Galaxy mergers and active nuclei. I - The luminosity function. II - Cosmological evolution

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GALAXY MERGERS AND ACTIVE NUCLEI. I. THE LUMINOSITY FUNCTION

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ABSTRACT

Galaxy mergers may boost the tidal disruption rate of stars near a massive central black hole in the nucleus of a galaxy, producing active galactic nuclei (AGNs) with nonthermal luminosities up to 10^{47} ergs s^{-1}. We derive a bolometric luminosity function for AGNs based on this process. Our main assumptions are: (1) galaxies contain massive central black holes, and (2) the density structure of galactic nuclei is similar to that of the Milky Way. The merging rate is estimated from the two-point correlation function of galaxies. Our bolometric luminosity function can be compared with observed radio, optical, and X-ray luminosity functions by assuming that the energy emitted at these wavebands is proportional to bolometric luminosity. This assumption is based on the similarity between observed luminosity functions at high luminosities. The observed and theoretical functions have the same characteristics: at high luminosities they behave as a power law with index of about -1.4. The function flattens below $L^{\otimes} \approx 10^{44}$ ergs s^{-1}. As an example we show that the model is capable of reproducing in detail the observed (bivariate) radio luminosity function. The luminosity coordinate of the break in the (bivariate) radio luminosity function at $L^{\otimes}$ yields an estimate of the central black-hole mass as a function of (stellar) galactic luminosity. The space-density coordinate of the break indicates that the mean mass ratio of the interacting galaxies is larger than 20.

Subject headings: black holes — galaxies: clustering — galaxies: nuclei — luminosity function

I. INTRODUCTION

In a previous paper (Roos 1981*b*, hereafter Paper I), the effect of a merger event on the tidal disruption rate of stars near a black hole embedded in a galactic nucleus was investigated. The intruding galaxy scatters stars from the stellar distribution around the central black hole into loss-cone orbits, thereby boosting the disruption rate of stars near the hole. This process is very attractive because it may account for the high nonthermal luminosities observed in active galactic nuclei (AGNs) without invoking conditions in AGNs that are qualitatively different from conditions in normal galaxies like the Milky Way. In the earlier paper we also made a first attempt to derive a local luminosity function of AGNs by combining a theoretical light curve for a galactic nucleus during a merger event with statistical data on the merging rate among galaxies. It was also suggested that the rapid decline of the merging rate among galaxies during the collapse and virialization of rich clusters might explain the steep cosmological evolution of powerful AGNs. In this paper and the following (Roos 1985, hereafter paper III), we will carry this investigation further to yield bolometric luminosity functions of AGNs now and in the past. An important feature of these luminosity functions is that they depend, via the central black-hole mass and central stellar density, on galaxy (stellar) luminosity or galaxy mass. Comparison of our luminosity function with observational data yields an estimate of central black-hole mass as a function of galaxy mass in this paper, and in paper III it yields an interpretation of the luminosity dependence of the cosmological evolution as the result of a difference in decay of the merging rate for galaxies in different ranges of galaxy luminosity.

In § II of this paper the bolometric luminosity function at the present epoch is derived and its properties are discussed. In § III this function is compared with observed luminosity functions. Finally, we briefly discuss some implications of the model.

II. THE LUMINOSITY FUNCTION

a) Conditions in Galactic Nuclei

Accretion of mass onto a central massive black hole is widely accepted as the most likely source of energy in AGNs. We therefore assume that the nuclei of bright ($M_v \lesssim -17$) galaxies contain central massive black holes. In order to calculate the fueling rate of such holes due to tidal disruption of stars near the hole, we have to adopt a model for star distribution in the nuclei of bright galaxies which is consistent with observations. The photometry of active galaxies justifies the assumption that the central star distribution in these galaxies is not basically different from that in a "normal" galaxy such as the Milky Way. The star distribution in the Milky Way is known at distances larger than about 1 pc of the galactic center. It is approximately given by[1]

$$\rho(r) \approx 0.1 r^{\gamma} , \quad (1)$$

where $\gamma = -1.8$ (Oort 1977). The three-dimensional stellar velocity dispersion at 1 pc is about 130 km s^{-1}. If a massive black hole of mass M is hiding in the nucleus of the galaxy, the mass density and the stellar velocity dispersion within the cusp radius, defined by

$$r_h = M\sigma^{-2} , \quad (2)$$

should vary as $r^{-7/4}$ and $r^{-1/2}$ respectively (Bahcall and Wolf 1976). The velocity dispersion of the stars in the galactic nucleus is approximately constant at radii larger than 1 pc, setting a upper limit of $\sim 4 \times 10^6 M_{\odot}$ to the mass of a central black hole. Taking the situation in the Milky Way as representative for all bright galaxies, we assume that the central

[1] If not specified otherwise, radii, masses, densities, and velocities will be expressed in pc, $10^7 M_{\odot}$, $10^7 M_{\odot}$ pc^{-3}, and 200 km s^{-1} respectively.

star distribution of bright galaxies outside the cusp radius varies as r^{-2}.

