Observing Cluster Galaxies and their Progenitors with JDEM

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Abstract

The Joint Dark Energy Mission (JDEM) is expected to have a field-of-view that is several orders of magnitude larger than that of current instruments on the Hubble Space Telescope, with only slightly reduced sensitivity and resolution. This contribution gives a brief discussion of the impact that JDEM would have on studies of galaxies in clusters at $0.5 < z < 2$ and of the most massive galaxies at higher redshift. Of particular importance is JDEM's unique wide-field near-IR capability, enabling the selection and morphological study of high redshift galaxies in the rest-frame optical rather than the rest-frame ultra-violet.

1 Introduction

The primary goal of the Joint Dark Energy Mission (JDEM) is to improve our understanding of the nature of dark energy through accurate brightness measurements of Type Ia supernovae (SNe) out to $z \approx 1.7$. However, JDEM could have a profound impact on many other fields of astronomy: if it is designed as a wide-field optical/near-IR survey telescope, whose full-resolution data are saved and sent to Earth, it will be a tremendous improvement over current facilities and an ideal complement to the “pencil-beam” JWST. Compared to the current capabilities of HST, JDEM would have a field-of-view 100× greater in the optical and 1500× greater in the near-infrared, with only slightly lower sensitivity and resolution. The Deep Survey envisioned by the SNAP collaboration (Aldering et al. 2004) would image an area of 15 degrees$^2$ in 9 optical/near-IR filters to greater depth than the Hubble Ultra Deep Field.

Many applications of JDEM were highlighted at the meeting, including the impact it will have on the studies of large scale structure (see contribution by Daniel Eisenstein), galaxy formation (Rachel Somerville), and galaxy evolution (David Hogg). This contribution focuses on the importance of JDEM for the study of galaxy clusters at $0.5 < z < 2$ and of the likely progenitors of
cluster galaxies at higher redshift. A SNAP-like design is assumed, i.e., a wide field optical/near-IR imager.

Studies of the formation and evolution of cluster galaxies give insight in the assembly and star formation history of the most massive disk- and spheroidal galaxies in the Universe. Because of their high masses and old stellar populations they provide important tests of the hierarchical paradigm for galaxy formation: in these models galaxies are built up slowly through a combination of mergers and star formation, and more massive galaxies are predicted to have assembled more recently (e.g., Meza et al. 2003). The evolution of cluster galaxies is also important for understanding galaxies at very high redshifts. In hierarchical models the first objects form preferentially in overdense regions, which evolve into groups and clusters at the present day. Specifically, Baugh et al. (1998) predict that the descendants of \( z \approx 3 \) Lyman break galaxies (LBGs) typically live in halos of circular velocity \( > 400 \, \text{km} \, \text{s}^{-1} \) today, compared to \( \sim 250 \, \text{km} \, \text{s}^{-1} \) for galaxies that did not have a LBG progenitor. These arguments also apply to the descendants of the brightest galaxies at \( z \approx 7 \) and beyond, and to the highest redshift quasars.

2 What are we learning from HST?

As so many other fields, the study of cluster galaxies has benefited greatly from the combination of HST imaging and spectroscopy with 8–10m ground-based telescopes in the past decade. At the time of the meeting, about 60 distant clusters had been observed with WFPC2 and about 30 with ACS (excluding snapshot programs). The clusters were selected in X-rays or in the optical/near-IR, and span a redshift range 0.2 \( \leq z \leq 1.4 \). The vast majority of the HST observations cover just a single central pointing of \(< 10 \, \text{arcmin}^2\), and only a handful studies have observed areas larger than the equivalent of \( \approx 4 \) independent pointings (e.g., van Dokkum et al. 1998a, Treu et al. 2003).

2.1 Evolution of early-type galaxies

Early-types (elliptical and S0 galaxies) constitute \( \sim 80\% \) of the galaxy population in the cores of nearby clusters (Dressler 1980). They form a very homogeneous population: at a given mass, they show a very small scatter in their colors, luminosities, and line indices. This high degree of regularity is expressed in tight scaling relations between color and magnitude (Bower et al. 1992), velocity dispersion and Mg line strength (e.g., Bender et al. 1993), and velocity dispersion, radius, and surface brightness (the Fundamental Plane; Djorgovski & Davis 1987).
Fig. 1. Early-type galaxies in the cores of rich clusters appear to evolve slowly and regularly. The evolution of their $M/L_B$ ratios is consistent with passive fading of stellar populations formed at $z \approx 3$ (panel a; van Dokkum et al. 1998b and in prep.), and there is no evidence for evolution in the slope or scatter of their color-magnitude relation (panel b; Blakeslee et al. 2003).

