay continues over 10 crossing times, the formation of such a tight binary black hole is the likely outcome of this evolution. The probability that the third black hole comes close to the binary before it collapses is of the order of 10% if the orbital eccentricity e of the orbit of the third body around the binary follows the usual distribution $f(e) \propto e$.

However, it is unlikely that the interplay continues uninterrupted for so long, and thus an energetic escape via this process is not very likely; its likelihood is probably below 10%. It is more likely that ejections occur. The ejection time scale may vary anywhere between $\sim 10^4$ and $\sim 10^9 \text{ yr}$. Since short-time scale ejections are more common, let us consider the time scale of 10^5 yr . In this time scale, the ejected black hole recedes about 5 pc outside the nucleus and returns.

If the temporary binary has the pericenter distance smaller than about 0.01 pc, then it is destroyed in 10^5 yr . The probability of such a binary forming, again using the standard distribution of binary eccentricities, is about 20%. In the remaining cases, the binary is still in existence when the third body returns. The orbital speed of the binary should be around $10,000 \text{ km s}^{-1}$. The likelihood that the returning black hole and the binary come into strong interaction should be about 50%, and the probability of an energetic escape via this process is probably below 50%. Otherwise, the likely result is a system in revolution. The close binary of the revolution system will eventually collapse.

There is the third major path of evolution, which may contain both periods of interplay and short ejections, but which does not have dramatically close encounters. Then, the gravitational radiation causes gradual energy loss in many small events, and the effective radius and the crossing time gradually decrease. In the end, a sufficiently close encounter takes place to form a tight binary. Because of the smaller scale of the system at that time, a strong three-body interaction is more probable than in the original system. Thus, an initial period of gradual compactification increases the likelihood of energetic escape events.

The presence of a fourth black hole in the system complicates the picture further. For example, now an interplay of three bodies and an ejection of the fourth body can occur simultaneously. Revolution is still possible, but it is much less likely. Consequently, in four-body systems, binaries are not left alone to develop and collapse as frequently as in three-body systems. This quiet evolution occurs mainly during an ejection of two binaries. Owing to the more chaotic nature of the general four-body problem, there is a high probability of a compact binary meeting another body as soon as the compact binary is formed, resulting in many escapes. Quite often, one of the four bodies is not participating in the strong interaction and is left in the center of the galaxy, while others escape from it. Even though it is possible to estimate various channels of evolution qualitatively, the four-body process in particular requires further quantitative calculations which are described in § III.

Escapes take place both in symmetric and asymmetric pairs. The escape speed distribution $f(V_e)$ of symmetric pairs may be approximated by

$$f(V_e) \propto 10^{-0.6V_e/V_{\text{esc}}}, \quad (1)$$

if V_{esc} is the escape velocity from the galaxy, and $V_e/V_{\text{esc}} \geq 2$ (Mikkola, Saarinen, and Valtonen 1984). In deriving this result, it was assumed that binaries of different orbital speeds exist owing to reasons mentioned above. The fraction of symmetric pairs among all escapes is generally below 50% even if the initial conditions are arranged such as to maximize symmetry (Valtonen 1976, 1977; Mikkola, Saarinen, and Valtonen 1984). This is a well-known problem in the slingshot theory of double radio sources (Saslaw, Valtonen, and Aarseth 1974; Valtonen 1984), where the double radio lobes are associated with the escaped black holes. Even though the process of multiple mergers of galaxies produces escaping black holes quite frequently, the symmetry consideration would seem to prohibit the association of black hole escapes with the double radio sources.

The work described above was not carried out with the multiple merger process in mind. In the following, we describe new calculations, where the choice of initial conditions as well as the method of orbital integration are specifically designed for the present problem.

III. ORBIT CALCULATIONS

a) The Method of Calculation

Both three- and four-body interactions have been studied, because both of them should be relevant to the multiple merger problem. The numerical method has been described in Mikkola (1983) and in Mikkola, Saarinen, and Valtonen (1984). The dynamics take place under the usual Newtonian formulation except at close encounters, where the prompt merger is assumed. As in Mikkola, Saarinen, and Valtonen (1984), the merger happens when the bodies are separated by 0.3 times the original radius of the closest binary in the system. Also, a smaller merger distance of 0.1 times the original binary radius was tried, but the results were essentially the same as in our standard case.

