Quasars in a merger model: comparison with the observed luminosity function

D. S. Krivitsky, V. M. Kontorovich

Institute of Radio Astronomy, Kharkov

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Abstract

Connection between the quasar luminosity function and galaxy mass function is investigated in the framework of a phenomenological approach which relates AGN formation to galaxy mergers. Quasars are assumed to be short-lived, the luminosity of a quasar is controlled by the masses and angular momenta of the merged galaxies which have formed the quasar, and the amount of gas in them (the masses and momenta determine the quantity of mass which loses its angular momentum and can fall to the center). The proposed model can explain the shape and evolution of the quasar luminosity function, and allows us to estimate the parameters: the fraction of matter which falls into the center \( \eta \) (which seems to be related to the quantity of gas in the galaxies) and \( \kappa \) (an average density contrast in the regions where quasars form). The obtained values of \( \kappa \) vary from \( \sim 4–7 \) at \( z = 0.5 \) to \( \sim 1–2 \) at \( z = 2 \), \( \eta \) vary from a few per cent at \( z = 0.5 \) to a few tens per cent or even values close to 1 at \( z = 2 \). In contrast to the cases considered earlier by the authors, the Eddington limit which, probably, can be exceeded in quasars plays an essential role.

1 Introduction

In present time, it has been established rather reliably that galaxy interaction (in particular, merging) correlates with the activity of galactic nuclei, at least, for powerful objects (see, e.g., reviews by Heckman, 1990; Kontorovich, 1994, and references therein). There is still some uncertainty for less powerful AGN, such as Seyfert galaxies. However, in the spirit of the unified AGN scheme (Antonucci, 1993) we may suppose that here we also deal with interaction.

Note, that such bright objects as quasars are a sort of markers: the quasar formation epoch which is often identified with the well-known cutoff in their distribution at \( z = z_{cr} \approx 2.5 \) (Schmidt et al., 1994; Shaver, 1993) may be also the epoch of massive galaxy formation due to mergers of less massive blocks (see Kats et al., 1992; Kontorovich et al., 1992). Note, that reality of the cutoff in the \( z \)-dependence of quasar density is confirmed by the counts of radio sources (see the review by Peacock, 1989 and the paper by Artyukh and Tyulbashev, 1996).

Last data from the Hubble Space Telescope seem to confirm this point of view. Observations of galaxy formation of blocks (merging process) in the redshift range \( 2.6 < z < 3.9 \) allows Clements...
and Couch (1996) to conclude that, possibly, an epoch of (massive, K. K.) galaxy formation has been discovered. Observations of subgalactic blocks at $z = 2.39$ (Pascarelle et al., 1995) and their relation to galaxy formation were discussed in details for the rich group which was discovered in connection with a faint blue galaxies investigation program (see also other works of the same group: Windhorst et al., 1993, 1994, and references therein). Recent source counts also allow to explain their rise to the past (for the standard cosmology and critical density) by evolution of the number of galaxies due to their mergers, assuming that this epoch corresponds to $z \approx 2$ (Metcalfe et al., 1995; see also Bender and Davis, 1996).

On the other hand, direct observations of close quasar host galaxies by the HST (Bahcall et al., 1994, 1995) gave a remarkable confirmation of the direct connection between the activity and the galaxy interaction and merging. In particular, in the case of PKS 2349 quasar host galaxy, a LMC-size sinking satellite galaxy was discovered.

So, there are strong reasons to continue investigation of the relation between the activity and galaxy mergers (Kontorovich, Krivitsky, 1995) and perform a more detailed comparison between the observations and the phenomenological scheme which was proposed earlier and improved below. We assume that pairwise mergers of galaxies, taking place due to their gravitational interaction and tidal forces, are the factor which triggers activity. In this approach, quasar luminosity function (LF) and galaxy mass function (MF) turn out to be related. Below we shall assume that galaxy MF is known and, thus, shall not make any assumptions about the mechanism of its formation. The activity, in turn, is controlled by mergers.

In this work we shall found the quasar LF and the values of parameters (the density contrast and the parameter which determines probably the amount of gas in galaxies) for which it agrees with observational data in the redshift range $0.5 \lesssim z \lesssim 2$; we shall analyze also the connection between galaxy MF and quasar LF asymptotical behavior.

2 Discussion of the model

The probable cause of the correlation between the galaxy interaction (in particular, merging) and their nuclear activity is that the interaction leads to redistribution of the angular momentum and, therefore, some part of matter (probably, gas) gets into the central region and gives material for accretion (see, e.g., Hernquist, Barnes, 1994).

In the proposed earlier model (Kats, Kontorovich, 1991; Kontorovich, Krivitsky, 1995) which describes appearing of activity due to mergers, the falling of matter to the center was assumed to be related to compensation of a part of the angular momentum at the merger. Below this assumption will be considered as a special case. According to this approach, the most important parameters of the problem are galaxy masses $M$, angular momenta $S$, and the amount of gas.

