

Galaxy Mergers and Active Galactic Nuclei

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Received May 4, accepted June 23, 1981

Summary. The tidal disruption rate of stars near a central black hole in a galactic nucleus may be considerably enhanced during a merger of a galaxy with a smaller companion due to scattering of stars into loss-cone orbits by the perturbing gravitational field of the intruding galaxy. For conditions in galactic nuclei similar to those in the nucleus of the Milky Way, a maximum luminosity of $\sim 10^{46}$ erg s $^{-1}$ and a total energy production of about 10^{59} [$M_{\text{hole}}/10^7 M_{\odot}$] erg in $\sim 10^7$ yr may be obtained in such an event. Using a merging rate consistent with observational data and with cosmological simulations the fraction of galaxies which are active at some level of total luminosity is estimated. The agreement between the model prediction and observed luminosity functions of active galactic nuclei is encouraging. The cosmological evolution of active galaxies is discussed briefly in the context of the merger model.

If both merging galaxies contain a central black hole, a binary black hole system will be formed at the centre of the combined galaxy. Numerical three-body experiments were performed to investigate the evolution of the binary due to three-body interactions with galactic stars. It is concluded that the minimum separation distance that the binary may reach via interactions with these stars is probably sufficiently small so that gravitational damping can take over and ensure merging of the holes within a Hubble time.

Key words : active galaxies – galaxy mergers – binary black holes

1. Introduction

Massive black holes are frequently invoked as the primary component of the powerful energy sources in QSO's and active galactic nuclei. Such objects may have grown by accretion of gas produced by tidal disruption of stars in the vicinity of the hole or by star-star collisions in the nuclei of galaxies (Hills, 1975; Young, 1977; Frank, 1978). Tidal disruption of stars near the black hole is a particular attractive fuelling mechanism because it occurs very close to the hole. The debris of the tidally disrupted stars will be strongly bound to the hole and is likely to be swallowed by it. In galactic nuclei of typical densities $10^7 M_{\odot} \text{ pc}^{-3}$ and core radii of about one pc this may yield luminosities of $\sim 10^{44}$ erg s $^{-1}$. The disruption rate of stars near the hole is limited by the existence of a loss-cone within some critical radius of the hole. Within this critical radius stars that are disrupted near the hole cannot be replaced by other stars via two-body relaxation in one stellar orbital time (Frank and Rees, 1976; Lightman and Shapiro, 1977). In order to

explain the high luminosities of $\gtrsim 10^{46}$ erg s $^{-1}$, observed in active galaxies and QSO's, higher central densities are required. In such nuclei, however, most gas is produced in star-star collisions occurring at a much larger distance from the hole (Frank, 1978) and the fraction of gas consumed by the hole is again uncertain.

In previous investigations the galaxies were considered as isolated systems, undisturbed by other galaxies. However, interactions among galaxies are probably quite common. Most galaxies are observed to have close companions (Holmberg, 1969) and the appearance of peculiar galaxies can often be interpreted as the result of tidal interactions with a nearby galaxy (Toomre and Toomre, 1972). Such interactions, which are likely to result in rapid merging of the two stellar systems within a few galactic crossing times, may have played an important role in the evolution of galaxies. It seems therefore worthwhile to investigate whether there might be a link between merging and activity in galactic nuclei. There are several reasons for suspecting such a relation. It is well known that strong radio sources are mostly associated with elliptical galaxies, and it has been argued that ellipticals may well be merger products (Toomre and Toomre, 1972; Jones and Efstathiou, 1979; Aarseth and Fall, 1980; Roos, 1981). Furthermore some nearby active elliptical galaxies show signs of recent merging, e.g. Fornax A (Schweizer, 1980) and Centaurus A (Tubbs, 1980). Finally, precession of radio beams, as inferred from rotational symmetry observed in many extended radio sources, may be explained by the existence of a binary black hole in the nucleus produced by merging (Begelman et al., 1980).

In this paper we will investigate a simple mechanism to enhance the tidal disruption of stars near a black hole in a galactic nucleus during a merger: repopulation of loss-cone orbits via scattering of stars by the intruding galaxy. The tidal disruption of stars near a black hole in a galactic nucleus may be enhanced considerably over the (quasi-) stationary disruption rate in this way, and luminosities of $\sim 10^{46}$ erg s $^{-1}$ may be obtained for nuclear densities of $\sim 10^7 M_{\odot} \text{ pc}^{-3}$.

We know very little about the conditions in galactic nuclei, but for our galaxy we have information on the mass distribution to within 1 pc of its centre (Oort, 1977). The density keeps rising with decreasing distance to the centre as $r^{-1.8}$ to within $r = 1$ pc, where it reaches a value of about $10^6 M_{\odot} \text{ pc}^{-3}$. If our galaxy contains a massive central object of a few times $10^6 M_{\odot}$ as suggested by infrared observations (Wollman et al., 1977), this is about the distance where the stellar distribution starts to obey the cusp solution with density rising as $r^{-7/4}$ and velocity dispersion as $r^{-1/2}$ (Bahcall and Wolf, 1976). There is no evidence for the existence of a core region where the density profile is flat. A similar situation may exist in other galaxies. Observed surface brightness profiles of

elliptical galaxies are often fitted to a Hubble or a King law. However, Schweizer (1979) has pointed out that if the effect of seeing is properly taken into account there is little evidence that galaxies have flat central density profiles. This has important implications for fuelling models of central black holes. The high central density in our galaxy is favourable for growth of a black hole via accretion of gas produced by tidal disruption of stars or in star-star collisions. These processes clearly cannot be very important if massive black holes are embedded in extended low-density cores. In this paper we will generally take the conditions in our galaxy as fairly representative for conditions in other galaxies and assume that galaxies do not have flat central density profiles.

In Sect. 2 we will first discuss the dynamical evolution of a merging pair of galaxies one or both of which containing a central massive black hole. If both stellar systems contain a black hole a binary black hole will be formed at the centre of the combined galaxy due to dynamical friction. The next stage of evolution of the binary depends on the amount of energy that it loses to stars coming within its orbital radius. Numerical three-body experiments were performed to explore this stage of the binary evolution. The results of these simulations are presented in Sect. 2.2 and their implications discussed in Sect. 2.3. In Sect. 3.1 we briefly review the (quasi-)stationary fuelling rate of a massive black hole in a galaxy which is not disturbed by intruders. In Sect. 3.2 the tidal disruption rate during a merger is estimated and discussed for some particular cases. Some other observable phenomena which may accompany the activity of a galaxy in the model presented here, such as precession of radio beams and activity of the secondary component, are also discussed. In Sect. 4 our knowledge of the merging rate among galaxies and of the dynamics of the merging process are combined with the results of Sect. 3 to estimate the fraction of galaxies that are active at a given level at the present epoch. The total luminosity function of active galaxies is then estimated from available radio, optical and X-ray luminosity functions and compared with our predictions. The cosmological evolution of the space density of active galaxies is also discussed briefly. Results are discussed and summarized in Sect. 5.

2. Dynamics of the Merging Process

2.1. Merging of Galaxies and the Formation of Binary Black Holes

The merging process of a small galaxy having mass m_g can be described in terms of dynamical friction. The smaller galaxy, moving with velocity V at a distance r from the centre of the larger galaxy, loses orbital energy E according to

$$\frac{dE}{dt} = -4\pi G^2 \frac{m_g^2 \varrho(r)}{V(r)} \ln A, \quad (1)$$

if $V(r) \gtrsim \sigma(r)$, the one-dimensional velocity dispersion of the stars in the larger galaxy (Spitzer, 1962). G is the gravitational constant. The standard Coulomb logarithm $\ln A$ will be of order unity if we take A equal to the ratio of the sizes of the two galaxies. The density of the larger galaxy at r is given by $\varrho(r)$. We assume that this density is given by a power law

$$\varrho(r) = \varrho_0 (r/r_0)^\gamma, \quad (2)$$

where ϱ_0 is the density at some reference distance r_0 . It will be generally assumed in this paper that the stellar distribution is isothermal, implying $\gamma \simeq -2$, ($\sigma(r) = \sigma$). Cosmological simulations

indicate that most mergers occur between galaxies in bound orbits (e.g. Aarseth and Fall, 1980). The orbital velocity V of the two galaxies will then be comparable to σ , and the dynamical friction time at r , defined as $t_{df} = [(1/E) (dE/dt)]^{-1}$ is well approximated by

