# Formation of cD galaxies

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## Contents

# 1 Introduction

cD galaxies are a class of elliptical galaxies that are solely found in galaxy clusters. They are the most luminous and most massive galaxies in the local universe. Traditionally they were characterised by a large halo of stars that envelopes the central galaxy. Recent observations cast doubt on the differentation of these two components based on photometry alone [1]. All cD galaxies are located in groups and galaxy cluster and the study of the cD charakteristics might give a clearer picture of the dynamic processes in galaxy clusters.

In this literature review in Section 2 a selection of mechanisms that are proposed to be responsible for the characteristics in cD galaxies is given. After that in Sections 3-7 a series of observations is presented in chronological order that helped us in our understanding of the formation of cD galaxies. Lastly a short summary of the nowadays favoured cD galaxy formation mechanism is given.

# 2 Proposed mechanisms of cD galaxy formation

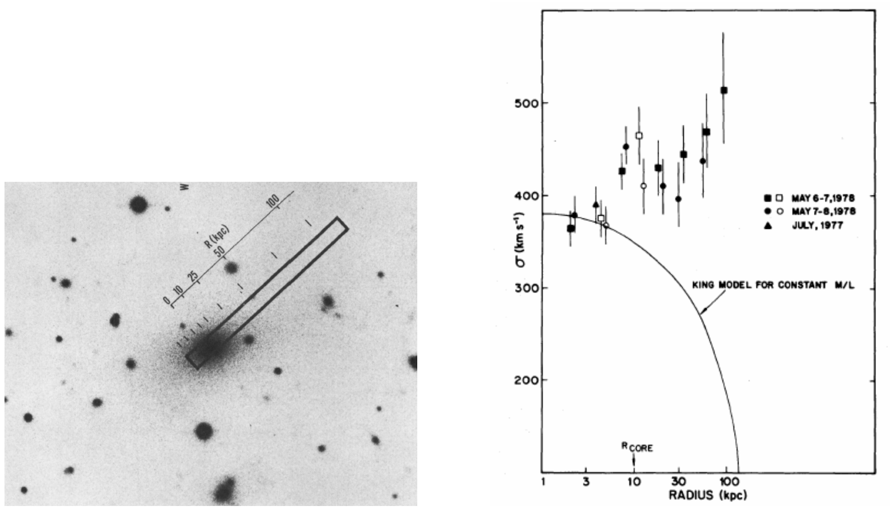
cD galaxies are either merely extreme examples of normal elliptical galaxies or they have to be the result of a special creation process or evolutionary growth.

The formation of cD galaxies has been the topic of considerable research. To understand the formation of the cD galaxies one needs to understand on the the formation of an elliptical galaxy at the center of a galaxy cluster and the origin of the cD halo. Those two characteristics of a cD galaxy might be instrinsically linked.

One idea suggested by Ostriker and Tremaine [8] proposes that the cD galaxy are built by tidal stripping of neighbor galaxies. The cluster galaxies undergo dynamical stripping in the cD envelope and lose their stars to the cD galaxy or merge with the central galaxy. Observations confirm that there are several cD galaxies with multiple nuclei. Another similar idea proposed by Richstone [9] is that a cD galaxy is normal elliptical galaxy that sits in the center of a sea of material that was stipped away by tidal encounters from other galaxies. In both those pictures the velocity dispersion of the cD halo differs from the velocity dispersion of the rest of the galaxy.

Most models of cD formation see the cD galaxy as the result of mergers of smaller galaxies. But when in the evolution of the cluster these mergers happen is different between the models. In the already described model by Ostriker and Tremaine the galaxy is at the center of the already virialized galaxy cluster. Merrit [6, 5] suggested that the cD galaxies form before or during the virialization of rich clusters. In this model the cD galaxy needs form roughly at the dynamical centre od the cluster to avoid having its outer envelope truncated.

An alternative model for the formation of the cD halo is the star formation in cooling flows [3]. In this model hot intracluster gas cools down and form stars in the cD halo.




