The Properties of High Redshift Galaxies

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Abstract. In recent years, a variety of techniques at optical, near-infrared, sub-mm, and radio wavelengths have opened complementary windows on the high-redshift Universe. Here we review the current understanding of the general properties of the $z \geq 2$ galaxies detected in the optical (Lyman-break galaxies) and in the sub-mm (SCUBA sources). We list some of the key questions that need to be answered in order to understand the nature and evolution of the high-redshift galaxies. Wherever possible, we present tentative answers given so far to those questions, in particular on the low-redshift counterparts of the high-redshift galaxies, on the impact of dust obscuration on the observed quantities, and on physical characteristics of the high-z systems as inferred from observations.

Keywords: Lyman-break Galaxies; SCUBA sources; Starbursts; Dust; Evolution: Galaxies and Intergalactic Medium

1. Introduction

This writing attempts at summarizing the lively discussion that followed the session on “The Evolution of Galaxies with Redshift”, the last one of a very stimulating Conference. Four major areas of discussion were identified during the session:

1. Identification of the low redshift counterparts of the high redshift galaxies;

2. The impact of dust on the interpretation of the observables;

3. The nature of the high redshift galaxies; and

4. The evolution of galaxies and of the intergalactic medium (IGM) with redshift.

For each of these topics, we will list some of the extant, unanswered questions and provide, wherever possible, what it is felt are preliminary answers. When talking of “high redshift galaxies”, we will mainly refer to galaxies at redshift $z \geq 2$. 

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2. The Low-z Counterparts of High-z Galaxies

The two major questions in this area are:

- Which are the optimal low redshift templates of the distant galaxies and how reliably have they been determined?
- Is there a difference between the spectral templates and the morphological templates? What are the differences?

The first question has been addressed by a number of authors, and their findings are summarized below.

The galaxy population identified with the Lyman-break technique at redshifts \( z \sim 3 \) and \( z \sim 4 \) (Steidel et al. 1996, 1999) has been likened to local starburst galaxies. The selection technique itself biases the candidates towards active star-forming objects with moderate amount of reddening by dust, due to the need of observing a measureable Lyman discontinuity in the restframe 912 Å. More specifically, the distant galaxies resemble the nearby ‘UV-bright’ starbursts, i.e. those with average \( A_V \lesssim 3 \) mag, in terms of UV stellar absorption features (Steidel et al. 1996), UV stellar continuum slope distribution (Meurer et al. 1999, Steidel et al. 1999), and optical nebular emission lines (Pettini et al. 1998). For reference, Figure 1 shows the comparison between the UV spectra of the \( z \sim 2.7 \) Lyman-break galaxy MS 1512-cB58 and the local starburst dwarf NGC5253 (Tremonti et al. 2000); the similarity between the two spectra is pretty striking, with the major differences due to the stronger interstellar absorption lines in the distant galaxy.

From a physical point of view, star formation rates (SFRs) per unit area in the Lyman-break galaxies (LBGs) are of order a few \( M_\odot \, yr^{-1} \, kpc^{-2} \), or \( \sim 10\% \) the maximum SFR per unit area measured in the local Universe (Lehnert & Heckman 1996, Meurer et al. 1997). This value is also relatively similar to what measured in the local UV-bright starbursts. Finally, blueshifts in the UV interstellar absorption lines of MS 1512-cB58 have been interpreted as bulk gas outflows with velocity \( v \sim 200 \) km s\(^{-1}\) (Pettini et al. 1998), very similar to what observed in local FIR-bright starbursts (Heckman et al. 1990). From a purely phenomenological point of view, what sets LBGs apart from local starbursts is the physical extent of the star formation: in nearby objects, starbursts are generally concentrated within the inner kpc\(^2\), confined in the inner region of solid body rotation (Lehnert & Heckman 1996) of the host galaxy; star formation covers areas \( \approx 10-15 \) kpc\(^2\) in the distant galaxies (Giavalisco et al. 1996), and apparently is extended to most of the “visible” part, as the comparison between the rest–frame UV and optical light suggests (Dickinson 2000; Giavalisco et al. in prep.). This translates into dust–corrected global SFRs that are on average 5–10
Figure 1. The comparison between the UV spectrum of the \( z=2.7 \) galaxy MS 1512-cB58 and that of the local (\( D \sim 4 \text{ Mpc} \)) starburst dwarf NGC5253 shows the similarity between the two (Tremonti et al. 2000). The local starburst UV spectrum has been constructed from a long-slit HST/STIS spectrum, by requiring that 50% of the UV light comes from stellar clusters and 50% from the diffuse stellar population, as observed in starbursts (Meurer et al. 1995). The main difference between the two spectra is in the intensity of the interstellar absorption lines, that are much stronger in the distant galaxy.

