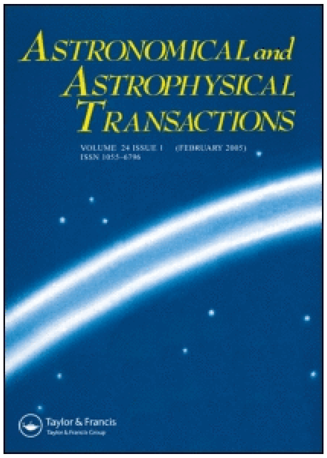

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Session 8 : Large Scale Structure of the Universe and Cosmology

THE LUMINOSITY FUNCTION OF QUASARS (ACTIVE GALACTIC NUCLEI) IN A MERGING MODEL WITH THE EDDINGTON LIMIT TAKEN INTO ACCOUNT

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The influence of Eddington's limit on the active galactic nuclei (AGN) luminosity function within the framework of a phenomenological activity model (Kats and Kontorovich, 1990, 1991) based on angular momentum compensation in the process of galaxy merging is investigated. In particular, it is shown that in spite of the essential dependence of the galaxy merging probability on their masses in the most important and interesting case it behaves effectively as a constant, so that the abovementioned (Kats and Kontorovich, 1991) correspondence between the observed galaxy mass function (Binggeli *et al.*, 1988) and quasar luminosity function power exponents (Boyle *et al.*, 1988; Koo and Kron, 1988; Cristiani *et al.*, 1993) for a constant merger probability takes place in reality. A break in the power-law dependence of the luminosity function due to Eddington's restriction (cf. Dibai, 1981; Padovani and Rafanelli, 1988) is obtained in certain cases. Possible correlation between masses of black holes in AGN and masses of their host galaxies is discussed. A more detailed paper containing the results presented at this conference was published in Pis'ma v Astron. Zh. (Kontorovich and Krivitsky, 1995). Here we have added also some additional notes and references.

KEY WORDS Galaxies, quasars, activity, interactions, merging, luminosity function, black holes, Eddington limit

1 INTRODUCTION: THE RELATIONSHIP EXCESSIVE MASS–LUMINOSITY

Observations of recent years have provided ever more arguments for interactions and mergers of galaxies as a possible cause of the activity of their nuclei (see references to a set of detailed reviews and research papers on this topic in a brief review by one of the authors (Kontorovich, 1994). Though mergers may be responsible even for the formation of massive galaxies (Kats *et al.*, 1992) (additional arguments for a significant role of mergers are given in works by Menci and Caldarnini (1994) and

Komberg and Lukash (1994)), and for the rapid disappearance of quasars† at large redshifts, we shall restrict ourselves below to discussing activity as a consequence of mergers (Kats and Kontorovich, 1991, hereafter KK), assuming the mass function (MF) of galaxies as given (Binggeli *et al.*, 1988; Tully, 1988), and we shall not discuss its appearance.

In the model, the luminosity of the active object appearing after merging

$$L = B\,\Delta m \tag{1}$$

is determined by the excessive disc mass $\Delta m \equiv m_1 + m_2 - m$ which has lost its angular momentum and may potentially fall to the centre (indices 1, 2 belong to the merging galaxies, m without the index belongs to the result of merging). The disc mass $m = S/\sqrt{GMR}$, where S is the angular momentum, M is the mass, and R is the radius of the galaxy. The coefficient $B \propto \eta c^2 t_{\rm ac}^{-1}$, where η is the share of Δm which reaches the black hole (BH) in the galaxy centre, and $t_{\rm ac}$ is the accretion time. It should be noted that the possibility of matter falling to the centre during merging is confirmed by many numerical experiments (see e.g. Barnes and Hernquist, 1991). The scheme under consideration leads to an integral source I_L, quadratic in the MF of galaxies, in the equation for the luminosity function (LF) of active objects $\phi(L,t)$: $\hat{K}\phi = I_L(t)$, which is the main subject of our consideration. In the simplest case $\hat{K} = \frac{\partial}{\partial t} + \frac{1}{t_{\rm act}}$, where $t_{\rm act}$ is the galactic activity time. Using equation (1), the source I_L can be expressed in terms of the source $I_{\Delta m}$ of objects with excessive mass Δm, which was computed earlier (KK):

