THE DIFFUSE LIGHT IN SIMULATIONS OF GALAXY CLUSTERS

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ABSTRACT

We study the properties of the diffuse light in galaxy clusters forming in a large hydrodynamical cosmological simulation of the Λ cold dark matter cosmology. The simulation includes a model for radiative cooling, star formation in dense cold gas, and feedback by Type II supernova explosions. We select clusters having mass $M > 10^{14} \, h^{-1} \, M_{\odot}$ and study the spatial distribution of their star particles. While most stellar light is concentrated in gravitationally bound galaxies orbiting in the cluster potential, we find evidence for a substantial diffuse component, which may account for the extended halos of light observed around central cD galaxies. We find that more massive simulated clusters have a larger fraction of stars in the diffuse light than the less massive ones. The intracluster light is more centrally concentrated than the galaxy light, and the stars in the diffuse component are on average older than the stars in cluster galaxies, supporting the view that the diffuse light is not a random sampling of the stellar population in the cluster galaxies. We thus expect that at least $\sim 10\%$ of the stars in a cluster may be distributed as intracluster light, largely hidden thus far because of its very low surface brightness.

Subject headings: galaxies: clusters: general — galaxies: elliptical and lenticular, cD — galaxies: evolution

On-line material: color figures

1. INTRODUCTION

The presence of diffuse “intracluster light” in galaxy groups and clusters is now well established; observations by several groups provide estimates of the fraction of diffuse light and its distribution, using different techniques (see Arnaboldi 2004 for a review). The fraction of stars contained in this space-filling component seems to increase strongly with the density of the environment: from loose groups ($<2\%$; Castro-Rodriguez et al. 2003; Durrell et al. 2004) to Virgo-like ($10\%$; Feldmeier et al. 2003; Arnaboldi et al. 2003) and rich clusters ($\sim 20\%$ or higher; Gonzalez et al. 2000; Feldmeier et al. 2002; Gal-Yam et al. 2003). This correlation may represent an important clue for understanding the mechanisms that produce intracluster (IC) light and drive its evolution in the cluster environment.

Cosmological simulations of structure formation facilitate studies of the diffuse light and its expected properties. Dubinski (1998) constructed compound models of disk galaxies and placed them into a partially evolved simulation of cluster formation, allowing an evolutionary study of the dark matter (DM) and stellar components independently. Using an empirical method to identify stellar tracer particles in high-resolution DM simulations, Napolitano et al. (2003) studied a Virgo-like cluster, finding evidence of a young dynamical age of the IC component. The main limitation in these approaches is the restriction to collisionless dynamics.

In this Letter, we analyze for the first time the IC light formed in a cosmological hydrodynamical simulation including a self-consistent model for star formation. In this method, no assumptions about the structural properties of the forming galaxies need to be made, and the gradual formation process of the stars, as well as their subsequent dynamical evolution in the nonlinearily evolving gravitational potential, can be seen as a direct consequence of the Λ cold dark matter (CDM) initial conditions. It is therefore of immediate interest whether this theoretical formation scenario makes predictions for IC light consistent with observations. Using a large volume of $192^3 \, h^{-3} \, $Mpc$^3$, we can furthermore study a statistically significant sample of clusters at $z = 0$ and analyze the correlations of properties of diffuse light with, e.g., cluster mass and X-ray temperatures.

2. COSMOLOGICAL SIMULATIONS

We analyze the large-scale cosmological hydrodynamical simulation (LSCS) of a “concordance” ΛCDM model ($\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $\Omega_b = 0.019 \, h^{-2}$, $h = 0.7$, and $\sigma_8 = 0.8$) of Borgani et al. (2004, hereafter B04). It was carried out with the massively parallel tree+SPH code GADGET (Springel et al. 2001), using $480^3$ DM particles and as many gas particles. For the periodic cube of size $192 \, h^{-1} \, $Mpc, the mass resolution was thus $m_{\text{DM}} = 4.62 \times 10^8 \, h^{-1} \, M_{\odot}$ and $m_{\text{gas}} = 6.93 \times 10^5 \, h^{-1} \, M_{\odot}$; the Plummer equivalent softening length was $\epsilon = 7.5 \, h^{-1} \, $kpc (at $z = 0$). Besides gravity and hydrodynamics, the simulation accounts for star formation using a subresolution multiphase model for the interstellar medium (Springel & Hernquist 2003), feedback from supernovae explosions (including the effect of galactic outflows), radiative cooling of the gas (assuming zero metallicity), and heating by photoionizing, uniform, time-dependent UV background (Haardt & Madau 1996).