We calculate the orbits of dynamical systems which are composed initially of two binaries in a parabolic orbit relative to each other, or of a single body in a parabolic orbit relative to the binary. The inner (binary) and the outer orbits are randomly oriented relative to each other. Binaries are initially circular, and the orbit size of the smaller binary is one distance unit. The

TABLE 1
THE MASSES IN SETS 1-5

SET	MASS NUMBER			
	1	2	3	4
1.....	1	1	1	1
2.....	2/3	4/3	2/3	4/3
3.....	1/2	3/2	1/2	3/2
4.....	1	1	2	...
5.....	1/2	3/2	2	...

orbital phases of the binaries are randomized. The semi-latus rectum of the outer orbit is chosen from a random uniform distribution between zero and some upper limit. Trials with different upper limits showed that values greater than six distance units are not dynamically interesting, because the energy exchange decreases rapidly with encounter distance (Huang and Valtonen 1987).

Table 1 summarizes the initial mass values in first five sets of experiments, each of which is composed of 600 orbit calculations. Bodies 1 and 2 form a binary initially, and in four-body systems bodies 3 and 4 also form a binary. The semimajor axes of the two binaries are equal in sets 1-3. In addition, a final set of 1800 experiments was carried out, where the masses and the semimajor axes of the binaries were drawn from given continuous distributions. These will be described in detail later.

The final states of the system are classified as follows:

- 2B Two bodies remain and form a stable binary;
- 2H Two bodies remain in a hyperbolic relative orbit;
- 3T Three bodies remain in a stable triple system;
- 3B Three bodies remain and form a binary and an escaper;
- 3H Three bodies remain and escape from each other;
- 4S Four bodies remain and form two binaries which usually escape from each other;
- 4T Four bodies remain and form a stable triple plus an escaper;
- 4B Four bodies remain and form a binary and two escapers.

b) Experiments with Fixed Mass Values

Table 2 shows how the different categories are distributed among the final systems in sets 1-3. We notice that the two initial binaries generally remain intact, and that quite often they escape from each other with a moderately high speed (category 4S). The two other common end states are a binary

TABLE 2

NUMBERS OF FOUR-BODY EXPERIMENTS ENDING UP IN DIFFERENT CATEGORIES

CATEGORY	BINARY MASS RATIO		
	1:1	2:1	3:1
2B	188	43	13
2H	42	18	12
3T	10	13	3
3B	125	110	64
3H	3	1	1
4S ^a	151	277	349
4T	1	2	0
4B	0	1	0

^a Escape speed greater than 0.07 of the binary speed.

plus an escaped body (3B) or just a binary (2B). In the relativistic regime which we are considering, all binaries will collapse relatively quickly and will be replaced by single black holes.

Escapes are the most spectacular result of the process and possibly provide the connection with observations. Table 3 summarizes those experiments in sets 1-5, where something was ejected with the speed of 0.14 units or greater relative to the center of the galaxy (here the velocity unit equals the orbital speed of the original binaries).

There is no particular significance to the choice of the cutoff value of 0.14 units; here we choose it as an illustrative example. However, this cutoff value is of the right order of magnitude. If the orbital speed of the binary is $10,000 \text{ km s}^{-1}$, then the cutoff value corresponds to 1400 km s^{-1} . This is just about the initial speed which a body must have in order to escape from the center of the galaxy to the distance of 1 kpc.

In a merger process, one will obtain binaries of different orbital speeds. When the orbital speed is much greater than $10,000 \text{ km s}^{-1}$, the lifetime of the binary owing to gravitational radiation is short, and the binary is unlikely to take part in a few-body escape event. On the other hand, if the orbital speed is much lower than $10,000 \text{ km s}^{-1}$, the escape speed is likely to be so small that the body does not escape far from the nucleus. These two conditions define a probability distribution for binary orbital speeds with the median around $10,000 \text{ km s}^{-1}$. We consider this distribution in § IIIc. Here we study the high end of the escape speed distribution ($V_e \geq 0.14$) in units where the binary speed equals one unit.

There always exists a counterescape corresponding to every escape, owing to conservation of linear momentum, but the process is frequently so asymmetric that the cutoff speed of 0.14 units is exceeded on only one side of the nucleus of the galaxy. Then we classify the escapes as one-sided, otherwise as two-sided. Among the two-sided escapes, there are various degrees of symmetry depending on the mass ratio. The distribution of the mass ratios is also shown in Table 3.

As in previous studies, one-sided escapes are more common than two-sided escapes. But what is surprising and has not been noticed previously is the fact that among two-sided escapes, the fully symmetric pairs are by far the most common type. Even though the dynamical process could in principle produce asymmetric two-sided escapes, they occur only infrequently. This is qualitatively what one observes also in double radio sources: the majority of doubles are quite symmetric, but occasionally we find asymmetric doubles as well.

