Advances in Astronomy and Space Physics, **3**, 131-134 (2013)

Explosive evolution of galaxies at high redshifts due to minor mergers

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In the case of minor mergers analytical solutions of kinetic Smoluchowski equation with a source that corresponds to separation of galaxies from the general expansion of the universe have been found. The solutions describe the explosive evolution of galaxy mass function in the presence of the dark matter. The evolution of power-law asymptote at large redshifts is discussed.

Key words: galaxies, minor mergers, galaxy mass function, galaxy evolutions

INTRODUCTION

The "sudden" appearance of massive galaxies at $z = 6$ discovered in ultra deep Hubble and Subaru fields [1, 7] (see also [4]) and observations of the secondary ionization final stage at the same time period [6] (see review [5]) as well as the quasars appearance epoch [13] can evidence for the explosive galaxy evolution while merging [3, 12], see also references in the review [8] and in our previous paper [9]. The new results on the role of mergers for galaxy evolution were presented at JENAM-2011[1]. The observed fast evolution of a number of massive galaxies can be explained by the explosive evolution of galaxies in the process of mergers in the presence of dark matter in galaxies.

In the case of predominance of the merging of massive galaxies with the galaxies of small masses, the integral kinetic equation is transformed to a differential form. This first-order equation in partial derivatives is solved by characteristics method. In some cases of physical interest it is possible to obtain the analytical solutions describing the explosive evolution in a closed form. Comparison of the explosive solutions with observational data will allow to make certain conclusions about the presence of the dark matter, and also about interaction of galaxies, taking into account the dark matter contribution.

THE METHOD OF CALCULATIONS

Below we study the explosive galaxy evolution resulting from the merger process with a low mass increase (minor mergers) assuming that along with the low-mass background, there exists a source $\Phi(M,t)$ of relatively high-mass galaxies, separating from the general expansion. In this case we may consider the Smoluchowski kinetic equation (KE) for the mass function (MF), $f(M,t)$, in the differential form supposing that the main contribution is due to mergers of the low-mass galaxies with the massive ones with the merging probability for the process $M_1, M_2 \Rightarrow M = M_1 + M_2$ such that $2U(M_1, M_2) \simeq CM_1^u$ for $M_2 \ll M_1$,

$$\frac{\partial}{\partial t} f(M,t) + C\Pi \frac{\partial}{\partial M}\left[M^u f(M,t)\right] = \varphi(M,t),$$
$$\Pi = \Pi(t) = \int dM_2 M_2 f(M_2,t). \quad (1)$$

Using the method of characteristics we find the KE solution $f(M,t) = f_s(M,t) + f_{in}(M,t)$:

$$f_s(M,t) = M^{-u} K\left(\tau(t) + \frac{1}{(u-1)M^{u-1}}, t\right), \quad (2)$$

$$f_{in}(M,t) = \left[(u-1)\tau M^{u-1} + 1\right]^{-\frac{u}{u-1}} \times$$
$$\times f_0\left\{M\left[(u-1)\tau M^{u-1} + 1\right]^{-\frac{1}{u-1}}\right\}, \quad (3)$$

where it is assumed that the source is localized, $\Phi(M,t) = M^u\varphi(M,t) = \delta\left(M - \bar{M}(t)\right)\Phi(t)$, $\tau = \tau(t) \equiv C\int_0^t dt\Pi(t)$, the function $K(a,t)$ is defined

