High-Redshift Galaxies: The HDF and More

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Abstract. We review our present knowledge of high-redshift galaxies, emphasizing particularly their physical properties and the ways in which they relate to present-day galaxies. We also present a catalogue of photometric redshifts of galaxies in the Hubble Deep Field and discuss the possibilities that this kind of study offers to complete the standard spectroscopically based surveys.

1 Introduction

For a long time models for galaxy formation and evolution advanced unhampered by observations. Nowadays, however, the rapid increase in both observational capabilities and efficiency of the selection methods (see Steidel et al. 1995 [S95]) has converted the task of looking for distant galaxies from one of the most difficult challenges to an almost routine job, and large databases of high-z galaxies are already being compiled (Dickinson 1998, this Volume). Observations can now constrain the models, and this obliges us to understand the properties of these objects in order to get a complete image of the processes involved in the formation and evolution of galaxies.

This study of the properties of high-z galaxies is twofold. We need to understand the information provided by the confirmed high-z galaxies. In this way we will learn about the spectral and morphological properties of the bright end of the galaxy population, i.e., the putative progenitors of present-day large ($L > L_*$) galaxies. Second, the use of photometric redshift techniques applied to deep multi-colour images (like the HDF, Williams et al. 1996) opens a wealth of statistical methods to study those faint objects for which we cannot obtain spectroscopic information in the near future. These studies will yield further results on the general distribution and evolution of galaxies. The main problem for both methods resides in the $z \approx 1–2$ range, where spectroscopic identification of galaxies at optical wavelengths is made difficult by the lack of spectral features.

2 Physical Properties of the High-Redshift Galaxies

We start with a brief review of the physical properties of high-z galaxies, most of which have been selected applying colour techniques (S95). The HDF triggered a wave of intense spectroscopic follow-up observation (Steidel et al. 1996 [S96], Lowenthal et al. 1997 [L97], Zepf et al. 1996) that added a large number of galaxies to the sample. Nature also provides us with a telescope capable of
amplifying the light from distant galaxies, although plagued by geometric aberrations: gravitational lensing has been used by several groups to discover some of the most distant known galaxies (Trager et al. 1997 [T97], Franx et al. 1997).

2.1 Spectral Features: Dust, Metal and Gas Content

High-z galaxies (see Fig. 1) are characterized by a flat continuum. Their Lyα emission lines vary considerably, from weak or even absent –with superposed damped absorption profiles– to rest EW of up to 60 Å. All galaxies show optically thick Lyman limits and a strong discontinuity in the continuum bluewards of Lyα, due to the onset of the Lyα forest. Stellar and interstellar absorption lines are present, showing narrow profiles that are weaker for high-ionization species. A detailed study of the different emission and absorption lines and the slopes of the observed spectra suggests that high-z galaxies are low metallicity systems \((Z \approx 0.1 Z_\odot)\), with high neutral gas content that allows them to imprint damped HI absorption profiles on background objects. The amount of dust seems to be moderate \((E(B-V) \approx 0.10)\), but a better measurement is necessary in order to establish firmer values for the extinctions, luminosities and star formation rates.

2.2 Morphology and Luminosity

Most of the observed galaxies show compact cores (with half-light radii on the order of a few kpc) surrounded by irregular asymmetric halos (Giavalisco et al. 1996 [G96]). Although far from homogeneous, they look more regular than the galaxies observed at \(z \approx 1\) –only one of the galaxies at \(z > 2\) shows the “chain” morphology reported by Cowie et al. (1995) to be usual in moderate-z galaxies. A joint analysis of our photometric redshift catalogue and a morphological catalogue of galaxies in the HDF is presented by Simon Driver in this same Volume (see also Driver et al. 1998 [D98]). It must be remarked that we are observing these objects in the rest-frame UV range, so passband effects are indeed
important. Direct comparison of their morphologies with those of their low-z counterparts will have to wait until high-resolution IR imaging is available.

The total $B$-band luminosities lie in the range $1 - 10L_\odot$, with a strong concentration in the compact, high surface brightness cores. The SFRs range from 1 to 50 $M_\odot$ yr$^{-1}$, although dust extinction might increase this by a factor of perhaps 3 or even more (Pettini et al. 1997).

2.3 Number Densities and Clustering

Some measured number densities are: $0.6 \pm 0.2$ ($R < 25.0, 3.0 < z < 3.5, S95$), $3.2 \pm 1.9$ ($R < 25.3, 2.4 < z < 3.4, S96$), $6.5 \pm 2.0$ ($R < 25.5, 2.0 < z < 3.5, L97$). For the same ranges our catalogue gives $0.6 \pm 0.3$, $3.2 \pm 0.8$ and $7.7 \pm 1.2$ galaxies per square arc minute, respectively. We also estimate that approximately 5, 15 and 25% of all galaxies brighter than $AB(8140) = 24, 26$ and 28 respectively are at $z > 2$. Evidence of large scale structure in the distribution of high-z galaxies is presented by Mark Dickinson in this Volume.

3 Photometric Redshifts in the HDF

The determination of redshift via photometric methods (the “Poor person’s z machine”, as stated in Koo 1985) is a long-known technique. We present here some results from our catalogue, based on $UBVIJHK$ photometry of the HDF –IR images provided by Mark Dickinson (Dickinson et al. 1998 in prep). Full details are given in Fernández-Soto et al. 1998, (in prep). The catalogue is essentially complete down to $AB(8140) = 28$ and contains 1067 objects.

Comparison with a sample of 106 spectroscopically determined redshifts shows that the results are very good up to $z = 1.4$ ($\Delta z_{\text{rms}} = 0.13$). At $z > 2$ there is a 7% rate of error (high-z galaxies that are assigned low redshift in our analysis), while for the rest we obtain $\Delta z_{\text{rms}} = 0.45$. Lanzetta et al. (1997) have shown that the number of wrong redshifts in the spectroscopic measurements (due to misidentification of lines or operator error) are comparable to this rate.

The advantage of this technique is the ability to estimate redshifts for large samples of objects that are too faint to have their redshifts spectroscopically measured ($AB(8140) \approx 28$ vs. $AB(8140) \approx 24$). With our sample we can estimate the $N - m - z$ distribution, the Hubble Diagram for different spectral types (see Fig. 2), the morphological evolution of galaxies (see D98), SFR densities (Lanzetta et al. 1998, in prep), and other characteristics.

4 Interpretation and Conclusions

The available data allow for different interpretations. While S95, S96 and G96 support the hypothesis that the observed high-z galaxies are the progenitors of present-day luminous galaxies at the epoch of formation of the first stars in their spheroidal components, T97 suggests that these objects will evolve to form
the Population II components of early-type spirals. Another interpretation (L97) maintains that these objects represent a range of physical processes and stages of galaxy formation and evolution rather than any particular class of object.

While this third interpretation might be closer to reality, we are still missing an important piece of the puzzle. Detailed IR imaging and spectroscopy is needed in order to: a) shed light on the $z = 1 - 2$ galaxies allowing us to constrain evolutionary models; b) obtain images of the $z > 2$ galaxies at optical rest-frame wavelengths to be compared with their low-$z$ counterparts and; c) perform moderate resolution spectroscopy of the $z > 2$ galaxies to accurately measure their metallicities and the importance of dust corrections.

We expect that these observations, with the support of techniques like cosmological simulations and stellar population evolutionary models, will lead us closer to the long-searched-for understanding of the process by which the Universe came to be as we see it. Perhaps it is not the moment for us to “look deeper in the Southern Sky”, but to look at it with different eyes.

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