In order to make a more quantitative comparison, we take the study by Laing, Riley, and Longair (1983) of a sample of 3C

TABLE 3

NUMBERS OF ESCAPES IN THREE- AND FOUR-BODY EXPERIMENTS

	TOTAL	MASS RATIO				
		1.0	1.7	2	3	4
Three-body experiments:						
One-sided	544	...	...	...	...	...
Two-sided	115	96	5	...	14	...
Four-body experiments:						
One-sided	1133	...	...	...	...	...
Two-sided	280	202	15	21	41	1

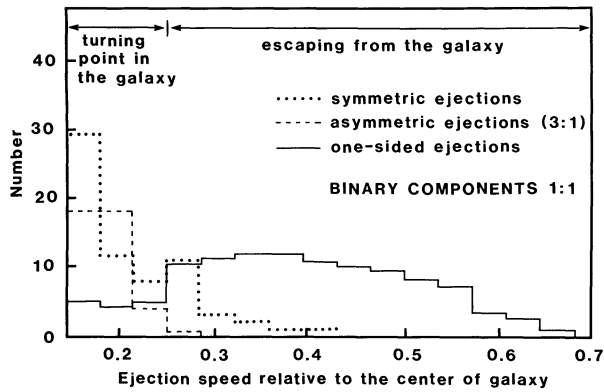


FIG. 1.—Distribution of escape speeds in set 1. Escape speed from the galaxy is assumed to be at 0.25 velocity units (original binary speed = 1). In asymmetric two-sided escapes, the velocity of the heavier body is shown (dashed line). In one-sided escapes, the solid line shows the speed distribution of the light ejected body, and in symmetric two-sided ejections, both bodies escape with the same speed, the distribution of which is shown by the line with circles.

double sources. Out of 111 double sources in this sample, 79 have the component distance ratio less than 1.6, 29 have the ratio in the range 1.6–3, and three sources are found with asymmetry greater than 3. These are very much the same relative numbers as we see in Table 3.

The reason for preferring complete symmetry over asymmetry in two-sided escapes is obvious: if the system splits up symmetrically, both parts obtain high escape velocity, but if it splits asymmetrically, only one of the parts (the lighter one) escapes with high speed. Thus, it is the high-velocity filter (i.e., the gravitational potential of the galaxy) which weeds away asymmetric two-sided escapes.

In Figures 1–3, we look at the escaped bodies in different escape velocity intervals. The figures show an interesting feature: two-sided escapes and one-sided escapes occur in quite different regimes of escape speed. If the typical value of the initial binary speed is $10,000 \text{ km s}^{-1}$, the escape velocity from a supergiant host galaxy is about 0.25 units (Paper I). Figures 1–3 then show that one-sided escapes almost always exceed the limit, while the two-sided escapes take place near the escape velocity or below it.

This separation in escape speeds may be significant when we consider double radio sources. The maximum brightness of a black hole trail in the models of Valtaoja and Valtonen (1984) drops by about two orders of magnitude when the escape speed crosses a threshold somewhere around $V_e \cong V_{\text{esc}}$. To some extent, this trail brightness model is supported by the observed power-size correlation of double radio sources (Valtaoja and Valtonen 1984).

Therefore, from the observational point of view, we only need to pay attention to a limited range of escape speeds. The width of this range is wide, because different escapes arise from systems of different degrees of compactness. Therefore, the escape velocity from the galaxy, in units of the binary speed, does not have a single well-defined value (such as 0.25), but a range of values (e.g., 0.15–0.3) in the scale of Figures 1–3. Some variations in the escape speed from the galaxy also come from the fact that we may have different escape speeds in different parent galaxies.