$$t_{df}(r) = t_{dyn}(r) M_g(r) / m_g. \quad (3)$$

The dynamical time $t_{dyn}(r)$ is defined as r/σ and $M_g(r)$ is the large galaxy's mass within r . As the smaller galaxy spirals inward, it will be tidally stripped and its density distribution will be truncated at some radius r_t where the densities of the two systems become comparable. If both galaxies have a density distribution of the form (2) with indices γ and γ' , the mass ratio of the two galaxies varies as $M_g(r)/m_g(r) \propto r^{3(\gamma-\gamma')/\gamma'}$. For $\gamma = \gamma'$ this is a constant and the smaller galaxy spirals inward with radial velocity $\sigma m_g/M_g$. At some distance the galactic density profiles must change: either there is a core or a central black hole. If the smaller galaxy does not contain a black hole it will lose its identity when the density of the large galaxy becomes equal to the core density of the smaller one. More interesting is the case in which both galaxies contain a massive central black hole. At some separation distance where $M_g(r)$ is comparable to M , the mass of the black hole at the centre of the more massive galaxy, the black holes form a binary. Dynamical friction tends to circularize the orbit of a pair of merging galaxies and the eccentricity of the black hole binary orbit is therefore probably very small. As the orbit shrinks dynamical friction becomes less effective since stars can only interact with the binary when the encounter lasts longer than one orbital period (Heggie, 1975). When the binary separation becomes less than the cusp radius, defined by

$$r_h = GM/\sigma^2 \quad (4)$$

the orbital velocity rises above σ (the binary becomes hard). In this regime the binary loses energy by the slingshot mechanism: stars that come within the orbit of the binary are ejected with velocities comparable to the orbital velocity of the binary. The evolution via three-body interactions is halted at a radius r_{lc} when the number of stars on orbits passing through r_{lc} becomes too small to carry away the binding energy of the binary. Before we can discuss the final evolutionary stages of the binary we have to know how efficient the slingshot mechanism is in removing energy from a massive binary, and since the three-body problem is a classic unresolved problem we must resort to numerical experiments to obtain the necessary information.

2.2. Numerical Calculations of Slingshot Efficiency

Large regions in the phase space of the three-body problem have been explored numerically by Saslaw et al. (1974), Valtonen (1975), and by Hills (1975a). More recently Hills and Fullerton (1980) have performed a numerical study of the energy transfer as a function of m_* , the mass of the incoming particle. Their experiments, however, are restricted to the case of an equal mass binary on a circular orbit.

Let us define the slingshot efficiency η_{sl} by

$$\langle \Delta E \rangle = \eta_{sl} \frac{1}{2} m_* V_{orb}^2 \quad (5)$$

where $\langle \Delta E \rangle$ is the mean energy loss of the binary per interaction and V_{orb} is the orbital velocity of the binary, having components of mass m and M . The binary is assumed to be surrounded by a spherically symmetric distribution of particles with an isotropic Maxwellian velocity distribution with dispersion smaller than the orbital velocity of the binary. The average in (5) is taken over interactions with particles that come within a specified distance

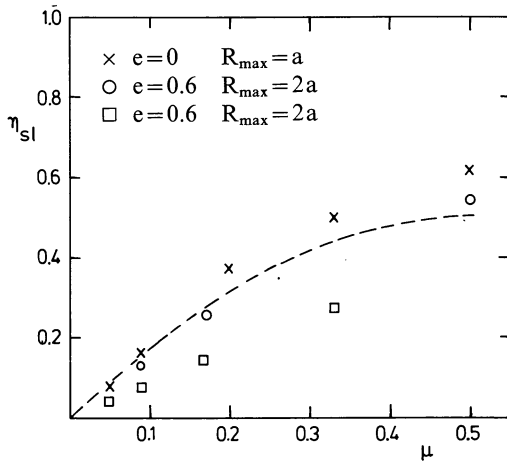


Fig. 1. Slingshot efficiency, defined by Eq. (5) as a function of reduced mass of massive binary. a is the maximum binary separation. The dashed line is the approximation given by (6)

$R_{\max}$ of the binary's centre of mass. The slingshot efficiency may depend on $R_{\max}$, m , M , and e , the eccentricity of the binary orbit.

A standard variable-order variable-step Adams integration routine was used to integrate the set of differential equations describing the three-body system (Hall and Watt, 1976). The fractional change in orbital energy due to numerical effects depends on e . It is less than 10^{-6} per orbital period for $e=0$ and rises to 10^{-4} for $e=0.99$ (cf. Van Albada, 1968). The values of η_{sl} were determined in runs in which 500 particles, having mass $m_* \ll m$, were allowed to interact one by one with the binary. The particles start from a shell, centered on the centre of mass of the binary, with a radius four times the semi-major axis of the binary. When a particle passes the shell again on its way outward its change in energy and angular momentum are measured and the next particle is sent off.

In Fig. 1 the slingshot efficiency is shown as a function of μ , the reduced mass of the binary. For $\mu = \frac{1}{2}$ ($e=0$) we find $\eta_{sl} \simeq 0.6$ in good agreement with the value ~ 0.5 found by Hills and Fullerton. Note that the experimental results are reasonably approximated by the relation

$$\eta_{sl} = 2 \frac{\mu}{m+M}. \quad (6)$$

We can understand this result assuming that the test particles interact either with m , with probability P_m , or with M with probability P_M , and that they fly off to infinity with the centre of mass (c.o.m.) velocity of m or M respectively, times some constant c . We then find

$$\langle \Delta E \rangle = \left[P_m \left(\frac{M}{m+M} \right)^2 + P_M \left(\frac{m}{m+M} \right)^2 \right] c^{\frac{1}{2}} m_* V_{\text{orb}}^2.$$

Assuming further that P_m is proportional to m^2 (as in dynamical friction) and to the c.o.m. velocity of m , we find $\eta_{sl} = c\mu/(m+M)$. The numerical result found here implies that the binary evolution is independent of the mass-ratio m/M for $m \ll M$. Note that this differs from the relation $\Delta E/E = m_*/M^2$ adopted by Begelman et al. (1980) to describe the evolution of a massive hard binary.

We have also measured the exchange of angular momentum between the binary and the test particles. The angular momentum of the binary is given by

$$L^2 = \mu \frac{GmM}{2E} (1-e^2).$$

In the simulations with $e=0$ we find $\langle (\Delta L/L) / (\Delta E/E) \rangle \simeq 0.5$, which implies that the eccentricity will not change. For $e=0.6$, however, we find a value of 0.7 ± 0.2 and the binary eccentricity may increase. More accurate numerical simulations are required to check this.

2.3. Further Evolution of the Binary

We have found that the dynamical evolution of the binary inside the cusp radius r_h is independent of the mass ratio m/M for $m \ll M$, in contrast to the region where the dynamical friction formula applies. The binary then interacts only with stars passing through its orbital radius r_b . The total mass of these 'loss-cone' stars is given by

$$M_{lc}(r_b) = 4\pi \int_{r_b}^{\infty} \varrho(r) r^2 \theta^2 dr \quad (7)$$

where θ^2 is the fraction of such stars at a distance r from the binary. In the case of an isotropic velocity distribution θ is given by

$$\theta = \begin{cases} (r_b r_h)^{1/2} / r & r > r_h \\ (r_b / r)^{1/2} & r < r_h \end{cases} \quad (8)$$

Frank and Rees (1976). The domain of integration may consist of three parts: a cusp region for $r < r_h$ with $\gamma_1 = -7/4$ (Bahcall and Wolf, 1976; Lightman and Shapiro, 1977; Cohn and Kulsrud, 1978), a core for $r_h < r < r_c$ with $\gamma = 0$ and an outer region with $-3 < \gamma_2 < -2$. We find

$$M_{lc}(r_b) = (\gamma_1 + 3) M_{\text{cusp}} \frac{r_b}{r_h} \left[\frac{1}{\gamma_1 + 2} + \frac{r_c}{r_h} \left(1 - \frac{1}{\gamma_2 + 1} \right) \right]. \quad (9)$$

M_{cusp} , the total mass of the stars within r_h , is given by

$$M_{\text{cusp}} \simeq \frac{4\pi}{\gamma_1 + 3} \varrho_h r_h^3$$

where ϱ_h is the density at r_h . Using $\varrho_h = \varrho_c$ and $r_c = GM_c/3\sigma^2$ we can write

$$M_{\text{cusp}} = \frac{81}{\gamma_1 + 3} M^3 / M_c^2 \quad (10)$$

where M_c is the core mass.