(a) (b)

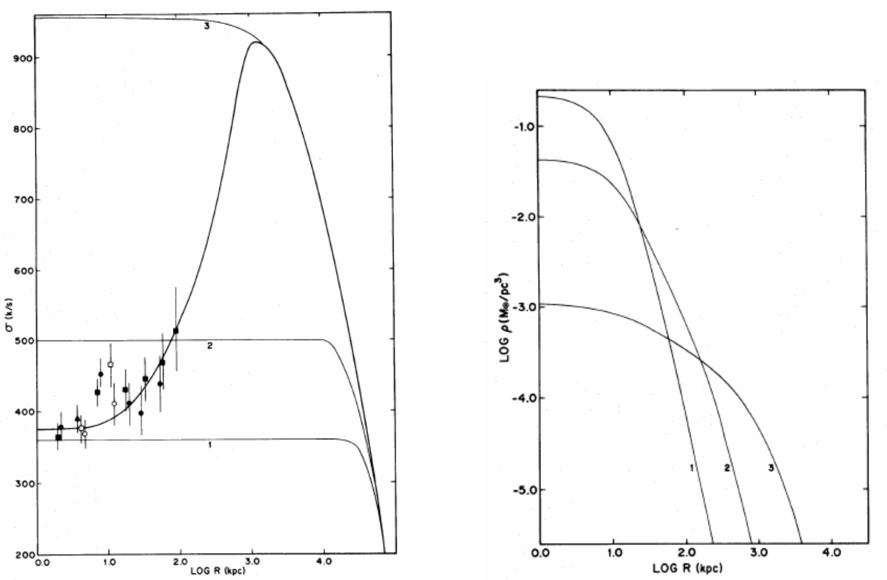
Figure 1: (a) The central 1 Mpc of A2029. The regions in which the spectral data were measured are indicated. (b) The run of the velocity dispersion of IC 1101 as a function of radius for different measurement dates. Open symbols are points to the NE; closed symbols are points to the SW. The solid curve is the velocity dispersion for a constant $M/L$ King model with $R_{CORE} = 10$ kpc.

## 3 cD galaxy in Abell 2029 (Dressler 1979)

Dressler investigated the dynamics of IC 1101, the brightest galaxy in the cluster Abell 2029, in the hope of unveiling the cD origin [2]. It was considered a prototypical cD galaxy due to it's size and it's luminosity but more recent observations have shown that it does not have a typical cD halo [10].

The spectra for 8 regions with a distance to galactic centre with up to 108 kpc were recorded. Figure 1a shows IC 1101 and how the measured regions are orientated towards the galaxy. The werese spectra werese used to determine the position, strength and width of the H and K lines of Ca II and the G band. Of primary interest in Dressler's work was the velocity dispersion which is shown in Figure 1b. The velocity dispersion increases with the radius. This is a necessary condition for theories where cD galaxies are built by tidal stripping of neighbor galaxies. The stripped material would necessarily have a velocity dispersion closer to those of the high-velocity cluster members.

In addition to measuring the velocity dispersion a three-component, nonrotating, isotropic King model was given that fits the luminosity profile and the velocity dispersion. In this model IC 1011 consists of component 1, which is similar to a "normal" elliptical galaxy. Component 1 has a low velocity dispersion and $M/L = 11$. Component 2 are the accreted luminous galaxies that




(a) (b)

Figure 2: Three-component nonrotation King model for IC 1101 (a) The velocity dispersion for the 3 components, the luminosity-weighted average and the measured velosity dispersion from Figure 1b. (b) The run of the space density of the three components.

surround the "normal" elliptical galaxy. They have a intermediate velocity dispersion and $M/L = 35$. Component 3 consists of the stripped dark halos from other galaxies. Component 3 has a high velocity dispersion and $M/L = 525$. The luminosity-weighted average of these 3 components results in a velocity dispersion that is similar to the measured velocity dispersion. On the basis of this model IC1101 is interpreted as being a "normal" elliptical galaxy that is surrounded by luminous material and dark matter that were stripped away from toher galaxies in the cluster.

# 4 Dynamics of 25 Abell Clusters (Oegerle & Hill 2001)

While Dressler's work in 1979 focussed on the inner motion of a cD galaxy, Oegerle and Hill looked at the dynamics of the cluster in which the cD galaxy is contained [7]. The final piece of their analysis was published in 2001.

The main point of interest in tis work was the measurement of the peculiar velocity ff the vD galaxy $v_p = v_{cD} - v_{cl}$. $v_{cl}$ is the mean velocity of the cluster, with all velocities cosmologically corrected. The significance of the peculiar velocites depends on the uncertainties in the velocity of the cD galaxy and the uncertainties in the mean velocity of the cluster. In the sample of 25 cD galaxies 4 galaxies show a significant peculiar velocity when you restrict the radius of the cluster do 1.5 $h_{75}^{-1}$ Mpc. If the radius of the cluster is set to 3.5 $h_{75}^{-1}$ Mpc then 7 of the 25 cD galaxies show a significant peculiar velocity. This shows that the computed peculiar velocities are highly reliant on how spatial and velocity outliers are sorted out.

