THE USE OF GRAVITATIONAL LENSES IN THE STUDY OF DISTANT GALAXY MERGERS

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Gravlens (GL) is currently one of the most popular astrophysical objects and they are efficiently explored for detecting the most distant galaxies (up to $z = 10$ redshifts). The first study by PV related to the subject was carried out when the mass interest to gravlensing did not arise. At the Institute Council meeting some of its members where trying to convince PV not to waste time on investigations of such weak effects but rather better to devote himself to (suggestions followed). One of the authors (VK) is proud that he had strongly supported these PV activities. The future has confirmed that PV was absolutely right. The interest in GL (and the corresponding bibliography) was increased with a high speed. We will only refer to the last (popular) publication by PV, where GL was dealt with, [1].

PV, in his turn, had played a significant role in our studying the galaxy mergers at a time when their essential contribution was not evident yet. In particular, PV supported the graduate student report devoted to this subject at his seminar (combined with the seminar on theoretical astrophysics) in spite of the ungrounded negative attitude of some influential persons in the Institute. It was made possible to submit the thesis at the Council and defend it with honors in Moscow at the ASC LPI.

We are interested in the possibility of finding and investigation the galaxy mergers at high z using GL. Mergers represent an important stage of the massive galaxy evolution, when their mass function (MF) is formed along with active nuclei. As an example of the role played by GL we will refer to the observation of the galaxy merger at $z = 2.9$, cf. now classical paper by Borys, et al, [2], along with Berciano Alba, et al, [3], comments.

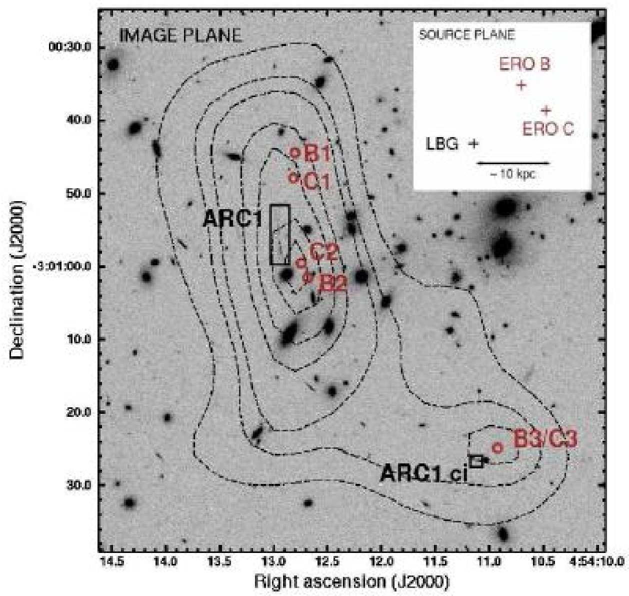

Fig. 1. SCUBA 850 μm contour map of SMM J04542 − 0301 superimposed upon a HST image of the center of the cluster MS0451.6−0305. In rectangles are an optical arc (ARC1) and its counter image (ARC1 ci), produced by a LBG at $z_{\rm spect} = 2.911$. Red circles indicate positions of five NIR sources that have been interpreted as multiple images produced by two EROs (ERO B, lensed as B1/B2/B3, and ERO C, lensed as C1/C2/C3) at $z_{\rm model} = 2.85 \pm 0.1$. Assuming $z = 2.9$ for both the LBG and the EROs, their predicted positions in the source plane would be located within a region of ~10 kps, suggesting that they constitute a merger [3]..

Here the following abbreviations are used: sub-mm source, SMM; Lyman Break Galaxy, LBG; sub-mm galaxy, SMG; extremely red object, ERO. Due to the radio-FIR correlation in star-forming galaxies the radio interferometric observations were used to obtain a high-resolution rest-frame FIR emission that observed in the sub-mm. (Here the astronomy scale of EM spectrum is used, i.e., FIR upper wavelength is about 300 μm.) As a result, the ERO pair and the LBG may constitute a merger at $z = 2.9$ (see the merger model in [2]).