The dynamical evolution time of the binary for $r_{lc} < r_b < r_h$ is approximately given by

$$t(r_b) = t_{\text{dyn}}(r_h) [M_{lc}(r_b) \eta_{sl} / \mu]^{-1} \simeq t_{\text{dyn}}(r_h) r_b / r_h. \quad (11)$$

From the definition of η_{sl} we see that the binary orbit stops shrinking at a binary separation $r_b = r_{lc}$, defined by

$$M_{lc}(r_{lc}) \eta_{sl} / \mu = 1. \quad (12)$$

This yields with (9) and (6)

$$\frac{r_{lc}}{r_h} = \frac{1}{81} \frac{\mu M_c^2}{\eta_{sl} M^3} \left[\frac{1}{\gamma_1 + 2} + \frac{1}{3} \frac{M_c}{M} \left(1 - \frac{1}{\gamma_2 + 1} \right) \right]^{-1}. \quad (13)$$

Clearly it is difficult to bring the two holes close together via three body scattering if they are embedded in a large galactic core.

However, if this is not the case we may use $M_{\text{cusp}} = M_c$. From (10) we see that $M_{\text{cusp}} \simeq 4M$ and Eq. (13) then yields, with $\gamma_1 = -7/4$, $\gamma_2 = -2$, and $\eta_{sl} = 2 \mu/M$

$$r_{lc}/r_h \simeq 0.015. \quad (14)$$

The minimum separation that the binary may reach via three-body interactions with stars passing through the binary orbit may be smaller than $\sim r_{lc}$ if only a fraction f of these stars interacts with the smaller binary component, acquires a velocity kick $\Delta V \sim V_{\text{orb}}$ and becomes unbound (to the binary), while the binding energy of the other stars is hardly affected. These stars may pass several times through the binary orbit until they are also flung out of the stellar system bound to the binary with velocity $\sim V_{\text{orb}}$. The minimum binary separation will then be smaller than r_{lc} by about a factor f . The argument below Eq. (6) suggests that $f \sim m/M$. In that case the minimum separation of the binary will be

$$\frac{m}{M} r_{lc} \lesssim r_{b,\text{min}} \lesssim r_{lc}.$$

Gravitational radiation ensures merging of the black holes within a time Δt when they reach a separation

$$\frac{r_{gr}}{r_h} = 0.01 \left[\frac{M}{10^7 M_\odot} \right]^{-1/4} \left(\frac{m}{M} \right)^{1/4} \cdot \left[\frac{\sigma}{200 \text{ km s}^{-1}} \right]^2 \left[\frac{\Delta t}{10^{10} \text{ yr}} \right]^{1/4} f(e), \quad (15)$$

where $f(e)$ is a function of the eccentricity of the orbit, which is of order unity for $e \simeq 0$ (Wagoner, 1975). Comparing (15) with (13) we conclude that merging of galaxies is likely to produce long-lived binary black holes if these holes are embedded in large galactic cores. If the density profile is not flat outside the cusp radius r_h , the holes may reach a separation where gravitational radiation will ensure merging within a Hubble time.

3. Fuelling the Black Hole

3.1. Stationary Fuelling of the Black Hole

We will first discuss briefly the fuelling of a black hole in the nucleus of a galaxy via tidal disruption and via star-star collisions, when the central region is undisturbed by other galaxies. We will use our galaxy as an example.

The stellar density at distance of ~ 1 pc from the centre of our galaxy is $\sim 10^6 M_\odot \text{ pc}^{-3}$ and the velocity dispersion of the stars $\sim 120 \text{ km s}^{-1}$ (Oort, 1977). Infrared observations of the galactic nucleus indicate the presence of gas at $r \sim 0.4$ pc with velocity dispersion $\sim 200 \text{ km s}^{-1}$ (Wollman et al., 1977). This is consistent with the presence of a black hole of mass $5 \cdot 10^6 M_\odot$.

Tidal disruption of solar-type stars occurs at¹

$$r_T/r_h \simeq 10^{-5} M^{-2/3} \sigma^2. \quad (16)$$

The gas produced at r_T is strongly bound to the black hole and a large fraction may be swallowed by the hole. Note that the Schwarzschild radius of the hole is $r_s/r_h = 5 \cdot 10^{-7} \sigma^2$ and that stars may be swallowed whole when $M \gtrsim 10^9 M_\odot$ (Hills, 1975). At a large distance r from the hole the flux of stars moving in orbits that will bring them within r_T is

$$F(r) = 2 \cdot 10^3 \varrho(r) r^2 \sigma(r) \pi \theta_{lc}^2(r) M_\odot \text{ yr}^{-1}$$

¹ Here and throughout the rest of the paper radii, masses, densities, and velocities will usually be expressed in 1 pc, $10^7 M_\odot$, $10^7 M_\odot \text{ pc}^{-3}$, and 200 km s^{-1} respectively

where θ_{lc} is defined by (8) with r_b replaced by r_T . Using

$$\sigma(r) = \begin{cases} \sigma, & r > r_h \\ \sigma(r/r_h)^{-1/2}, & r < r_h \end{cases}$$

we find

$$\frac{F(r)}{M_\odot \text{ yr}^{-1}} = 0.06 \varrho_h \sigma^{-1} M^{4/3} \begin{cases} (r/r_h)^{\gamma_2}, & r > r_h \\ (r/r_h)^{\gamma_1+1/2}, & r < r_h, \end{cases} \quad (17)$$

where $\varrho_h = \varrho(r_h)$. Within a critical radius r_{crit} , stars cannot be scattered in or out of loss-cone orbits by interactions with other stars in one dynamical time scale and these orbits become depleted. Equation (17) is valid only outside r_{crit} where the velocity distribution is isotropic. The largest contribution to the tidal disruption rate comes from the region near r_{crit} and the tidal disruption rate is about $F(r_{\text{crit}})/7$ (Frank, 1978). Following the discussion by Frank and Rees (1976) and using

$$\varrho_h \simeq M^{-2} \sigma^6 \quad (18)$$

which is valid for $r_c = r_h$, we find

$$\text{for } r_{\text{crit}} > r_h, \left(\frac{r_{\text{crit}}}{r_h} \right)^{\frac{3+\gamma_2}{2}} \left\{ \begin{array}{l} \\ \end{array} \right\} = 2.3 \varrho_h^{-1/12} \sigma^{3/2}.$$

$$\text{for } r_{\text{crit}} < r_h, \left(\frac{r_{\text{crit}}}{r_h} \right)^{\frac{4+\gamma_1}{2}} \left\{ \begin{array}{l} \\ \end{array} \right\}$$

In our galaxy $r_{\text{crit}}/r_h \simeq 1.5$ and the tidal disruption rate is about $5 \cdot 10^{-4} M_\odot \text{ yr}^{-1}$.

The inner edge of the cusp around black holes is set by star-star collisions. Within a radius r_{coll} , defined by

$$r_{\text{coll}}/r_h = 0.2 \sigma^2. \quad (19)$$

Solar-type stars cannot be deflected over large angles without colliding. The cusp only extends over the region $r_{\text{coll}} < r < r_h$. Most collisions occur at r_{coll} which is much larger than r_T . The fate of the gas liberated in collisions with other stars may therefore be different from that of stars disrupted by the tidal force of the black hole. The collision rate in the cusp is about (cf. Van Bueren, 1978)

$$C \simeq 5 \cdot 10^{-3} M^3 \varrho_h^2 \sigma^{-7} \text{ yr}^{-1}. \quad (20)$$

In our galaxy this is about 10^{-3} yr^{-1} , a value comparable with the tidal disruption rate. A fuelling rate F of a black hole yields a luminosity

$$L \simeq 6 \cdot 10^{45} \text{ erg s}^{-1} \left[\frac{F}{1 M_\odot \text{ yr}^{-1}} \right] \left[\frac{\eta}{0.1} \right]$$

where η is the fraction of the rest mass energy that is radiated during accretion of the mass by the black hole. This efficiency factor may vary from 0.057 to 0.42 depending on the angular momentum of the black hole (Bardeen, 1970). A tidal disruption rate of $5 \cdot 10^{-4} M_\odot \text{ yr}^{-1}$ yields a luminosity of $3 \cdot 10^{42} (\eta/0.1) \text{ erg s}^{-1}$. The limits to the present energy output of the galactic nucleus are much lower, but there is evidence for recurrent explosions from the nucleus yielding an average energy output of $\sim 10^{42} \text{ erg s}^{-1}$ (van Bueren, 1978).