... times larger in LBGs than in local UV-bright starbursts, and closer to the values measured in FIR-bright starbursts (e.g., NGC1614).

The similarity between local starbursts and LBGs brings forward another consideration. The number density at the bright end of the \( z \sim 3 \) galaxies is similar to that of the \( z \sim 4 \) galaxies (Steidel et al. 1999), and the time interval between \( z=4 \) and \( z=3 \) is \( \sim 350-600 \text{ Myr} \), depending on the cosmology. Preliminary results suggest that star formation can last a few 100 Myr in local starbursts (Calzetti 1997, Calzetti et al. 1997). If this is true also for the LBGs (Dickinson 2000, private communication), by \( z=3 \) these systems have formed \( \gtrsim 10^{10} \text{ M}_\odot \), or a large fraction of the stellar mass of an \( L^* \) galaxy.

Increasing evidence suggests that dust-corrected LBGs may account for \( \sim 50\% \) of the star formation at \( z \geq 2 \), with the other \( \sim 50\% \) provided by the FIR-bright SCUBA sources (e.g., Barger et al. 2000 and references therein). Within the uncertainties, actual numbers are in the 20-80% range for both type of objects, depending on the adopted dust correction for the UV-bright galaxies and on the adopted completeness corrections and AGN fraction for the FIR-bright objects (Hughes et al. 1998, Almaini et al. 1999, Barger et al. 2000). The brightest SCUBA sources detected at 850 \( \mu \text{m} \) seem to be characterized by very faint optical/near infrared emission and by thermal spectral energy distributions in the far infrared (Barger et al. 2000). It has been suggested...
that their most immediate local counterparts are the Ultraluminous Infrared Galaxies (ULIRGs, Sanders & Mirabel 1996).

### 3. The Impact of Dust

Here the two main questions are:

- How relevant is dust and dust obscuration in the high-z galaxies?
- Is there dust in the IGM, and at what level?

Measurements of the Cosmic Infrared background with COBE (Fixsen et al. 1998, Hauser et al. 1998) have shown that the amount of energy detected beyond 40 $\mu$m is comparable or higher (up to a factor of $\sim2$) than the UV-optical background (Pei, Fall & Hauser 1999). Thus the stellar energy absorbed by dust and re-radiated in the FIR represents a non-negligible ingredient in the energy balance of galaxies at all redshifts.