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[1]http://jenam2011.org/conf/submission/special/s5.php; http://aramis.obspm.fr/JENAM11/index.php?body=prog.html

by the following integral relation:

$$K(a,t) = \int_0^t dt \delta\left[\mu(a,t) - \bar{M}(t)\right]\Phi(t) =$$
$$= \sum_n \Phi(t_n)\,\theta(t - t_n)\left|\frac{d}{dt}\left[\mu(a,t) - \bar{M}(t)\right]\right|^{-1}_{t=t_n},$$
$$\mu(a,t) = \left[(u-1)(a - \tau(t))\right]^{-\frac{1}{u-1}}, \quad (4)$$

where, t_n denotes roots of the equation $\mu(a,t) - \bar{M}(t) = 0$, and $f_0(M) = f(M,0)$ is the initial distribution. The main problem for obtaining the solution consists in solving the equation for $\mu(a,t)$, which gives us zeros of the corresponding delta-function in (4). For a simple case ($u = 2$, $\bar{M}(t) = t/A$, $\Pi(t) = \Pi = \text{const}$) the solution was considered in [10]. Here we discuss much more general case with $u > 1$, $\bar{M}(t) = t^s/A$, $A > 0$, $\Pi(t) = \Pi = \text{const}$. Respectively,

$$\tau(t) = C\Pi t,$$
$$\mu(a,t) = \left[(u-1)(a - C\Pi t)\right]^{-\frac{1}{u-1}}, \quad (5)$$

and the principal equation, $\mu(a,t) - \bar{M}(t) = 0$, becomes $\left[(u-1)(a - C\Pi t)\right]^{-\frac{1}{u-1}} - t^s A^{-1} = 0$, or

$$\frac{1}{a - C\Pi t} = \frac{u-1}{A^{u-1}} \cdot t^{(u-1)s}. \quad (6)$$

For $a > 0$ the left-hand side is a hyperbole with a vertical asymptote, $t = t_{as}(a) = a(C\Pi)^{-1}$, and only this case is of interest. If $s > 0$ the r.h.s. is a growing power function. Then the lines defined by the left and right-hand sides do not intersect, intersect at two points, or possess a single contact point, i. e., Eq. (6) can possess none, two, or one double root. Let us find first the double root condition. At the contact point along with equation (6) its time derivative holds true also. This additional condition in terms of the logarithmic derivative is

$$\frac{C\Pi}{a - C\Pi t} = (u-1)\,s t^{-1}. \quad (7)$$

Therefore, for the tangency point, $t = t_{tan}$, we obtain from equations (6)-(7):

$$t_{tan}^{(u-1)s+1} = \frac{s}{C\Pi}A^{u-1}. \quad (8)$$

This time value specifies the corresponding (critical) value of $a = a_{cr}$:

$$C\Pi = a_{cr}(u-1)\,s t_{tan}^{-1} - (u-1)\,sC\Pi,$$

or

$$a_{cr} = C\Pi\left[1 + \frac{1}{(u-1)s}\right]t_{tan} =$$
$$= C\Pi\left[1 + \frac{1}{(u-1)s}\right]\left[\frac{s}{C\Pi}A^{u-1}\right]^{\frac{1}{(u-1)s+1}}. \quad (9)$$

Noteworthy,

$$t_{as}(a_{cr}) = a_{cr}(C\Pi)^{-1} = \frac{s(u-1)+1}{s(u-1)}t_{tan}.$$

Specifically, for $s = 1$ and $u = 2$ we get (cf. [10]):

$$t_{tan} = \sqrt{A/(C\Pi)}, \quad a_{cr} = 2\sqrt{AC\Pi},$$
$$t_{as}(a_{cr}) = 2t_{tan}, (s = 1,\ u = 2). \quad (10)$$

Thus, for $a > a_{cr}$ we obtain two roots, $t_- < t_{tan}$, $t_+ > t_{tan}$, and for $a = a_{cr}$ we get one double root, $t = t_{tan}$. It is convenient to introduce the normalized variables, $\tilde{a} = a/a_{cr}$, $\tilde{T} = t/t_{tan}$. Then the basic equation (6) becomes

$$\frac{1}{\tilde{a} - \dfrac{(u-1)s}{(u-1)s+1}\tilde{T}} = \left[(u-1)s+1\right]\tilde{T}^{(u-1)s}. \quad (11)$$