The luminosity of bulges of spiral galaxies and elliptical galaxies increases with stellar velocity dispersion as

$$L \propto \sigma^n , \tag{3}$$

with $n \approx 4$ (Faber and Jackson 1976; Kormendy and Illingworth 1983; Davies and Illingworth 1983). This relation together with the virial theorem can be used to scale the stellar density (or luminosity) of the central part of galaxies with stellar-velocity dispersion. Using equation (1) with $\gamma = -2$ we find that the density at a fixed distance from a galactic center scales as σ^2. We then find for the density at the cusp radius, using equations (1) and (2),

$$\rho_h = 0.28 M^{-2} \sigma^6 . \tag{4}$$

In the next sections we will see that the conditions in galactic nuclei defined above are sufficient to explain the activity of normal galaxies as well as that of active galaxies as due to tidal disruption and accretion of stars by a central massive black hole.

b) *Tidal Disruption Rate in Normal Galaxies*

The phase-space distribution of the stars in the nucleus is evolving due to two-body relaxation. Stars are continuously being scattered into or out of orbits that bring them so close to the black hole that they will be tidally disrupted (Hills 1975; Frank and Rees 1976). At radii smaller than some critical radius $r_{\rm crit}$, the distribution of stellar velocity vectors is anisotropic and we have a "loss cone" (Lightman and Shapiro 1977): low angular momentum (death) orbits are underpopulated because stars that are tidally disrupted cannot be replaced by other stars via star-star scattering (two-body relaxation) within one orbital time. The tidal disruption rate is determined by the stellar density and velocity dispersion at $r_{\rm crit}$, which is given by (cf. paper I)

$$r_{\rm crit}/r_h = (2.3 M^{1/6} \sigma)^{\alpha} , \tag{5}$$

where

$$\alpha = \begin{cases} 2 & \text{for } r_{\rm crit} > r_h , \\ 0.889 & \text{for } r_{\rm crit} < r_h . \end{cases}$$

The tidal disruption rate is given by

$$\frac{F^{\rm tid}}{M_\odot \ {\rm yr}^{-1}} = 10^{-2} \rho_h \sigma^{-1} M^{4/3} \begin{cases} (r_{\rm crit}/r_h)^{-2} & , r_{\rm crit} > r_h , \\ (r_{\rm crit}/r_h)^{-7/4+1/2} & , r_{\rm crit} < r_h , \end{cases}$$

or

$$\frac{F^{\rm tid}}{M_\odot \ {\rm yr}^{-1}} = \begin{cases} 10^{-4} \ M^{-4/3} \sigma & \text{for } M\sigma^6 > 6.7 \times 10^{-3} , \\ 1.11^{-3} \ M^{-0.85} \sigma^{3.9} & \text{for } M\sigma^6 < 6.7 \times 10^{-3} . \end{cases} \tag{6}$$

It is interesting to compare this with an estimate of the mass-loss rate from stars due to star-star collisions, which is about

$$\frac{F^{\rm coll}}{M_\odot \ {\rm yr}^{-1}} = 4 \times 10^{-4} M^{-1} \sigma^5 . \tag{7}$$

With a fueling rate F and a mass-to-energy conversion factor η, the energy radiated during accretion is

$$L = 6.10^{45} \ {\rm ergs \ s^{-1}} \frac{F}{M_\odot \ {\rm yr}^{-1}} \frac{\eta}{0.1} \tag{8}$$

Tidal disruption of stars occurs close to the hole, at about 20 $M^{-2/3}$ Schwarzschild radii. We assume that all the gas from tidally disrupted stars is accreted by the hole. Star-star collisions occur at a much larger distance of about 2×10^5 Schwarzschild radii of the hole. The fate of gas produced in such collisions as well as gas from other sources at large distances from the hole is uncertain (for instance, outflow or star formation may occur), and its contribution to the accretion rate might be much smaller than the contribution from stars that are tidally disrupted by the central hole.