Studies of the redshift evolution of these relations are in remarkable agreement. The evolution of their colors (e.g., Ellis et al. 1997, Stanford et al. 1998, Blakeslee et al. 2003), $M/L$ ratios and Fundamental Plane (e.g., van Dokkum et al. 1998b, Kelson et al. 2000, van Dokkum & Stanford 2003, Wuyts et al. 2004), and line indices (Bender et al. 1998, Kelson et al. 2001) show that massive early-type galaxies remain a very homogeneous population over the entire redshift range $0 < z < 1.3$.

The strongest constraints on the mean age of the stars in early-type galaxies have come from studies of the Fundamental Plane (FP). Figure 1a shows the evolution of the mean $M/L_B$ ratio of early-type galaxies with masses $> 10^{11} M_\odot$, as determined from the FP (van Dokkum et al. in prep.). The evolution is well described by the passive fading of a stellar population formed at $z \approx 2.8$ (indicated by the line), with very small cluster-to-cluster scatter. The best constraints on the galaxy-galaxy scatter in the ages have come from HST studies of the color-magnitude relation. By combining data from the literature with new ACS images of a cluster at $z = 1.24$ Blakeslee et al. (2003) find that the scatter in rest-frame $U - B$ colors is only a few percent independent of redshift (Fig. 1b).

2.2 Morphological evolution: interaction with the environment

It has been known for a long time that this simple picture of early formation and passive evolution cannot be complete. The earliest evidence for significant
recent evolution in cluster environments was the discovery of the Butcher-Oemler effect: the increase with redshift of the fraction of blue galaxies in clusters (e.g., Butcher & Oemler 1978, Ellingson et al. 2001, de Propris et al. 2003). Furthermore, HST studies of the central regions of clusters have demonstrated a decreasing fraction of early-type galaxies with redshift (Dressler et al. 1997; van Dokkum & Franx 2001; Smith et al. 2004): the early-type fraction in clusters at $z \sim 1$ is $\approx 50 \%$, compared to $\approx 80 \%$ in the local universe. This trend is qualitatively consistent with the larger fraction of blue galaxies at higher redshift, although there is no one-to-one relation between morphology and color, in particular at bright magnitudes (e.g., Poggianti et al. 1999, de Propris et al. 2003). Also, galaxies have been “caught in the act” of transforming their morphology and/or spectral type. Examples are “E+A” galaxies, which have early-type spectra with strong Balmer lines indicating a recent star burst; red merger systems found in several clusters at $z \sim 1$ (e.g., van Dokkum et al. 1999); and galaxies being stripped of their cold gas in the Virgo cluster (e.g., Kenney et al. 2004).

These effects are probably at least in part driven by infall of galaxies from the field. Clusters are expected to accrete a significant fraction of their final mass after their initial collapse (e.g., Diaferio et al. 2001). Simulations and observations suggest that the infalling galaxies are likely to radically change their star formation rate and morphology as a result of interactions with other galaxies and the hot X-ray gas (e.g., Abraham et al. 1996, Moore et al. 1996, Abadi et al. 1999, Poggianti et al. 1999, Ellingson et al. 2001, Kodama et al. 2001). The details of these processes are not well understood, largely because of the difficulty of studying clusters out to the virial radius and beyond (i.e., to $R \sim 10 \text{ Mpc}$). Treu et al. (2003) showed that with a large investment of HST time radial trends in morphology can be established out to the virial radius. However, as demonstrated in Fig. 2 HST is very inefficient in covering such large areas, in particular in the near-infrared.

Whatever the cause, morphological transformations severely complicate the interpretation of studies of galaxy evolution in clusters. First of all, it means that we cannot equate the mean age of the stars in a galaxy to its “assembly age”, the time since the galaxy took on its current appearance. Furthermore, if many present-day early-types were recently transformed from (field) spiral galaxies their progenitors are not included in samples of $z \sim 1$ cluster early-type galaxies. This “progenitor bias” may cause us to underestimate the evolution of early-type galaxies in clusters (van Dokkum & Franx 2001). The effects of this bias can be quantified by determining the mechanism and rate of morphological transformations in clusters, or by interpreting the observed evolution of cluster galaxies in the context of a full cosmological simulation (e.g., Diaferio et al. 2001). Both approaches are ambitious, and require a much better understanding of physical processes in the infall regions.
Fig. 2. Wide angle views of the cluster CL 0024+16 at \( z = 0.39 \). Left: mass map, with dark matter shown in blue and luminous matter in red (Kneib et al. 2003). Right: 39 HST WFPC2 pointings sparsely sample a \( \sim 27' \) diameter field (Treu et al. 2003). Imaging such large areas with HST is inefficient in the optical, and virtually impossible in the near-infrared.

