"Explosive" evolution of galaxies in a model of coalescence events and an epoch of quasar formation

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An explanation for the "sudden" appearance of quasars is proposed. The (fast) time evolution of the number of quasars and their luminosity distribution are calculated.

A significant number of diverse pieces of observational evidence point to an important role for events in which galaxies coalesce. These processes are probably responsible for manifestations of activity at relatively small redshifts z (see, for example, the bibliographies in Refs. 1–3). However, they can apparently also play an important cosmological role, explaining in particular the "sudden" disappearance of quasars at $z > 2$–3. The population of quasars increases with increasing z at smaller values of z.

Indeed, if we know the joint distribution of galaxies with respect to mass and momentum, then we can also find the rate of creation of active objects (quasars) in, for example, a model in which the activity stems from accretion on a compact nucleus as the result of a cancellation of momentum upon coalescence.[1] Solutions of the kinetic equation which give the mass distributions during instances of coalescence (these distributions can be associated with the observable luminosity distribution of galaxies) depend strongly on how rapidly the coagulation coefficient $U = \overline{\sigma v}$ (σ is the coalescence cross section, v is the relative velocity, and the superior bar means an average over velocities) increases with increasing mass. If $U \propto M^u$, then values $u > 1$ correspond to an "explosive" evolution, in which a power-law distribution at large masses is established from an initial distribution, localized at small masses $\sim M_*$ over a finite time.[4] If $U = cM_1M_2$, this conclusion follows from an exact solution of the kinetic equation.[4,5] For the function $U = c(M_1 + M_2)^2$, which arises in a model of coalescence events which are bounded by the contact condition and by velocities $v < v_g = \sqrt{2GM/R}$ (R is a characteristic sum of the radii of the colliding galaxies, and $M = M_1 + M_2$ is the sum of their masses), then we can go over from an integral kinetic equation to a differential equation for the mass distribution function f, taking into account the predominant interaction of large masses with small masses:

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial M}(c\mathscr{M}M^2 f) = 0, \quad \mathscr{M} = \int_0 dMMf(M,t). \tag{1}$$

Here $\mathscr{M}$ is an integral of motion if the integral is dominated by small masses; we mean to emphasize this point by writing only a lower limit here. Equation (1) reflects conservation of the number of massive galaxies under these conditions.

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The coefficient c here is given by $c \simeq G^2/v^3(t)$, where G is the gravitational constant, and $v(t)$ is the mean square velocity of the galaxies. The latter velocity depends on the time by virtue of the expansion of the universe. For the same reason, there is a change in the number of density of galaxies used in the normalization of the distribution of galaxies. In Eq. (1), however, we have $c = c(t_{\rm H}) = {\rm const}$ (more on this below). We assume that the average density of matter in the universe is equal to the critical density, and we assume that the $v(t)$ law is the one which arises in the linear theory of gravitational instability.[6] In general, the result is sensitive to this choice. The "slow" time dependence (slow in comparison with an explosive dependence), in particular, determines the boundary of the region of a relatively "hot" subsystem of galaxies, $M_b(t)/10^9 M_\odot \sim kt/t_{\rm H}$ [$k = v^3(t_{\rm H}/\sqrt{G^3\rho}\cdot 10^9 M_\odot \sim 1$, and $t_{\rm H}$ is the Hubble time], in which the expression used above for U is valid. Correspondingly, it determines the limiting masses which can be reached as the result of an explosive evolution in this region. (Scenarios in which an explosive evolution plays out in a "cold" region of large masses are possible.)

