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Galaxy collisions as a mechanism of ultra diffuse galaxy (UDG) formation

A.N. Baushev

[a] Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia
[b] Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Correo Central, Santiago, Chile

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ABSTRACT

We suggest a possible mechanism of ultra diffuse galaxy formation: the UDGs may occur as a result of a central collision of galaxies. If the galaxies are young and contain a lot of gas, the collision may kick all the gas off the systems and thus strongly suppress any further star formation. As a result, the galaxies now have a very low surface brightness and other properties typical of the ultra diffuse galaxies. We use the Coma cluster (where numerous UDGs were recently discovered) to test the efficiency of the process. The mechanism works very well and can transform a significant fraction of the cluster population into ultra diffuse galaxies. The UDGs formed by the process concentrate towards the center of the cluster, and their globular cluster systems remain undamaged, in accordance with observational results. The projected surface density of UDGs in the cluster may help us to recognize the mechanism of UDG formation, or clarify relative contributions of several possible competitive mechanisms at work.

1. Introduction

Unusual properties of the ultra diffuse galaxies (hereafter UDGs) has drawn a lot of attention to these objects. While some properties of them are similar to that of long-known low surface brightness galaxies (hereafter LSBs), recent observations allow us to separate UDGs among LSBs and even may give reason to suppose that UDGs form a separate class of objects.

As with LSBs, the UDGs have unusually low central surface brightness $\mu_{g,0} \sim 24 - 26$ mag/arcsec^2, while their effective radii are $r_e = 1.5 - 4.6$ kpc, which is comparable with that of the Milky Way ($r_e \simeq 3.6$ kpc) (Koda et al., 0000). However, recent observations (van Dokkum et al., c) have surprisingly found 47 UDGs in the Coma cluster, while the standard theory of the LSBs suggests that they hardly can be formed in high-density environments (see, for instance, Dekel and Silk, 1986). Meanwhile, Koda et al. (0000) found 854 UDGs in the Coma cluster, and their density grows towards the center. It means that UDGs can occur in dense clusters and even be numerous there. Their survival in the environment with strong tidal perturbations suggests that UDGs are highly dark matter-dominated systems.

UDGs are quite red and show no feature. The featurelessness and low brightness makes the mass measurements very challenging. However, the object VCC 1287 in the Virgo cluster has a rich system of globular clusters, and the mass of the galaxy was recently estimated as $\sim 8 \times 10^{10} M_\odot$ (Beasley et al., 0000), i.e., this is a dwarf. On the contrary, van Dokkum et al. (a) estimated the mass of the Dragonfly 44 galaxy in the Coma cluster as $\sim 10^{12} M_\odot$ and reported about ~ 100 globular clusters surrounding this object. If this estimate is correct, Dragonfly 44 has a giant dark matter component, comparable with that of the Milky Way. From globular cluster counts, the median UDG halo mass $\sim 1.5 \cdot 10^{11} M_\odot$ (van Dokkum et al., b).

The fact of the presence of many globular clusters around some UDGs seems very noteworthy: whatever the UDG formation mechanism is, it does not destroy the globular system around the objects. Originally UDGs were believed to be round objects (Amorisco and Loeb, 2016), but resent observations suggest that UDGs are prolate rather than oblate spheroids (Burkert, 0000).

An extensive literature discussing the origin of the UDGs has evolved. A very interesting explanation was offered by Amorisco and Loeb (2016): as the surface brightness is believed to depend on the galaxy spin, the UDGs can be just the most rapidly rotating tail of the dwarf galaxy distribution. An UDG may occur if the star formation in the young galaxy was interrupted by AGN feedback (Reines et al., 0000), gas stripping (Yozin and Bekki, 2015), or too strong feedback from massive star winds and supernovae (Calura et al., 0000).

We will not discuss the applicability the above-listed models. The aim of this short paper is to suggest another possible mechanism of UDG formation.

2. The mechanism

The idea of the mechanism is that UDGs may occur as a result of central collisions of galaxies. The collision-less components of the galaxies (dark matter and the stars) should penetrate through each other freely in such a collision, while the gaseous components collide. The collision heats the gas and kicks it off the galaxies (see the proof in the next section). As a result, we have two galaxies with relatively unaffected dark matter and stellar components, but with little gas, and a

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separated cloud of hot gas between them. Of course, further star formation is strongly suppressed in the galaxies. The well-known Bullet cluster gives us a striking illustration of the process (Markevitch et al., 2004), though on much larger scales. Apparently, the parallels between the Bullet cluster and the cluster formation are imperfect, since the picture of cluster formation is quite complicated. However, Bullet cluster illustrates how almost all the gas can be removed from the system.