The conclusions we can draw on inspection of (6), (7), and (8) are: (1) black holes of $\sim 10^6 \ M_\odot$ have a growth time, defined as $(dM/dt)^{-1} M$, of about one Hubble time, and (2) the nuclei of bright galaxies should have luminosities typically of the order of $\sim 10^{41}$ ergs s^{-1}. This is not in conflict with observed luminosity functions (see Fig. 1), which reach the space density of galaxies at about 10^{40} ergs s^{-1} (see also Keel 1983).

c) *The Luminosity of Active Galactic Nuclei*

The tidal disruption rate of stars may be enhanced several orders of magnitude when the stars within $r_{\rm crit}$ are scattered into loss-cone orbits by the perturbing gravitational field of an intruding galaxy. In paper I the enhanced tidal disruption rate during a merger was estimated using an "effective critical radius," defined as the distance to the central black hole within which loss-cone orbits cannot be repopulated within one orbital time by stars that are scattered by the intruder. It should be noted, however, that this approach is probably no longer valid if the effective critical radius is comparable to the separation between the interacting galaxies, for instance, when the mass ratio of the interacting galaxies is very small. In Paper I we found for the tidal disruption rate as a function of separation r between the intruder and the central black hole

$$\frac{F(r)}{M_\odot \ {\rm yr}^{-1}} = \begin{cases} 4.14 r^{-4/3} \ \rho_h M^{26/9} \ \sigma^{-13/3} \ f^{2/3} , & F < F^{\otimes} , \\ 0.63 r^{-5/7} \ \rho_h M^{13/6} \ \sigma^{-78/28} f^{5/14}, & F > F^{\otimes} , \\ 0.63 r^{-15/14} \rho_h M^{53/21} \sigma^{-7/2} \ f^{5/14}, & F < F(r_h) . \end{cases} \tag{9}$$

Here f is m_g/M_g, the mass ratio of the merging galaxies. The break at $F^{\otimes}$ occurs when the "effective critical radius" for star scattering by the intruder becomes equal to r_h. It is given by

$$\frac{F^{\otimes}}{M_\odot \ {\rm yr}^{-1}} = 0.06 \rho_h{}^{-2} \sigma^{-1} M^{4/3} = 1.7 \times 10^{-2} M^{-2/3} \sigma^5 . \tag{10}$$

A second break occurs when the intruder crosses the cusp radius. The fueling rate at that moment is given by

$$\frac{F(r_h)}{M_\odot \ {\rm yr}^{-1}} = 0.17 M^{-23/42} \sigma^{41/14} f^{5/14} . \tag{11}$$

Within a distance $r_{\rm coll}/r_h = 0.2\sigma^2$ of the hole, the $r^{-7/4}$ density distribution cannot build up by two-body relaxation because stars cannot be reflected over large angles without colliding. If the density distribution has a maximum at $r_{\rm coll}$, the maximum tidal disruption rate is $0.12 M^{-2/3} \sigma^{5/2} \ M_\odot \ {\rm yr}^{-1}$. However, orbits at $r < r_{\rm coll}$ may become populated as a result of mergers. In that case the density might rise with decreasing r until the collision time becomes smaller than the time between subsequent mergers. The collision time is

$$t_{\rm coll} \approx 10^{12} M^{-1/4} \sigma^{21/2} r^{9/4} \ {\rm yr} . \tag{12}$$

If a galaxy undergoes a few mergers during a Hubble time, the cusp may extend to within $0.1M^{1/9}\sigma^{-42/9}$ pc, yielding a maximum fueling rate

$$\frac{F_{\max}}{M_\odot \text{ yr}^{-1}} \approx M^{22/9}\sigma^{93/9} . \quad (13)$$

Note that the maximum luminosity may be given by the Eddington luminosity $L_E = 1.3 \times 10^{45} M$ ergs s^{-1}.

d) *The Merging Rate of Galaxies*

The merging rate of galaxies at the present epoch can be inferred from the observed number of interacting galaxies (Toomre 1977), from numerical simulations of an expanding universe (Aarseth and Fall 1980; Roos, 1981*b*), and perhaps also from the fraction of (elliptical) galaxies with shells (Carter, Allen, and Malin, 1982). The mean density of neighbor galaxies at a distance of about one galactic radius from the center of a typical bright galaxy can be estimated from the two-point correlation function. We will obtain an estimate of the merging rate among galaxies by combining this density with the mean relative velocity of nearest neighbors and the stellar density in bright galaxies and applying the dynamical friction formula first derived by Chandrasekhar (1943).

The two-point correlation function is defined by

$$n(r) = \bar{n}[1 + \xi(r)] , \quad (14)$$

where $\bar{n}$ is the mean number density of galaxies and $n(r)$ is the mean number density of galaxies and a separation r of a galaxy. The correlation function can be described by a power law for 10 kpc $< r <$ 10 Mpc,

$$\xi(r) = A_0 r_M{}^\gamma , \quad (15)$$

where $r_M = r$/Mpc, $\gamma = -1.8$ and (using $H_0 = 50$ km s^{-1} Mpc^{-1}) $A_0 \approx 70$ (Peebles 1974; Totsuji and Kihara 1969; Gott and Turner 1979). The mass within a distance r of a galactic center due to neighbors having a mean mass $\bar{M}$ is given by

$$M(r) = 4\pi\bar{n}A_0 r_M{}^{3+\gamma}\bar{M} . \quad (16)$$

The mass distribution inside (typical bright) spiral galaxies can be described by the same equation if we take $\bar{M} \approx 10^{13}$ $M_\odot$ (Peebles 1980). Note that if this mass is associated with galaxies, the universe would be closed. We do not assume that galaxies have this mass, but we use $\bar{M}$ only as a factor to fix the mass within $\sim$10 kpc of the center of a galaxy at about 10^{11} $M_\odot$.

