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EXPLOSIVE GALAXY EVOLUTION AT HIGH REDSHIFTS AND HIDDEN MASS PROBLEM

The "sudden" appearance of massive galaxies at the redshift z = 6 discovered in ultradeep Hubble and Subaru fields and observation of the secondary ionization final stage at the same time period can be explained by explosive evolution due to galaxy mergings in the presence of a hidden mass in galaxies.

"Раптове виникнення" масивних галактик на червоному зміщенні z = 6, знайдене в надглибоких полях Хаббла й Субару, та спостереження заключного етапу вторинної іонізації в той же період часу можна пояснити вибуховою еволюцією галактик за рахунок злиттів у присутності схованої маси в галактиках.

Information presented in [1, 6] concerning detection of "sudden'' appearance of massive galaxies at the redshift $z=6$ in ultradeep Hubble and Subaru fields (see also [3] and corresponding literature and discussion in review [4]), and observation of the secondary ionization final stage at the same time period [5], as well as the quasars appearance epoch [13], for our opinion can argue for the explosive galaxy evolution while merging, see papers [2, 9] and review [7].

It was long thought that the galaxies tend to evolve in a purely individual fashion after their formation (from protogalaxy clouds) due to development of the gravitational instability The observational data obtained over the past three decades, in particular, the data provided by the space Hubble telescope and the largest ground-based instruments, clearly demonstrate the crucial role of the merging process in the cosmogony of galaxies. A comprehensive overview presented by Kennecutt, Schweizer and Barnes [8], dedicated to the interaction and merging of galaxies as well as to the star formation induced by these phenomena (there are more than 1000 citations and 200 illustrations), allows us to omit a detailed description of the corresponding bibliography and observational arguments.

Such rapid evolution of the massive galaxy number at z = 6 redshift discovered in the last years via analysis of the ultradeep Hubble and Subaru field may be explained by the explosive evolution of galaxy merging process in the presence of a hidden mass in galaxies. Reconstructing of the star formation rate gives possibility to discuss the data of the reionization process in this epoch, which confirms the explosive character of the evolution. The merging processes occur in cold dark matter in which the Jeans length is short, although the evolution takes place in the hot Universe.

In the 1990s the Roman and Kharkov (Ukraine) groups [2, 9, 10–12] demonstrated that the kinetic "phase transition" [14,15] may hold in the system of galaxies. This transition shows up as the self-accelerating process of massive galaxy formation through merging of the small mass galaxies: specifically, this is an epoch of galaxy origin. In other words, the process of mergings in the gravitational interaction is of "explosive character". The explosive behavior of coalescences is closely related to the dependence of coalescence probability upon the galaxy masses. To be more exact, the explosive evolution and the corresponding phase transition are attributed to a more rapid increase in probability than the first degree of mass [15, 9]. In modern cosmological theories of hierarchical clustering [16, 17] this situation is either ignored or is not taken into account completely: as result the distributions are self-similar and any redshift is no select.

An attempt can be made to regard the "sudden" occurrence of galaxies at *z* = 6 as the observational evidence of "explosive" evolution. This particular phenomenon is precisely what the present paper is devoted to. We restrict here ourselves by a differential version of equations, which describe this process.

Explosive galaxy evolution. Consider solutions of the Smoluchowski kinetic equation (KE) [15]

$$\begin{aligned}
&\frac{\partial}{\partial t} f(M,t) = I_{st}\,, \\
&I_{st} = \iint dM_1 dM_2 \begin{Bmatrix} W_{M|M_1,M_2} f_1 f_2 - W_{M_1|M_2,M} f_2 f - \\ -W_{M_2|M,M_1} f f_1 \end{Bmatrix}, \\
&W_{M|M_1,M_2} = U(M_1,M_2)\,\delta(M - M_1 - M_2), \\
&U(M_2,M_1) = U(M_1,M_2), \\
&f = f(M,t), \quad etc\,.
\end{aligned} \tag{1}$$