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 of high-mass galaxies (the ones, segregating from the general expansion). Note that the resulting MF possesses power-law asymptote with the exponent coinciding with the Shechter index, $\alpha = 1.25$.

Consider solutions of the Smoluchowski kinetic equation (KE) in the differential form supposing that the main contribution is due to mergers of the low-mass galaxies with the massive ones with the corresponding merging probability, $U(M_1, M_2) \simeq 0.5CM_1^u$ for $M_2 \ll M_1$. The main contribution to the collision integral follows from small masses of order M_* and less:

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

where Π is approximately the total mass of low-mass galaxies. Rewriting Eq. (1) as

$$\frac{\partial}{\partial t} F(M,t) + C\Pi M^u \frac{\partial}{\partial M} F(M,t) = \Phi(M,t), \quad F(M,t) = M^u f(M,t), \quad \Phi(M,t) = M^u \phi(M,t), \tag{2}$$

and using the method of characteristics we arrive at the following system of ordinary differential equations (ODEs), $dM/dt = C\Pi M^u$, $dF/dt = \Phi$. It is easy to find one of the first integrals, $a(M,t)$, by strict integration of the first relation:

$$\tau(t) - \frac{M^{1-u}}{1-u} = a(M,t) = const, \quad \tau(t) \equiv C\int_0^t dt \Pi(t). \tag{3}$$

For $\Phi \neq 0$ the second independent integral of the system is to be obtained from the second ODE. The mass variable, M, here in is the solution of the first ODE and thus it is to be treated as time-dependent. Namely, $M = \mu(a,t)$, $\mu(a,t) = \left[(u-1)(a-\tau(t))\right]^{\frac{1}{1-u}}$, where a is the integration constant. In order to solve this equation we have to specify the source term, $\Phi(M,t)$. Let us restrict ourselves with a localized source, i.e., suppose that $\Phi(M,t) = \delta(M - \bar{M}(t))\Phi(t)$, where $\Phi(t)$ is some time-dependent function. Such representation simulates the mass $\bar{M}(t)$ separation from the global expansion at the moment t. Integrating now the second ODE, we obtain the following independent first integral of the ODEs system, $F - K(a,t) = b(M,t) = const$, where

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

and t_n denote the roots of equation $\mu(a,t) - \bar{M}(t) = 0$. Using the initial condition, $f(M,0) = f_0(M)$, we find the KE solution:

$$f(M,t) = f_s(M,t) + f_{in}(M,t),$$
$$f_s(M,t) = M^{-u}K\left(\tau + \frac{M^{1-u}}{u-1}, t\right), \quad f_{in}(M,t) = \left[(u-1)\tau M^{u-1}+1\right]^{\frac{u}{1-u}} f_0\left\{M\left[(u-1)\tau M^{u-1}+1\right]^{\frac{1}{1-u}}\right\}. \tag{5}$$

In order to specify the source-induced contribution to the mass function, $f_s(M,t)$, we need to derive an explicit expression for the function $K(a,t)$, cf. Eq.(4), i.e. to find corresponding roots. For the simplest case, $u = 2$, $\bar{M}(t) = t/A$, $\Pi(t) = \Pi = const$, we have $\mu(a,t) = (a - C\Pi t)^{-1}$, and the equation for the roots becomes $C\Pi t^2 - at + A = 0$. Consequently, real roots exist under the condition, $a \geq a_{cr} \equiv 2\sqrt{AC\Pi}$, and in terms of the normalized quantities, $T \equiv t\sqrt{C\Pi/A}$, $\tilde{a} \equiv a/a_{cr}$, they are $T_\pm = \tilde{a} \pm \sqrt{\tilde{a}^2 - 1}$. Then the source-induced term of the MF becomes

$$M^u f_s(M,t) = K\left(\tau + \frac{1}{M}, t\right) = \frac{A}{2\sqrt{\tilde{a}^2(M,t) - 1}} \sum_\pm \frac{\Phi(t_\pm(M,t))}{|T_\pm(M,t)|}\theta(\tilde{a}(M,t) - 1)\theta(T - T_\pm(M,t)). \tag{6}$$