The mean relative velocity in galaxy pairs is given by Davis and Peebles (1983) as

$$\sigma(r) = 310 \pm 40 \text{ km s}^{-1}\, r_M{}^{0.13 \pm 0.04} . \quad (17)$$

For $\bar{M} = 10^{13}$ $M_\odot$ and $\gamma = -1.8$, this agrees with the three-dimensional velocity dispersion at a distance r of a galaxy which follows from equation (16) assuming virial equilibrium:

$$\sigma(r) = 290 \text{ km s}^{-1}\, r_M{}^{(2+\gamma)/2}\left(\frac{\bar{M}}{10^{13}\, M_\odot}\right)^{1/2} . \quad (18)$$

The drag force on a satellite galaxy with mass $m_s(r)$ moving with velocity $v(r)$ at a distance r of a system with density distribution $\rho(r)$ is (Chandrasekhar 1943)

$$\frac{d}{dt}\, v(r) = -4\pi \frac{G^2 m_s \rho(r) \ln \Lambda}{v^2(r)} , \quad (19)$$

where G is the gravitational constant and Λ is the ratio of the maximum and minimum impact parameter $p_{\max}/p_{\min}$. For $p_{\max}$ we may take the size of the larger system, and for $p_{\min}$ the maximum of Gm_s/v^2 and the size of the satellite (e.g., Tremaine and Weinberg 1984). We expect not to make a large error by putting ln Λ equal to 1. The satellite mass m_s depends on r because it will be tidally stripped as it spirals inward on an orbit which will become more and more circular. The intruder loses its mass outside the radius where its internal density approximately equals the density of the larger galaxy at the position of the intruder. This criterion, together with our assumption that the central mass distributions of all bright galaxies obeys a power law with the same index, implies that the mass ratio $m_s(r)/M(r)$ is a constant and equal to f. Note that only the final stages of the merging process and the central parts of galaxies are important for our discussion of galactic nuclei activated by mergers, because activation generally will occur at separations much smaller than 1 kpc. For a power-law density profile, $v(r)$ will also be some power of r and

$$\frac{dr}{dt} = \frac{r}{v(r)} \frac{d}{dt}\, v(r) . \quad (20)$$

Combining equations (16), (19), and (20) and using $\rho(r) = \bar{M}n(r)$, we find

$$\frac{dr}{dt} = \sigma(r)\left[\frac{\sigma(r)}{v(r)}\right]^3 \frac{m_s}{M(r)} ,$$

$$\approx 10^{-4}\left[\frac{\sigma}{200 \text{ km s}^{-1}}\right] f \text{ pc yr}^{-1} . \quad (21)$$

Under stationary conditions the infall or merging rate per galaxy among bright galaxies of about equal mass follows from

$$E_0 = -4\pi n(r) r^2 \frac{dr}{dt} . \quad (22)$$

Evaluating this expression at the galactic radius $r = 10$ kpc yields, using $\bar{n} = 2.2 \times 10^{-3}$ Mpc^{-3},

$$E_0 = 4\pi\bar{n}A_0 r_M{}^{\gamma+2}\sigma \approx 1.5(10^{10} \text{ yr})^{-1}\left(\frac{\sigma}{200 \text{ km s}^{-1}}\right) . \quad (23)$$

At small separations the neighbor density depends on the mass of the interacting galaxies. First, the merging rate is proportional to galactic mass (Roos 1981*a*; Roos and Aarseth 1982), and second, small neighbors are more numerous than larger galaxies by some factor $X(f)$, where f is again the mass ratio of the interacting galaxies. There are two factors contributing to $X(f)$: (1) the galaxy luminosity function indicates that smaller galaxies outnumber larger ones by about a factor of $f^{-0.25}$ (Felten 1977); (2) the dynamical friction time is proportional to f^{-1}, making the number of satellites that are merging with bright galaxies larger by the same factor. The neighbor density of galaxies having mass m_s that are merging with galaxies having mass $M_g(>m_s)$ can now be given by (assuming constant mass-to-light ratio)

$$A(L_g, f) \approx A_0 X(f) L_g/L_g{}^* , \quad (24)$$

where $L_g{}^*$ is the luminosity of galaxies at the break of the galaxy luminosity function, and $X(f)$ is expected to be of the order $f^{-1.25}$.