An important inference may then be made from Figures 1–3: the ratio of two-sided to one-sided escapes R , in the escape

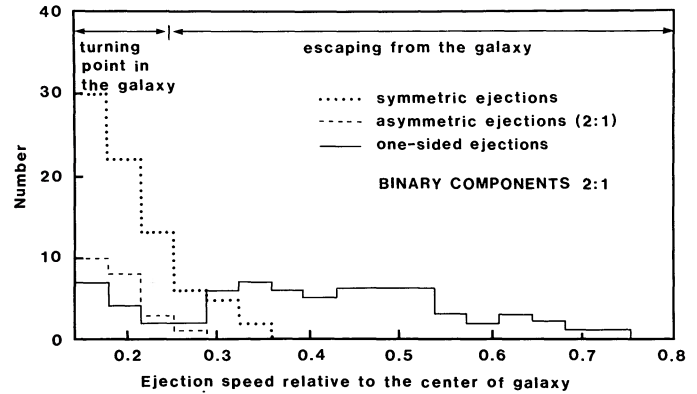


FIG. 2.—Distribution of escape speeds in set 2. For details, see the caption of Fig. 1.

speed range of interest, say from 0.15–0.3, is

$$R \cong 4, \text{ set 1;}$$

$$R \cong 6, \text{ set 2;}$$

$$R \cong 10, \text{ set 3.}$$

We see that the quantity R depends on the mass ratios in the system. It also depends on the choice of the range of interest in escape speeds. If we consider “all possible ranges” of interest (see eq. [7] below), they should follow a distribution with the median around the range chosen here (0.15–0.3), because this corresponds to the median at $10,000 \text{ km s}^{-1}$ in the distribution of binary speeds. If the range is smaller (e.g., 0.1–0.2), then the R ratio is increased, while if the range is greater (e.g., 0.2–0.4), then the R -ratio is decreased. Altogether, we would expect that $R \cong 10$ when the appropriate mass distributions and binary speed distributions (see § IIIc) are taken into account.

In a comparison with observations, we have to look for a sample which is not heavily biased by the radio power, because black holes involved in one-sided escapes tend to be less massive and presumably also less powerful radio sources than the black holes in two-sided escapes. An appropriate sample appears to be Schmidt's (1974) complete optical sample of the 4C quasars. Radio structures of 56 quasars in the sample were observed and classified by Potash and Wardle (1979), with the following result:

Single component sources, 19 examples;

Two-sided doubles, eight examples;

One-sided doubles, seven examples;

Triple sources, with optical object on the central component, 22 examples.

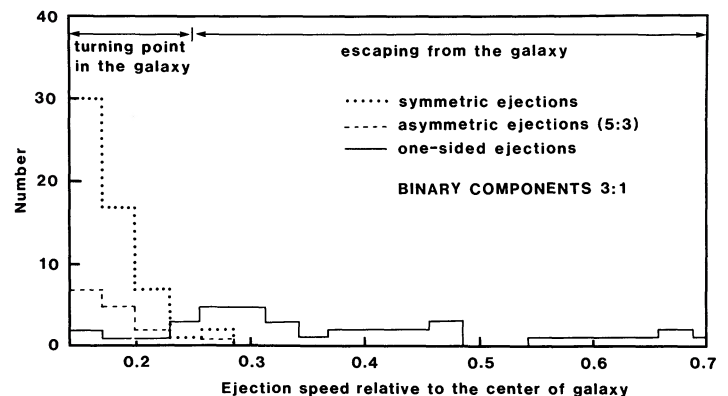


FIG. 3.—Distribution of escape speeds in set 3. For details, see the caption of Fig. 1.

For the purposes of comparison with the theoretical results, we may combine the two-sided doubles and the triple sources into a single category of two-sided escapes. One-sided doubles are associated naturally with one-sided escapes, and single-component sources are those where escapes did not take place or where the escape speed was too low to bring the black holes far from the nucleus. We will not discuss the nature of the central component in triple sources, but only remark that if the dynamical process involves two unequal binaries, then it is likely that the escape is a three-body process, and that the fourth black hole does not escape from the nucleus during the symmetric ejection.

One straightforward deduction from the data of Potash and Wardle (1979) is that the observed R value is

$$R_{\text{obs}} \cong 4.3(+4, -2).$$

It falls close enough to what we expect from our few-body simulations. A new study of one-sided structure has been carried out by Saikia *et al.* (1989). In their sample of more than 100 3C/4C quasars, the ratio $R_{\text{obs}} \cong 4.2$. This should be considered a lower limit, because all candidates of one-sided structure have not yet been observed with sufficient dynamical range. Considering only the secure cases of one-sided structure where the degree of flux asymmetry between the two sides exceeds a factor of 50, the ratio becomes $R_{\text{obs}} \cong 8.9$.