Clusters are identified at $z = 0$ using a standard friends-of-friend algorithm, with a linking length of 0.15 times the mean DM interparticle separation. We identified 117 clusters with $M > 10^{14} \, h^{-1} \, M_{\odot}$. Cluster centers were placed at the position...
of the most bound particle belonging to each group. X-ray temperatures and masses were evaluated at the radius $R_{200}$, which encloses an average density of 200 times the critical density. A detailed study of the X-ray properties of our clusters, together with a full description of the numerical simulation, can be found in B04.

This cosmological simulation shows an encouraging agreement with some of the most important observed X-ray cluster properties. However, there are also a number of discrepancies that remain unaccounted for, as in other comparable numerical work. For instance, the observed radial temperature profiles in the cluster centers are not reproduced, and the fraction of collapsed baryonic mass (“cold” gas and stars) appears still too large. While it is likely that the solution of these problems will require an improved treatment of the IC gas physics, nonetheless this simulation represents a useful tool to study the physical properties of the diffuse light.

2.1. Presence of Diffuse Light

For all clusters identified in the cosmological simulation, we analyze the stellar distribution in the cluster volume. To compare with surface brightness measurements, we compute the projected density of stars by integrating along a line of sight (LOS). We then extract the two-dimensional radial profile of each cluster centered on its most bound particle, computing density profiles in 100 shells for the star component from 0.05$R_{200}$ to 2$R_{200}$. A stacked profile is obtained by averaging the shell densities with the same radius $R/R_{200}$ over all clusters. For each cluster, only stars in the cD or brightest cluster galaxies (BCGs) and in the field are included.

For the galaxy identification we use the publicly available package SKID (Stadel 2001') to identify self-bound gas and star particle groups within individual clusters. We selected a scale of 20 $h^{-1}$ kpc, comparable to our physical force resolution, as the typical SKID length scale. SKID groups together particles lying near local maxima of the density field, as determined using DM, star, and gas particles. Then those star and gas particles that have a total energy $T + V > 0$, where $T$ is the kinetic energy and $V$ the local gravitational energy, are removed from each group. All particles in a sphere of radius $2r_c$ are considered for evaluating the gravitational energy. We discarded groups having fewer than 32 star particles.

We then look for a halo stellar component in the stacked two-dimensional profile, following Schombert (1986), by checking whether the average radial surface brightness profile curves upward in a $(\mu, R^{1/4})$-diagram, over significant intervals in $R^{1/4}$. We fit a Sersic law to the inner parts of the stacked surface brightness profile, in a range of radii from the center out to a radius where the surface density is about one-third of the central value. The result is shown in Figure 1: a light excess to the inner Sersic profile is evident for radii $R/R_{200} > 0.18$. The deviation at large $R$ of the stacked surface brightness profile from the Sersic’s law is interpreted as being due to an extensive luminous halo. In observed cDs this occurs at $R \sim 50/80$ kpc, which is smaller than our measured value. Previous studies of cluster evolution (Dubinski 1998; Napolitano et al. 2003) produced clusters with BCGs whose density profile followed a de Vaucouleurs’ law at all radii. In our simulations, in which gas, star, and DM particles are followed self-consistently during structure formation, cD halos do form.

According to Dressler (1980) and Kormendy (1980), the up-turn in the cD surface brightness $(\mu, R^{1/4})$-plot, indicating the additional luminous halo, would occur at the projected radius where the stars become unbound from the central elliptical galaxy and orbit in the cluster potential. The velocity dispersion profile would then rise at the radius where the change of slope takes place. A similar effect is observed in NGC 1399, a nearby cD galaxy (Arnaboldi et al. 1994; Napolitano et al. 2002).