We shall assume that the luminosity of an active galaxy formed as a result of merging between two galaxies is controlled by their masses $M_{1,2}$ and momenta $S_{1,2}$, as well as the collision orbital momentum $J = L(M_{1}, M_{2}, S_{1}, S_{2}, J)$ (taking into account the amount of gas will be discussed below). To compute this function, a detailed theory is needed, which would deal with a very complicated multi-step process due to which a part of matter lose its momentum and gets into the center after the merger. However, we shall restrict ourselves by a simplified phenomenological

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2In some sense, it is rather the absolutely unperturbed elliptical host galaxies, discovered by the same group, to be a puzzle.
approach. The number of active galaxies formed per unit time and unit luminosity range is, obviously, expressed as

\[ I(L) = \int f(M_1, S_1)f(M_2, S_2)U(M_1, M_2)F(J) \times \delta(L - L(M_1, M_2, S_1, S_2, J)) dM_1 dM_2 d^3S_1 d^3S_2 d^3J, \]  

(1)

Here \( f(M, S) \) is the galaxy mass and angular momentum distribution function; \( U(M_1, M_2) \) is a characteristic of the probability of a merger between galaxies with masses \( M_1 \) and \( M_2 \) (in general, \( U \) depends not only on masses, but also on momenta, however, this dependence seems to be less essential and will not be taken into account in this work); \( F(J) \) is the angular momentum distribution function. Thus, given \( f(M, S) \), we can found the rate of active objects formation, as a function of their luminosity \( I(L) \).

Next, it is possible to relate \( I(L, t) \) to the active nuclei LF \( \phi(L, t) \). To do it, we have to make some assumptions about the evolution (i.e., in our case, the light curves) of active nuclei forming by mergers. Thus, if we assume that the light curve is step-shaped, with the average duration \( t_{\text{act}} \), then \( \phi(L, t) \) can be described by the model equation \( \frac{\partial \phi}{\partial t} = I - \phi/t_{\text{act}} \) (here \( t_{\text{act}} \) may, in general, depend on \( L \)). Another possible case: if we assume that the luminosity of an active galaxy decreases exponentially, with the e-fold time \( t_{\text{act}} \), then \( \phi(L, t) \) is described by the equation \( \frac{\partial \phi}{\partial t} - \frac{\partial}{\partial L} \left( \frac{L\phi}{t_{\text{act}}} \right) = I \) (an analogue of the continuity equation in the luminosity space; cf. Cavaliere et al., 1985). In the latter case, large lifetime \( (t_{\text{act}} \gtrsim 10^9 \) years) and small AGN formation rate \( (I \ll \left| \frac{\partial}{\partial L} \left( \frac{L\phi}{t_{\text{act}}} \right) \right|) \) corresponds to the “luminosity evolution”: changing \( \phi \) reflects, mainly, reducing luminosity of the existing objects. The case of small lifetime \( (t_{\text{act}} \lesssim 10^8 \) years) for both equations corresponds to existence of many AGN generations, which change each other in the course of the Universe evolution (“number evolution”). In this paper we shall consider the case of number evolution (see more detailed discussion below, in section 4). Assuming \( t_{\text{act}} \) much less than a characteristic time of \( I(L, t) \) changing, we have for the former equation\(^3\)

\[ \phi(L, t) \approx t_{\text{act}} I(L, t); \]  

(2)

and, for the latter equation

\[ \phi(L, t) \approx \frac{t_{\text{act}}}{L} \int_L^\infty I(L', t) dL'. \]  

(3)

Qualitatively these two expressions are very similar: if \( I(L) \) has a power law region and an exponential decrease region, then the shape of \( \phi(L) \) is approximately the same as the one of \( I(L) \) (we shall not consider the case when \( t_{\text{act}} \) depends\(^4\) on \( L \), though it can be easily done if there appear some observational data about a dependence of \( t_{\text{act}} \) on \( L \) or some other galaxy parameters). So, in fact, we shall investigate the source \( I(L) \) in the equation for the LF.

In our previous works we considered an expression for \( f(M, S) \), which corresponds to the “anisotropic” momentum distribution. This distribution appeared in Kats, Kontorovich (1990)\(^\text{3}\).

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\(^3\)The solutions of both equations can be easily written in an explicit form for arbitrary \( t_{\text{act}} \), but below only the case of small \( t_{\text{act}} \) will be of interest for us. It is possible also to write an explicit solution for arbitrary (not necessarily exponential) light curve.

\(^4\)In particular, the Eddington time does not depend of galaxy parameters.
as a solution of the generalized Smoluchowski kinetic equation (which describes galaxy mergers) without allowance for the orbital momentum, if there is some initial anisotropy. In this case, the initial anisotropy is amplified in the course of time, the momentum distribution tends to a \( \delta \)-function, and the momentum of a galaxy is proportional to its mass:

\[
f(M, S) \approx \Phi(M) \delta \left( S - \frac{S_0 M}{M_0} \right),
\]

where \( \Phi(M) \) is the MF. Distribution (4) is useful from the methodical point of view, because the asymptotical behavior of \( I(L) \) can be computed analytically for it. However, from the astrophysical point of view, isotropic distribution

\[
f(M, S) = \Phi(M) \frac{1}{\left( \frac{2\pi}{3} S^2(M) \right)^{3/2}} \exp \left( -\frac{3}{2} S^2 / S^2(M) \right),
\]

which will be considered in this work, is more interesting.