3 The role of JDEM

3.1 The infall regions of clusters

The large field-of-view of JDEM will enable simultaneous study of clusters and the large scale structure in which they are embedded. The build-up of clusters through infall of galaxies and groups along filaments can be studied in detail, and the morphological changes that are thought to occur in the infall regions can be quantified. A SNAP-like JDEM design will observe the entire field shown in Fig. 2 in a single exposure, and owing to its unique near-IR capability can extend wide-field studies of clusters to \( z \sim 2 \). Among specific questions that JDEM would address are the morphological composition of galaxies in filaments and infalling groups; the merger rate as a function of local density and dynamical state; and the prevalence of “passive spirals” (e.g., Goto et al. 2003). The broader aims are to determine the rate and mechanisms of morphological transformations as a function of redshift.

A cluster survey could target specific clusters (selected in X-rays, or by their Sunyaev-Zel’dovich effect), but could also piggyback on planned SNe searches. Extrapolating from lower redshifts one may expect \( > 10 \) rich clusters in SNAP’s Deep Survey and \( > 500 \) in its Wide-field Survey, depending on the imposed mass and redshift cutoff. The clusters can be selected from the weak lensing maps produced as part of the survey (Wittman et al. 2001, Aldering et al. 2004); from X-ray surveys that will likely be planned in the Deep Sur-
vey area (see the contribution by Neil Brandt); and with the Gladders & Yee (2000) red sequence technique, which is probably the most efficient method beyond \( z \sim 1 \). The detailed weak lensing maps are not only useful for selecting clusters, but also characterize the dark matter substructure of clusters and their surroundings at \( 0.5 \lesssim z \lesssim 1.2 \) (Hoekstra et al. 2000).

The extreme depth of the Deep Survey also opens up the interesting possibility of seeing the “tidal tracks” left by infalling galaxies. Simulations suggest that clusters should be riddled with ultra-low surface brightness tidal debris (e.g., Dubinski 1999), providing a fossil record of the orbits of galaxies similar to that provided by stars in the Galactic halo. It may also be possible to see faint tidal features around a large fraction of elliptical galaxies, if they were assembled at relatively low redshift through “dry mergers”\(^\text{1}\) involving little gas (van Dokkum et al. 1999; Bell et al. 2004).

3.2 Progenitors at \( z > 2 \)

Galaxy overdensities have been identified out to \( z \sim 4 \) and beyond, by selecting galaxies in narrowband filters centered on the redshifted Ly\( \alpha \) line (e.g., Venemans et al. 2002) or by the Lyman break technique (Steidel et al. 1998). However, normal galaxies in the nearby universe and known cluster galaxies out to \( z \sim 1.5 \) would not be selected in this way, as they are too faint in the rest-frame ultraviolet. The top panels of Fig. 4 illustrate the effect of selecting galaxies in the UV: the GALEX view of M31 only shows the OB associations, missing most of the stellar mass.

The bias toward unobscured star forming galaxies inherent in the Lyman break technique can be avoided by selecting galaxies in the rest-frame optical rather than the rest-frame UV, using their redshifted Balmer- or 4000 \( \text{Å} \)-break. This selection is difficult due to the relative weakness of the Balmer break and the high sky brightness in the near-IR, and has only recently become feasible with the advent of high quality, large format near-IR detectors on large telescopes. Using very deep VLT images with a total area of \( \approx 30 \text{arcmin}^2 \) we recently found a large population of galaxies at \( 2 < z < 3 \) whose rest-frame optical colors are much redder than those of LBGs (Franx et al. 2003; van Dokkum et al. 2003; Förster Schreiber et al. 2004). The galaxies are efficiently selected by the simple observed color criterion \( J - K_s > 2.3 \). They are very massive (up to \( \sim 5 \times 10^{11} M_\odot \); van Dokkum et al. 2004) and appear to be highly clustered (Daddi et al. 2003). Their colors, \( H\alpha \) equivalent widths, line widths, stellar masses, and metallicities are similar to massive star forming galaxies in the nearby universe (van Dokkum et al. 2004; Förster Schreiber et al. 2004; Fig. 3). Most are bright in the near-IR but too faint in the observer’s optical to be