It is interesting to note that a stationary fuelling rate of $5 \cdot 10^{-4} M_\odot \text{ yr}^{-1}$ is consistent with the growth of a $5 \cdot 10^6 M_\odot$ black hole in one Hubble time. If the growth time of black holes in galactic nuclei is about one Hubble time we can derive a relation between the central velocity dispersion of stars and the mass of a black hole in the nucleus of a galaxy.

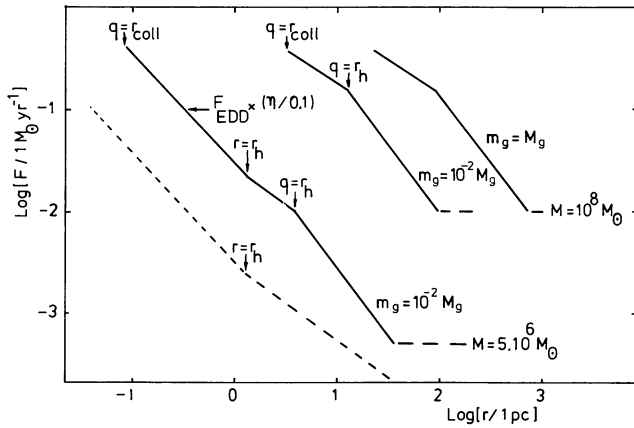


Fig. 2. Tidal disruption rate of a central black hole during a merger of a galaxy with a smaller companion. The mass-ratio of the two galaxies is assumed constant. The stellar density and velocity dispersion at the cusp radius r_h are $2.5 \cdot 10^6 M_\odot \text{ pc}^{-3}$ and 120 km s^{-1} respectively for $M = 5 \cdot 10^6 M_\odot$ (Case 1) and $1.6 \cdot 10^6 M_\odot \text{ pc}^{-3}$ and 300 km s^{-1} for $M = 10^8 M_\odot$ (Case 2). The dashed line is the tidal disruption rate near a secondary black hole of mass $5 \cdot 10^5 M_\odot$ assumed present in the smaller galaxy in Case 1 (see Sect. 3.3)

Using (18) we find from the tidal disruption rate

$$M = \begin{cases} 3.5 \sigma^{2.1}, & r_{\text{crit}} > r_h \\ \sigma^{3/7}, & r_{\text{crit}} < r_h \end{cases}$$

and from the collision rate

$$M \simeq 5 \sigma^{5/2}.$$

Collisions may dominate the growth for $\sigma > 1/2$, just before r_{crit} becomes smaller than r_h . The mass given by the relations $M = 3.5 \sigma^{2.1}$ for $\sigma < 1/2$ and $M = 5 \sigma^{5/2}$ for $\sigma > 1/2$ may be regarded as an upper limit to the mass of a black hole in a galactic nucleus if tidal disruption of stars and star-star collisions are the dominant fuelling mechanisms.

3.2. Enhanced Tidal Disruption Rate During Mergers

Stars within a distance r_{crit} of a black hole in a galactic nucleus may be scattered into loss-cone orbits by the tidal force of an intruding galaxy, leading to an increase of the tidal disruption rate. The enhanced disruption rate will then be determined by the effective critical radius q , at which stars can be scattered into loss-cone orbits within one (stellar) orbital period. The perturbation of a stellar orbit by the intruder can be calculated analytically if the stellar orbital period is much shorter than the orbital period of the merging galaxies (cf. Heggie, 1975). A mean value of q ($\ll r$, the distance between the centres of the merging galaxies) could then be obtained by integrating over all stellar orbits. However, if the orbital periods are comparable we have to deal with the full complexity of the three-body problem for which there are no general solutions. We will give here a very simple, but crude estimate for q , ignoring its dependence on the orientation of the stellar orbits with respect to the direction of the perturber and neglecting the motion of the perturber. Our basic assumption is that the scattering of stars by the perturbing mass can be treated as a random process analogous to two-body relaxation.

In order to scatter stars into loss-cone orbits we need a mean velocity change in one dynamical time of

$$\Delta V = h_T / q,$$

where h_T , the angular momentum per unit mass of stars passing the black hole near r_T , is given by

$$h_T = \sigma r_h^{1/2} r_T^{1/2}.$$

The dynamical time of the stars at q is given by

$$t_{\text{dyn}} \simeq \begin{cases} q/\sigma, & q > r_h \\ (q/r_h)^{1/2} q/\sigma, & q < r_h \end{cases} \quad (21)$$

and the required acceleration is

$$\Delta V / t_{\text{dyn}} = \begin{cases} \sigma^2 r_h^{1/2} r_T^{1/2} q^{-2}, & q > r_h \\ \sigma^2 r_h r_T^{1/2} q^{-5/2}, & q < r_h. \end{cases} \quad (22)$$

The tidal acceleration of a star at q due to a mass m_g at r is

$$a_{\text{tidal}} \simeq 2 G m_g q / r^3.$$

Using $G M_g(r) = r \sigma^2$ we find

$$a_{\text{tidal}} = \begin{cases} \sigma^2 f q / r^2, & r > r_h \\ \sigma^2 f r_h / r^3, & r < r_h \end{cases} \quad (23)$$

where f is $m_g / M_g(r)$. The tidal acceleration equals the required acceleration for

$$q = \begin{cases} 0.12 r^{2/3} M^{2/9} \sigma^{-1/3} f^{-1/3} & q, r > r_h \\ 0.16 r^{4/7} M^{1/3} \sigma^{-4/7} f^{-2/7} & q < r_h < r \\ 0.16 r^{6/7} M^{1/21} f^{-2/7} & q, r < r_h, \end{cases} \quad (24)$$

where M is again the mass of the black hole at the centre of the most massive galaxy. Calculating $F(q(r))$ from (17) and (24) and substituting $\gamma_1 = -7/4$ we find for the tidal disruption rate as a function of the distance of the intruding galaxy from the centre of the larger galaxy

$$\frac{F(r)}{1 M_\odot \text{ yr}^{-1}} = \begin{cases} 6.10^{-2} (0.12)^{\gamma_1} r^{2\gamma_1/3} q_h M^{(12-7\gamma_1)/9} \cdot \sigma^{(5\gamma_1-3)/3} f^{-\gamma_1/3}, & q, r > r_h \\ 0.6 r^{-5/7} q_h M^{13/6} \sigma^{-78/28} f^{5/14}, & q < r_h < r \\ 0.6 r^{-15/14} q_h M^{53/21} \sigma^{-7/2} f^{5/14}, & q, r < r_h. \end{cases} \quad (25)$$

This relation is valid only for $q > r_{\text{coll}}$. The precise behaviour of the density profile at $r < r_{\text{coll}}$ is not known. However, it seems plausible that the collision time does not increase with decreasing r within r_{coll} implying $\gamma \lesssim -1/2$ in that region. The fuelling rate then reaches a maximum value determined by the conditions at this inner edge of the cusp

$$F_{\text{max}} = 0.45 q_h \sigma^{-7/2} M^{4/3} M_\odot \text{ yr}^{-1}.$$

Note that this value is not very sensitive to M if (18) and the relations at the end of Sect. 3.1 are valid.

We will now discuss this result for some particular cases. We will assume that both merging galaxies have a power law density distribution with $\gamma_2 = -2$, implying that f is a constant.