Another interesting quantity is the ratio of two-sided extended sources to single sources, which is observed by Potash and Wardle (1979) to be around 1.5. In our experiments, the same ratio varies from 0.6 (set 1) to 1.8 (set 2) and 4.5 (set 3), when the threshold escape speed is 0.15. At higher threshold speeds, the ratio is lowered. We note also that this number is of the right order of magnitude in comparison with observations.

c) Experiments with a Distribution of Masses

The expected mass distributions of single and binary black holes in merged galaxies are discussed in Paper I. The initial mass function of black holes should be broad, perhaps as broad as the mass function of galaxies. However, the dynamics of galaxy mergers are likely to narrow the range of black hole masses. Even then, large mass ratios are possible. The distribution of the black hole masses M_0 is expected to follow

$$f(M_0) \propto M_0^{-3/2}, \quad (2)$$

and the distribution of the binary mass ratio r is expected to be

$$f(r) \propto r^{-3/2}. \quad (3)$$

This result was obtained in Paper I by assuming that the mass of the central black hole is a certain fraction of the mass of its host galaxy, by making use of the merger probability as a function of galaxy mass, and by using the well-known luminosity functions for galaxies.

In the final set, we have studied systems in which the mass values are randomly drawn from a given distribution (see Fig. 4). Using these mass values, two binaries are constructed. The semimajor axis of the tighter binary is drawn from a random distribution of a particular form. The form of this distribution is determined by two considerations: (a) the lifetime of a binary with a given semimajor axis a ; (b) the probability that ejections over some cutoff speed take place when a binary of semimajor axis a exists in the system. If the semimajor axis (and thus lifetime) is too short, then the system degenerates through a

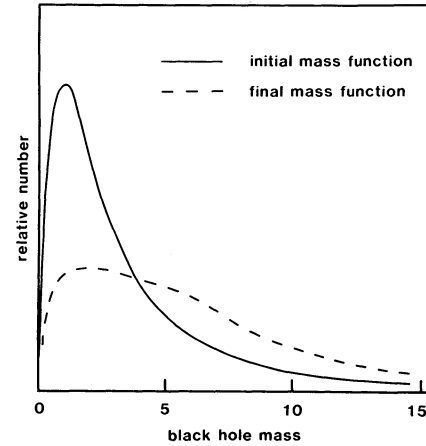


FIG. 4.—Distribution of black hole masses used in forming the two pairs of interacting binaries (solid line). Final distribution of black hole masses after mergers is given by the dashed line.

merger of the binary members before ejections have a chance to take place. On the other hand, if the semimajor axis is too long, then the ejections are not energetic enough to exceed the cutoff speed for observable escapes.

Condition a leads to a probability distribution

$$f_1(a) \propto a^4 \quad (4)$$

(Peters 1964), while condition b gives us

$$f_2(a) \propto a^{-(g+1)}, \quad (5)$$

where $g \geq 4$ in systems of relatively large angular momentum (Mikkola and Valtonen 1986). The total probability distribution is then

$$f(a) = f_1(a)f_2(a) \propto a^{3-g}. \quad (6)$$

In actual fact, we use the escape velocity from the galaxy V_{esc} as a scaling parameter. Because $V_{\text{esc}}^2 \propto a$, the distribution of V_{esc} should be

$$f(V_{\text{esc}}) \propto V_{\text{esc}}^{2(3-g)+1} = V_{\text{esc}}^{-1}, \quad (7)$$

when $g = 4$.

The result depends on the choice of g . In order for the encounter not to lead to immediate coalescence of two black holes, the pericenter distance of the third body has to be greater than or equal to the binary semimajor axis. This condition leads directly to $g \geq 4$ (Mikkola and Valtonen 1986). If g is greater than 4, then a larger fraction of escapes comes from very energetic binaries (orbital speeds above 10,000 km s⁻¹) and consequently, the escape velocities are also higher. Then, the escape speeds shown in Table 4 should be scaled to higher values.

Consequently, we use equation (7) to distribute parameters of the tight binary. Because the distribution goes to infinity when $V_{\text{esc}} \rightarrow 0$, we truncate the distribution at $V_{\text{esc}} = 0.1$. This corresponds to the maximum binary orbital speed of about 30,000 km s⁻¹. The semimajor axis of the wider binary does not depend strongly on the above constraints because its lifetime is longer and the energetics of the escape are determined almost exclusively by the tighter binary. Thus, we give a random uniform distribution in the interval $[a, 3a]$ to the semimajor axis of the wider binary. A random uniform distribution is appropriate because the closest encounter distances follow this distribution (Valtonen 1988) and presumably the semi-