e) The Luminosity Function of Active Galactic Nuclei

The fraction of galaxies having a nearest neighbor between r and $r + dr$ can be calculated from the two-point correlation function (Saslaw 1979):

$$w(r)dr = 4\pi\bar{n}r_M{}^2(1 + A_0 r_M{}^{\gamma}) \times \exp\,[-(4/3)\bar{n}r_M{}^3(1 + 3A_0 r_M{}^{\gamma})]dr\ ,$$

which can be approximated by

$$w(r)dr = 4\pi\bar{n}A_0 r_M{}^{2+\gamma} \exp\,(-4\pi\bar{n}A_0 r_M{}^{3+\gamma})dr \quad (25)$$

for small separations ($A_0 r_M{}^{\gamma} \gg 1$). The fraction of galaxies having a fueling rate in the interval $(F, 2.5F)$ is given by

$$\phi(F) = -0.4 \ln (10) w(r) F \frac{dr_M}{dF}\ . \quad (26)$$

Extending this result to galaxies with luminosity L_g having a nearest neighbour of luminosity L_s by replacing A_0 by A, and using (23), (24), and (25), we get

$$\phi(L_g, f, F) = -0.92\left[\frac{E(L_g, f)}{\sigma_g}\right] \exp\left[\frac{-E(L_g, f)}{\sigma_g} r_M\right] F \frac{dr_M}{dF}\ , \quad (27)$$

where $E(L_g, f) = E_0 X(f) L_g/L_g{}^*$. Equations (9) and (4) yield

$$F\frac{dr_M}{dF} = \frac{7}{5} r_M = \begin{cases} -1.6 \quad 10^{-6}F^{-3/4}M^{2/3}\ \sigma^{5/4}f^{1/2}, \text{ for } F < F^{\otimes}\ , \\ -0.11 \quad 10^{-6}F^{-7/5}M^{7/30}\sigma^{9/2}f^{1/2}, \text{ for } F > F^{\otimes}\ . \end{cases} \quad (28)$$

We ignore that part of the luminosity function beyond the second break given by (11) because the binary evolution is probably considerably faster there and F soon reaches its maximum value. The space density of galaxies whose central engines have fueling rates in the range $(F, 2.5F)$ is given by

$$\Phi = \int dL_g\, \phi(L_g, \bar{f}, F) N(L_g)\ . \quad (29)$$

Small satellites are more important for the activation of galactic nuclei than mergers between galaxies of comparable mass (§ II*d*). However, if satellites become too small they are probably no longer capable of enhancing the tidal disruption rate significantly (§ II*c*). Therefore we assume that we may use in (29) some characteristic value $\bar{f}$ for the luminosity ratio of the interacting galaxies. A good description of the observed space density of galaxies with luminosity between L_g and $L_g + dL_g$ is given by

$$N(L_g)dL_g = \begin{cases} 2.2 \times 10^{-3}(L_g/L_g{}^*)^{-1.25} \exp\,(-L_g/L_g{}^*)dL_g\ , \\ \qquad \text{for } L_g \le 2.5L_g{}^*\ , \\ N(2.5L_g{}^*)(L_g/2.5L_g{}^*)^{-4.2}dL_g\ , \\ \qquad \text{for } L_g > 2.5L_g{}^*\ , \end{cases} \quad (30)$$

where $L_g{}^*$ corresponds to $M_{B(0)}{}^* = -20.75$ (Felten 1977). The integral in equation (29) was evaluated numerically over the range $-23.5 < M_{B(0)} < -19.5$. Note that our luminosity function "saturates" at low F (or large r_M) due to the exponential in (27).

How does our luminosity function depend on the parameters of the model? (1) The merging rate determines the height of the luminosity function at high luminosities and the luminosity where "saturation" occurs. If we take the merging rate defined below equation (17), we have the factor $X(\bar{f})\bar{f}^{1/2}$ as a free parameter entering Φ. (2) The central velocity dispersion and black hole mass in our standard galaxy with $L_g \approx L_g{}^*$ determine the height of the luminosity function and the position of the break. (3) The scaling of the black-hole mass with galaxy luminosity determines the relative contribution to the luminosity function of the heavy and light galaxies and the sharpness of the break. Such a scaling relation can be estimated from the bivariate luminosity function (§ III).