Case 1

A merger of a small galaxy with our galaxy assumed to contain a central black hole of $5 \cdot 10^6 M_\odot$. We use the same galactic parameters as in the previous section ($q_h = 0.25$, $\sigma = 0.6$). In Fig. 2 the tidal disruption rate is given for a mass ratio $f = 10^{-2}$. At a separation distance of the merging galaxies of $360 f^{1/2}$ pc the tidal disruption rate overtakes the stationary rate of $\sim 5 \cdot 10^{-4} M_\odot \text{ yr}^{-1}$, calculated in the previous section. The dynamical friction time, given by

$$t_{df} = 10^4 r \sigma^{-1} f^{-1} \text{ yr} \quad (26)$$

is then about $6 \cdot 10^6 f^{-1/2}$ yr. At $r = 38 f^{1/2}$ pc ($F = 10^{-2} M_\odot \text{ yr}^{-1}$, $t_{df} = 6 \cdot 10^5 f^{-1/2}$ yr) the value of q reaches that of the cusp radius and the disruption rate subsequently increases less rapidly with decreasing r . The total number of stars disrupted by the black hole in this first stage is $\sim 10^4 f^{-1/2}$, only about a factor three higher than in the unperturbed case. $F(r)$ changes its slope again at $r = r_h$ ($F(r_h) = 0.11 f^{5/14} M_\odot \text{ yr}^{-1}$, $t_{df} = 2 \cdot 10^4 f^{-1/2}$ yr). In the present case this occurs when $q/r_h = 0.15 f^{-2/7}$, before the tidal disruption rate reaches its maximum value at $q = r_{\text{coll}} = 0.07 r_h$. During this stage about $10^4 f^{-9/14}$ stars are disrupted. The binary evolution time is given by (11) for $r < r_h$. The disruption rate rises above the Eddington rate

$$F_{\text{EDD}} = 0.2 M (0.1/\eta) M_\odot \text{ yr}^{-1}$$

and reaches the value $0.4 M_\odot \text{ yr}^{-1}$ when $q = r_{\text{coll}}$ at $r = 0.4 f^{1/3}$. The binary evolution time is then $3 \cdot 10^4 f^{-1/3}$ yr. The stellar debris produced in this stage can keep the black hole radiating at the Eddington luminosity for $10^5 (\eta/0.1) f^{-1/3}$ yr. If the fuelling rate stays at a level of $0.4 M_\odot \text{ yr}^{-1}$ until $r = r_{\text{coll}}$ this is about 10^6 yr. For this period the merger may enhance the fuelling rate by more than two orders of magnitude.

Case 2

Merging of two galaxies, one of which containing a massive black hole of mass $10^8 M_\odot$. We have chosen a velocity dispersion at r_h of 300 km s^{-1} and $q_h = 1.6 \cdot 10^6 M_\odot \text{ pc}^{-3}$ [see Eq. (18)] yielding a black hole growth time via accretion of gas produced in star-star collisions of $\sim 10^{10}$ yr. Now q becomes equal to r_{coll} at $r = 34 f^{1/2}$ pc which is larger than $r_h = 4.4$ pc for $f > 0.02$. The total number of stars disrupted during the whole period of enhanced activity, which lasts $\sim 10^7 f^{-1/2}$ yr, is $10^6 f^{-1/2}$, about 10 times more than in the unperturbed case. Most of these stars are disrupted in the second evolutionary stage ($r_{\text{coll}} < q < r_h$), where a maximum luminosity of $\sim 3 \cdot 10^{45} \text{ erg s}^{-1}$ is obtained during $\sim 10^6 f^{-1/2}$ yr.

We conclude that under conditions similar to those in the nucleus of our galaxy, merging of galaxies may yield luminosities of $\sim 3 \cdot 10^{45} (\eta/0.1) \text{ erg s}^{-1}$. Small galaxies ($f \approx 10^{-2}$) are probably most effective in causing activity in galaxies (see Sect. 4). The total energy production during a merger with such a small companion is of the order $10^{59} [M/10^7 M_\odot] (\eta/0.1) \text{ erg}$ in $\sim 10^7$ yr.

3.3. The Secondary Component

If the smaller infalling galaxy also contains a massive black hole the tidal disruption rate of stars near this secondary black hole may be enhanced as well. The tidal disruption rate is then also given by Eq. (25) with $f \approx 1$, if the parameters of the larger galaxy are replaced by those of the smaller one. The dotted line in Fig. 2 gives the tidal

disruption rate of the secondary black hole in case 1 of the preceding section. The velocity dispersion in the smaller galaxy is 40 km s^{-1} , the black hole mass $5 \cdot 10^5 M_\odot$. The stellar density at its cusp radius is $3.5 \cdot 10^5 M_\odot \text{ pc}^{-3}$. Note that the mass-ratio of the two galaxies is not a constant anymore. At a separation distance $r \sim r_h$ the mass-ratio changes from 10^{-2} to 10^{-1} , the mass-ratio of the black holes. This will probably not effect the dynamical evolution since inside the cusp radius the binary evolution is independent of the mass ratio. The only difference may be that the primary black hole reaches F_{max} at a slightly larger separation. The important conclusion we can draw from the dashed line in Fig. 2 is that the fuelling mechanism discussed in this paper probably implies the existence of double sources of energy with small separations.

3.4. Precession of Beams

The observed large scale symmetry in many extended radio sources may be explained as due to precession of radio beams or jets through which energy is being transported from the nucleus to the outer lobes of the source (e.g. Ekers et al., 1978). Such beams will be aligned with the rotation axis of a hole, presumed to be in the galactic nucleus, even when the angular momentum of the matter feeding the hole has a different orientation (Rees, 1978). If a binary black hole is formed during a merger the spin axes of the holes will generally precess around their orbital angular momentum vector, the precession period being given by

$$t_{\text{prec}} \approx 3 \cdot 10^{10} r^{5/2} (M/m) M^{-3/2} \text{ yr} \quad (27)$$

(Begelman et al., 1980). From the discussion of the binary evolution we conclude that the probability to observe a binary with some separation r has a minimum at $r = r_h$, increases with $t_{ev} \propto r_h/r$ for $r < r_h$ [Eq. (11)], and goes rapidly to zero at $r \lesssim 10^{-3}$ pc when energy loss due to gravitational radiation becomes important. For $r > r_h$ the precession period is larger than a Hubble time. The most probable binary separations for $r < r_h$ are $10^{-3} \lesssim r/r_h \lesssim 10^{-2}$ yielding precession periods of $\sim 10^3$ to $\sim 10^7$ yr. The time spent at these separation distances is probably larger than the evolution time given by Eq. 11 due to depletion of stars on orbits through the binary orbit. The maximum probability at $r < r_h$ may be estimated from $t_{ev} \approx t_{gr}$, where $t_{ev} \approx 10^4 M^2 \sigma^{-5} r^{-1} \text{ yr}$ and t_{gr} , the time scale for loss of orbital energy due to gravitational radiation is given by

$$t_{gr} = 2.4 \cdot 10^{18} (M/m) M^{-3} r^{-4} \text{ yr.} \quad (28)$$

This occurs at $r = 1.3 \cdot 10^{-3} (m/M)^{1/5} M \sigma^{-1} \text{ pc}$, yielding a most probable precession period of $2 \cdot 10^3 (M/m)^{1/2} M \sigma^{-5/2} \text{ yr}$. Begelman et al. (1980) derive a precession period of ~ 500 yr from the observed curvature of the jet in 3C 273 on a scale of $0''.01$. This implies a rather short gravitational radiation time scale of a few million years. The probability that the presence of a secondary black hole in this nearby QSO is accidental seems very small. If the explanation of the jet curvature in 3C 273 proposed by Begelman et al. is right, then the short lifetime of the binary suggests that its occurrence is causally related to the QSO phenomenon.

4. Total Luminosity Function of Active Galaxies

The maximum total luminosity of active galactic nuclei at the present epoch is about $10^{46} \text{ erg s}^{-1}$. Radio observations of active galaxies indicate that the total energy production in active nuclei can be $\sim 10^{60} \text{ erg}$ in $10^{6 \text{ to } 8} \text{ yr}$. These values are compatible with

the activity produced during a merger of a galaxy with a smaller companion (Sect. 3.2) and it seems therefore worthwhile to investigate what fraction of galaxies is expected to be active in the merger model, and to make a comparison with observations.

4.1. The Model

The merging rate of galaxies can be estimated from observations as well as from numerical experiments. Most galaxies have a smaller companion ($m_g/M_g \sim 0.1$) within a few galactic radii (Holmberg, 1969). Assuming that galaxies have dark halos extending to ~ 100 kpc, the dynamical friction time for these companions is about 10^{10} yr (see also Tremaine, 1976) yielding a growth rate for the larger galaxies of about $M_g(10^{11} \text{ yr})^{-1}$. The number of neighbours (of comparable size) within a distance r of a galaxy can also be calculated from the two-point correlation function (Peebles, 1980; Gott and Turner, 1979). From this function we find that the mean number of neighbours within a distance r ($10 \text{ kpc} \lesssim r \lesssim 10 \text{ Mpc}$) is about $4\pi\bar{n}70(r/1 \text{ Mpc})^{1.2}$ (we adopt $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$) where $\bar{n}$, the mean number density of galaxies brighter than L^* , the break in the luminosity function, is about $2 \cdot 10^{-3} \text{ Mpc}^{-3}$. The relative velocities of close neighbours is a few hundred km s^{-1} . Most of these binaries will therefore experience strong dynamical friction and will merge within a few galactic rotation periods if galaxies have extended halos. This also yields a growth rate for bright galaxies of about $M_g(10^{11} \text{ yr})^{-1}$. A similar merging rate was deduced by Toomre (1977) from the fraction of galaxies that are observed to be tidally distorted due to interaction with a nearby neighbour. The merging rate at the present epoch derived from observations is in good agreement with the value found in cosmological simulations (Roos, 1981, Paper I).