It is convenient to introduce the normalized mass, m, $m = a_{cr}M = 2\sqrt{AC\Pi} \cdot M$. Then $\tilde{a}(M,t) = T/2 + m^{-1}$ and it becomes evident that we arrive at the MF explosive evolution: the MF expands to the infinite mass region at finite time, $T \to T_{cr} = 2$, i.e., $t \to t_{cr} = \sqrt{A/(C\Pi)}$. The asymptotic behavior of the exact solution obtained with such a source term is of the power-law type: within the region $1 \ll m \ll (1-T/2)^{-1} \equiv m_{\max}(t)$ we obtain $f(M,t) \propto M^{-3/2}$. In the general case we also have the explosive evolution with power-law asymptotic at high masses "$M \to \infty$": $f(M, t \to t_{cr}) \propto M^{-(u+1)/2}$. 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 as z increases (up to $\alpha \approx 2$ at $z = 6$ [4]) 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} (5) 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 (5), f_s , 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 $z = 0$.

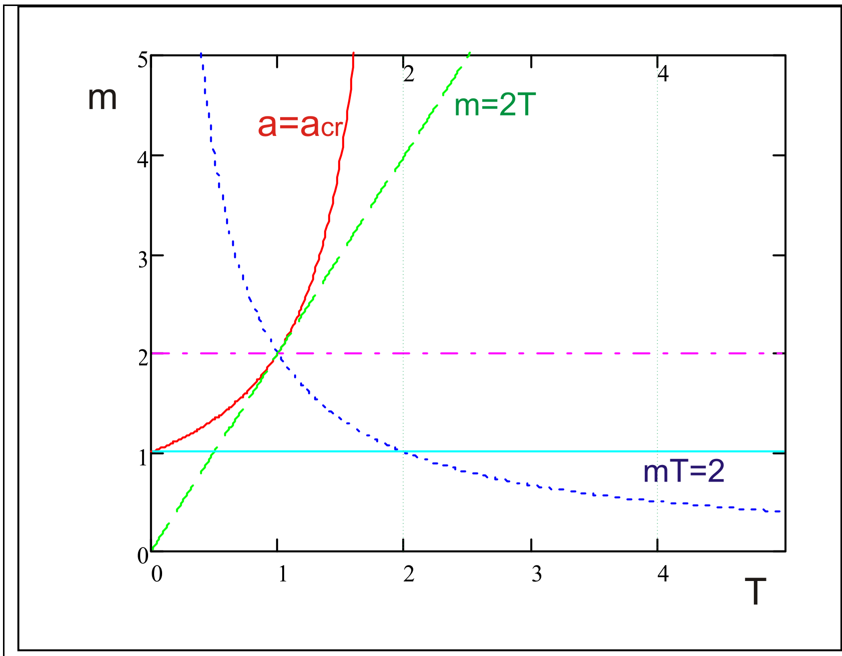

Fig. 2. To the exact solution of KE (1) at $u = 2$. Lines in m-T plane correspond to restrictions on the first integral a , Eq. (3), and roots of δ – function in Eq. (4). The MF explosive evolution is described by the asymptote $f \propto M^{-3/2}$ for $M \to \infty$ at $T \to T_{cr} = 2$.

In the general case the MF spectral index $\alpha = (u+1)/2$ depends only on the merging probability index u contrary to t_{cr} and $M_{\max}$, which depend on all parameters.

Conclusion

The galaxy merger process via the gravitational interaction possesses the "explosive character" due to the coalescence probability dependence on the galaxy masses such that the probability increases with a mass faster than its first power. As a result, there arises the critical time moment that may correspond to the epoch of the massive galaxies formation (see refs in [4-7]). The gravlensing observations of galaxy mergings offer great opportunities for approval of this process.

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