TABLE 4
NUMBERS OF ESCAPES IN DIFFERENT INTERVALS OF ESCAPE SPEED V_1

V_1/V_{esc}	MASS RATIO (m_2/m_1)								
	9	5.67	4	3	2.33	1.86	1.5	1.22	1
0.25–0.5	2390	2125	2301	2700	2251	2305	2603	2965	2545
0.5–1.0	0	0	0	666	1715	1673	2161	1761	1320
1.0–1.5	0	0	0	0	291	605	604	420	285
1.5–2.0	0	0	0	0	36	135	149	49	17
2.0–2.5	0	0	0	0	10	65	55	37	0
2.5–3.0	0	0	0	0	0	29	0	0	0
3.0–3.5	0	0	0	0	0	0	0	0	0
3.5–4.0	0	0	0	0	0	20	0	0	0
Total:									
0.5–4.0	0	0	0	666	2052	2527	2969	2267	1662
Observed	0	1	1	1	1	10	23	28	46

major axes are in the first instance closely related to close encounter distances, as was explained in § II. The upper limit of the range (3a) is dictated by practical considerations, because very unequal binaries interact like a three-body system plus an external noninteracting body. The compactification process works on both binaries so that their semimajor axes should not wildly differ from each other; but if they do, the wider binary is likely to be disrupted. Then, usually only one of the original members of the wider binary takes part in the escape, and the other remains more or less at the nucleus. This is one possible reason why the triple sources are the most common type of radio source in the sample of Potash and Wardle (1979).

The results of the experiments in the final set are summarized in Table 4. The numbers in the table are much greater than the actual number of experiments. In order to obtain better statistics, the initial experiments were carried out with a fixed value of the scaling parameter V_{esc} . Subsequently, the resulting distributions were superposed on each other with different scalings such that the distribution of eq. (7) follows. Thus, the original experiment numbers are multiplied by a factor of 100 in Table 4. However, the numbers themselves are not significant, since our scaling produces plenty of low-velocity escapes which immediately return to the nucleus. Each such attempt is counted, and consequently the total number of escapes becomes unrealistically large. What we have to pay attention to is the relative numbers of high-velocity escapes.

In Table 4, we give the distribution of the escape speed V_1 of the lighter component in cases where the system is split in two subsystems which escape from each other (this is by far the dominant end result with equal binaries; see § IIIb). We include both one-sided and two-sided escapes, but not the cases where two black holes escape independently at different times. The distribution is given separately in different ranges of the mass ratio m_2/m_1 of the final subsystems (m_1 is the mass of the lighter subsystem). We note that the mass ratios of the escaped pairs are usually between 1 and 3. The last line refers to the observations by Laing, Riley, and Longair (1983). A closer comparison shows that the escaped black hole pairs are not as symmetric as the 3C double radio sources. Here we assume that the mass ratio translates directly to the distance ratio of the objects which escaped from the center of the parent galaxy.

d) Selection Effects

However, at this point we have to remember that rather strong selection effects have been at work in producing the

sample of Laing, Riley, and Longair (1983). First and foremost, the 3C sample is a flux-limited sample with a strong bias for absolutely bright radio sources. We will argue in the following that as a consequence of this bias, our Table 4 should be weighted by the escaped mass before a comparison with the 3C sample can be performed appropriately.

The visibility of the supermassive black hole is based on the accretion disk which surrounds it. The accretion disk is thought to be a source of radiation and relativistic plasma. It was pointed out in Paper I that the brightness P of the accretion disk is likely to be proportional to the third power of the black hole mass M_0 :

$$P \propto M_0^3. \quad (8)$$

This was based on the models of Sun and Malkan (1988), as well as the observed luminosity function of active galactic nuclei (Marshall 1987). Even if the power is not exactly three, arguments can be made that it should not be very far from it (Valtonen 1984). However, one should consider equation (8) to be tentative and subject to modification when more is known about radiation of supermassive black holes.

In a flux-limited sample such as 3C radio sources, there is an important selection factor: the numbers entering the sample are weighted as $3/2$ -power of the absolute radio luminosity. Considering the correlation of equation (8), this gives a mass-weight factor $M_0^{4.5}$.

In order for a pair of ejected black holes to enter a double radio source sample, the less massive, and, consequently, the less visible black hole has to be observable. Therefore, we weight the numbers in Table 4 by m_1^m , where $m \cong 4-5$. In Table 5, we use the weight index $m = 5$, but $m = 4$ gives a very similar result. A comparison of the last two lines of the table shows that now the symmetry distributions of escaped black holes and of 3C doubles agree quite closely. We consider escapes only with $V_1 > 0.5V_{\text{esc}}$, because otherwise the escaped object never goes further than 1 kpc from the nucleus of the galaxy.