LBGs are characterized by a distribution of UV stellar continuum slopes with median value $\beta \sim -1.4$ (Dickinson 1998), much redder than the value $\beta_0 \sim -2.1$ expected for a dust-free star forming population (Leitherer & Heckman 1995). In local starburst galaxies, the measured slope of the UV stellar continuum is a sensitive tracer of dust reddening and obscuration (Calzetti et al. 1994, 2000, Meurer, Heckman & Calzetti 1999). If local starbursts are accurate representations of the LBGs, dust is probably present in the latter population, to the level of obscuring about 80% of the UV light (Steidel et al. 1999). Despite most of their UV stellar light is reprocessed by dust into the FIR, LBGs do not seem to be prominent FIR emitters, with predicted 850 $\mu$m fluxes at the $\sim1$ mJy level or less (e.g., Calzetti et al. 2000, Chapman et al. 2000); indeed they are mostly undetected with SCUBA (Chapman et al. 2000). However, because of their large number density, $n(z=3)\sim1.2 \times 10^{-2}$ Mpc$^{-3}$ (for $\Omega_{\Lambda}=0.7$, $\Omega_{\text{matter}}=0.3$, $H_0=65$ km/s/Mpc, Giavalisco et al. 2000), LBGs can still provide a non-negligible contribution to the FIR background. Estimates range from 25% up to most of the 850 $\mu$m background flux, depending on assumptions on both observables and theoretical prescriptions for the FIR SEDs (Adelberger & Steidel 2000, Dunlop 2000). Direct 850 $\mu$m counts done with SCUBA down to 0.25 $\mu$m reproduce almost entirely (94% of) the COBE background (Blain et al. 1999), with the brightest SCUBA sources, those above 2 mJy, accounting for $\sim30\%$ of it. These results strongly indicate that up to 90% of the early star formation emission has been reprocessed by dust into the FIR, and that dust is a widespread constituent of galaxies at $z>2$. 
The amount of dust distributed in the IGM is even less constrained. Metals have been observed in z=3 Lyman-α Forest clouds down to column densities N(HI)~10^{14.5} cm^{-2} (Ellison et al. 2000). In hierarchical CDM models these clouds are naturally arising as a consequence of the growth of density fluctuations in the presence of a UV ionizing background (Hernquist et al. 1996). The processes for polluting the high-z IGM with metals and, therefore, dust have not been completely clarified yet. The proposed scenarios go from widespread metal injection by Pop. III stars or by subgalactic structures to in-situ pollution by metal-enriched, supernova-driven gas outflows from the early galaxies (Gnedin & Ostriker 1997, Madau et al. 2000). Whatever the mechanism, the resulting metallicity of the IGM at z<0.5 appears to be ≈10% solar (Barlow & Tytler 1998) or possibly higher. Much less agreed-upon is the amount of dust that went into the IGM with the metals (conditions in the IGM do not favor dust formation, see Aguirre 1999). The evolution of the quasars UV spectral index indicates that the total IGM dust opacity is A_V(z<1.5)<0.05, for a Milky Way-type dust (Cheng et al. 1991). Aguirre (1999) argued that sputtering in galaxy haloes and in the IGM could destroy the small grain dust population, thus changing the extinction curve to a grey one; in particular, small reddening values, E(B−V)~0.02, would co-exist with large obscurations, A_V ~0.3. However, a recent analysis of distant Type 1A SNe (Riess et al. 2000) seems to disfavor the substantial IGM dust optical depth predicted by Aguirre, even in the presence of grey opacity.

4. The Nature of the High-z Galaxies

There are a number of important and unanswered questions in this area, and a few are:

- What is the nature of the high-z galaxies?
- Are the UV-bright (Lyman-break) galaxies linked to the FIR-bright (SCUBA) ones?
- How accurate are the metallicity measurements in galaxies and IGM, and what are these measurements telling us?
- What is the nature of the Damped Lyman-α systems?
- From an observational point of view, how can we access the critical redshift range between z=1 and z=2?

In this contribution we will address only the first two questions.

The mass spectrum of the high redshift galaxies heavily bears on the first question. Current estimates are very uncertain, and no conclusions have yet been reached. Inferred masses of relatively bright LBGs based on the width of the optical nebular lines (Pettini et al. 1998) suggest
values around $10^{10}$–$10^{11} \, M_\odot$, one to two order of magnitudes smaller than the dynamical mass of local bright (i.e. $L^*$) galaxies. However, the reliability of the nebular lines kinematics as tracer of the galaxy dynamics has not been demonstrated yet. The strong spatial clustering of the LBGs (Giavalisco et al. 1998, 2000; Adelberger et al. 1998) suggest values in the range $10^{11}$–$10^{12} \, M_\odot$ for the bright LBGs, depending on the cosmology (for $\Omega_{\text{matter}} \sim 0.3$, $\Omega_\Lambda \sim 0.7$, bright LBGs have dynamical masses $\sim 10^{12} \, M_\odot$).