As it was shown in the above specific case ($u = 2$, $s = 1$) the explosive evolution corresponds to the vicinity of the point $\tilde{a} = 1$, $\tilde{T} = \tilde{T}_{tan} = 1$, where the delta-function argument possesses double root. Therefore, let us seek the solution of Eq. (11) for $\tilde{a} = 1 + \delta\tilde{a}$, $0 < \delta\tilde{a} \ll 1$. Then we arrive at two real roots, $\tilde{T}_\pm = 1 + \delta\tilde{T}_\pm$, $\left|\delta\tilde{T}_\pm\right| \ll 1$, which in the lowest in $\delta\tilde{a}$ order are as follows:

$$\delta\tilde{T}_\pm \simeq \pm\sqrt{2\frac{\tilde{a}-1}{s(u-1)}}. \quad (12)$$

Now we can proceed with the Smoluchowski KE asymptotic solution in the region $0 < \tau(t) + \dfrac{1}{(u-1)M^{u-1}} - a_{cr} \ll a_{cr}$. For this aim we have to simplify expression $K(a,t)$ for $a = a_{cr}+0$. Following (4) we proceed for $t_n = t_\pm = t_{tan}\left(1 + \delta\tilde{T}_\pm\right)$:

$$K(a,t) = \sum_\pm \Phi(t_\pm)\theta(t - t_\pm)\times$$
$$\times\left|\frac{d}{dt}\left[\mu(a,t) - \bar{M}(t)\right]\right|^{-1}_{t=t_\pm} \simeq \Phi(t_{tan})\sum_\pm \theta(t - t_\pm)\times$$
$$\times\left|\frac{d}{dt}\left[\mu(a,t) - \bar{M}(t)\right]\right|^{-1}_{t=t_\pm},$$
$$|a - a_{cr}| \ll a_{cr}, \quad (13)$$

where it is supposed that $\Phi(t)$ is rather smooth. To calculate the derivative entering Eq. (13) it is necessary to take into account that

$$\left[\mu\left(a_{cr}+\delta a, t_{\pm}\right)-\bar{M}\left(t_{\pm}\right)\right]=0,$$
$$\frac{d}{dt}\left[\mu\left(a_{cr}+\delta a, t\right)-\bar{M}\left(t\right)\right]\Big|_{t=t_{tan}+\delta t_{\pm}} \simeq$$
$$\simeq\left[\frac{d}{dt}\mu\left(a_{cr}, t\right)-\frac{d}{dt}\bar{M}\left(t\right)\right]\Big|_{t=t_{tan}+\delta t_{\pm}} \simeq \pm q\sqrt{\delta a}, \quad (14)$$

where the term linear in δa is omitted as compared with that linear in $\delta t_{\pm}$. The coefficient q is rather complicated, but it depends only on the parameters of the problem, u, s, A, C and Π, and thus it does not influence the mass and time dependencies. Proceeding with $K(a,t)$ we obtain

$$K(a,t)\simeq\frac{\Phi\left(t_{tan}\right)}{|q|\sqrt{a-a_{cr}}}\times$$
$$\times\theta\left(a-a_{cr}\right)\sum_{\pm}\theta\left(t-t_{tan}-\delta t_{\pm}\right), \quad \left|a-a_{cr}\right|\ll a_{cr},$$
$$\delta t_{\pm}=\delta t_{\pm}(a)=\pm t_{tan}\sqrt{2\frac{a-a_{cr}}{s\left(u-1\right)a_{cr}}}. \quad (15)$$

