CHAPTER 7.

Galaxy Formation & Evolution in the Cosmic Web

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Traditional Estonian Culture and Music.
Performance of the Estonian TV girl's choir,
directed by Arne Saluveer.

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CHAPTER 7A.

Galaxy Formation & Evolution

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from first galaxies to lonely galaxies:
Saleem Zaroubi and Kathryn Kreckel
pondering where to find them

Photo courtesy: Steven Rieder

Dick Bond and Carlos Frenk
contemplating the wonders of the Universe.

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The Zeldovich Universe: Genesis and Growth of the Cosmic Web
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The origin of the galaxy color bimodality

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Abstract. The star formation history of galaxies is a complex process usually considered to be stochastic in nature, for which we can only give average descriptions such as the color-density relation. In this work we follow star-forming gas particles in a hydrodynamical N-body simulation back in time in order to study their initial spatial configuration. By keeping record of the time when a gas particle started forming stars we can produce Lagrangian *gas-star isochrone surfaces* delineating the surfaces of accreting gas that begin producing stars at different times. These surfaces form a complex a network of filaments in Eulerian space from which galaxies accrete cold gas. Lagrangian accretion surfaces are *closely packed* inside dense regions, intersecting each other, and as a result galaxies inside proto-clusters stop accreting gas early, naturally explaining the color dependence on density. The process described here has a purely gravitational / geometrical origin, arguably operating at a more fundamental level than complex processes such as AGN and supernovae, and providing a conceptual origin for the color-density relation.

Keywords. Large-scale structure of Universe; Galaxy formation, N-body simulations

1. Introduction

The observed properties of galaxies are the combined result of complex internal mechanisms (secular evolution) such as supernovae, AGN feedback, etc. (Powell *et al.* 2011; Larson *et al.* 1980), and ii) external environmental mechanisms such as galaxy interactions and mergers, harassment, etc. (Gunn & Gott 1972; Moore *et al.* 1996; Kawata & Mulchaey 2008). The role of cosmic environment on star formation is evident in processes such as the morphology-density relation (Dressler 1980) and the related color-density relation, which encode the effect of environment (density) on star formation history (color) (Bell *et al.* 2004; Blanton *et al.* 2005). Several mechanisms are assumed to contribute to the observed bimodality in the color distribution and the decreasing fraction of blue galaxies with increasing density, such as galaxy mergers and harassment (Gunn & Gott 1972; Larson *et al.* 1980; Moore *et al.* 1996). These mechanisms however, do not offer a direct link between star formation and environment (Blanton *et al.* 2005; Skibba *et al.* 2009).

Galaxies accrete cold gas via a network of narrow filamentary streams that penetrate deep into the galaxy (Kereš *et al.* 2005; Dekel & Birnboim 2006; Dekel *et al.* 2009; van de Voort *et al.* 2011), fueling star formation shortly after accretion (Bauermeister *et al.* 2010). The gravitational collapse of matter into the galaxy sets a natural order in the accretion of gas, i.e. nearby gas is accreted first while gas in distant reservoirs is accreted later. If star formation closely follows gas accretion, we should then expect a simple relation between star formation time and the original distance between the gas cloud that formed the stars and the galaxy, at least approximately, providing a link between the stellar populations of galaxies, encoded in their color, and their initial spatial configuration.

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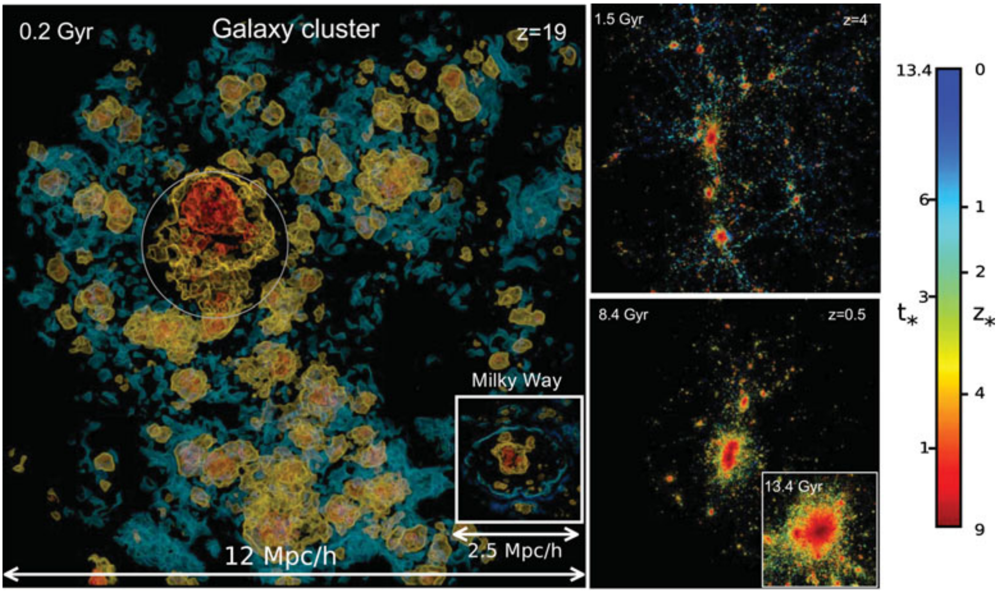