III. COMPARISON WITH OBSERVATIONS

We compare our bolometric luminosity function with observed luminosity functions by assuming that the energy emitted in some waveband is a constant fraction of the total energy emitted. In other words: observed luminosity functions are just scaled-down versions of the bolometric luminosity function. This is supported by the similarity between the different luminosity functions at high luminosities and by the fact that the required conversion factors are consistent with the spectrum of a typical powerful galactic nucleus. These spectra indicate that the amount of energy deposited at optical wavelengths is a good measure of the total energy emitted. In Figure 1 we give the most recent luminosity functions available in the radio, optical, and X-ray wavebands. We will discuss them shortly (note that we use $H_0 = 50$ km s^{-1} Mpc^{-1}).

i) First, consider the combined radio luminosity function at 1.4 GHz for E+SO galaxies (Auriemma *et al.* 1977), Seyfert galaxies (Meurs 1982), and spiral galaxies (Hummel 1980). Taking a mean radio-to-optical spectral index $\alpha_{RO} = -0.6$, or $L_{\rm opt}/L_{\rm radio} = 10^{2.4}$, we find $\log\,[L/\text{ergs s}^{-1}] = \log\,[P_{1.4\,\rm GHz}/10^{24.5}\ \text{W Hz}^{-1}] + 43.4$, where L is the bolometric luminosity. In Figure 1 we also give the luminosity function of radio galaxies recently determined by Windhorst (1984).

ii) Next, consider the optical luminosity function of Seyfert galaxies from Huchra (1977). Here we have used $\log\,[L/\text{ergs s}^{-1}] = 0.4\,(89.3 - M_B)$.

iii) Finally, we take the X-ray luminosity function of active galaxies from Piccinotti *et al.* (1982). As in Paper I we use $L/L_X = 10^{2/3}$, based on a mean optical–to–X-ray spectral index $\alpha_{OX} = -1.25$. Avni and Tananbaum (1982) and Tananbaum *et al.* (1983) have found $L_X \propto L_{\rm opt}{}^{0.5-0.7}$ suggesting that $L \propto L_X{}^{1.4-2}$. The bolometric luminosity function would then be less steep than the function drawn in Figure 1, and the agreement with the other luminosity functions would be better.

Note that especially the optical and X-ray luminosity functions may be too high at low luminosities because the contribution from another, more extended source becomes important. The similarity between the different luminosity functions at high luminosity indicates that we are dealing here with one population of AGNs having a basic spectrum, but at lower luminosity this picture is too simple. The nuclei of low-luminosity Seyfert galaxies, for instance, are underluminous relative to their optical luminosity. At low luminosities the population of AGNs seems to split up into AGNs in which either the radio or the optical part of the spectrum has been suppressed by some process related to the galactic environment of the active nucleus. This may reflect the splitting of QSOs into radio-quiet and radio-loud objects.

The radio luminosity function shows a break at $L^{\otimes} = 10^{44}$ ergs s^{-1}. There is strong indication of a similar flattening in the