The mass dependence of an average mass to luminosity ratio for normal galaxies is rather weak. We shall neglect this dependence\(^5\) and take \( \frac{M}{L} \sim 10 \). Then the MF just coincides with the LF (except for the normalization). Below, in section 3, for computing \( I(L) \), we shall take the MF in Schechter’s form

\[
\Phi(M) = \Phi_0 M^{-\alpha} e^{-M/\mu}.
\]

The index \( \alpha \approx 1 \) for field galaxies and \( \alpha \gtrsim 1.25 \) for clusters (see, e.g., Binggeli et al., 1988; Loveday et al., 1992). As the integral which expresses the total number of galaxies for (6) diverges, we shall assume \( \Phi = 0 \) at small masses \( M < M_0 \). Observational data obtained in recent years testify to possible steepening of \( \Phi \) at small masses. This steepening will be taken into account in section 4.

We will use a rather common merger criterion: (i) minimal distance between the colliding galaxies is less that the sum of their radii \( (R_1 + R_2) \); (ii) the relative velocity at infinity \( v \) is less than \( v_g = \sqrt{\frac{2G(M_1 + M_2)}{R_1 + R_2}} \). Then the merger cross-section (taking into account gravitational focusing) is \( \sigma = \pi(R_1 + R_2)^2(1 + v_g^2/v^2) \) for \( v < v_g \) and \( \sigma = 0 \) for \( v > v_g \). It results in the following expression for \( U \):

\[
U(M_1, M_2) = \bar{\sigma} \nu \approx \begin{cases} c_2(M_1 + M_2)^2, & M \ll M_b \\ c_{1+\beta}(M_1 + M_2)(M_1^2 + M_2), & M \gg M_b \end{cases}
\]

(cf. Kats, Kontorovich, 1990; Krivitsky, Kontorovich, 1997; Ca
vilier, Menci, 1997). Here the bar means an average over velocities; galaxy radius \( R \) relates to the mass as \( R = C^2 \beta \) \( (\beta = 1/3 \) corresponds to constant density, \( \beta = 1/2 \) to the observational Faber—Jackson and Tully—Fisher laws\); \( c_2 = (9/2)(3\pi)^{1/2}G^2/v_{\text{rms}}^3 \), \( c_{1+\beta} = 2(3\pi)^{1/2}CG/v_{\text{rms}}^2 \), \( M_b \sim (Cv_{\text{rms}}^2/G)^{1/(1-\beta)} \). For the function \( U(M_1, M_2) \), it is convenient to introduce its homogeneity power \( u \) and exponents \( u_{1,2} \) which describe its asymptotics for very different masses:

\[
U \propto M_1^{u_1} M_2^{u_2}, \quad M_1 \ll M_2, \quad u_1 + u_2 = u.
\]

Obviously, for (7) \( u_1 = 0, u_2 = u \) if \( M \ll M_b \) and \( 1 + \beta \) if \( M \gg M_b \). Note that it is the parameters \( u_{1,2} \) (that is the asymptotical behavior of \( U \)) to determine the asymptotical behavior of \( I(L) \).

\(^5\) Evolution of this ratio which reflects evolution of star formation determined, in particular, by mergers may be very important, cf. Madau (1997).
3 Asymptotics and the relation between indices

Given the asymptotics of \( L(\mathcal{M}_1, \mathcal{M}_2, S_1, S_2, J) \), \( U(\mathcal{M}_1, \mathcal{M}_2) \) and \( f(\mathcal{M}, S) \), it is possible to find the asymptotical behavior of \( I(L) \). In particular, the model predicts that \( I(L) \) has a power-law region, the slope of which depends on the slope of the galaxy MF power-law region.

First we shall consider the simplest variant: “anisotropic” momentum distribution \((i)\) without taking into account the orbital momentum \((J = 0)\). In this case momenta can be expressed in terms of masses \((S \propto \mathcal{M})\) and, so, \( L = L(\mathcal{M}_1, \mathcal{M}_2) \). We shall assume that \( L(\mathcal{M}_1, \mathcal{M}_2) \) has power-law asymptotical behavior at \( \mathcal{M}_1 \ll \mathcal{M}_2 \):

\[
L(\mathcal{M}_1, \mathcal{M}_2) \propto \mathcal{M}_1^{\lambda_1} \mathcal{M}_2^{\lambda_2}, \quad \mathcal{M}_1 \ll \mathcal{M}_2, \tag{9}
\]

i.e., \( L(\mathcal{M}_1, \mathcal{M}_2) \) can be expressed as an asymptotical power series with respect to both arguments. The right-hand part of \((9)\) is a homogeneous function of power \( \lambda = \lambda_1 + \lambda_2 \). Sewing together the asymptotics for \( \mathcal{M}_1 \ll \mathcal{M}_2 \) and \( \mathcal{M}_1 \gg \mathcal{M}_2 \), we shall assume below that \( L(\mathcal{M}_1, \mathcal{M}_2) \) is a homogeneous function of power \( \lambda \) in the whole range of \( \mathcal{M}_1, \mathcal{M}_2 \). Expression \((9)\) is analogous to \((8)\) for \( U(\mathcal{M}_1, \mathcal{M}_2) \). Knowing \( \lambda_{1,2} \) is enough to find the slope of the power-law intermediate asymptotics of \((9)\).