We will now estimate the fraction of galaxies $\phi(L)$ having bolometric luminosities L [equal to $6 \cdot 10^{45} (\eta/0.1) \text{ erg s}^{-1}$ times the fuelling rate] in the interval $[L, 2.5 \times L]$. We will do this for galaxies of mass M_g containing a central black hole of mass M . We assume that the galaxies have power law density profiles with $\gamma = -2$ and stellar velocity dispersion σ . Assuming that the infall rate is proportional to mass (Papers I and II) and that the mass function of infalling galaxies is about proportional to m_g^{-1} for small m_g (Schechter, 1976) we find for the mean time between subsequent mergers of a galaxy of mass M_g with smaller galaxies of mass m_g $\Delta t = 10^{11} m_g/M_g \text{ yr}$. The fraction $\phi'(r)$ of galaxies having a companion at a distance in the interval $[r, r+dr]$ is

$$\phi'(r) = \frac{1}{\Delta t} \frac{dt}{dr} \quad (29)$$

for r smaller than some distance r_{sat} , defined by $\int_0^{r_{\text{sat}}} \phi'(r) dr = 1$, where “saturation” of $\phi'(r)$ occurs (see next section). As discussed in Sect. 2 the smaller galaxy will spiral inward with constant velocity ($r > r_h$)

$$\frac{dr}{dt} = 10^{-4} f \sigma \text{ pc yr}^{-1},$$

if the two galaxies have similar density profiles. Knowing $\phi'(r)$ we can calculate the fraction of galaxies having a fuelling rate F in the interval $[F, 2.5 \times F]$ from

$$\phi(F) = \phi'(r) \frac{F}{2.5} \frac{dr}{dF}.$$

This yields with (25) and (18)

$$\phi(F) \simeq \begin{cases} 10^{-7} F^{-3/4} M^{2/3} \sigma^{1/4} f^{-3/2}, & F < F^* \\ 0.2 \cdot 10^{-7} F^{-7/5} M^{5/42} \sigma^{3.5} f^{-3/2}, & F > F^* \end{cases} \quad (30)$$

The break in this function occurs at $F^* = 0.06 q_h M^{4/3} \sigma^{-1} M_\odot \text{ yr}^{-1}$ when $q = r_h$. As dynamical friction is taken over by three-body scattering at $r \lesssim r_h$ the dynamical evolution speeds up (if $f < 1$) and $\phi(F)$ probably decreases strongly upon extrapolation of (30) to larger F . Note that the part of $\phi(F)$ with an index $-7/5$ does not extend to large F . The maximum F for this part of $\phi(F)$ is determined by the condition $r = r_h$ (as in case 1 of the previous section) yielding $F = 0.59 q_h M^{1.45} \sigma^{-1.36} f^{5/14} M_\odot \text{ yr}^{-1}$, or $q = r_{\text{coll}}$, yielding

$$F = 0.45 q_h M^{4/3} \sigma^{-7/2} M_\odot \text{ yr}^{-1}.$$

The largest contribution to $\phi(F)$ comes from mergers with small companions. Firstly, because the dynamical friction time at some fuelling level is longer, and secondly because these galaxies are more abundant. However, the galaxies that are being swallowed may not be smaller than $\sim 10^{-2} M_g$ since the dynamical friction time then exceeds the Hubble time. Converting fuelling rates F to luminosities L and taking $f = 10^{-2}$, the fraction of galaxies having luminosity within $[L, 2.5 \times L]$ due to infall of small galaxies is given by

$$\phi(L) = \begin{cases} 2 \cdot 10^{-3} L_{44}^{-3/4} (\eta/0.1)^{3/4} M^{2/3} \sigma^{1/4}, & L < L^* \\ 6 \cdot 10^{-3} L_{44}^{-7/5} (\eta/0.1)^{7/5} M^{5/42} \sigma^{3.5}, & L > L^*, \end{cases} \quad (31)$$

where $L_{44} = L/10^{44} \text{ erg s}^{-1}$ and $L_{44}^* = 5 M^{-2/3} \sigma^5 (\eta/0.1)$. As in (30) the region with $\phi(L) \propto L^{-7/5}$ extends over a small range in L to $L_{44} = 30 (\eta/0.1) M^{-0.55} \sigma^{4.64} f^{5/14}$ for $r = r_h$ ($q > r_{\text{coll}}$), or to $L_{44} = 30 (\eta/0.1) M^{-2/3} \sigma^{2.5}$ for $q = r_{\text{coll}}$ ($r > r_h$). Note that the choice of f introduces a considerable uncertainty in the absolute value of $\phi(L)$.

The luminosity function of active galaxies could in principle be obtained from (31) by performing an integration over the product of $\phi(L)$ and the mass function of central black holes in galactic nuclei. This requires information about the relation between galactic luminosity (or central velocity dispersion) and central black hole mass. For the moment we are merely interested to see whether Eq. (31) is consistent with luminosity functions of active galactic nuclei derived from observations. We will use as a first approximation for the theoretical function of active nuclei having total luminosity L in the interval $[L, 2.5 \times L]$

$$q(L) = n^* \phi(L, M^*, \sigma^*), \quad (32)$$

where n^* is the number density of bright galaxies above the break of the galaxy luminosity function, and M^* and σ^* are the mass of the central black hole and the velocity dispersion in these galaxies. In Fig. 3 $q(L)$ is drawn for $n^* = 2 \cdot 10^6 \text{ Gpc}^{-3}$ (Felten, 1977). $M^* = 10^7 M_\odot$ and $\sigma^* = 150 \text{ km s}^{-1}$. Note that a proper calculation of $q(L)$ will yield a luminosity function extending over a larger range in luminosity.

4.2. The Observations

Our next task is to compare this result with available observational data on the space density of active galaxies at the present epoch. Luminosity functions for active galaxies have been determined for radio, optical and X-ray wavebands. However, the determination of the bolometric (total) luminosity function requires information on the spectral distribution of the radiation emitted by active

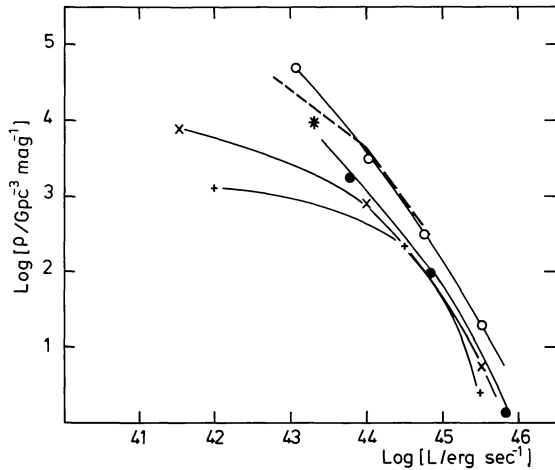


Fig. 3. Luminosity functions of active galaxies. Luminosities are converted to total luminosities as described in the text (Sect. 4.2). $\circ$ X-ray luminosity function of Seyfert galaxies. $\bullet$ Local, optical luminosity function of QSO's. $*$ Space density of Seyfert nuclei (optical). $\times$ Radio luminosity function of E+SO galaxies (1.4 GHz). $+$ Radio luminosity function of E+SO cores (5 GHz). The dashed line gives the estimated luminosity function of active galaxies derived from (31) using the parameters given in the text (Sect. 4.1)