In the case when the main contribution to the collision integral follows from small masses of order of M_* we have (cf. [9, 10]):

$$U(M,M_2) = \frac{C}{2} M^u \quad for \quad M_2 \ll M\,. \tag{2}$$

Expanding the integrand for $M_2 \ll M$ we arrive to KE in the differential form, cf. [9],

$$\frac{\partial}{\partial t} f(M,t) + c\Pi \frac{\partial}{\partial M}\left[M^u f(M,t)\right] = 0\,,\ \Pi = \int dM_2 M_2 f(M_2,t)\,, \tag{3}$$

where Π is the total mass of interacting galaxies, the number galaxy flux along the mass spectrum is $J(M,t) = C\Pi M^u f(M,t)$. We suppose that the main contribution to the integrals follows from the region $M_2 \ll M$, so the upper limit (M) in the corresponding integrals is omitted.
The solution of Eq. (3) can be received by the method of characteristics and is

$$f(M,t) = \left[(u-1)M^{u-1}\tau(t)+1\right]^{-\frac{u}{u-1}} f_0\left\{M\left[(u-1)M^{u-1}\tau(t)+1\right]^{-\frac{1}{u-1}}\right\}, \qquad (4)$$

where $\tau(t)$ is to be found from the equation

$$\frac{1}{C}\frac{d\tau}{dt} = \Pi(t) = \int_0 dMM\left[(u-1)M^{u-1}\tau+1\right]^{-\frac{u}{u-1}} f_0\left\{M\left[(u-1)M^{u-1}\tau+1\right]^{-\frac{1}{u-1}}\right\}. \qquad (5)$$

Here $f_0(M) = f(M,t=0)$ is the initial mass distribution. For $u=2$ (galaxy merging in the small mass region) we have

$$f(M,t) = \frac{1}{\left[M\tau(t)+1\right]^2} f_0\left\{\frac{M}{M\tau(t)+1}\right\},$$

$$\frac{1}{C}\frac{d\tau}{dt} = \int_0 dM \frac{M}{\left[M\tau(t)+1\right]^2} f_0\left\{\frac{M}{M\tau(t)+1}\right\}. \qquad (6)$$

Let us illustrate the solution by example of the delta-function initial distribution, $f_0\{M\} = N_0\delta(M-M_*)$, which can be easily analyzed completely. The solution is

$$f(M,t) = \frac{N_0}{\left[M\tau+1\right]^2}\delta\left\{\frac{M}{M\tau+1} - M_*\right\}, \quad \frac{1}{CN_0}\frac{d\tau}{dt} = \frac{M_*}{1-M_*\tau}. \qquad (7)$$

Performing simple integration we obtain

$$\tau - M_*\frac{\tau^2}{2} = CN_0M_*t. \qquad (8)$$

Evidently, the galaxy mass evolves as $M = M(t) \equiv \frac{M_*}{1-M_*\tau(t)}$ and it turns infinity at $\tau(t_{cr}) = 1/M_*$. For $\tau \le M_*^{-1}$ Eq. (8) possesses only single root, $M_*\tau(t) = 1-\sqrt{1-2CN_0M_*^2 t}$ and we obtain for the critical time t_{cr}:

$$t_{cr} = \left(2CN_0M_*^2\right)^{-1}. \qquad (9)$$

That is the final form of the solution describing the explosive evolution in this case is

$$f(M,t) = N_0\delta\{M - M(t)\}, \quad M(t) = M_* \big/ \sqrt{1-t/t_{cr}}. \qquad (10)$$

The very long time of the explosive evolution (9) in this case (longer than Hubble time, see estimation below) results from the absence of galaxies with large enough masses in the initial distribution (estimations for clusters and groups see in [11]). Thus, consider more appropriate for comparison with observations the power-law initial distributions.