Restricting the discussion here to the solution of the initial-value problem for (1), we find this solution by the method of characteristics (Fig. 1):

$$f(M,t) = \left(\frac{\mu(M,t)}{M}\right)^2 f_0(\mu(M,t)), \tag{2}$$

$$\mu(M,t) = \frac{M\mu(t)}{M+\mu(t)}, \quad \mu(t) = (cM(t-t_0))^{-1}. \tag{3}$$

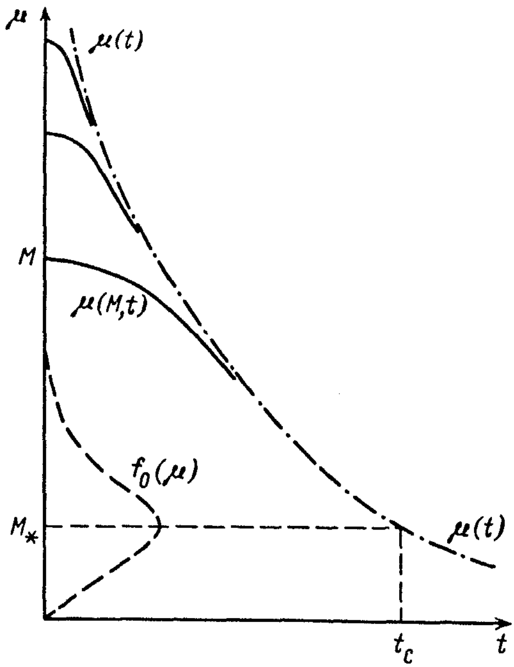

FIG. 1. Behavior of the argument $\mu(M,t)$ (solid line) of the initial mass distribution $f_0(\mu)$ (dashed line) in a solution of a kinetic equation which is of an explosive nature as $t \to t_{\rm cr}$. Here $\mu(M,t) = {\rm const}$ is a characteristic of chiral equation (1).

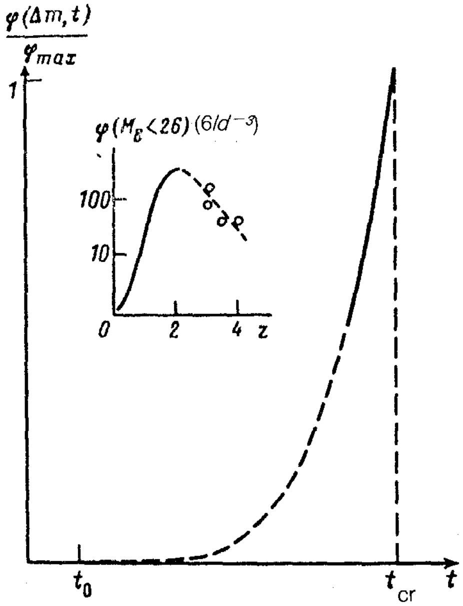

FIG. 2. Explosive increase in the number of quasars according to expression (9), thought of as an interpolation between t_0 and t_{cr}. Here we have $\varphi_{max} \equiv \varphi(t_{cr}) \to \infty$ as $M_b \to \infty$ [see (8)]. Here t_0 is the epoch at which (spiral) galaxies of small mass ($\sim M_*$) appear. A reduced time scale is being used here. The inset shows observational data of Ref. 10.

Since the initial distribution $f_0(M) \equiv f(M,t_0)$ is localized at $M \lesssim M_*$, at the time $t = t_{cr}$ [at which the argument f_0 in (2) reaches the value $\mu(t_{cr}) \simeq M_*$], a power-law distribution is established in an explosive manner over the broad mass region $M \gg M_*$. For $U = c_u(M_1 + M_2)^u$ we thus find

$$t_{cr} - t_0 \simeq ((u-1)c_u \tilde{\mathcal{M}} M_*^{u-1})^{-1}. \tag{4}$$

With $U = c(M_1 + M_2)^2$, the existence of t_{cr} is a rigorous assertion (cf. Ref. 4). Incidentally, the logarithmic divergence of $\mathcal{M}$ on the M^{-2} power-law asymptotic function in the case $u = 2$ means that the exact value t_{cr} and the shape of the mass spectrum are slightly different from (2)–(4). The value of t_{cr} is given here in the reduced scale of Silk and White, in which the expansion of the universe is taken into account, and Eq. (1) holds.

As a result, galaxies appear over a short time interval Δt near t_{cr} in the region of fairly large masses. This time interval is shorter, the larger the value of M: $\Delta t / t_{cr} \sim \sqrt{M_*/M}$. This explosive formation of galaxies in turn generates an explosive formation of active objects, as the result of coalescence events, as we are discussing in this letter.