$$I_L(t) = \int d\Delta m\, \delta(\Delta m - L/B) J_{\Delta m}(t). \tag{2}$$

We give a detailed discussion of this expression below, taking into consideration restrictions associated with the nucleus Eddington luminosity (EL). The latter is essential (Dibai, 1981; Padovani and Rafanelli, 1988) and must be taken into account in the formulation of the activity model.

2 NUCLEUS BH MASSES VERSUS MASSES OF HOST GALAXIES

Taking the EL into account introduces a new parameter to the theory: BH mass M_H. Here we discuss two variants of the BH mass distribution (two limiting cases). In the first one M_H is connected with the galaxy mass by the relation $M_H \propto M^h$ ($L_{\rm Edd} = lM^h$). In the second variant M_H is an independent parameter, described by its distribution function $\psi(M_H)$. (Computation of such a function in the scope of the Feast or Famine scheme was made by Small and Blandford (1992)). A preliminary analysis (Table 1) shows a possible correlation of M and M_H, and h is likely to be within the range $1 \le h \le 3$.

†Keeping in mind the unified model and extended unified scheme (Antonucci, 1994; Komberg, 1995) we mean also radio galaxies and other active objects.

Table 1. Possible correlation between masses of galaxies and masses of black holes in their nuclei (preliminary data).

Galaxy	*Galaxy mass*	*Mass of probable BH in galaxy nucleus*
M 32	$2.1 \times 10^9 M_\odot$	$8 \times 10^6 M_\odot$
M 33	$3.9 \times 10^{10} M_\odot$	$\lesssim 5 \times 10^4 M_\odot$
M 31	$3.1 \times 10^{11} M_\odot$	$3\text{–}7 \times 10^7 M_\odot$
NGC 3377	$2.3 \times 10^{11} M_\odot$	$10^8 M_\odot$
M 104	$4.5 \times 10^{11} M_\odot$	$10^9 M_\odot$
NGC 3115	$7.4 \times 10^{11} M_\odot$	$1\text{–}2 \times 10^9 M_\odot$
M 87	$2.1 \times 10^{12} M_\odot$	$< 4 \times 10^9 M_\odot$
NGC 6240	$2.6 \times 10^{12} M_\odot$	$> 4 \times 10^{10} M_\odot$
The Galaxy	$1.5\text{–}2 \times 10^{11} M_\odot$	$2 \times 10^6 M_\odot$

Note. The coefficient of correlation is 0.7. If we assume $M_H \propto M^h$, the method of least squares gives $h = 1.32$ (if we exclude M 32 from the sample then $h = 2.93$). The data were taken from the following sources. Masses of nuclei: Dressler and Richstone (1988, *Astrophys. J.* **324**, 701 (M 31, M 32)), Dressler and Richstone (1990, *Astrophys. J.* **348**, 120 (M 87)), Kormendy and Richstone (1992, *Astrophys. J.* **393**, 559 (NGC 3115)), Kormendy (1988, *Astrophys. J.* **335**, 40 (M 104)), Bland-Hawthorn, Wilson and Tully (1991, *Astrophys. J.* **371**, L19 (NGC 6240)), Small and Blandford (1992, *Mon. Not. R. Astron. Soc.* **259**, 725 (M 33, NGC 3377, the Galaxy)). Masses of galaxies: Leng, *Astrophysical Formulae*, Springer Verlag (1974) (M 31, M 32, M 33, M 87), Wagner, Dettmar and Bender (1989, *Astron. Astrophys.* **215**, 243 (M 104)), Marochnik and Suchkov, The Galaxy, Moscow, Nauka (1984). The masses of the NGC 3115, NGC 3377, NGC 6240 galaxies were estimated by their luminosities, assuming $M/L \sim 10$. To compute the luminosities we took the values of m_B from the RC3 catalogue (de Vaucouleurs *et al.*, Springer Verlag, 1991) and estimated the distance by the radial velocity given in the same catalogue, assuming $H_0 = 50$ km s^{-1} Mpc^{-1}. For NGC 6240 the data for extinction were not available in the catalogue; we estimated the Galactic extinction according to the work by Sharov, (1963, *Astron. Zh.*, XL (5), 900).