galactic nuclei (and/or QSO's). For some individual sources like 3C 273 the spectrum is reasonably well known from 10^9 – 10^{20} Hz (Ulrich, 1981), but this is still an exception. Nevertheless, the presently available observational data indicate that the luminosities at different wave-bands are correlated, and that the global spectral distribution of the radiation emitted in the range 10^{13} – 10^{18} Hz can be characterized by a power law with a spectral index which is similar for different objects. The energy emitted at optical wavelengths seems a good indicator of the total energy emitted by Seyferts and QSO's. The mean radio-to-optical spectral index α_{RO} of radio-loud QSO's is about 0.6, implying $L_{opt}/L_{radio} \approx 10^{2.4}$ and the optical-to-X-ray index α_{OX} is about 1.25 (Ku et al., 1980; Zomorani et al., 1980) implying $L_{opt}/L_X \approx 10^{3/4}$, where L_{radio} , L_{opt} and L_X are the luminosities integrated over one decade in frequency at 10^9 , 10^{15} , and 10^{18} Hz respectively. The scatter in the values of α is large and in some cases most energy is emitted in the infrared (Rieke and Lebofsky, 1979), or in the gamma-ray domain as in 3C 273 (Swanenburg et al., 1978), but in these cases too the optical luminosity may give a good order of magnitude estimate of the bolometric luminosity. Radio galaxies seem to behave differently. While the energy emitted at radio wavelengths is comparable to that of radio-loud QSO's, the optical luminosity of the nuclei of radio galaxies is in most cases much less than that of QSO's. Still there is some evidence that the energy production rate in these objects may also be larger by about two orders of magnitude than their radio luminosity which is about 10^{43} – 10^{44} erg s^{-1} for the most luminous sources. The energy contained in the particle fluxes filling the extended radio lobes may well exceed 10^{61} erg in some cases. This would imply a total mean energy production rate of $\sim 10^{45.5}$ erg s^{-1} if the lifetime of these sources is about 10^8 yr. Therefore we have assumed that also for radio galaxies $L/L_{radio} = 10^{2.4}$. Using the crude conversion factors given above we now estimate 'bolometric' luminosity functions from observationally determined radio, optical and X-ray luminosity functions of active galaxies at the present epoch. The following

luminosity functions (scaled to $H_0 = 50$ km s^{-1} Mpc $^{-1}$) were used to obtain the results given in Fig. 3.

(i) X-ray luminosity function of Seyfert galaxies from Weedman (1979). $\log(L/\text{erg } s^{-1}) = \log(L_X/\text{erg } s^{-1}) + 3/4$.

(ii) Optical luminosity function of QSO's at the present epoch from Braccetti et al. (1980). The total luminosity was calculated from $\log(L/\text{erg } s^{-1}) = \log(L_{opt}/\text{erg } s^{-1}) + 0.4(90 - M_B)$. Note that the determination of this luminosity function depends on the cosmological evolution of the QSO luminosity function.

(iii) Space density of Seyfert nuclei (optical) from Huchra and Sargent (1973). $\log(L/\text{erg } s^{-1}) = 0.4(90 - M_B)$. As noted by Braccetti et al. this point agrees well with the low luminosity extrapolation of the optical (local) luminosity function of QSO's.

(iv) Radio luminosity function of E+SO galaxies from Auriemma et al. (1977). Here we have used $\log(L/\text{erg } s^{-1}) = 41 + \log(P_{1.4}/10^{24.5} \text{ WHz}^{-1}) + 2.4$, where $P_{1.4}$ is the radio power at 1.4 GHz. A large fraction of the radio luminosity of these sources comes from the extended radio structures at large distances from the centre of the parent galaxy. The luminosity from these radio lobes may not be representative for the luminosity of the nucleus. Therefore we also give the radio luminosity function of the cores of E+SO galaxies (determined at 5 GHz) from Fanti and Perola (1977).

The agreement between the observational functions given in Fig. 3 is surprisingly good in particular for $L > 10^{44}$ erg s^{-1} . Not only the slopes but also the absolute values of these functions are very similar. This strongly suggests that the different types of active galaxies such as Seyferts (QSO's) and radio galaxies belong to a single class of objects having a basic spectrum which can indeed be characterized by the values for α used above. The scatter in the relative portions of energy emitted at different wavelengths may then be the result of different physical conditions in galactic nuclei. The fraction of active E+SO galaxies, for instance, is comparable to the fraction of active Spirals (Seyferts). For some reason the relative amount of energy produced by active E+SO galaxies in the optical regime is lower than that of Seyferts while active Spirals (Seyferts) are underluminous at radio wavelengths, but it seems likely that the activity in both types is caused by the same mechanism.

4.3. Comparison of the Model with Observations

The crude model estimate from Eq. (32) (see Fig. 3) was done for a single set of parameters assumed to be typical for the nucleus of a bright galaxy. Nevertheless, the agreement with observed luminosity functions in the range $10^{42.5} \leq L \leq 10^{44.5}$ is already quite good indicating that the model may be consistent with observations.

Equation (31) may be compared more directly with the observed bivariate radio luminosity function of E+SO galaxies, determined by Auriemma et al. (1977), which gives the fraction of E+SO galaxies within a certain (1 mag) bin of optical (stellar) luminosity having a certain radio power (at 1.4 GHz). This function has the following properties.

1. It can be described by a single power law for $P > P^* = 10^{25} \text{ WHz}^{-1} \approx 10^{42} \text{ erg } s^{-1}$. The power law index is about -1.4 , independent of the optical luminosity L_g of the galaxy.
2. P^* is not very sensitive to L_g .
3. The fraction of galaxies having a certain radio power scales as $L_g^{1.5 \pm 0.2}$ for $P > P^*$.
4. Below P^* the index of the power law fit to the radio luminosity function varies from ~ -0.7 for the faintest galaxies to

~ -0.1 for the most luminous galaxies in the sample. Auriemma et al. remark that the flattening may be due to some of saturation since, for the most luminous galaxies the fraction having radio power larger than P is already close to 1 at $P=10^{24}$ WHz^{-1} .

These properties resemble some of the properties of $\phi(L)$ given by (31).

1. $\phi(L)$ has a power law index -1.4 for $L > L^*$, where $L^* = 5 \cdot 10^{44}$ erg s^{-1} , which would imply a radio luminosity of 10^{42} erg s^{-1} using the conversion factor discussed in the previous section. A difficulty with the model may be that $\phi(L)$ extends over only a small range in luminosity beyond L^* .

2. Assuming $L_g \propto \sigma^4$ (Faber and Jackson, 1976) we find that $L^* \propto L_g^{0.9 \text{ to } 0.6}$ for $M \propto \sigma^2$ to 4 .

3. For $L > L^*$, $\phi(L)$ scales approximately as σ^4 which goes as L_g .

4. Below L^* the power law index of $\phi(L)$ is -0.75 . In the merger model saturation may occur also for the most massive galaxies when the mean time between subsequent mergers is smaller for these galaxies than for the smaller ones. Observations indicate that for the brightest members of rich clusters it may be as short as $\sim 3 \cdot 10^9$ yr for $f \sim 1/3$ (Hoessel, 1980). For $f = 10^{-2}$ it may then be as short as $\sim 10^8$ yr, implying a time-averaged activity of $\sim 10^{44}$ erg s^{-1} .

4.4. Cosmological Evolution

So far we have only considered the luminosity function of active galaxies at the present epoch. This function, however, has evolved quite strongly between $z=0$ and $z=2.5$ (Schmidt, 1968). The observations seem to yield two global characteristics of the evolution: (i) the strong, steep spectrum radio source population has evolved most rapidly, while the evolution of fainter sources may have been very weak (e. g. Longair, 1978; Wall et al., 1980). (ii) This strong evolution may have occurred during a relatively recent epoch ($0.25 \lesssim z \lesssim 1$, Katgert et al., 1979) and may be related to the epoch of cluster formation. These points suggest that the strong evolution may be correlated with the evolution of giant ellipticals in regions where the number density of galaxies is high.

The over-all merging rate in cosmological simulations declines slowly as t^{-1} and the merging rate between $z=2.5$ and $z=0$ differs by a factor ~ 6.5 . Note, however, that this may be a lower limit to the real over-all evolution as pointed out in Paper I, because the calculations are relevant only for galaxies in the field and in poor clusters. In rich clusters the merging rate declines on a dynamical time scale of a few times 10^9 yr by a factor of about one hundred due to (i) the increase in velocity dispersion of the galaxies during collapse of the cluster, and (ii) rapid tidal stripping of galaxy halos during and after collapse of the cluster (Paper II). The steepest evolution may therefore be associated with the massive ellipticals that are formed in the central regions of rich clusters. These results imply that at earlier cosmological epochs cluster galaxies form a much more dominant fraction of active galaxies.