Power-law initial distribution. Let

$$f_0\{M\} = KM^{-\alpha}\theta(M-M_*)\theta(M_{**}-M), \quad \alpha \ge 2. \qquad (11)$$

For the case of interest $u=2$ the corresponding solution is

$$f(M,t) = KM^{-\alpha}\left[M\tau+1\right]^{\alpha-2}\theta\left[M - \frac{M_*}{1-M_*\tau}\right]\theta\left[\frac{M_{**}}{1-M_{**}\tau} - M\right], \qquad (12)$$

$$\frac{1}{C}\frac{d\tau}{dt} = \Pi = \int_0 dMM\left[M\tau+1\right]^{-2} f_0\left\{\frac{M}{M\tau+1}\right\}. \quad (13)$$

Below we suppose $M_{**} \gg M_*$. As one can see the τ critical value, τ_{cr}, is $\tau_{cr} = 1/M_{**}$. For the time small as compared with that relating to the explosive evolution the solution can be transformed as

$$f(M,t) = KM^{-\alpha}\theta\left[M - \frac{M_*}{1-M_*\tau}\right]\theta\left[\frac{M_{**}}{1-M_{**}\tau} - M\right], \qquad M\tau \ll 1. \quad (14)$$

Let the initial distribution power index $\alpha = 3$. Then Eq. (13) results in

$$\frac{1}{CK}\frac{d\tau}{dt} = \frac{1}{M_*} - \frac{1}{M_{**}} + \tau\ln\left(\frac{1-M_*\tau}{1-M_{**}\tau}\right).$$

For estimations limit ourselves with small time intervals, $M_{**}\tau \ll 1$. Then $\frac{1}{CK}\frac{d\tau}{dt} = \left(M_{**} - M_*\right)\left[\frac{1}{M_*M_{**}} + \tau^2\right]$ and, neglecting the quadratic in τ term, we obtain $t_{cr} \approx \frac{M_*}{M_{**}}\frac{1}{CK}$.

Taking into account the relation $K \equiv M_*\Pi = 2N_0M_*^2$ rewrite the critical time expression as (the dimensionless coefficient ξ results from comparison with the numerical solution of the integral equation, [12, 11]):

$$t_{cr} = \frac{\xi}{C\Pi M_{**}} = \frac{\xi}{2CN_0M_*M_{**}}. \quad (15)$$

As one can see the critical time increases as compared with that given by Eq. (9). This is due to existence of large masses in the initial distribution. The most interesting case for the evolution time decrease corresponds to $\alpha = 2$. Then the solution is

$$f(M,t) = KM^{-2}\theta\left[M - \frac{M_*}{1-M_*\tau}\right]\theta\left[\frac{M_{**}}{1-M_{**}\tau} - M\right], \quad (16)$$

$$\frac{1}{C}\frac{d\tau}{dt} = \Pi = K\int_a^b dM/M = K\left(\ln\frac{M_{**}}{M_*} + \ln\frac{1-\tau M_*}{1-\tau M_{**}}\right);\ a = \frac{M_*}{1-\tau M_*},\ b = \frac{M_{**}}{1-\tau M_{**}}. \quad (17)$$

Here, as before, $\tau_{cr} = 1/M_{**}$ and for $M_{**}\tau \ll 1$ we obtain: $\Pi \simeq K\ln\left(M_{**}/M_*\right)$, $\tau = CKt\ln\left(M_{**}/M_*\right)$. From the concentration definition,

$$N_0 = \int_{M_*}^{M_{**}} dM\cdot f_0(M) = K\left(\frac{1}{M_*} - \frac{1}{M_{**}}\right),$$

we get $K \simeq N_0M_*$. Consequently, the critical time is

$$t_{cr} = \frac{\xi}{2CN_0M_*M_{**}\ln\left(M_{**}/M_*\right)}. \quad (18)$$

Taking into account that $C \simeq G^2/v^3$, where G is the gravitational constant and v denotes characteristic random relative velocity of galaxies, and the evolution law of the form $\overline{v^2} \sim \frac{1}{z+1} \sim a(t) \sim t^{2/3}$ we receive $t_{cr} \approx 0.05t_H$, that corresponds to $z \approx 6$ (for $M_* \sim 10^6M_\odot$, $M_{**} \sim 10^9M_\odot$, $N_0M_* \sim 0.25\rho$, where $M_\odot$ is the solar mass, ρ is the average mass density of the Universe at z=6, $\xi = 2\cdot10^{-2}$, t_H is the Hubble time).