3 TAKING INTO ACCOUNT THE EDDINGTON LUMINOSITY

As already known, the radiation pressure restricts the luminosity of an object on the level $L_{\rm Edd} = \kappa M_H \sim 10^{38} M_H/M_\odot$ erg s^{-1}. It is natural to assume that if $B\Delta m > L_{\rm Edd}$ in the model, then the accretion will be restricted (cf. Blandford, 1989). Equation (2) allows one to easily take this fact into account. It is enough to replace

$$\begin{aligned} \delta(\Delta m - L/B) \quad &\rightarrow \quad \delta(\Delta m - L/B)\theta(L_{\rm Edd} - B\Delta m) \\ &+ \quad B\delta(L - L_{\rm Edd})\theta(B\Delta M - L_{\rm Edd}), \end{aligned} \tag{3}$$

where $\theta(x)$ is the Heaviside unit step function. The result is

$$I_L = \int dM_1 dM_2 dM_H \psi(M_H)\Phi_1\Phi_2 U_{12}\delta(L - L_{12}). \tag{4}$$

Here $\Phi_{1,2} \equiv (M_{1,2})$ are the MF of the merging galaxies, $U_{12} \equiv U(M_1, M_2)$ is the probability density of their merging, $L_{12} = \min(B\Delta m, L_{\rm Edd})$ is the luminosity of the active object arising after the merging, ψ is the MF of massive black holes, normalized to unity (in the case $M_H = \zeta M^h$ it changes to $\delta(M_H - \zeta M^h)$). Just as in KK we assume here that the joint mass and angular momentum distribution function of galaxies is factorized and the momentum distribution is close to δ-function (the anisotropic model). In this case

$$\Delta m \propto M_1^\lambda + M_2^\lambda - (M_1 + M_2)^\lambda, \tag{5}$$

where the radius of a galaxy is assumed to depend on its mass as $R \propto M^\beta$ and the parameter λ is $(1-\beta)/2$. (In a more general case the source can be expressed in terms of the joint mass and momentum distribution, which is known rather poorly). For constant density, obviously, $\beta = 1/3 = \lambda$. For the Faber–Jackson and Tully–Fisher laws ($L \propto V^4$), using the virial theorem and assuming $L \propto M$, one can obtain $\beta = 1/2$, $\lambda = 1/4$.

We shall take the coefficient $U = \overline{\sigma v}$ (σ is the merging cross-section, v is the relative velocity at infinity, the bar means average over velocities) in the form which corresponds to $\sigma = \pi(R_1+R_2)^2(1+\gamma)\varphi(\gamma)$, where $\gamma = 2G(M_1+M_2)/[(R_1+R_2)v^2]$ is the gravitational focusing parameter, and φ is the merging probability in a head-on collision. In the simplest case $\varphi(\gamma)$ can be approximated by the step-like function $\varphi(\gamma) = \theta(\gamma - 1)$. Averaging over velocities leads to the mass dependence of U of the form

$$U_{12} \propto (M_1 + M_2)(M_1^\beta + M_2^\beta) \tag{6}$$

for large masses (see Kats and Kontorovich, 1990). In analysing integral (4) an important role is played by both the homogeneity power $U_{12} \sim M^u$ and the asymptotics for largely different masses:

$$U_{12} \propto M_1^{u_1} M_2^{u_2}, \quad M_1 \ll M_2, \quad u_1 + u_2 = u. \tag{7}$$

According to equation (6), $u_1 = 0$ and hence U_{12} is determined by the larger mass.