Figure 1. Gas-star conversion times in a galaxy cluster with mass of $\sim 3 \times 10^{14} h^{-1}\mathrm{M}_{\odot}$. Star–forming gas is accreted from increasingly distant isochrone surfaces, centered in the progenitors of massive galaxies (red blobs). Proto-cluster galaxies, being closely packed, are surrounded by a layer of galaxies and are effectively isolated from late star-forming gas (light blue isochrone surfaces). The white circle in the top panel shows the central proto-galaxy in a window carved through the gas cloud. For comparison, we show the Milky Way galaxy (small white square) on the left panel.

2. Simulations and results

We ran a full hydrodynamic zoom resimulation of a galaxy cluster with a present-time mass of $3 \times 10^{14} h^{-1}\mathrm{M}_{\odot(z=0)}$. selected from a 64 h^{-1}Mpc box. The high-resolution region was populated with $2.2 \times 10^{6} h^{-1}\mathrm{M}_{\odot}$ particles and run using the Gadget-3 code, which implements simple recipes for hydrodynamics and chemical enrichment including stochastic star formation, SN feedback and winds (Springel & Hernquist 2003). From the simulation we identified and followed star-forming gas particles, i.e. gas particles that at some point during the simulation's history produced stars, from the present time back to the initial conditions. For each gas particle we also stored the time when it started producing stars, here referred to as the gas→star conversion time, t_*. By doing so, we were able not only to follow stars after they are formed, but to trace their "progenitor" gas particles back to their Lagrangian positions and study their initial spatial arrangement. Having identified star coming particles and their t_* we produced *gas→star isochrone surfaces*, $\mathcal{S}_{t_*}$ define regions of gas that, after being accreted into galaxies, started forming stars at the same time.

Figure 1 shows the *star formation isochrone surfaces* for a galaxy cluster. The central proto-galaxy is the prominent structure near the center of the proto-cluster. The isochrone surfaces are remarkably regular and there is a clear relation between gas-star conversion time and radial distance from centers of proto-galaxies even for this complex cluster formed by a triple major merger. Early star-forming gas is accreted first and so $\mathcal{S}_{z_*=9}$ (red surfaces) mark the centers of galaxies. The $\mathcal{S}_{z_*=3}$ surfaces (yellow) surrounding satellite galaxies are relatively isolated compared to the $\mathcal{S}_{z_*=3}$ surfaces around the central galaxy where surfaces from adjacent galaxies are intersecting. The central galaxy, being

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surrounded by a compact shell of adjacent satellite galaxies is geometrically constrained to accrete star-forming gas beyond the $\mathcal{S}_{z_*=3}$ surface. This can be seen in the almost total lack of $\mathcal{S}_{z_*=1}$ surfaces (light blue) around the central galaxy. Satellite galaxies on the other hand are still able to accrete gas at this time although there is no noticeable accretion of star-forming gas after $z \sim 1$.

Figure 1 shows that as a galaxy grows, it carves out increasingly large surfaces (in Lagrangian coordinates) of star-forming gas from it surroundings. These surfaces extend from the center of the proto-galaxy until the maximum radius of influence from which a galaxy can gravitationally accrete mass. Galaxies in dense environments can be seen as a *closely packed system* of $\mathcal{S}_{z_*}$ spheres where adjacent galaxies compete for the available gas as they "carve" the proto-cluster's volume. The intersection of isochrone surfaces from adjacent galaxies marks the time where no more gas is available for accretion and star formation. This occurs roughly at half the mean inter-galaxy separation, imposing a fundamental geometric limit to gas accretion in dense environments. On the other hand, galaxies in the outskirts of proto-clusters can have an extended star formation history due to their access to gas in the vicinity of the proto-cluster (Papadopoulos *et al.* 2001; Wolfe *et al.* 2013).

3. Discussion and conclusions

The most straightforward consequence of "galaxy close packing" is that the massive galaxies which are the progenitors of present-time groups and clusters, being surrounded by gas-competing galaxies, become cut off from their gas supply, becoming "quenched" already at early times. The mechanism described here offers a conceptual origin for the observed color-density relation by limiting gas accretion and star formation in dense environments. Galaxies in low-density regions, on the other hand, are not geometrically constrained and can, in principle, freely continue to accrete gas. In addition to this, other processes such as AGN and SN feedback play an important role.

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