Expression

\[
L = B \Delta m, \quad B = \varepsilon \eta c^2 t_{ac}^{-1}, \quad \Delta m = m_1 + m_2 - m, \quad m = S/\sqrt{G\mathcal{M}R}, \tag{10}
\]

which was considered in Kats, Kontorovich (1991); Kontorovich, Krivitsky (1993) is a particular case of \((9)\), corresponding to \( \lambda_2 = 0, \lambda_1 = \lambda > 0 \). Here \( \Delta m \) is the mass which has lost its momentum due to momentum compensation at the merger; \( \varepsilon \) the accretion effectivity; \( \eta \) the fraction of \( \Delta m \), which gets to the central black hole; \( t_{ac} \) the accretion time (we shall assume \( t_{ac} = t_{ac1} \)); \( c \) is the light speed. Note that, though expression \((9)\) was based on an oversimplified scheme of the origin of activity, the assumption \( \lambda_2 = 0, \lambda_1 > 0 \) is much more general and seems to be rather plausible even without any connection with model \((10)\). Its physical sense is that when a massive galaxy merges with a low-mass one, the luminosity is determined mainly by the latter mass. Thus, results obtained from \((9)\) are more general than the model \((10)\). In this case, the slope of the power-law region is determined by equations (15) and (16) from the cited above work by Kontorovich and Krivitsky. The opposite case, \( \lambda_1 = 0, \lambda_2 > 0 \) (i.e., the luminosity is determined, mainly, by the more massive galaxy) was considered (equation (18) in the same work) in connection with the situation when the luminosity equals to the Eddington one \( L = L_{Edd} \), and \( L_{Edd} \propto \mathcal{M}_H \propto \mathcal{M}^h \) (here \( \mathcal{M}_H \) stands for the mass of the black hole in the galaxy center, \( \mathcal{M} \) is the galaxy mass, \( \lambda = h \)). The combined case \( L = \min(B \Delta m, L_{Edd}) \) which also was considered there corresponds formally to a function \( L(\mathcal{M}_1, \mathcal{M}_2) \) which is described by two different expressions of the form \((9)\), with different \( \lambda_{1,2} \), in different regions. Asymptotics of \( I(L) \) for \( \lambda_1 > 0, \lambda_2 > 0 \) can be calculated similarly to how it was done in Kontorovich, Krivitsky (1995) for \( \lambda_1 = 0 \) or \( \lambda_2 = 0 \). Here we give the result, without the derivation, for completeness:

\[
\gamma = \begin{cases} 
1 - (u + 2 - 2\alpha)/\lambda, & k < 0, \\
1 - (u + 2 - 2\alpha)/\lambda - k/\lambda_2, & k > 0, \quad L \ll L(\mathcal{M}_0, \mu), \\
1 - (u + 2 - 2\alpha)/\lambda + k/\lambda_1, & k > 0, \quad L \gg L(\mathcal{M}_0, \mu),
\end{cases} \tag{11}
\]

where \( k = -\lambda_2(u - 2\alpha + 2 - \lambda)/\lambda - \alpha + u_2 - \lambda_2 + 1 \).
For \( k > 0 \), the plot of \( I(L) \) has a break; a more flat region change to a more steep one at \( L \sim L(\mathcal{M}_0, \mu) \).

Now we shall consider \( I(L) \) for the isotropic distribution (3) and with the orbital momentum taken into account. Unlike (4), for (5) with \( J \) the asymptotics cannot be determined analytically. The reason is that the dimension of integral (1) for (5) is much higher then for (4), due to the \( \delta \)-function in (4). In the same time, there are some heuristic arguments which lead to the supposition that the results mentioned above will not essentially change. Indeed, for (4) \( L \) was completely determined by the masses, and the \( \delta \)-function in the integral cut a one-dimensional integration path in the \((\mathcal{M}_1, \mathcal{M}_2)\) plane (fig. 2 in Kontorovich, Krivitsky, 1997). In the case of (5) \( L \) depends not only on masses, but, averaging over momenta, we can introduce \( L(\mathcal{M}_1, \mathcal{M}_2) \). Due to the scattering of the momenta, not only a one-dimensional line, but also a whole band close to the line will make a contribution to the integral over \( \mathcal{M}_1, \mathcal{M}_2 \) (after averaging over \( S_1, S_2, J \)). However, if \( L(\mathcal{M}_1, \mathcal{M}_2) \) can be still described by an expression of the form (3) then one may expect that the asymptotics of the integral will not change.

To verify this supposition, we carried out numerical Monte Carlo simulation. Momentum distribution was taken in the form (3), mass distribution \( \Phi(\mathcal{M}) \) was assumed to be a Schechter function (1) for \( \mathcal{M} > \mathcal{M}_0 \) and \( \Phi(\mathcal{M}) = 0 \) for \( \mathcal{M} < \mathcal{M}_0 \). A root mean square momentum was assumed proportional to the mass in the power \((3+\beta)/2 \) (such a dependence is formed by mergers in the case \( U \propto (\mathcal{M}_1 + \mathcal{M}_2)(\mathcal{M}_1^{\beta} + \mathcal{M}_2^{\beta}) \) and is close to the really observed one, see discussion in Kontorovich et al. (1995); Krivitsky and Kontorovich (1997)). The luminosity was calculated as \( L = \min(B\Delta m, L_{Edd}) \), where \( m = S/\sqrt{GM\mathcal{R}} \). Unlike the previous section, the orbital angular momentum was taken into account too.