We conclude that the discrepancy between the symmetry properties of 3C doubles and escaped black holes may be a selection effect. It remains an observational project to find out whether the true symmetry properties of double radio sources, when selected independent of radio power, do actually agree with the statistics in Table 4.

Another feature of interest in Tables 4 and 5 are the escapes with the very highest velocity. As was already found out in § IIIb, these tend to be less symmetric than the lower velocity escapes. The expected symmetry ratio of the very largest

TABLE 5
MASS-WEIGHTED NUMBERS OF ESCAPES IN DIFFERENT INTERVALS OF
ESCAPE SPEED V_1

V_1/V_{esc}	MASS RATIO (m_2/m_1)								
	9	5.67	4	3	2.33	1.86	1.5	1.22	1
0.25–0.5	2	9	1	8	11	12	65	88	170
0.5–1.0	0	0	0	4	35	17	68	142	327
1.0–1.5	0	0	0	0	5	18	69	118	132
1.5–2.0	0	0	0	0	0	4	7	41	1
2.0–2.5	0	0	0	0	0	15	16	39	0
2.5–3.0	0	0	0	0	0	4	0	0	0
3.0–3.5	0	0	0	0	0	0	0	0	0
3.5–4.0	0	0	0	0	0	25	0	0	0
Total:									
0.5–4.0	0	0	0	4	40	83	160	240	460
Observed	0	1	1	1	1	10	23	28	46

sources, if they are to be associated with the fastest escapes, should be around 2. In fact, observations show this tendency (Valtonen 1980), including the largest known double, 3C 236, which is remarkably asymmetric (Willis, Strom, and Wilson 1974).

The first velocity interval in Tables 4 and 5 refers to very low speed escapes, $0.25V_{esc} \leq V_1 \leq 0.5V_{esc}$. The orbits of these black holes are constrained to the central area of the galaxy, within about 1 kpc from the center. There should be a large number of these escapes, according to Table 4: their number should be almost double the number of wider pairs. However, in Table 5, the number of kiloparsec escapes has diminished to about one-third of the higher speed escapes. Thus, a study of samples not selected by radio power should reveal many more of these small doubles. It is also worth remarking that these small doubles should be much more asymmetric than the wide doubles. In this respect, it is interesting to note that the size distribution of a volume-limited sample by Shaver *et al.* (1982) is more concentrated toward small sources than the flux-limited 3C sources (Baldwin 1982).

IV. CONCLUSIONS

In multiple mergers of galaxies, systems of many black holes arise. We have calculated the evolution of these systems. There are two main possibilities: either the black hole system collapses to a single large black hole in the center of the galaxy, or black holes escape from the center of the merged galaxy, usually leaving only one black hole in the center. Generally, escapes are the most common line of evolution. Escapes in their turn may be classified in two main categories: two-sided escapes, where black holes are thrown in two opposite directions with nearly equal speeds, and one-sided escapes, where a single light black hole escapes. The numbers of the two types of escapes are usually comparable to each other.

Two-sided and one-sided escapes have a significant difference which may bear directly on their visibility: one-sided escapes occur at high speed, typically twice the escape speed from the galaxy, and two-sided escapes take place at low speeds, close to the escape velocity from the galaxy. Thus, we estimate that the black holes in one-sided ejections remain close enough to the parent galaxy for observational identification only about 1/10 of the time of the corresponding two-sided escapes. Moreover, the trail of a fast-moving black hole is

expected to be weaker than the trail of a slow-moving black hole by as much as two orders of magnitude (Valtaoja and Valtonen 1984). In addition, black holes in one-sided escapes are less massive than the black holes in two-sided escapes. A power-mass correlation of supermassive black holes would make the trail weaker in one-sided escapes than in two-sided escapes by a large factor, perhaps as much as a factor of 10. All in all, we expect to observe rather few fast one-sided escapes. In a flux-limited sample, the slow two-sided escapes should dominate over the fast one-sided escapes by a factor of $\sim 10^6$. In a complete volume sample, compiled to very low detection levels of the trails, the slow two-sided/fast one-sided ratio may be as low as ~ 10 .

Because fast one-sided escapes are so hard to detect, even though they should be as common as two-sided escapes, how do we find evidence for them? The best way is to concentrate on the tail end of them, or the slow one-sided escapes. Even though they are few (only about 1/10–1/4 of the number of two-sided escapes), there is a reasonable chance of seeing them. Neither the speed factor nor the proximity factor discriminates against them. Only the power-mass correlation works against them in flux-limited samples. In such samples, we estimate that one-sided systems should turn up in about 1% of all systems.