Conclusion. The galaxy merger process at the gravitational interaction 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 arises the critical time moment that corresponds to the epoch of the massive galaxies formation. The estimates include not only the masses but also the interaction of the dark matter that may be investigated using this process. The Lynden-Bell violent relaxation also may play a nontrivial role in this interaction, [4, 17]. See also new results on the role of mergings in galaxy evolution in [18].

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INTENSITY CONTOURS STRUCTURE OF THE SOURCE IMAGE IN THE GRAVITATIONAL FIELDS OF GALAXY AND MICROLENS

In the approximation of Sobolev method and paraxial optics, analysis of the focusing effect of a complex gravitational lens formed by the gravitational fields of a macrolens - galaxy and a microlens – star was performed. The problem solving at an arbitrary location of the microlens in the line of the path source - macrolens – observer was found. Intensity contours of images were constructed and magnification factor of a complex lens was calculated. It is shown that the microlens has the most influence on the focusing effect when it is located on the path macrolens - observer.

У наближеннях методів Соболева і параксіальної оптики проведено аналіз ефекту фокусування складної гравітаційної лінзи, утвореної полями тяжіння макролінзи – галактики і мікролінзи – зірки. Знайдено рішення задачі при довільному розташуванні мікролінзи уздовж траси джерело – макролінза – спостерігач. Побудовано ізофоти зображень і пораховано коефіцієнт підсилення складної лінзи. Показано, що найбільший вплив на ефект фокусування мікролінза чинить у тому випадку, коли вона знаходиться на ділянці траси макролінза - спостерігач.

Introduction. In problems connected with the radiation propagation in near space and cosmic space, there are situations when medium inhomogeneities have several spatial scales. It can be inhomogeneities in the Earth atmosphere, solar corona, pulsars in globular clusters. In all these cases, it must be considered both rays refraction caused by large-scale structures and scattering of waves by small-scale inhomogeneities. Another example is the focusing of quasar radiation in the gravitational field of a massive galaxy inside of which microlenses are located. Within the framework of the method of thin phase screen, combined effect of gravitational fields of microlens and all galaxies on the source radiation can be accounted by introduction two independent phase correctors. One of them is connected to a microlens and the second one to the macrolens. It is assumed that the two phase correctors can be combined into one. This approximation does not take into account the effect of gravitational field of the global structure on the "local" radiation focusing in the microlens gravitational field. The presence of different scales in the focusing properties of systems may lead to effects which cannot be tracked in the approximation of the combined phase screens. In the present work, the problem has been solved when two screens are not combined in one plane and are separated by some distance. And small-scale inhomogeneities randomly located in the line of the radiation propagation path.

Analysis of radiation focusing as the approximation of Sobolev method. At the analysis of radiation focusing in the gravitational field of the galaxy with microlens, two cases were considered. At first, solution was obtained for the case when the microlens is located between source and galaxy mass centre, and then when the microlens is between galaxy centre and observer. The radiation propagation through the gravitational field of the galaxy and the microlenses is shown schematically on fig. 1. In present consideration, microlens is situated between the galaxy center and the observer.

Superpose the coordinate system origin with the centre of mass of a macrolens, and dispose the oz axis through the point of observation P. Extended source of radiation S is given in the plane $z = -Z_s$. Microlens is located in the plane $z = Z_m$ at some distance $\vec{P}_m$ from the OZ axis.

Sobolev method allows to obtain a solution of the wave equation written for a medium with a refractive index in a form of Kirchhoff formula for free space. At this, a field in an arbitrary point of space is expressed through the initial distribution of field over the surface surrounding the point [1].

As the approximation of Sobolev method and paraxial optics, the propagation path of radiation $-Z_s \le z \le Z_p$ is divided into three regions: 1 - source - macrolens $(-Z_s \le z \le 0)$; 2 - macrolens - microlens $(0 \le z \le Z_m)$; 3 - microlens - observer $\left(Z_m \le z \le Z_p\right)$.