Equation (5) was obtained in KK only in the simplest case of the anisotropic angular momentum distribution and without considering the orbital momentum. It allows one to compute the asymptotics of equation (4) analytically. In a more interesting case, when the momentum distribution is isotropic and the orbital momentum is taken into consideration, the integral becomes too complex and can be computed only numerically. However, the qualitative consideration shows that the results obtained below are still valid in this case. The computations presented below are based on the fact that $L = B\Delta m$ is a homogeneous function of λth power of the colliding galaxy masses $M_{1,2}$, with asymptotical behaviour at $M_2 \gg M_1$ being determined by the smaller mass: $L \propto M_1^\lambda$. Both these properties of $L(M_1, M_2)$ are more general than the anisotropic distribution. Observations show that the average momentum of a galaxy $S \propto M^k$, with k close to $(3+\beta)/2$ (see Kontorovich and Khodyachikh, 1993, and cited there in). This means that on average $L \propto M^{\lambda_{\mathrm{eff}}}$, with λ_{eff} close to 1 (because $m \propto S/M^{(1+\beta)/2}$). In the asymptotic case $M_2 \gg M_1$ the excessive mass which has lost its momentum and can fall to the centre is determined by the smaller galaxy mass. Thus, the results given below must remain† (though λ changes) if we abandon the anisotropic distribution (on condition $\lambda_{\text{eff}} < h$).

4 THE INTEGRAL CONNECTION BETWEEN QUASAR LF AND GALAXY MF

Let us first consider the expression for the source of active galaxies I_L equation (4) without EL ($L_{12} = b(M_1^\lambda + M_2^\lambda) - (M_1 + M_2)^\lambda$). We take the MF in Schechter's form

$$\Phi(M) = \Phi_0 M^{-\alpha} e^{-M/\mu}, \quad M \gg M_0. \tag{8}$$

The mass distribution at $M < M_0$ must satisfy the condition that the integral expressing the total number of galaxies must converge (cf. KK).

The internal integral with respect to M_H in equation (4) equals 1, as L_{12} does not depend on M_H; so the integral becomes double. The δ-function makes the domain of integration in the (M_1, M_2) plane one dimensional: the hyperbola-like curve with the asymptotes $M_{1,2} = \text{const} = (L/b)^{1/\lambda}$.

There are three asymptotical regions of L. For $L \lesssim L_1 = bM_0^\lambda$ the path of integration passes along the domain where one of the masses is less than M_0 and the value of I_L depends on the behaviour of the MF at small masses. For $L_1 \ll L \ll L_2$ ($L_2 = b\mu^\lambda$) a part of the curve is within the domain $M_0 \ll M \ll \mu$ — here we have power-law intermediate asymptotics of I_L which is of major interest for us. At last, for $L \gtrsim L_2$ the path is in the domain where the MF decreases exponentially, and I_L drops rapidly with L.

For $M_0 \sim 10^6 M_\odot$, $\mu \sim 10^{11} M_\odot$, $\lambda = 1/3$ and the coefficient between m and M^λ corresponding to $m \sim M$ for $M \sim M_0$ we have $L_1 \sim 10^9$–10^{10} and $L_2 \sim 10^{11}$–10^{12} in units of

$$L_\odot \eta \left(\frac{t_{\text{ac}}}{10^8\text{year}}\right)^{-1}.$$

The latter value depends essentially on λ: if $\lambda_{\text{eff}} \sim 1$ (see above) then

$$L_2 \sim 10^{15} \left(\frac{m}{M}\right)$$

in the same units.