Measuring dynamical masses of distant galaxies with traditional methods requires observing rotation curves with very high angular resolution and/or velocity dispersions from spectroscopy of stellar absorption or nebular emission lines. It also requires to detect the outer regions of the galaxies, which are strongly biased against by the $(1+z)^4$ cosmological surface brightness dimming. It is a rather difficult task for the 8–meter class telescopes. Very likely it will be NGST that will enable systematic kinematical observations of distant galaxies, if a near-infrared spectrograph with spectral resolution $R \sim 3,000$–$5,000$ and coverage up to $\sim 5 \, \mu m$ will be part of the instruments complement (Stiavelli, 1998). With such an instrument, the kinematical measurements of Milky Way-like galaxies will be possible up to $z \sim 5$ and of LMC-like galaxies up to $z \sim 1$–$2$, using the restframe Hα emission. Measuring masses of, e.g. $z \sim 3$ LBGs will settle the fundamental, ongoing debate over the nature of these systems: whether they are the massive progenitors of today’s spheroids (Giavalisco et al. 1996) or the low-mass fragments of present-day galaxies predicted by the hierarchical structure formation in CDM models (e.g., Lowenthal et al. 1997).

The morphology of the LBGs also offers indication as to their nature. Imaging with HST and WFPC2 has shown that these galaxies exhibit a variety of UV morphologies, although only galaxies fainter than $m^* \[1\] have been observed. Some galaxies have compact and regular morphology, with light profiles well described by an $r^{1/4}$ or an exponential law (e.g. Giavalisco et al. 1996). Other galaxies have fragmented and distorted morphology, sometime with multiple components embedded in irregular diffuse light, suggestive of merging and interaction (Lowenthal et al. 1997). The size is, in general, smaller than today’s bright galaxies, with half–light radii $0.2'' \lesssim r_{1/2} \lesssim 0.4''$ (at $z=3$, $1'' = 8.3$ kpc in the cosmology adopted in this paper). Thus, the regions where stars are being formed in these objects are larger than local dwarf and irregular galaxies, but smaller than the Milky Way, although the reported size is probably an underestimate of the true one, because of the $(1+z)^4$.

\[1\] The luminosity parameter of the Schechter fit to the UV luminosity function of the $z \sim 3$ LBGs, which is $m^* = 24.5$ (Steidel et al. 1999).
Figure 2. A comparison between the rest-frame UV (left) and optical (right) morphology of Lyman-break galaxies. The shown examples are 0000-2619-C10 at \( z = 3.238 \) (top), and 0000-2619-D6 at \( z = 2.969 \) (bottom). Overall, the UV and optical images are the same, showing that morphological segregation due to a spatially variable obscuration is not a factor in these galaxies. Dickinson (2000) finds the same result from a larger sample from the HDF.

surface brightness dimming. Very interestingly, imaging with NICMOS on *HST* has revealed that the rest-frame optical morphology in almost all of the observed cases is essentially the same as the UV one (see Figure 2 and Dickinson 2000). This is consistent with these objects being relatively young galaxies, and suggests that the ongoing activity of star formation (traced by the UV light) is the one that assembled most of the galaxies’ structures.