Substituting now $a=C\Pi t+\dfrac{1}{(u-1)M^{u-1}}$ into the source governed part of FM (and changing, respectively, $\delta t_{\pm}(a)$ by $\delta t_{\pm}=\pm t_{tan}\sqrt{2\dfrac{\delta a(M,t)}{s(u-1)a_{cr}}}$, $\delta a(M,t)\equiv C\Pi t+\dfrac{1}{(u-1)M^{u-1}}-a_{cr}$) we get

$$f_s(M,t)\simeq\frac{M^{-u}\Phi\left(t_{tan}\right)}{|q|\sqrt{\delta a(M,t)}}\theta\left(\delta a(M,t)\right)\times$$
$$\times\sum_{\pm}\theta\left(t-t_{tan}-\delta t_{\pm}\right), \quad 0<\delta a(M,t)\ll a_{cr},$$
$$\delta t_{\pm}=\pm t_{tan}\sqrt{2\frac{\delta a(M,t)}{s\left(u-1\right)a_{cr}}}. \quad (16)$$

In the large mass region, $M_{*} << M < M_{max}(t)=\left[(u-1)\left(C\Pi t-a_{cr}\right)\right]^{-\frac{1}{u-1}}$, $M_{max}(t)\to\infty$ at $t\to t_{as}\left(a_{cr}\right)=a_{cr}/(C\Pi)\equiv t_{cr}$, the applicability condition, $0<\delta a(M,t)\ll a_{cr}$, holds true for

$$0<C\Pi t-a_{cr}\ll a_{cr}, \quad \text{or} \quad t\simeq t_{cr}-0. \quad (17)$$

In this asymptotic region the source governed term of the mass function is of power-law type $f\left(M,t\to t_{cr}\right)\propto M^{-\alpha}$ with the universal exponent, $\alpha=(u+1)/2$,

$$f_s(M,t)\simeq\frac{2\sqrt{u-1}\Phi\left(t_{tan}\right)}{|q|}\times$$
$$\times\theta\left(C\Pi t+\frac{1}{(u-1)M^{u-1}}-a_{cr}\right)M^{-\frac{u+1}{2}},$$
$$a_{cr}\gg\frac{1}{(u-1)M^{u-1}}\gg C\Pi t-a_{cr}>0,$$
$$t\to t_{cr}=\frac{s(u-1)+1}{s(u-1)}t_{tan}. \quad (18)$$

In the general case we have the explosive evolution with power-law asymptotic behaviour at high masses "$M\to\infty$": $f_s\left(M,t\to t_{cr}\right)\propto M^{-(u+1)/2}$. The MF spectral index α depends only on the merging probability index u contrary to t_{cr} and $M_{max}(t)$, which depend on all parameters. For small masses $u=2$ and within the asymptotic region we obtain $f_s(M,t)\propto M^{-3/2}$. For gravitational focusing and Tally-Fisher or Faber-Jackson laws $u=3/2$, and for the MF we obtain $\alpha=1.25$, which agrees with the well-known from observations value for $z=0$.

The observed growth of the MF power index with z increase (up to $\alpha\approx 2$ at $z>6$ [2]) may result from the evolutionary change of the merger mechanisms. The steepest MF may arise due to the evolution of the initial distribution f_{in}, Eq. (2-3), with $\alpha=u=2$ for large z values and relatively small masses. At lower z and larger masses the gravitational focusing results in $\alpha=u=1.5$. The source-governed term of MF, Eq. (4), results in $\alpha=1.5$ for $u=2$ (small masses), and $\alpha=1.25$ for $u=1.5$ (large masses, gravitational focusing). The latter corresponds to $z=0$.

CONCLUSIONS

The galaxy merger process possesses the "explosive character" due to the coalescence probability dependence on the galaxy masses such, that the probability grows with mass faster than its first power. As a result, there arise critical time moments corresponding to different epochs of the massive galaxies formation. The power-law MF asymptotic behaviour corresponds to the observational data [2].

If the assumption about the discovery of explosive evolution of galaxies through mergers is confirmed, it will give not only new opportunities for studies of galaxy evolution, but also the new data on the hidden mass and the dark matter in galaxies, which has significant influence on these processes.

More detailed description and evaluation of maximal masses see in [11].

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