5. Discussion and Summary

We have attempted to link the merging phenomenon and the occurrence of activity in galactic nuclei. It has often been suggested that infall of gas from outside the stellar cusp surrounding a black hole may be responsible for enhanced activity. This may be gas which is released during stellar evolution or gas which is accreted in a merger (Gunn, 1979) or cooling intra-cluster gas sinking into the

potential well of the most massive galaxy (Matthews and Bregman, 1978). A serious difficulty with these models is that the fraction of the gas which is finally accreted by the hole is unknown. Large portions of the gas may form stars or be heated in shocks and expelled from the nuclear region, or even from the galaxy (Matthews and Baker, 1971). As an alternative mechanism to fuel the central engine in active nuclei we suggest here tidal disruption near the black hole of stars scattered into loss-cone orbits by the perturbing gravitational field of an intruding galaxy. Fuelling by tidal disruption of stars is attractive because (i) the stars are disrupted very close to the Schwarzschild radius of the black hole and a large fraction of their mass probably accreted by the hole, (ii) the tidal disruption rate can be estimated and predictions can be made both for the stationary case and for the case of galaxy mergers. In this paper we have given a very crude estimate of the enhanced tidal disruption rate during mergers, treating the perturbation of stellar orbits by the intruding galaxy as a random process similar to two-body relaxation. Detailed theoretical and numerical investigations are required to check this approach or to improve upon it. The results should therefore be regarded as tentative.

A vital condition for the model to yield sufficiently high tidal disruption rates during mergers is that the cusp mass should be comparable to the black hole mass. This situation can only occur if the black hole is not embedded in a galactic core with core radius larger than the cusp radius. If our galaxy contains a black hole of $\sim 5 \cdot 10^6 M_\odot$ this condition is fulfilled. In other galaxies the situation may be similar since in the cases where a resolved core may have been found it is in most cases not significantly larger than the seeing disk (Schweizer, 1979). Our assumption that central black holes in galactic nuclei are not embedded in cores has some important consequences:

(i) the tidal disruption rate in unperturbed galaxies containing a black hole of $\sim 10^7 M_\odot$ is of the order $\sim 10^{-3} M_\odot \text{ yr}^{-1}$ yielding a time-averaged luminosity of $\sim 10^{42}$ erg s^{-1} . If the Milky Way is representative for normal galaxies in this respect then this implies a space density of $\sim 10^6 \text{ Gpc}^{-3} \text{ mag}^{-1}$ for galaxies having a luminosity of $\sim 10^{42}$ erg s^{-1} . Note that this is in good agreement with the low luminosity extension of the Seyfert luminosity function given in Fig. 3.

(ii) The tidal disruption rate may be considerably enhanced during mergers yielding maximum luminosities, determined by the inner edge of the cusp at r_{coll} , of $\sim 10^{46}$ erg s^{-1} and a total energy production during mergers with small ($m_g/M_g \simeq 10^{-2}$) galaxies of about $10^{59} [M/10^7 M_\odot] \text{ erg}$ in $\sim 10^7$ yr. This is high enough to explain the maximum luminosities of active galaxies at the present epoch. Some QSO's at larger redshifts appear to have luminosities of 10^{48} erg s^{-1} . It is possible, however, that the luminosity of these objects is overestimated if the emitted radiation is beamed or if the emission of radiation occurs in short bursts. Also, these high luminosities would imply black hole masses of $10^{10} M_\odot$, if they are radiating at the Eddington limit, yielding a cusp radius of ~ 1 kpc, which exceeds observational limits in galaxies at low redshifts.

(iii) The binary black hole, which will be formed if both merging galaxies contain a central black hole, will lose orbital energy due to three-body interactions with stars and the binary orbit may shrink to a size where loss of orbital energy via emission of gravitational waves takes over and assures merging of the holes within a Hubble time.

As pointed out by Begelman et al. (1980) a binary black hole system in active galaxies may manifest itself via its orbital period or via precession of the spin axes of the holes. Short orbital periods of ~ 10 yr and precession periods of $\sim 10^4$ yr

may be most likely. The time scale for loss of orbital energy due to emission of gravitational radiation is expected to be about 10^{6-7} yr. If such a system is present in 3C 273 as proposed by Begelman et al. its short evolution time suggests a causal relation between the occurrence of the binary black hole and the activity in galactic nuclei.

Another phenomenon which may be observable is the activity of the secondary component. A merger of two similar galaxies may yield a double nucleus with a separation of order $1-10^2$ pc. Shklovskii (1978) has proposed just such a model for the nucleus of NGC 1275. He argues that the asymmetry of the narrow emission lines and the results of radio interferometric observations (at 1.35 cm) with intercontinental baselines are both consistent with the existence of a central binary system in this galaxy, having a separation of 1 pc and total mass $> 1.5 \cdot 10^8 M_\odot$. However, recent spectroscopic observations of Seyfert galaxies reveal that most asymmetric narrow lines extend further towards short wavelengths, which is most likely due to outflow of the radiating gas from the nucleus (Heckman et al., 1981). Double active nuclei may be found by observations with high spatial resolution, using for instance very long baseline interferometers, or, in the near future, the Space Telescope. Information on the (gas) dynamics of such systems may be obtained from the broad emission lines observed in many active nuclei.

In most cases activity must have been triggered by mergers of galaxies with mass ratio $f \approx 10^{-2}$. Such small companions are not likely to cause significant distortions of the optical appearance of galaxies. The (less frequent) interactions among galaxies having mass-ratio 0.1–1, however, can yield significant distortions in spiral galaxies such as rings and tails (Toomre and Toomre, 1972; Lynds and Toomre, 1976). The merging process then takes a few dynamical times and some of the distortions may still be photometrically apparent in active galaxies. Such distortions are most pronounced in spiral galaxies due to their large systematic rotation velocities and due to the presence of gas which will respond to the density perturbations leading to bursts of star formation. Many Seyfert galaxies are indeed disturbed (Adams, 1977; Simkin et al., 1980). It seems possible that many of the distortions in these galaxies can be explained if they have recently accreted a smaller companion. Note that the nucleus of this companion has to be at a distance smaller than ~ 100 pc from the centre of the galaxy in order to enhance the tidal disruption rate significantly.

The estimated merging rate of galaxies of mass M_g with companions of mass $10^{-2} M_g$ is about 1 per 10^9 yr. It is interesting to note that this merging rate may be sufficient to dominate the growth of black holes in galactic nuclei. The central black hole may grow by $\sim 10\%$ during a merger, yielding a growth rate of $\sim 10^{-3} [M/10^7 M_\odot] M_\odot \text{ yr}^{-1}$, which is comparable to the growth via tidal disruption of stars or star-star collisions in the absence of mergers. Using the above merging rate we have estimated the fraction $\phi(L)$ of galaxies having total energy outflow from their nucleus L due to merging with smaller companions. We must be careful when comparing this luminosity function with observed luminosity functions. Firstly, because we have made a number of assumptions to arrive at Eq. 31. Secondly, because the relation between the energy emitted in some waveband with the total energy released near the black hole is not clear. In view of this second point we have compared several observed luminosity functions of active galaxies at the present epoch. The results suggest that there is indeed a single population of active galaxy nuclei having a basic continuum spectrum. The variations in spectral index for different types of active galaxies may then be due to different physical conditions in their nuclei. We find that our predicted luminosity function agrees

well with observed luminosity functions of active galaxies at the present epoch. It is also capable of explaining some features of the bivariate radio luminosity function of E + S0 galaxies.

The merger model naturally leads to a (slow) cosmological evolution in the over-all number density of active galaxies. The strong evolution of powerful steep spectrum sources may be correlated with the strong decrease of the merging rate during the collapse of rich clusters. The spectra of active nuclei may also evolve during the epoch of cluster formation, as the gas content of galaxies becomes depleted, due to mergers and sweeping. The differences between the spectra of active E and S0 galaxies and of active spiral galaxies (Seyferts) could be the result of such a process.

In a previous study (Paper I) it was shown that in a hierarchical clustering scenario merging among galaxies during the epoch of cluster formation may well be responsible for an evolution of galaxies along the sequence (Sc–Sb–Sa)–SO–E. In this paper we have considered some of the possible implications of the merging process for models of active galactic nuclei. Assuming conditions in galactic nuclei similar to those in the nucleus of the Milky Way, we have argued that merging with smaller galaxies will enhance the tidal disruption rate of stars near a central black hole and may yield a luminosity which is typical for a Seyfert galaxy. The fraction of galaxies that is estimated to be active at a certain level is consistent with observed luminosity functions of active galaxies. These encouraging results indicate that enhanced tidal disruption of stars during galaxy mergers may be very important in causing activity in galactic nuclei.

Acknowledgements. I thank Harry van der Laan and Colin Norman for their comments on the manuscript. I have also benefitted from discussions with Ernst van Groningen, Peter Katgert, and George Miley.

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