In this case we may expect that an effective value of \( \lambda \) will be 1, \( \lambda_1 = 1, \lambda_2 = 0 \) (as we mentioned earlier). Indeed, for \( \mathcal{M}_1 \ll \mathcal{M}_2 \) average proper momenta are \( \overline{S_1} \propto \mathcal{M}_1^{1+\beta}, \overline{S_2} \propto \mathcal{M}_2^{1+\beta}, \) the orbital one is \( \overline{S} \propto (\mathcal{M}_1 v_g(R_1 + R_2))^2 \propto \mathcal{M}_1^{2+\beta} \mathcal{M}_2^{1+\beta}, \) after the merger \( \overline{S'} = \overline{S_1} + \overline{S_2} + \overline{J}^2 \propto \mathcal{M}_2^{2+\beta} \left(1 + O\left(\frac{\mathcal{M}_1^2}{\mathcal{M}_2^2}\right)\right), \overline{m} = \sqrt{\overline{S'}} = m_2 \left(1 - O\left(\frac{m_1}{m_2}\right)\right), \Delta m = m_1 + m_2 - m \propto m_1. \)

We used the following simulation algorithm (a simplified description):

1. Two random numbers, \( \mathcal{M}_{1,2} \), distributed according to the given MF \( \Phi(\mathcal{M}) \), were simulated.
2. Two random vectors, \( S_{1,2} \), with distribution (3), were simulated.
3. Galaxies 1, 2 merged with the probability proportional to \( U(\mathcal{M}_1, \mathcal{M}_2) \).
4. According to the merger cross-section assumed in our work (see page 3), the impact parameter and the relative velocity were simulated, then the merger orbital momentum \( J \) was computed.
5. The black hole mass \( \mathcal{M}_H \) was simulated (variant 1: \( \mathcal{M}_H = \zeta \mathcal{M}^h \); variant 2: \( \mathcal{M}_H \) is an independent random value with a power-law distribution).
6. Using \( \mathcal{M}_1, \mathcal{M}_2, \mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2, S_1, S_2, J, S = S_1 + S_2 + J, \mathcal{M}_H \) the luminosity of the active object \( L \) was calculated.

\(^6\text{The orbital momentum } \overline{J}^2 = (\mathcal{M}_1 \mathcal{M}_2/(\mathcal{M}_1 + \mathcal{M}_2))^2 v^2 p_{\infty}^2, \text{ the impact parameter } p_{\infty} \sim (R_1 + R_2)^2 v_2^2/v^2, \text{ so, } \overline{J}^2 \propto \mathcal{M}_1^2 \mathcal{M}_2^{1+\beta}.\)
Thus, the algorithm gave a random value as an output, which was distributed according to the same law as the desired luminosity. Repeating the computations many times, it is possible to find its distribution function, i.e., $I(L)$.

The procedure of simulation which was actually used was a bit different from the simplified scheme given above. In item 3, the simulated galaxies merge with some probability $p$, with probability $(1 - p)$ they are rejected. The probability $p$ must be proportional to $U(\mathcal{M}_1, \mathcal{M}_2)$, e.g., if $U(\mathcal{M}_1, \mathcal{M}_2)$ is bounded above by some $\mathcal{M}_{\text{max}}$, we may chose $p = U(\mathcal{M}_1, \mathcal{M}_2)/U_{\text{max}}$. However, in our case $U(\mathcal{M}_1, \mathcal{M}_2)$ is an unbounded function. Moreover, even if we introduce a limit galaxy mass $\mathcal{M}_{\text{max}}$ and the corresponding value $U_{\text{max}}$ then $p = U(\mathcal{M}_1, \mathcal{M}_2)/U_{\text{max}}$ will be very small for majority of galaxies and they will be rejected. This will cause very large computation time. To overcome this difficulty, we transformed the integrand in (1) as

$$
\int f_1 f_2 U_{12} \delta(L - L_{12}) F(J) \, d^3J \, d\mathcal{M}_1 \, d\mathcal{M}_2 \, d^3S_1 \, d^3S_2 =
2 \int \frac{U_{12}}{\mathcal{M}_1^u + \mathcal{M}_2^u} \delta(L - L_{12}) F(J) \, d^3J \, d\mathcal{M}_1 \, d\mathcal{M}_2 \, d^3S_1 \, d^3S_2
$$

$$
(f_1 \equiv f(\mathcal{M}_1, S_1), \ f_2 \equiv f(\mathcal{M}_2, S_2),
U_{12} \equiv U(\mathcal{M}_1, \mathcal{M}_2), \ L_{12} \equiv L(\mathcal{M}_1, \mathcal{M}_2, S_1, S_2, J)).
$$

(12)

In item 3 of the algorithm we took $U(\mathcal{M}_1, \mathcal{M}_2)/(\mathcal{M}_1^u + \mathcal{M}_2^u)$ instead of $U(\mathcal{M}_1, \mathcal{M}_2)$, and in item 2 we took $\mathcal{M}_1^u \Phi_1$ and $\Phi_2$ instead of $\Phi_1$ and $\Phi_2$.

The results of simulations confirmed the above supposition: the slope of the power-law region of $I(L)$ coincides with the predicted value, and $\lambda_{\text{eff}} = 1 = \lambda_1$, $\lambda_2 = 0$. As an example, fig. 4 shows the distribution function for a particular case (see the parameters in the caption).
Thus, in the most interesting case, when $\lambda_2 = 0$, $\lambda_{\text{eff}} = 1$, $u_1 = 0$, $u_2 = 1 + \beta$ or 2, the slope of the power-law region of $I(L)$ (and, therefore, the active objects LF too) just coincides with the slope of the galaxy MF $\alpha$, according to equation (16) in Kontorovich, Krivitsky (1995). This result agrees well with observational data: according to Binggeli et al. (1988); Boyle et al. (1988), both $\alpha$ and $\gamma$ are close to 1 (somewhat more).