\(^{1}\) Rachel Somerville’s term.
Fig. 3. Properties of $z \sim 3$ galaxies selected in the rest-frame UV (LBGs/open circles; from Pettini et al. 2001 and Shapley et al. 2001) and $z \sim 2.5$ galaxies selected by their red rest-frame optical colors (solid circles). The small sample of red $z \sim 2.5$ galaxies has lower H$\alpha$ equivalent widths, higher stellar masses, and higher line widths than typical UV-selected $z \sim 3$ galaxies (from van Dokkum et al. 2004).

selected by the Lyman break technique. Their masses, clustering, and colors strongly suggest that they are progenitors of today’s early-type galaxies.

The strong field-to-field variations induced by their clustering (see, e.g., Labbé et al. 2003) imply that large areas need to be imaged to determine accurate surface densities and correlation functions. However, deep, large area near-IR surveys are notoriously difficult. Using $\sim 200$ hours of VLT observing time FIRES surveyed an area of only 30 arcmin$^2$ for red $z > 2$ galaxies (Franx et al. 2003; Förster Schreiber et al. 2004). Although we are currently extending this area in the MUSYC project$^2$, there is no telescope/instrument configuration on the horizon that can compete with JDEM in the near-IR. In addition to exquisite photometry JDEM will provide morphologies in the rest-frame UV and optical of all detected $z > 2$ galaxies. The bottom panels of Fig. 4 illustrate the importance of having multi-wavelength morphological information for any $z > 2$ galaxy which has a mix of young and old stars. This near-IR selected galaxy in the UDF has an irregular morphology in the optical ACS image, but is regular and concentrated in the near-IR NICMOS image (Toft et al., in prep). SNAP’s Deep Survey would cover a $\sim 5000 \times$ larger area and go $\sim 3$ mag deeper in the near-IR than the UDF NICMOS campaign (Thompson et al., in prep), at comparable resolution. If stellar mass correlates with line width at $z > 2$ (as indicated by current data; see Fig. 3b), it may be possible to determine the distribution function of halo circular velocities of galaxies at $z \sim 2.5$ from JDEM photometry alone.

$^2$ Multi-wavelength Survey by Yale-Chile; www.astro.yale.edu/MUSYC/
Fig. 4. Comparison of morphology in the rest-frame UV and the rest-frame optical, for M31 (top panels) and a red galaxy at $z \approx 2$ in the HST Ultra Deep Field (bottom panels; Toft et al., in prep). The images have the same resolution and physical scale (40 × 40 kpc), but arbitrary relative intensity scaling. Galaxies whose stars have a range of ages can look very different in the rest-frame UV and the rest-frame optical. For such objects the rest-frame UV will miss most of the stellar mass.

3.3 JDEM design considerations

JDEM will obviously be optimized for the identification and follow-up of high redshift SNe. Nevertheless, it is interesting to consider how well the current design specifications are suited for the study of high redshift galaxies. In terms of resolution the current SNAP design is similar to the Wide Field camera of WFPC2 in the optical and the NIC3 camera in the near-IR. As demonstrated in Fig. 4, NIC3’s resolution is sufficient to determine the morphologies of normal spiral and elliptical galaxies at arbitrary redshift. However, for resolving bulges, dwarf galaxies, and individual star forming complexes at $z \gtrsim 0.5$ one would have to sacrifice area for smaller ($\sim 0.10''$) pixels in the near-IR.

The reddest JDEM filters determine the highest redshifts at which the Lyman- and Balmer-breaks can be isolated. In the current design SNAP’s reddest filters are at 1.24 $\mu m$ and 1.44 $\mu m$, implying a maximum redshift for measuring the Balmer break of $\sim 2.4$, and a maximum Lyman “dropout” redshift of 9 – 10. Given the potential of JDEM as a survey companion to JWST the addition of a redder filter at $\sim 1.6 \mu m$ or beyond would be highly valuable.
Taking spectra of JDEM sources will be a formidable challenge, in particular in the near-infrared. As even the spectroscopic limit of a 30m ground-based telescope will be $5 - 6$ magnitudes brighter in the near-IR than the limit of SNAPs Deep Survey, the best follow-up capability will be offered by the multi-object NIRSpec on JWST.

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