The observed peculiar velocities are in contrast with the traditional hypothesis that every cD galaxy rests at the bottom of the potential well of the cluster. Still the peculiar velocities of the cD galaxies are below those of the other glaxies in the cluster.

In 3 of the 4 galaxies with a significant peculiar velocity substructure can be observed. This substructure might be the cause of the peculiar velocity when the cD galaxy is nearly at the rest in the local subcluster that is still falling into the parent cluster.

The observations seem to support the idea that cD galaxies live in clusters that are dynamically young and not completely virialized.

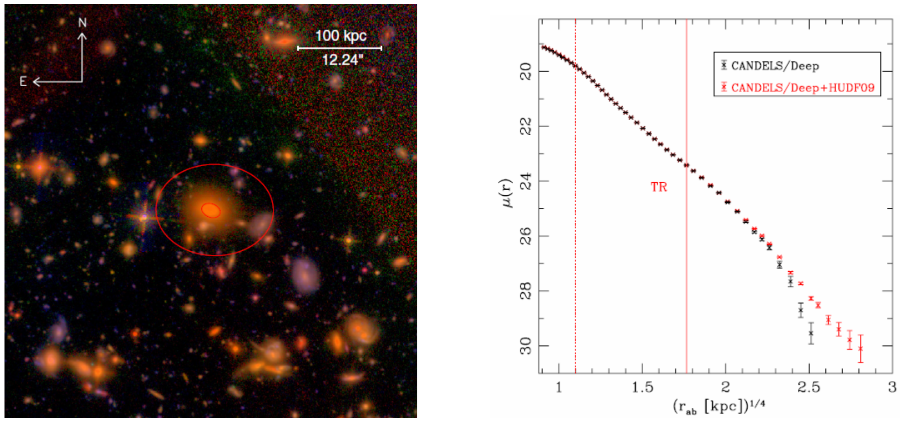
There is no definite conclusion from Oegerle and Hill's observations on the formation mechanism of cD galaxies. But whatever the mechanism it needs to result in a cD galaxy that is roughly at rest in the cluster potential but not exactly. The small peculiar velocities is suspected to be either a residual effect of the cD galaxy formation or the result of recent interactions and mergers of the cluster. They suspect that cD galaxy at high redshifts might lead to conclusions about the origin of cD galaxies.

# 5 Large peculiar velocity of the cD galaxy in Abell 3653 (Pimbblet et. al 2006)

While looking at a dark galaxy candidate Pimbblet et. al discovered that the cD galaxy in Abell 3653 has a large peculiar velocity. Abell 3653 is a galaxy cluster with 111 cluster members and a redshift of $z \approx 0.11$.

The cD galaxy has a peculiar velocity of $v_p = 683 \pm 96$ km s$^{-1}$ in the cluster rest frame which is $7.1\sigma$ away from the mean cluster velocity. Similary to Oegerle and Hill's work Abell 3653 was also tested for substurcture in the cluster. No Substructure of any sort was found.

The observatios made in Abell 3653 do not favour a scenario where a cD galaxy sits at the bottom of a gravitational well and grows there. Instead they favour a picture where the galaxy cluster grows in a hierarchical fashion from subclumps and groups infalling into a gravitational well. The cd galaxy is formed in one of those groups through the collapse and virialization of this group.




(a) (b)

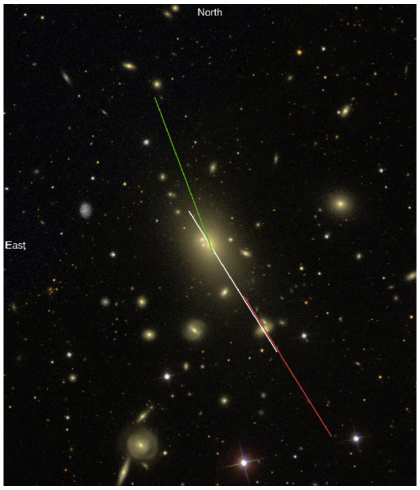
Figure 3: Measurements of GOODS-S J033237.19−274608.1 (a) Pseudo-color image with the transitional and maximum measured isophote marked with red ellipses. (b) Comparison of the surface brigthness profiles for two measurements. The transitional isophote is marked with a red line and the dotted line marks twice the PSF radius.