5 THE RELATIONSHIP BETWEEN QUASAR LF AND GALAXY MF INDICES WITHOUT EDDINGTON LIMIT

The behaviour of I_L for $L_1 \ll L \ll L_2$ depends on how rapidly MF decreases in the power region, that is on the value of α. Here we omit the derivation and give

†We have carried out numerical computations of I_L for the isotropic case. The results confirm this conclusion.

the final result:

$$I_L \propto L^{-1+(u+2-2\alpha)/\lambda} \text{ (depends on } u\text{)}, \quad u_2+1-\alpha<0, \tag{9}$$

$$I_L \propto L^{-1+(u_1+1-\alpha)/\lambda} \text{ (depends on } u_1!\text{)}, \quad u_2+1-\alpha>0. \tag{10}$$

In the former case the main contribution to the integral (4) is associated with $M_1 \sim M_2 \sim (L/b)^{1/\lambda} \ll \mu$; in the latter case merger of large masses with small ones $(L/b)^{1/\lambda} \sim M_1 \ll M_2 \sim \mu$ gives the main contribution.

Relations (9) and (10) are a generalization of the results by Kats and Kontorovich (KK) for U = const. The case of equation (9) was discussed earlier. It gives the observed index ≈ -1 for the quasar LF if $\alpha \approx (u+2)/2$ (for any u). Realistic dependence of U_{12} on masses (equation 6) corresponds to the latter result (equation 10). The appropriate index of the quasar LF is approximately -1 for $\alpha \approx 1$. The latter value is close to the observed Schechter index for field galaxies, according to Tully's data (1988) and the review Binggeli *et al.* (1988). Quasar LF index ≈ -1, obtained by Koo and Kron (1988) and Boyle *et al.* (1988), was recently confirmed by Cristiani *et al.* (1993). So, our model results in a plausible relation between the indices of the galaxy MF and quasar LF for the likely merging probability (equation 6). The contribution of large masses is essential, which is determined by the asymptotical behaviour of the merging probability (equation 7), but not only its homogeneity power.

6 EFFECT OF THE EL: THE CASE $M_H \propto M^h$

In the case when the masses are proportional ($M_H = \zeta M^h$) one should replace $L_{12} = B\Delta m$ by $L_{12} = \min[B\Delta m, l(M_1+M_2)^h]$ in equation (4) to take EL into consideration. Then there is a domain where $L = L_{\rm Edd}$ in the (M_1,M_2) plane. (It should be noted that $L = L_{\rm Edd}$ at *small* masses, because $B\Delta m$ increases with M more slowly then $L_{\rm Edd}$ for $\lambda < h$.) The characteristic size of this domain is $M_c \sim (b/l)^{1/(h-\lambda)}$, and the corresponding active object luminosity is $L_c \sim l^{-\lambda/(h-\lambda)} b^{h/(h-\lambda)}$. The numerical value of M_c depends largely upon h and λ and may vary from $10^7 M_\odot$ for $h=1$, $\lambda = 1/3$ to $10^{13} M_\odot$ for $h=2$, $\lambda_{\rm eff}=1$ (the parameters being the same as above, p. 5, and ζ corresponding to $M_H \sim 10^9 M_\odot$ for $M \sim 10^{12} M_\odot$).

Integral (4) may be split into two terms, corresponding to the two segments of the path, with $L = L_{\rm Edd}$ and $L < L_{\rm Edd}$ (Kontorovich and Krivitsky, 1995, Figure 2), and corresponding to the two terms in equation (3). The results for the intermediate asymptotics of equation (4) in this case are as follows. For $M_c \ll \mu$ the Eddington restriction does not influence essentially the value of I_L (either the whole path of integration or the part responsible for the main contribution is beyond the region $L = L_{\rm Edd}$). So, equations (9) and (10) are still valid. The term associated with the EL gives an essential contribution if $M_c \gtrsim \mu$. The upper bound of the power-law region is determined by the Eddington luminosity in this case: $L_2 = l\mu^h$. If $u_1+1-\alpha<0$ then the term with $L = L_{\rm Edd}$ in equations (3) and (4) is not negligibly small only in the luminosity range $L_2 \lesssim L \lesssim L_c$, that is in the region of I_L exponential decreasing. If $u_1 + 1 - \alpha > 0$ then the Eddington term may be important in a part of the power-law region (in the large luminosity end). It results in a break in LF: the slope $-1 + (u_1 + 1 - \alpha)/\lambda \approx -1$ changes to a more flat one $-1 + (u + 2 - 2\alpha)/h$.