In a cosmological simulation we have the phase-space information for all particles; thus, we can study the dynamical behavior of those particles that populate the outer halo of cD galaxies. We refer to all star particles grouped to any substructures by SKID as “bound,” while the others are named “unbound.” The distinction between stars bound to a galaxy and unbound stars is workable except for the cluster center, where the most bound IC stars and the stars of the central cD fall in the same part of phase space.

Once the stellar particles in a given cluster are flagged, we build up the global three-dimensional radial profiles for the bound and the unbound stars. Then we group all the clusters in classes with different X-ray temperature and derive the average three-dimensional stellar density profiles for the bound and unbound components. Figure 2 shows that the unbound stars have a shallower radial profile than the bound component, in the range of radii from 0.05$R_{200}$ to 0.3$R_{200}$. These stars are responsible for the additional light detected in cD halos and build up the diffuse light in our clusters.

3. Properties of Diffuse Light

The size of our simulated volume allows us to study the physical properties of the IC stellar light in clusters statistically and explore their dependence on the total mass and/or the X-ray temperatures of clusters. For all the clusters selected in our database, we evaluate the logarithmic slope of the three-
Fig. 2.—Three-dimensional radial density profiles of the bound (open triangles) and unbound (filled diamonds) stars, for clusters divided in X-ray temperature classes. From top to bottom, the lines are for global average, $T < 2$ keV, $2$ keV $< T < 3$ keV, $3$ keV $< T < 4$ keV, and $T > 4$ keV. The last four couples of density profiles have been divided by $10^5$, $10^4$, $10^3$, and $10^2$ for clarity. The radius where the bound component dominates shifts toward smaller fractions of the average $R_{\text{cD}}$, while the temperature, and thus the mass, with the more massive clusters having a larger fraction of diffuse versus total stellar mass depends on the value of the SKID length parameter $\tau$, but the slope of this correlation is almost unchanged when $\tau$ changes. This is connected with the difficulty of separating the stars in the cD from the IC stars near the cluster center. Large values of $\tau$ increase the number of stars in galaxies, but the fraction of unbound stars never drops to zero. In the most extreme case that we tested ($\tau = 40$ h$^{-1}$ kpc), only a few of our 117 clusters drop to $f < 10\%$. These objects are in the low-mass range ($M < 2 \times 10^{14}$ h$^{-1} M_\odot$).

We checked that $\tau = 20$ h$^{-1}$ kpc ensures a clear dynamical separation between bound and unbound stars. The unbound stars have a three-dimensional velocity dispersion comparable to that of the DM particles, while bound particles have a smaller velocity dispersion. Typical values for the most massive cluster in our LSCS are $\sigma_{\text{unbound}} \approx 3000$ km s$^{-1}$, $\sigma_{\text{bound}} \approx 800$ km s$^{-1}$ at $R = 100$ h$^{-1}$ kpc.

The simulation also records the age of formation of each star particle. In Figure 3 we investigate the age distribution of the IC stellar components: stars in the diffuse component formed from their parent gas particles at an earlier average redshift ($z \approx 1.9$) than bound stars ($z \approx 1.7$), with no evidence for a dependence on cluster mass. Our cosmological simulation predicts that the stars in the IC component are older.

Two numerical effects can influence our results: the numerical resolution and the parameter $\tau$ for substructure identification. To study the first effect, we simulated a cluster with total mass $2.9 \times 10^{14}$ h$^{-1} M_\odot$ and a mass resolution increased by a factor 3 and 10, respectively (R3 and R10 runs; see below). Softening was rescaled as $m^{-1/3}$. Initial conditions for these simulations were generated using the “zoomed initial conditions” technique (Tormen et al. 1997), which increases the resolution in the cluster Lagrangian region while maintaining a coarse sampling of the surrounding structures to account for their tidal field. We find that the amplitude and slopes of the density profiles for both bound and unbound stars are almost unchanged at radii as large as $\approx 200$ h$^{-1}$ kpc (see Fig. 2). The lower resolution in our simulation may lead to an enhancement of the unbound population because of numerical overmerging. However, when we increase the resolution by a factor of 10 in mass and $\approx 2$ in force, the fraction $f$ does not change substantially: we find $f = 0.41$ in LSCS, $f = 0.43$ for R3, and $f = 0.38$ for
R10 for the same cluster, suggesting that the numerical resolution has only a small effect. Moreover, a recent analysis of simulations of clusters having similar resolution to our R3 (Sommer-Larsen et al. 2004) has independently confirmed the f-value reported here.