However, in samples not based on the brightness of the escaped bodies, the one-sided systems should be well represented. A good sample for this purpose is a sample of optically selected quasars (Schmidt 1974), where the escaped black holes show up not in optical but in radio emission. In this sample, there are about 4 times as many two-sided radio sources as there are one-sided sources (Potash and Wardle 1979). This is more or less the number which comes from our galaxy merger simulations. Also, the relative numbers of compact radio sources and extended radio sources agree with the expectations of the merger theory.

Thus, it appears that the black hole escapes which necessarily follow multiple mergers of galaxies have the same general properties as the double radio sources. For some flux-limited samples, e.g., the 3C sources, there also exist detailed structural data. Leaving aside such fine details as hot spots or jets, we have studied the main symmetry index in double radio sources: the component-distance ratio. The distribution of this quantity has been derived in the multiple merger scenario, assuming that the sample is observed in a flux-limited manner. It is found that the distribution agrees rather exactly with the corresponding distribution in the complete sample of 3C sources (Laing, Riley, and Longair 1983).

The mobility of supermassive black holes which results from galaxy mergers may have other observational consequences besides the double radio sources. For example, we would expect to find nuclear-like phenomena also outside the nucleus of an active galaxy, such as was observed by Tadhunter *et al.* (1987).

Saslaw and De Young (1972) and Rees and Saslaw (1975) discuss the effects on the interstellar medium of a passing supermassive object. They argue that hot gas, magnetic fields, cosmic rays, and other debris is ablated in a turbulent stream behind the black hole. De Young (1977) has carried out numerical simulations of the stream and has found similarities between the calculated appearance of the stream and components of double radio sources. Valtaoja and Valtonen (1984) developed a simplified model for calculating the properties of the streams with various initial parameters. De Young (1981) discusses further the triggering of star formation in the streams.

Lin and Saslaw (1977) discuss the survival of an accretion disk during a dynamical escape.

We may finally remark on the difference of the original slingshot theory (Saslaw, Valtonen, and Aarseth 1974) and the multiple merger theory. In both theories, it is assumed that supermassive black holes escape from the center of a galaxy and that the escaped bodies create radio components. It is well known that in the slingshot theory, the symmetry of double radio sources is difficult to achieve. It is not impossible, but one has to appeal to specific symmetric processes, such as spinar fragmentation (Mikkola, Saarinen, and Valtonen 1984).

Contrary to the slingshot model, in the multiple merger theory the origin of the multiple black hole system is not inside the galaxy itself, but the black holes come together from outside. Therefore, there cannot be a strong connection between the properties of the black holes, e.g., their masses. Rather, it is assumed that the black hole masses follow a wide distribution. The likely form of the black hole mass function was determined in Paper I. In this paper, we follow what happens to these black holes of different masses when they come together in the merger process.

The interesting and rather surprising result of the calculations is that the dynamical processes tend to seek symmetric pairs and to create symmetric escapes. Even though a certain degree of asymmetry has to be present (because masses are not equal), that degree is no greater than the degree of asymmetry in double radio sources. Thus, we may state that in the connection of multiple mergers of galaxies, symmetric escapes of black

hole pairs take place under rather general and plausible assumptions. The overall agreement of the symmetry properties of double radio sources with the symmetry properties of these escapes gives a strong indication that in double radio sources we are witnessing escapes of supermassive black holes.

The multiple merger theory makes some clear predictions:

1. There should exist a population of one-sided radio sources, where the escaped black hole moves fast and is typically far away from the parent galaxy. The brightness of these radio lobes should be about 0.1% of the brightness of a typical lobe in a two-sided double source.

2. The symmetry properties of double radio sources should change systematically with the sample definition. Flux-limited samples of powerful sources should show greater degree of symmetry than volume samples of faint sources.

3. In optically selected quasar samples, there should exist a genuine one-sided population which comprises some 1/10–1/4 of all sources. 3C 273 may be an example of this population. An increase in the dynamical range of the observations should not bring out a counterjet in such sources.

These predictions should provide clear-cut tests against theories where the double source production mechanism is intrinsically two-sided, such as the twin-exhaust model (Rees 1971).

The authors would like to thank Nico Roos for valuable comments on the manuscript which helped to improve the presentation of the results.

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