4 Luminosity function of active objects

In the previous sections we described rather a general approach which relates AGN formation to galaxy mergers. Below we shall consider a concrete application of this approach. The purpose of this section is to obtain the LF from (2), (3) and find the parameter $s$ for which it agrees with the observed one.

We shall take the following input data.

1. Galaxy mass function. The bright end of LF (and, so, MF) of normal galaxies is described well by Schechter's formula (6). According to the data obtained in last years, the LF steepens at its faint end, the slope $\alpha$ reaches $\sim 2$ (see, e.g., de Propris et al., 1995; Kashikawa et al., 1995; Loveday, 1997). So, we shall take MF at $z = 0$ as a Schechter function with an additional break:

$$\Phi(M) = \Phi_0(1 + (M/M_{\text{br}})^{\alpha_2 - \alpha_1})M^{-\alpha_2}e^{-M/\mu}. \quad (13)$$

We shall assume $\alpha_1 = 2$, $\alpha_2 = 1.25$, $\mu$ corresponds to the magnitude $M_B = -21$ (the mass to luminosity ratio being $M/L \sim 10$), $\Phi_0 = 5 \cdot 10^{-3} \mu^{-\alpha_2 - 1} \text{Mpc}^{-3}$, and the break $M_{\text{br}}$ corresponds to $M_B = -16$. Possible change of MF with $z$ will be discussed below.

2. The momentum distribution will be taken in the form (5), with the root mean square momentum

$$\left(\frac{S^2(MR)}{M R (\frac{2GM^2}{R})^{1/2}}\right)^{1/2} = \text{const} = 0.1 \quad (14)$$

(Krivitsky, Kontorovich, 1997).

3. Merger probability. We shall use model (7), assuming $C = \frac{R}{M R} = \frac{20 \text{ kpc}}{(2 \cdot 10^{11} \text{ M}_\odot)^{1/2}}$, $\beta = 1/2$, and $v_{\text{rms}} \sim 100(1 + z)^{-1/2} \text{ km/s}$, which corresponds to $M_{\text{br}} \sim 10^{10}(1 + z)^{-3/2} \text{ M}_\odot$ (such a dependence $v(t)$ takes place in the linear gravitational instability theory for $\Omega = 1$).

4. Active galaxy luminosity. We shall assume $L = \min(L_{\text{Edd}}, \varepsilon \eta c^2 t_{\text{sc}}^{-1} \Delta m)$, $\varepsilon \sim 0.1$; the (bolometric) luminosity is calculated according to $L/L_\odot = b \cdot 10^{0.4(M_B - M_\odot)}$, the bolometric correction factor being $b \sim 10$ (cf. Sanders et al., 1989; Weedman, 1986).

5. Black hole mass. Correlation of the masses of black holes and host galaxies was discussed by Kormendy, Richstone (1995) (for spirals, the bulge masses were taken instead of the galaxy masses). It was found, that, in average, $M_H \propto M$. These results were confirmed by recent HST data (Press release No. STScI-PRC97-01). However, there is large scattering of

\footnote{Independently, this correlation was considered in Kontorovich, Krivitsky (1993).}
the ratio $M_H/M$ around its average value. Thus, $M_H \sim 2 \cdot 10^6 M_\odot$ in our Galaxy, whereas $M_H \sim 3 \cdot 10^9 M_\odot$ in M87. Below we shall use a more complicated model than in the previous section: we shall assume $M_H = \zeta M$, where $\zeta$ is a random value the decimal logarithm of which is distributed uniformly in the range $-3 \pm 1$.

It is well known that the observed quasar LF essentially depends on the redshift: in the past quasars were much brighter than now (Boyle et al., 1988). There are two points of view on this fact in the literature. The simplest interpretation is that active nuclei are comparatively long-lived objects (with lifetimes of billions years), but the luminosity of each quasar decreases in the course of time (“luminosity evolution”). However, this hypothesis encounters some difficulties. In particular, if we assume that the luminosity of high-$z$ bright quasars cannot exceed the Eddington limit then the contemporary active galaxies, as their “descendants”, must have very massive black holes ($\gtrsim 10^9 M_\odot$), which seems to be ruled out by observational data (e.g., Schmidt, 1988). The other point of view is that quasars are a comparatively short ($\lesssim 10^8$ years) evolution stage of the majority of galaxies. Thus, Haehnelt and Rees (1993) assume that an active nuclear grows in almost every galaxy just after its formation, the initial luminosity equals the Eddington one and so the LF reflects the MF of black holes. The physical reason of decreasing the luminosity, proposed by these authors, is that more massive galaxies form later, their density is lower, the central potential well is less deep, and the black hole forming there is, in average, less massive. So, negative correlation between the mass of the newly formed galaxy and the initial mass of the black hole in its center is assumed. Small and Blandford (1992) assume that the observed break in the quasar LF is associated with the transition between the two modes of accretion: the continuous one ($L = L_{\text{Edd}}$) and the intermittent one ($L < L_{\text{Edd}}$ and is controlled by the amount of “fuel”). So, decreasing of the break luminosity is associated with decreasing of the average amount of “fuel”. Note that both Haehnelt and Rees (1993) and Small and Blandford (1992) assume that the lifetime of an individual quasar is much less than a characteristic evolution time.