The SKID length parameter does influence the behavior of both bound and unbound components in a number of expected trends, i.e., the mass of the cD galaxy and the value of $R_{\nu}$ increase. However, even when $\tau = 40 \ h^{-1} \ \text{kpc}$, the fraction of IC light is not smaller than 0.1 in the less massive clusters. Among those $\tau$-values that we checked, $\tau = 20 \ h^{-1} \ \text{kpc}$ ensures the best dynamical separation between the two stellar components at the cluster centers.

4. DISCUSSION

We used a cosmological simulation of (192 $h^{-1}$ Mpc)$^3$ to study the statistical properties of the IC light in clusters of galaxies and the dependence of its physical properties on cluster mass and X-ray temperature. These predictions can be tested against known properties of cD halos and used to plan observational tests to understand the physical properties of IC light.

The presence of the IC component is evident when the whole distribution of stars in the simulated clusters is analyzed in a way similar to Schombert’s (1986) photometry of BCGs. Galaxies at the center of our simulated clusters have surface brightness profiles that turn strongly upward in a $(\mu, R^{1/4})$ plot. This light excess can be explained as IC stars orbiting in the cluster potential. Integrating its density distribution along the LOS, the slopes from our simulations are in agreement with those observed for the surface brightness profiles of the diffuse light in nearby clusters. In the Coma Cluster, Bernstein et al. (1995) parameterize the surface brightness as $R^p$ and find that the diffuse light is best fitted by $\beta = -1.3 \pm 0.1$. In the Fornax Cluster, the surface brightness profile of the cD envelope of NGC 1399 follows a power law of the form proportional to $R^\beta$ with $\beta = -1.5$ (Bicknell et al. 1989).

At large cluster radii, the surface brightness profile of the IC light appears more centrally concentrated than the surface brightness profile of cluster galaxies (see Figs. 1 and 2). From the simulations we also obtained the redshifts $z_{\text{form}}$ at which the stars formed: those in the IC component have a $z_{\text{form}}$ distribution that differs from that in cluster galaxies (see Fig. 3). The unbound stars are formed earlier than the stars in galaxies. The prediction for an old star’s age in the diffuse component agrees with the Hubble Space Telescope observation of the IC red giant stars in the Virgo IC field, e.g., $t > 2$ Gyr (Durrell et al. 2002), and points toward the early tidal interactions as the preferred formation process for the IC light. The different age and spatial distribution of the stars in the diffuse component indicate that it is a stellar population that is not a random sampling of the stellar populations in cluster galaxies.

The more massive clusters have the largest fraction f of diffuse light (Fig. 3). It is $f > 0.1$ for cluster masses $M > 10^{14} h^{-1} M_\odot$. Our simulations may thus explain the low inferred star formation efficiency in clusters versus less massive structures (David 1997). If only the bound stellar mass is accounted for in the ratio of the total cluster stellar mass versus cluster gas mass in our LSCS, then this ratio decreases from groups to rich clusters. The observational trend would then be reproduced in the simulation. Similarly, the disagreement found between the amount of stars produced in clusters in our LSCS and in observed clusters (see B04) is less severe, if an IC component is present in real clusters and has been systematically neglected when evaluating their internal stellar mass budget.

The main result of this work is that large cosmological hydrodynamical simulations are in qualitative agreement with the observed properties of diffuse light in galaxy clusters. A quantitative assessment will require additional numerical efforts and more observations. A detailed study of the dynamical history of the unbound stellar population in our simulation will be presented in a forthcoming paper.

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