While the luminosity L of ordinary galaxies is proportional to their mass, that of active objects, which is determined by accretion on the nucleus of the galaxy, is linked in the model of Ref. 1 with an excess disk mass Δm, which is capable, by virtue of a cancellation of momenta, of reaching the center: $L = B\Delta m$. To find the number density of quasars with a given luminosity (the luminosity function), $\varphi(\Delta m)$, we work from

$$\frac{\partial \varphi(\Delta m)}{\partial t} = I_{\Delta m} \equiv \int dM_1 dM_2 f(M_1,t) f(M_2,t) U \delta[\Delta m - (m_1 + m_2 - m)], \quad (5)$$

where the momentum distribution is assumed to be narrow, and where the disk masses m are expressed in terms of M: $m \sim M^{\lambda}$ ($R \sim M^{1-2\lambda}$). Introducing the dimensionless difference between the masses of the coalescing galaxies, x, as an integration variable, and also introducing the sum of these masses, $a(x) = [(1+x)^{\lambda} + (1-x)^{\lambda} - 2^{\lambda}]^{1/\lambda}$, we find $[x(M_b \to \infty) \to 1]$

$$I_{\Delta m} = \frac{16}{\lambda} c \frac{\xi^4}{\Delta m} \int_0^{x(M_b)} dx a^4(x) f_1 f_2, \quad \xi \sim \Delta m^{1/\lambda}, \quad M_{1,2} = \xi(1 \pm x) a(x). \quad (6)$$

At high luminosities, $\xi/\mu \gg 1$, we find the following expression for the mass function of galaxies which undergo an explosive evolution, according to (2):

$$f_{1,2} \sim \frac{\mu^2(t)}{\xi^2 a^2 (1 \pm x)^2} f_0(\mu(t)) \, . \quad (7)$$

Correspondingly, we find (the quantities ξ containing Δm cancel out!)

$$I_{\Delta m} = \frac{4c}{\lambda} \frac{\mu^4(t) f_0^2(\mu(t))}{1 - x(M_b)} \frac{1}{\Delta m}. \quad (8)$$

Choosing $f_0(M) \sim \exp(-M/M_*)$ for $M \gg M_*$, we find the following result for an explosive time evolution in the critical region:

$$I_{\Delta m}(t) \sim \exp\left(-\frac{2(t_{cr} - t_0)}{t - t_0}\right), \quad t_{cr} - t \ll t_{cr}. \quad (9)$$

Significantly, the slope of the spectrum in this model, $I_{\Delta m} \sim (\Delta m)^{-1}$ is close to the observed slope of the steady-state part of the quasar luminosity function.[7,8] By virtue of the explosive evolution, a steady-state distribution is initially established; at $t > t_{cr}$, it slowly "burns up." This agreement of spectra is, of course, probably simply fortuitous. The shape of the spectrum is sensitive to the particular choice of coagulation coefficient in the activity model. However, the very fact that the population of quasars appears explosively is relatively insensitive to many details of the mechanism for the coalescence events which are responsible, in this scenario, for both the establishment of the galaxy mass spectrum (this point imposes certain restrictions of its own[9]) and the appearance of an activity.

The explosive scenario thus qualitatively explains both the disappearance of quasars beyond[10] z_{cr} and the appearance of a "steady-state" quasar luminosity function $[\Phi(L) \sim L^{-1}]$, which later burns up at the bright end.[7,8] On the other hand, if this process is to be realized by the time t_{cr}, then a sufficient number of coalescence events, $M_b(t_{cr})/M_* \gg 1$, must occur. This condition imposes constraints on t_0 and M_*.