# 6 Discovery of a cD Galaxy at z = 1.096 (Liu et. al 2013)

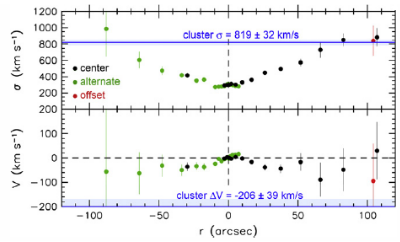
In the Hubble Ultra Deep Field a massive cD Galaxy was discovnered biy Liu et. al [4] at $z = 1.096$. This galaxy was the most distant cD galaxy to that date. Such a discovery of a high redshift cD galaxy enables the investigation of early history of cD galaxies.

The observed galaxy (GOODS-S J033237.19−274608.1) shows an extended cD envelope between $\sim 10$ kpc and $\sim 70$ kpc. The surface brightness profile that is shown in Figure 3b is typical for a cD galaxy.

The mass of GOODS-S J033237.19−274608.1 was derived to be $\sim 5 \times 10^{11} M_\odot$ and the half-light radius is $5.02 \pm 0.12$ kpc. The observed galaxy has a similar velocity dispersion but a higher stellar mass surface density than the more-massive, nearby cD galaxies. To evolve GOODS-S J033237.19−274608.1 into a a galaxy that is today similar to the massive nearby galaxies, the size and the stellar mass have to increase by factors of $3.4 \pm 1.1$ and $3.3 \pm 1.1$ over the past $\sim 8$ Gyr. The growth of the galaxy by dry mergers is proposed to induce the growth of the galaxy. These dry mergers would increase the half-light radius of the galaxy while not affectin the velocity dispersion much. If the already visible cD envelope is the result of such dry mergers then in at least part of the cD galaxies the dry mergers need to start at earlier epochs than $z = 1$.




(a)




(b)

Figure 4: (a) Image of NGC6166 showing the three slit positions for the spectroscopy. White: central; red: offset; green: alternate. (b) Velocity dispersion (top) and velocity with respect to the systemic velocity of NGC 6166 (bottom) for the three slit positions in NGC6166. Also shown are the cluster systemic velocity and the velocity dispersion of the cluster.

## 7 NGC 6166 in Abell 2199 (Bender et. al 2015)

In 2015 Bender et. al took a more xtended look at the inner kinematics and the photometry of the cD galaxy NGC 6166 in the cluster Abell 2199 [1]. This galaxy was already determined to have a large peculiar velocity by Oegerle and Hill [7].

NGC6166 and the position of the slits used for the spectroscopy are shown in Figure 4a. The results for velocity dispersion $\sigma$ and thevelocity $V$ are shown in Figure 4b. Similar to Dressler's measurements on IC1101 [2] the velocity dispersion rises for higher radii. The velocity dispersion rises to values of $\sigma = 865 \pm 58$ km s$^{-1}$ which is as high as the the cluster velocity dispersion of $819 \pm 32$ km s$^{-1}$. Also the velocity of the inner cD halo is $\sim 70$ km s$^{-1}$ closer to the cluster velosity than the velocity of NGC6166. Those two results indicate that the cD halo is controlled dynamically by cluster gravity and not by the cD galaxy. This falls in line with theories of cD evolution where the cD halos consists of stars that were stripped from individual cluster galaxies by fast tidal encounters. In this picture the main body of the galaxy is formed by hierarchical clustering and galaxy merging in small groups that predate the present-day, rich clusters. Some stars get splashed to large radii but the cD halo is created through cluster-related processes such as the stripping of stars from other cluster galaxies by dynamical harassment and the cannibalism of dwarf galaxies.

## 8 Conclusion

The evolution history of cD galaxies is not conclusively clear. But the observations show that the formation and evolution is closely related to the evolution of the cluster.

The cooling flow hypothesis for the creation of the cD halo is mostly ruled out since the hot gas does not cool down low enough.

The measurements of the peculiar velocities of the cD galaxies give hints that the cluster formed from hierarchical clustering of smaller groups of galaxies. The peculiar velocity of the cD galaxy may be a remnant of such a preceding structure, which might be still visible in the substructure of the cluster. Through the hierarchical clustering a elliptical galaxy must have formed near the dynamical center of the cluster from where the cD could grow from tidal stripping of cluster galaxies and minor mergers with small galaxies.

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