How can the evolution of the quasar LF be described in the merger model? In this model the characteristic luminosity corresponding to the break is related to the mass $\mu$ in (4), (13). Since less massive galaxies form earlier, $\mu$ cannot decrease with time. So, cosmological evolution of $\Phi(\mathcal{M})$ cannot be the cause of the decreasing of the quasar luminosity. One of the possible explanation (which we shall assume in this work) is cosmological evolution of $\eta$ (fraction of mass which actually gets into the center). Here quasar lifetime is assumed much less than the age of the Universe, so we may use (4), (3). We shall take $t_{\text{act}} \sim 10^8$ years. Cosmological decreasing of $\eta$ may be caused, for example, by decreasing of the amount of gas in galaxies. Indeed, gas and stars behave in different ways at merging; the matter which gets into the center is, mainly, gas (Hernquist, Barnes, 1994).

To obtain the quasar LF for such a high $z$ as 2, we must take into consideration cosmological evolution of $\Phi(\mathcal{M})$. Possible reasons of such evolution are galaxy mergers, birth of new galaxies of gas, etc. Reliable observational data on the normal galaxy LF are available only for moderate redshifts ($z \lesssim 0.5$), and the main contribution to the change in this LF seems to be given by the change of the star formation rate rather than alteration of the MF (e.g., Small et al., 1997). Thus, we have to take the time evolution of $\Phi(\mathcal{M})$ from model theoretical calculations. The existing theories for galaxy formation cannot yet give a detailed and reliable description of this process. However, they make some qualitative predictions. The evolution of the LF was considered, e.g., by

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8Siemiginowska and Elvis (1997) also suppose that active black hole masses decrease with time.
Kauffmann et al. (1994); Cole et al. (1994). They concluded, in particular, that an average galaxy luminosity at \( z \approx 2 \) is several times less than at \( z = 0 \), whereas the amount of dwarf galaxies is several times higher. In the same time, both groups of authors notice that they cannot account for the observational data for both faint galaxy counts and the slope of the galaxy LF simultaneously: the calculated LF has much higher \( \alpha \) than the observed one. Gnedin (1996) obtained the value of \( \alpha \) and the shape of the MF which agree very well with the observed ones (may be, except for the observed steepening at very small masses) but he did not compute the time evolution of \( \Phi(M) \).

In this paper we shall compute \( \phi(L, t) \) for two variants of \( \Phi(M, t) \): 1. non-evolving \( \Phi(M) \) in the form (13); 2. “maximal” evolution of \( \Phi(M) \). In the second variant we shall take a composed MF and assume that the shape of \( \Phi(M) \) is described by (13), \( \mu \) and \( \Phi_0 \) depend on time approximately as in fig. 3 by Kauffmann et al. (1994) and fig. 19 (right bottom) by Cole et al. (1994), but, in the same time, \( \alpha_1 \) and \( \alpha_2 \) has the observed values (see page 8), i.e., the MF is more flat than in Kauffmann et al. (1994) and Cole et al. (1994). Namely, we assume \( \mu \propto (1 + z)^{-5/3} \), \( \Phi_0 \propto (1 + z)^{4/3} \). The break mass \( M_{br} \) is assumed to be constant, as there are no data for its evolution.

As merging occurs, mainly, in higher density regions, we should take into account the non-homogeneity of the galaxy spatial distribution. Due to this inhomogeneity, \( I(L) \) depends on coordinates, and the right-hand part of (1) will contain a factor \( \langle \rho / \rho \rangle^2 \), where \( \langle \rho \rangle \) is the average galaxy density (because the MF will be \( \rho / \langle \rho \rangle \) times higher). Integrating \( I(L) \) over a large volume \( V \), we obtain that the average density of quasars\(^9\) is \( \kappa = \frac{\int \rho^2 \, dV}{\langle \rho \rangle^2 V} \) times higher as compared to the homogeneous situation, and \( \kappa \) can be expressed as

\[
\kappa = \frac{\int \rho^2 \, dV}{\langle \rho \rangle^2 V} = \frac{\int \rho \, dM}{\langle \rho \rangle M} = \frac{\int \rho \, dN}{\langle \rho \rangle N},
\]

where \( dM = \rho \, dV \) is the mass in the volume \( dV \), \( dN \) is the number of galaxies in this volume, \( M = \langle \rho \rangle V \) and \( N \) are the total mass and number of galaxies. Below the quantity \( \kappa = \frac{1}{N} \int \langle \rho \rangle \, dN \) will be referred to as the average density contrast.

We will use two \( z \)-dependent fitting parameters in comparing the quasar LF with the observed one: the fraction of matter \( \eta \) and the average density contrast \( \kappa \).

The results are shown in figs. 3 (the AGN LF) and 4 (the corresponding values of the parameters for which \( \phi(L) \) has best agreement with the observational data by Boyle et al. (1988) for the quasar LF). The figures show that the model presented above is able to account for the observed evolution of \( \phi(L) \). In the case of non-evolving MF the fraction of matter which gets into the center \( \eta \) changes from \( \approx 0.12-0.3 \) for \( z \approx 2 \) to \( \approx 0.025-0.043 \) for \( z \approx 0.5 \), whereas the average density contrast in the regions of quasar formation \( \kappa \) is \( \approx 1.4-2.4 \) for \( z \approx 2 \) and \( \approx 4.5-7.2 \) for \( z \approx 0.5 \). In the case of “maximal” MF evolution the parameter \( \eta \) for large redshifts is much higher: \( \approx 0.8-1.3 \) for \( z \approx 2 \) (see the discussion below), \( \approx 0.05-0.11 \) for \( z \approx 0.5 \), and \( \kappa \) is somewhat lower: \( \approx 0.7-0.9 \) for \( z \approx 2 \), \( \approx 3-4.6 \) for \( z \approx 0.5 \). Taking into account the Eddington restriction gives in most cases an increase of \( \eta \) and \( \kappa \); for (3) \( \eta \) is somewhat higher, whereas \( \kappa \) is somewhat lower, as compared to (2).