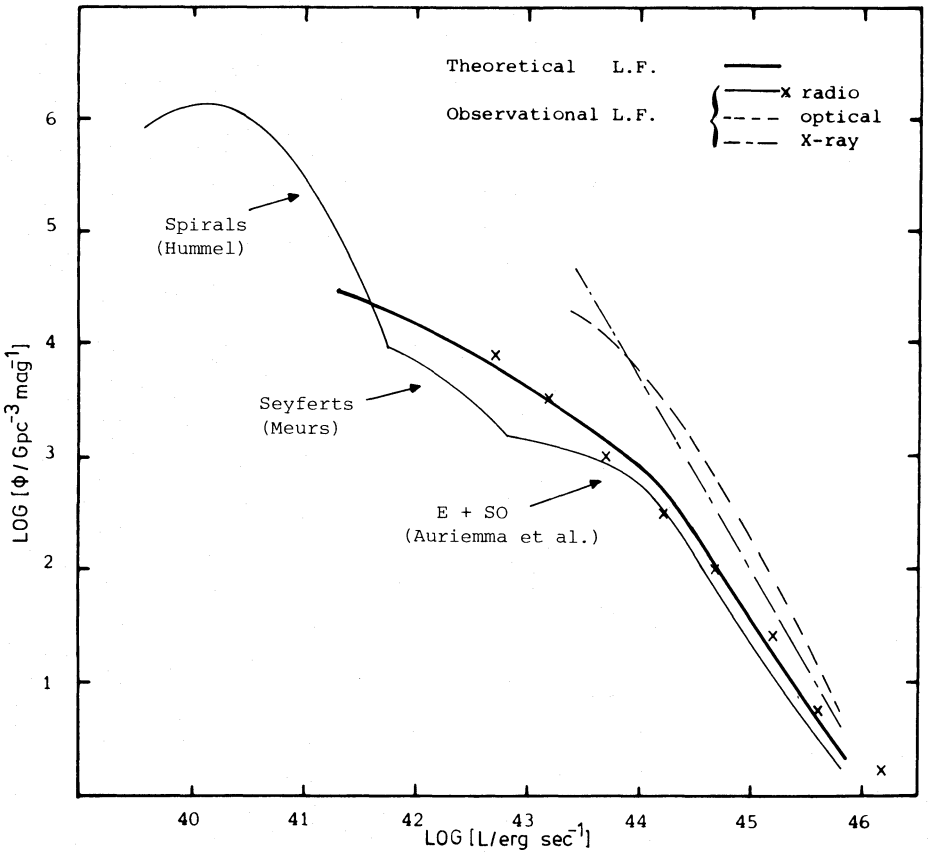

FIG. 1.—Theoretical and observational luminosity functions (LFs) of AGNs. The observational LFs are: (1) The radio LF for spirals (Hummel 1980), Seyfert (Meurs 1982), and E-S0 galaxies (Auriemma *et al.* 1977). The crosses give the radio luminosity function from Windhorst. (2) The optical LF for Seyferts (Huchra 1977). (3) The X-ray LF (Piccinotti *et al.* 1982). The theoretical LF is discussed in § II*e*. The parameters determining the position of the break are given by eqs. (33) and (34).

optical luminosity function. The X-ray luminosity function must also flatten below $\sim 10^{44}$ ergs s^{-1} (Piccinotti *et al.* 1982). We identify this break in the luminosity function with $F^{\otimes}$, defined in equation (10). The corresponding luminosity is

$$L^{\otimes} = 10^{44} \text{ ergs s}^{-1}\left(\frac{M}{10^7 M_{\odot}}\right)^{-2/3}\left(\frac{\sigma}{200 \text{ km s}^{-1}}\right)^{5}\left(\frac{\eta}{0.1}\right). \quad (31)$$

The position of the break can be used to estimate model parameters. The radio luminosity function is best suited for a more detailed comparison with the model, first, because it is best known, and second, because the contribution from an extended source will be less important than for the optical and X-ray luminosity functions. In Figure 2 the bivariate radio luminosity function determined by Auriemma *et al.* is given (see also Meier *et al.* 1979). The position of the break at $P^{\otimes}$ together with equation (31) and $L/L_{\text{radio}} = 10^{2.4}$ yields a central black-hole mass

$$M = 10^7 M_{\odot}\left(\frac{P^{\otimes}}{10^{25.1}}\right)^{-3/2}\left[\frac{\sigma}{200 \text{ km s}^{-1}}\right]^{15/2}\eta_{\text{radio}}^{3/2}, \quad (32)$$

where

$$\eta_{\text{radio}} = \frac{\eta}{0.1}\left(\frac{L/L_{\text{radio}}}{10^{2.4}}\right) \approx 1 .$$

The break in the bivariate luminosity function might depend on galaxy luminosity, but the observational data indicate that such a dependence, if present, must be weak. We obtained a good visual fit to the data using $P^{\otimes}(L_g) =$ constant, implying $M \propto \sigma^{15/2}$, or $M \propto L_g{}^{15/8}$. The mass of the central black hole in galaxies of stellar luminosity L_g is determined by $P^{\otimes}$ if we know the stellar velocity dispersion at the cusp radius can be written as $\sigma = \sigma^*(L_g/L_g{}^*)$. In the Milky Way it is about 130 km s^{-1} (§ II*a*). The Milky Way has $M_V \approx -20.5$. It seems therefore reasonable to adopt a range of $\sigma^* = 150$–200 km s^{-1} for galaxies having luminosity $L_g{}^*$. The model reproduces the correct luminisoty coordinate of the break in the bivariate radio luminosity function for

$$M = 1.5 \times 10^7 M_{\odot}\left(\frac{\sigma^*}{200 \text{ km s}^{-1}}\right)^{15/2}\left(\frac{L_g}{L_g{}^*}\right)^{15/8}\eta^{3/2}. \quad (33)$$

Note, however, that a somewhat different relation between black-hole mass and galaxy luminosity might still give a satisfactory fit to the data. The vertical position of the break depends on the factor $X(\bar{f})\bar{f}^{1/2}$. From equation (27) we see that our luminosity function is also proportional to $(\sigma^*)^{6.25}$. The fit in Figure 2 is obtained using

$$X(\bar{f})\bar{f} = 10\left(\frac{\sigma^*}{200 \text{ km s}^{-1}}\right)^{-6.25}, \quad (34)$$