Going over to the real time (but using the same symbol) in accordance with[1,9] $dt \to (t_H/t)^3 dt$, and requiring $t_0 \ll t_{cr} < t_H$, we find $[v(t_H) \to v]$

$$10^{12}M_{\odot}(t_0/t_{\rm H})^2(v/10^7)^3(\vec{\mathscr{M}}/\rho_{\rm H})^{-1}\cong M_*\ll 10^9 M_{\odot}(v/10^7)^3(t_{\rm cr}/t_{\rm H}).$$

Here v is in centimeters per second. The equality here corresponds to the case in which $t_{\rm cr}$ becomes infinite; a slight change in the parameter values leads to the necessary choice of $t_{\rm cr}$. We have omitted a coefficient on the order of one. Here $\rho_{\rm H}\equiv(6\pi G t_{\rm H}^2)^{-1}$. If we assume that the entire mass, including the dark mass, is concentrated in galaxies, then we have $\mathscr{M}/\rho_{\rm H}\sim 1$, and for $t_{\rm cr}/t_{\rm H}\sim 10^{-1}$ the ratio $t_0/t_{\rm H}$ cannot be greater than 3×10^{-3}. We then find $M_*\lesssim 10^7 M_{\odot}(v/10^7)^3$, where v is again in centimeters per second. The condition $M_*<M_b(t_0)$ is more restrictive, leading to $t_0/t_{\rm H}\lesssim 10^{-3}(\vec{\mathscr{M}}/\rho_{\rm H})$. This condition can be satisfied either by virtue of the condition[1)] $\vec{\mathscr{M}}/\rho_{\rm H}\gg 1$ or by virtue of a decrease in t_0.

The limitations on masses can be lifted by going over to the region $M>M_b$, where $U\simeq\pi R^2 v(t)\cdot GM/Rv^2(t)\propto M^{1+\beta}$ ($\beta=1-2\lambda\to 1/3$ in the case $\rho=\text{const}$). In this region, an explosive evolution[2)] (with $\beta>0$) is probably also possible, with $t_{\rm cr}$ again taken from (4) (Ref. 4). Unfortunately, the divergence of $\vec{\mathscr{M}}$ at large masses becomes a power-law function (on the order of $1-\beta$), so the differential approach taken above becomes unreliable.

We make the transition to real time through the replacement $dt\to(t_{\rm H}/t)^{7/3}dt$; the relationship between t_0 and M_* becomes

$$10^{21}M_{\odot}(t_0/t_{\rm H})^4(v/10^7)^3(\vec{\mathscr{M}}/\rho_{\rm H})^{-3}\simeq M_*\ll M_{\rm max},$$

where v is yet again in centimeters per second. If we instead estimate $M_{\rm max}$ from the luminosity of quasars on the basis of the model which we are using here,[1] we find a mass $M_{\rm max}\gtrsim 10^{13}M_{\odot}$, which corresponds to large elliptic galaxies (this result is found only within a large uncertainty, because of our ignorance of the fraction of the mass which actually reaches the center, the ratio of the disk mass to the spheroidal mass, including the dark mass, etc.). With $\vec{\mathscr{M}}/\rho_{\rm H}\sim 1$, we find, for the maximum possible value $t_0/t_{\rm H}\sim 3\times 10^{-3}$, the result $M_*\approx 10^{11}M_{\odot}(v/10^7)^3$, but the condition $\vec{\mathscr{M}}/\rho{\rm H}\gg 1$ would make is possible both to lower this value of the initial mass and to approach the time at which it forms.

[1)]The value of $\vec{\mathscr{M}}/\rho_{\rm H}$ may exceed unity because of a local density fluctuation in the region in the quasar formation region. On the other hand, the choice $\vec{\mathscr{M}}/\rho_{\rm H}>1$ should not be taken literally. The decrease in the probability for coalescence events in the past which is achieved by means of this increase might also correspond to a more rapid decrease in the relative velocity of the galaxies, a larger role of tidal forces, or a greater porosity of the galaxies themselves at large z. Observations of close objects also indicate that the actual number of events in which galaxies coalesce is significantly greater than the simple kinetic-theory estimates (see the bibliographies in Refs. 1–3 and 9).

[2)]A nonexplosive version of the evolution was analyzed in Ref. 11 through the replacement of U by $U_{\rm eff}$ with $\beta=0$.

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