\(^9\)We have chosen the cases of the fastest evolution of the MF, and neglect the difference between the MF and the LF evolution.

\(^{10}\)Here we average the equation for \( \phi \) (or (2), (3)) and keep the notation \( \phi \) for the averaged LF.
Figure 2: Quasar luminosity function: observed (Boyle et al., 1988) and predicted by the model described in section 3. The corresponding values of the parameters \( \eta \) and \( \kappa \) are shown in fig. 3. Symbols \( \triangle, \square, \times, \bullet \) stand for observational data for \( z = 0.3-0.7, 0.7-1.2, 1.2-1.7, 1.7-2.2 \) (with \( q_0 = 0.5 \)), solid lines show the merger model results for \( z = 0.5, 0.95, 1.45, 1.95 \). Figures (a)–(d) show the results for no Eddington restriction. The left panel corresponds to (2), the right one to (3); Figs. (a) and (b) correspond to non-evolving mass function, (c) and (d) are the same for the evolving mass function. Figures (e)–(h) show the same with the Eddington restriction. Figures (g) and (h) do not show the plots for large \( z \), see the text.
Figure 3: Mass fraction $\eta$ which gets into the center and density contrast $\kappa$, necessary for agreement between the predicted and observed luminosity functions (fig. 2). Solid line corresponds to (4), dotted line to (3), 1 stands for the case without the allowance for the Eddington restriction, 2 for the case with the restriction, (a) is for non-evolving mass function, (b) is for the evolved one.

Alteration of $t_{ac}$, $\varepsilon$, $b$ results in alteration of $\eta$ and $\kappa$, according to

$$\eta \propto t_{ac}^{-1} \varepsilon^{-1} b, \quad \kappa \propto t_{ac}^{-1}.$$  \hspace{1cm} (16)

Besides, $\eta$ increases with decreasing the average angular momentum in (14).

In some cases (namely, the evolving MF and (3)) the values given in fig. 3 fall beyond the physically allowed range (the fraction of matter which falls into the center cannot exceed 1, and the density contrast must be higher than 1). It does not mean that the model fails: according to (14), the values falls into the required range if, for example, $t_{ac}$ is $5 \cdot 10^7$ years instead of $10^8$.

Note that the obtained $\eta$ values for $z \approx 0.5$ (several per cent) have the same order of magnitude as an average gas fraction in modern galaxies, $\kappa \approx 10$ corresponds to an average density contrast in the large-scale structure filaments, and the value $z \sim 1$ corresponds to the epoch of intensive star formation accompanying by decreasing of the amount of gas. Next, if the parameter $\eta$ is really related to the gas fraction in galaxies, then such high $\eta$ values for $z \sim 2$ as several tenth looks rather natural: a large quantity of gas has not yet turned into stars. However, for galaxies with such a high gas fraction the merger criterion described in section 2 should be modified, as well as the expression for $U$, because in a high-speed collision ($v \gg v_g$) two stellar systems will pass through each other, whereas two colliding gas clouds will show quite a different behavior, forming a dissipative discontinuity system (e.g., Chernin, 1998).

In the variant with the “maximal” MF evolution and the Eddington luminosity taken into account, the obtained LF at large redshifts ($z \gtrsim 1.5$) disagrees with the data by Boyle et al. (1988) for any values of the parameters: the number of the brightest quasars ($L \sim 10^{48}$ erg/s) is much lower than the observed one (that is why the last two curves are not shown in figs. 2a and 2b). It is related to the influence of the Eddington restriction. Indeed, if we assume $L \leq L_{Edd}$, then such quasars must have a black hole of a mass $\mathcal{M} \sim 10^{10} \mathcal{M}_\odot$. In the same time, the “maximal” MF
evolution assumed here implies that the masses of galaxies at $z \sim 2$ are approximately one order lower than the modern ones, whereas the black hole masses $M_H = \zeta M$. Thus, there are too few black holes with $M \sim 10^{10} M_\odot$, even in spite of the $\zeta$ scattering assumed here. There are many possible reasons for this discrepancy: 1. the luminosity may be much higher than the Eddington one due to anisotropy of the quasar “central machine”; 2. in a model where periods of activity alternate with pauses, the peak luminosity may be higher than the Eddington one; 3. gravitational lensing may cause an increase of the apparent brightness; 4. the case for “maximal” MF evolution may not be realized. Allowing for the former two factors should result in an increase of the luminosity (therefore, lower $\eta$ required) and decrease of the normalization (higher $\kappa$ required), which gives one more explanation of the curves in fig. 3b which falls beyond the allowed region.

Thus, the merger model can explain the observed shape and evolution of the quasar LF and give an estimate for the parameters $\eta$ and $\kappa$. Also, in the case of evolving MF the results agree well with the hypothesis that the quasar luminosity may much exceed the Eddington limit.

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