We can make a simple estimation of the number of UDGs that could be generated in the Coma cluster by this mechanism. We suppose that the cluster contains $N_1 \sim 700$ giant galaxies of mass $\gtrsim 10^{11} M_\odot$ and $N_2 \sim 3\cdot 10^3$ galaxies[1] of mass $\gtrsim 10^{10} M_\odot$ (Colless and Dunn, 1996). The galaxies have the King's distribution in space $n(r) \propto (1+(r/r_k)^2)^{-3/2}$, where n is the space density of the galaxies, $r_k \simeq 170$ kpc (which corresponds to the angular distance $\theta_k = 6'.4$) (King, 1972). We assume that the characteristic radius of the galactic dense gas zone is $r_1 = 8$ kpc for the first above-mentioned group and $r_2 = 3$ kpc for the second one, respectively, in accordance with the SDSS galaxy mass-size relation (Shen et al., 2003), and the characteristic "cross-sections" are $\sigma_1 = \pi r_1^2$ and $\sigma_2 = \pi r_2^2$. We assume that the averaged relative speed of the galaxies in the Coma cluster is approximately equal to[2] the doubled velocity dispersion $D[v]$ in the cluster $\bar{v}_{col} \simeq 2D[v] \simeq 2\cdot 1000$ km/s. Then the number of the central collisions k in a time interval t is

$$k = \int \frac{1}{2} t\sigma \bar{v}_{col} n^2(r)\cdot 4\pi r^2 dr \simeq 9.2\cdot 10^{-4} \frac{t\sigma \bar{v}_{col} N^2}{r_k^3} \quad (1)$$

Substituting the above-listed parameters and $t = 10^9$ years into equation 1, we obtain approximately 40 central collisions between massive galaxies ($M \gtrsim 10^{11} M_\odot$), ~ 150 collisions between a massive and a middle-mass galaxy ($M \gtrsim 10^{10} M_\odot$), and ~ 100 collisions between middle-mass galaxies each 10^9 years.

Before proceeding further, we need to clarify several important issues. First of all, we have neglected several effects in our consideration. We assume that the averaged collision speed $\bar{v}_{col}$ of the galaxies is approximately equal to the doubled velocity dispersion $D[v]$ in the Coma cluster. We may neglect the dispersion variations with radius in our estimate: the dispersion at $10 r_k$ is only 25% less than in the center, while the galaxy density already decreases ~ 1000 times (King, 1972). The interrelation between $\bar{v}_{col}$ and $D[v]$ depends on the velocity distribution of galaxies, specifically on its anisotropy (on the other hand, the distribution affects the mechanism efficiency only through v_{col}). For the Maxwell one $\bar{v}_{col} \simeq 2.26 D[v]$, but the radial motion typically dominates in clusters, and we may expect a highly anisotropic velocity distribution. The extent to which $\bar{v}_{col}$ is affected by the anisotropy depends on the space distribution of galaxies in the Coma cluster, as well as on its gravitational field profile. Both these quantities lack precision now. However, the solution may be found analytically for a much simpler, but rather similar case: Baushev (2011) compared the velocity distribution of the dark matter particles on the Solar System orbit for the isotropic and for the limiting anisotropic cases. It turned out that $\bar{v}_{col}$ is only 1.27 times higher for the radial case than for the isotropic one. The factor 1.27 is within the accuracy of our analysis. On the other hand, $\bar{v}_{col} \simeq 2.26 D[v]$ and even higher for the anisotropic case. It means that by the supposition we underestimate the number of galaxy collisions.

When we introduce the characteristic "cross-sections" of the gaseous components σ_1 and σ_2, we imply that the gas in the galaxies forms spherical clouds of radii r_1 and r_2. The question of real gas distribution in young galaxies is not quite clear, but it was hardly spherically symmetric, and some form-factors should be introduced to take into account real galaxy shapes and their mutual arrangements. A precise calculation of the form-factor requires detailed information about the gaseous component of the young galaxies, as well as a reliable model of the cluster formation. For simplicity, we consider σ_1 and σ_2 as the quantities already averaged over all possible geometries.