The metallicity is another important parameter to understand the nature of LBGs and to establish an evolutionary link with present-day galaxies. Currently the distribution of the metallicity of these galaxies is essentially unknown, and only a few measures have been made. Kobulnicky & Koo (2000), and Teplitz et al. (2000) estimate the metallicity of the nebular gas from the optical emission lines in a few objects, finding values in the range \( 0.3 \lesssim Z_{\text{LBG}}/Z_\odot \lesssim 1 \). Thus, the gas out of which the last generation of stars has just formed has already reached a considerable degree of enrichment. This conclusion is supported by the estimate by Pettini et al. (2000), who find similar values of metallicity from stellar and interstellar lines from the UV spectrum of MS 1512–cB58\(^2\). This metallicity is higher than that found in the local HII galaxies, and is similar to that observed in Galactic

\(^2\) While the agreement is certainly encouraging, it should be taken with caution, because of the possibility that the interstellar lines used in the analysis are saturated. See the discussion in Pettini et al. (2000).
bulge stars and metal–rich globular clusters (e.g. see the discussion in Kobulnicky & Koo 2000).

All of the above suggests that the stellar systems observed as LBGs at \( z \sim 3 \) would appear today as bright, old and relatively metal–rich objects. The dust-corrected SFRs, the preliminary indications about the total mass, the observed morphology, and the fairly large metallicities are all in qualitative agreement with the interpretation that these systems have the characteristics of the progenitors of the spheroids, i.e. bulges of \( L^* \) galaxies and ellipticals.

The link between the LBGs (or galaxy fragments) and the SCUBA sources is also a controversial issue. To the level that the SCUBA sources are mostly powered by star formation (i.e, the AGN fraction can be considered small, see Almaini et al. 1999) the two classes of objects could be considered the two extremes of the starburst phenomenon, with the UV-bright end occupied by the bluest LBGs and the FIR-bright end occupied by the most luminous SCUBA sources. Red LBGs and faint SCUBA sources could lie in between a continuum of properties parametrized by the SFR and by the dust (metal) content. This scenario is in agreement with the two recent results that most of the SCUBA sources have very faint optical/near infrared counterparts (Barger et al. 2000) and that the FIR detectability of the Lyman-break galaxies is low (Chapman et al. 2000). In the local Universe, the positive correlation between SFR, dust (metal) content, and mass of the host galaxy is a known property of starbursts (Heckman et al. 1998). Care, however, should be taken in concluding that the LBGs represent only or mainly low-SFR (low-mass?) systems; among these galaxies there are many with dust-corrected SFRs of a few \( 100 \, M_\odot \, yr^{-1} \) (e.g., Dickinson 1998), thus comparable in bolometric luminosity to ULIRGs, although with much less extreme values of the dust obscuration.

While the space density of LBGs is comparable to that of local galaxies \( (n_{\text{local}} \sim 1.6 \times 10^{-2} \, Mpc^{-3} \) for our cosmology, Marzke et al. 1994), the space density of the bright \( (>6 \, mJy) \) SCUBA sources at \( z=1–3 \) is \( \approx 100 \) times higher than that of local ULIRGs \( (n_{\text{SCUBA}} \sim 1.1 \times 10^{-5} \, Mpc^{-3}) \), see Barger et al. 2000). Although this figure is potentially affected by large uncertainties due to the small number statistics of the SCUBA detections, the FIR-bright objects appear to have been more common at high redshift than at low redshift. A scenario that can fit both the UV-bright and the FIR-bright sources within the cosmological context is one where the LBGs are the progenitors of the present–day bulges and elliptical galaxies of intermediate to normal luminosity (around \( L^* \)), while the bright SCUBA sources are more directly related to massive ellipticals \( (L > L^*, \) see also Dunlop 2000).
5. Galaxy and IGM Evolution

The number of unaddressed issues in the realm of galaxy and IGM evolution is too large to be summarized by the limited scope of this discussion. We pose here, without attempting answers, a non-exhaustive list of the questions that most directly bear on our understanding of the evolution of the luminous and non-luminous matter.

- How did the Hubble sequence originate? Which are the high-z progenitors of the local Hubble types? How does the galaxy mass spectrum evolve with redshift?
- How does the stellar Initial Mass Function (IMF) evolve with redshift, if it evolves at all?
- Do we have a reliable inventory of all the metals in the local Universe? How well are they accounted for by chemical evolution models?

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