In conclusion we consider the limiting case $L_{12} = L_{\rm Edd}$ ($M_c \to \infty$). There exists a power-law region with bounds $L_1 = lM_0^h$ and $L_2 = l\mu^h$:

$$I_L \propto L^{-1+(u_2+1-\alpha)/h} \begin{cases} L^{u_1+1-\alpha)/h}, & u_1 + 1 - \alpha > 0 \\ 1, & u_1 + 1 - \alpha < 0. \end{cases} \tag{11}$$

7 EFFECT OF THE EL: INDEPENDENT BH DISTRIBUTION

In the case of independent BH distribution $\psi(M_H)$ we shall restrict ourselves to giving the result for the power law ψ:

$$\psi(M_H) \propto M_H^{-\xi}, \quad M_{\rm min} < M_H < M_{\rm max}. \tag{12}$$

The power-law I_L region remains (now it is the region $\max(L_1, \kappa M_{\rm min}) \ll L \ll \min(L_2, \kappa M_{\rm max})$):

$$I_L \propto \begin{cases} L^{-1+(u_1+1-\alpha)/\lambda}, & u_1 + 1 - \alpha < 0, \quad \xi < 1 \\ L^{-\xi+(u_1+1-\alpha)/\lambda}, & u_1 + 1 - \alpha < 0, \quad \xi > 1 \\ L^{-\xi}, & u_1 + 1 - \alpha > 0, \quad \xi > 1 \end{cases} \tag{13}$$

(on condition $u_2 + 1 - \alpha > 0$, $u + 2 - 2\alpha > 0$).

For $\xi < 1$, $u_1 + 1 - \alpha > 0$ the power region splits into two parts, $L^{-\xi}$ and $L^{-1+(u_1+1-\alpha)/\lambda}$. The index $-1 + (u_1 + 1 - \alpha)/\lambda$ corresponds to the contribution of the term with $L < L_{\rm Edd}$; the index $-\xi$ to the term with $L = L_{\rm Edd}$; the index $-\xi+(u_1+1-\alpha)/\lambda$ appears when both terms are of the same order. The behaviour of I_L beyond the power region is rather complicated and depends on relations between parameters.

8 CONCLUSION

Thus, the observed value of the LF index, close to -1, can be obtained in the merging model. It requires the galaxy MF index, close to -1 (equation 10), which agrees with observational data, and $\xi < 1$ (equation 13) for the independent BH distribution, that is the mass distribution function of the black holes in galaxy centres must decrease slowly enough.

One should note, that, although the dependence of the merging probability U_{12} on galaxy masses is essential, in the most interesting case of merging between large and small mass galaxies the function U_{12} behaves effectively as if it were constant: dependence on the lesser mass vanishes due to equation (6), whereas the larger mass is of order of μ in the domain responsible for the main contribution to the integral. Owing to this fact, the correspondence between the observed galaxy MF and quasar LF indices, obtained earlier in KK for $U_{12} = \text{const}$, is still valid (equation 10).

The Eddington restriction is essential at luminosities more than or of the order of the upper bound of the power-law region (and, on certain conditions, in a part of the power-law region, which leads to a break), if $M_c \sim \mu$ (which may be realized, for example, for $\lambda_{\text{eff}} \approx 1$, $h \approx 2$).

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