In deriving equation (1) we assume that the galaxies move along straight lines. However, their gravitational attraction pulls the trajectories together, and their pericenter distance is always less than the impact parameter. Thus the gravitational interaction increases the collision rate, and the magnitude of this effect is defined by the ratio of the galaxy virial speed $v_{vir} = \sqrt{GM_{vir}/R_{vir}}$ to the collision speed v_{col}. The ratio is small in our case, and so is the effect of attraction.

3. Can the galaxy collision remove the gas from the systems?

Let us perform a tentative analytical calculation suggesting that a head-on collision of even a middle-mass galaxy with a massive one very likely removes most of the gas from both the systems, either by direct kicking it off, or by strong shock heating that just evaporates the gas from the system. The smaller galaxy necessarily loses a very significant part of the gas component in such a collision.

Indeed, the typical speed of the collisions ($\bar{v}_{col} \sim 2000$ km/s) significantly exceeds the escape speed from the centra of even massive galaxies. This relation appears to be valid for any galaxy cluster, not only for Coma. If we suppose that the galaxies, as well as the cluster, have the NFW density profile, their central potential is $\phi_c = -\frac{GM_{vir} c_{vir}}{R_{vir} A(c_{vir})}$, where M_{vir}, R_{vir}, c_{vir} are halo virial mass, radius, and concentration; $A(c_{vir}) \equiv \ln(c_{vir}+1) - \frac{c_{vir}}{c_{vir}+1}$ (Baushev, 2012). If we introduce the average halo density $\langle\rho\rangle = M_{vir}/\frac{4}{3}\pi R_{vir}^3$, we obtain $M_{vir}/R_{vir} = \left(\frac{4}{3}\pi\langle\rho\rangle M_{vir}^2\right)^{1/3}$ and

$$\phi_c = -\frac{Gc_{vir}}{A(c_{vir})}\left(\frac{4}{3}\pi\right)^{\frac{1}{3}} \langle\rho\rangle^{1/3} M_{vir}^{2/3}$$

Since $\langle\rho\rangle$ and $A(c_{vir})$ have only a weak dependence on M_{vir} (Gorbunov and Rubakov, 2011), $\phi_c \propto c_{vir} M_{vir}^{2/3}$ to sufficient accuracy. The galaxy velocity dispersion is mainly defined by ϕ_c of the cluster, concentrations c_{vir} for galaxies unlikely can exceed more then ten times the one for the cluster, while the galaxy masses (excepting the central galaxy) are $2-3$ orders of magnitude less than the cluster mass. Therefore, the typical galaxy collision speed in the central area of a cluster (where the mechanism under consideration is the most effective) should significantly exceed the escape speed from the centra of galaxies.

A precise calculation of the gas fraction a galaxy can lose as a result of collision is very challenging and requires a reliable model of the galactic gaseous component (especially, for high redshifts), as well as complex magnetohydrodynamic simulations. However, we may obtain quite reasonable estimations by mere usage of a toy model and the momentum conservation law. Moreover, we need to clarify what we mean under the 'central galaxy collision'.

The gaseous interstellar medium in galaxies is a very complex object; however, it can be roughly subdivided into three components (Ferrière, 2001). Let us use the Milky Way galaxy to illustrate. Cold medium (CM) is composed of separate clouds with the temperature $T \sim 100$ K, particle density $\varrho \sim (20-50)$ cm^{-3}, and scale height $h \sim 200$ pc; it is the only component where the star formation may occur. Warm medium (WM) has the temperature $T \sim 10^4$ K, particle density $\varrho \sim (0.2-0.5)$ cm^{-3}, and scale height $h \sim 300$ pc. The coronal gas has the temperature $T \sim 10^6 - 10^7$ K, scale height $h \sim 3000$ pc, and the particle density that rapidly drops with radius from 10^{-2} cm^{-3} to 10^{-4} cm^{-3}. It is significant that, despite its low density, the interstellar medium (ISM) is not in vacuum state: the free path of the particles is typically much shorter than the area size.

Let us take up a collision of two galaxies with velocities v_1 and v_2 ($v_1 + v_2 = v_{col}$). Consider a narrow cylinder of cross section S and with

[1] This value may seem overestimated. However, considering that 854 UDGs have just been found in the cluster, N_2 hardly can be much less than $2\cdot 10^3$, while the results of our estimate are not that sensitive to N_2.

[2] See the next section for details.