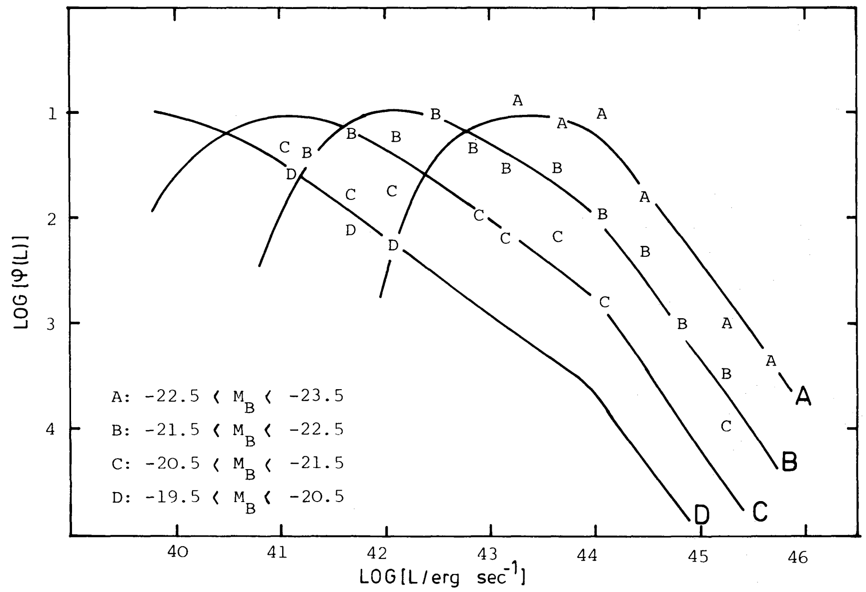

FIG. 2.—The observational fractional bivariate luminosity function for radio galaxies (Auriemma *et al.* 1977) and the theoretical one (*solid lines*) for the same parameters as in Fig. 1 (see § III).

implying $\bar{f} \approx 10^{-4/3}(\sigma^*/200 \text{ km s}^{-1})^{25/3}$. We conclude that galaxies with $M_{B(0)} > -18$ are most important in activating the nuclei of typical bright galaxies.

In Figure 1 we give our luminosity function defined in equation (29) using the parameters given by (33) and (34). The agreement with the observed luminosity functions, particularly the radio luminosity function of Windhorst (1984), is very good. Note that the radio luminosity function of Auriemma *et al.* underestimates the space density of radio sources at low radio power because they have selected E and S0 galaxies.

Most galaxies are not experiencing a merger at the moment. These normal galaxies have a space density of about 10^6 Gpc^{-3}. As noted in § II*b*, their level of activity might be of order 10^{41} ergs s^{-1}, which seems consistent with the luminosity functions given in Figure 1.

IV. DISCUSSION

The best known examples of galaxy mergers are the violently interacting galaxies in Arp's *Atlas of Peculiar Galaxies* (1966*a*, *b*). Such interactions between galaxies of comparable mass are likely to change the galaxy's morphology and produce elliptical galaxies, as first suggested by Toomre and Toomre (1972). If elliptical galaxies are formed by mergers, then other galaxies must have grown also in the last ten billion years by cannibalizing smaller galaxies. A natural generalization of Toomre and Toomre's idea is then that many initially flat galaxies must have formed a central heap of stars (i.e., a bulge) due to mergers with smaller galaxies, leading to an evolution of the galaxy along the sequence S-S0-E. This scenario for the origin of the Hubble sequence also seems consistent with other properties of galaxies of different morphological type such as luminosity function and neighbor density (Roos 1981*a*). The merger events that are thought to be responsible for triggering activity in galactic nuclei are somewhat different. First, the mass ratio of the interacting galaxies is usually quite large, and the larger galaxy will in most cases not be distorted very much. Second, the intruder will increase the central activity only when the galaxy separation is very small (~0.1–100 pc), and during a time which is short compared with the dynamical time scale of the galaxy. So a galaxy which looks very distorted on the kpc scale has only a small chance of being active. On the other hand, a galaxy with an active nucleus does not necessarily look very distorted on the kpc scale. Nevertheless, an active galaxy is likely to show signs of a recent merger, for instance a burst of star formation induced by shock waves in the interstellar gas. In this context it is interesting that most Seyfert galaxies seem to have a relatively high infrared emission, which may be due to heating of dust grains by newly formed stars or directly by the central nonthermal source (Carter 1984; de Grijp *et al.* 1985). Another consequence of the model is the existence of a seccndary nucleus in AGNs at a distance of ~0.1–100 pc from the center. If the mass ratio of the merging galaxies is small enough, both nuclei may be detectable at radio wavelength using the VLBI technique. Note, however, that the most probable mass ratio of the galaxies is larger than about 20, implying a mass ratio of about $20^{15/8}$ for the central black holes. If both holes are radiating at the Eddington limit, the luminosity ratio of the interacting nuclei will be larger than 10^{2-3}. Another natural consequence of the model discussed here is jet precession due to the interaction of a central spinning black hole with a secondary hole (Begelman, Blandford, and Rees 1980). Since both the precession time and the fueling rate depend on the separation between the interacting nuclei, we expect that jet precession time and central luminosity are correlated.

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