The Nature of Compact Galaxies at z~0.2-1.3: Implications for Galaxy Evolution and the Star Formation History of the Universe.

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Abstract. We study the global scaling-laws of 51 compact field galaxies with redshifts $z \sim 0.2 - 1.3$ and apparent magnitudes $I_{814} < 23.74$ in the flanking fields of the Hubble Deep Field. Roughly 60% of the 45 compact emission-line galaxies have sizes, surface brightnesses, luminosities, velocity widths, excitations, star formation rates (SFR), and mass-to-light ratios characteristic of young star-forming HII galaxies. The remaining 40% form a more heterogeneous class of evolved starbursts, similar to local disk star-burst galaxies. Without additional star formation, HII-like distant compacts will most likely fade to resemble today's spheroidal galaxies such as NGC 205. Our sample implies a lower limit for the global comoving SFR density of $\sim 0.004 M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ at $z = 0.55$, and $\sim 0.008 M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ at $z = 0.85$. These values, when compared to a similar sample of local galaxies, support a history of the universe in which the SFR density declines by a factor $\sim 10$ from $z = 1$ to today. From the comparison with the SFR densities derived from previous data sets, we conclude that compact emission-line galaxies, though only $\sim 20\%$ of the general field population, may contribute as much as $\sim 45\%$ to the global SFR of the universe at $0.4 < z < 1$.

1 Introduction

Galaxies exhibit a wide variety of correlations among global parameters (such as luminosity, size, surface brightness, velocity dispersion, colors, and line strength indices). These empirical scaling-laws have been widely used to constrain current theories of galaxy formation, and to measure distances and peculiar velocities of galaxies to map the large-scale distribution of matter in the nearby universe. With the advent of the Hubble Space Telescope (HST) and the new generation of 10-m class telescopes, it is now possible to extend the study of scaling-laws to galaxies at high redshift (e.g., Koo et al. 1995; Van Dokkum & Franx 1996; Bender et al. 1996; Guzmán et al. 1996; Vogt et al. 1996). These new studies are proving key in our understanding of one of the major unresolved questions in modern cosmology: how galaxies evolve with look-back time.

One of the most controversial issues related to this question is the nature of the numerous faint blue galaxies observed in deep images of the sky (see reviews by Koo 1996, Ellis 1996, and references therein). The high surface density and weak clustering of these galaxies argue against their being either the progenitors or the merging components of present-day bright galaxies (Lilly et al. 1991; Efstathiou et al. 1991). Various theoretical scenarios have instead suggested that
the faint blue galaxies are low-mass stellar systems experiencing their initial starburst at redshifts \( z \leq 1 \), some of which turn into the present population of spheroidal galaxies (Sph), such as NGC 205 (Babul & Ferguson 1996). Given their likely starburst nature, faint blue galaxies may also be major contributors to the global star formation rate (SFR) density already found to increase with lookback time to at least redshift \( z \sim 1 \) (Cowie et al. 1995, Lilly et al. 1996).

In this project we investigate the ideas above on the nature of the faint blue galaxies by comparing the scaling-laws of distant low-mass starbursts to those of nearby galaxies. The goals are: to identify their local counterparts, to assess their evolution with look-back time, and to study their role on the star formation history of the universe. A full description of the results summarized here can be found in Koo et al. (1995), Guzmán et al. (1996,1997), and Phillips et al. (1997).

2 The Data

The galaxy sample consists of 51 compact galaxies selected from \( I_{814} \) HST images of the flanking fields around the Hubble Deep Field (HDF; Williams et al. 1996). These objects are compact in the sense that they have small apparent half-light radii \( (r_{1/2} \leq 0.5 \text{ arcsec}) \) and high surface brightnesses \( (\mu_{I_{814}} \leq 22.2 \text{ mag arcsec}^{-2}) \). With no color information, the “compactness” criterion optimizes the selection of dwarf stellar systems which are likely to be low-mass starbursts. Spectra for these objects were obtained using LRIS at the Keck telescope with a slitwidth of 1.1 arcsec and a 600 l/mm grating. The effective resolution is \( \sim 3.1 \text{ Å FWHM} \). Typical exposure times were 3000s. The total spectral range is \( \sim 4000-9000 \text{ Å} \). In addition, we obtained two 300s direct V-band exposures with LRIS in order to provide some color information. Our final data set includes: redshifts, \( V_{606} - I_{814} \) colors, absolute blue magnitudes \( (M_B) \), half-light radii \( (R_e) \), surface brightnesses \( (SB_e) \), velocity widths \( (\sigma) \), masses \( (M) \), mass-to-light ratios \( (M/L) \), [OIII]/H\( \beta \) line ratios, and SFRs.

Of the 51 galaxies, 6 (or 12%) show absorption-line spectra characteristic of elliptical and S0 galaxies, while the remaining 45 (88%) exhibit prominent oxygen and/or Balmer emission lines and blue continua characteristic of vigorous star-forming systems or narrow-line active galaxies. Most of the emission-line objects are very blue with nearly constant \( V_{606} - I_{814} \sim 0.9 \), while those with early-type spectra form a reasonably tight red sequence just blueward of the color track expected for non-evolving elliptical galaxies (Figure 1). Hereafter we focus our study on the emission-line compact galaxies. For convenience, we divide this sample into intermediate- \( (z < 0.7) \) and high-redshift \( (z > 0.7) \) samples.

3 Scaling-Laws

The global structural properties of galaxies can be adequately described using the \( M_B - SB_e \) and \( R_e - \sigma \) diagrams. In these diagrams, various galaxy types define distinct correlations, albeit with large scatter (Figures 2a and 2b). Most
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![Graph showing $V_{606} - I_{814}$ color as a function of redshift. The tracks of local elliptical, Sbc and starburst (NGC 4449) galaxies are based on observed SEDs (no color evolution). Objects with absorption-line dominated spectra are marked with (◦).](image)

Fig. 1. $V_{606} - I_{814}$ color as a function of redshift. The tracks of local elliptical, Sbc and starburst (NGC 4449) galaxies are based on observed SEDs (no color evolution). Objects with absorption-line dominated spectra are marked with (◦).

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To parametrize the starburst properties of the compact galaxy sample we use the $[OIII]/H\beta - M_B$ and the $M - SFR/M$ diagrams (Figures 3a and 3b). These diagrams discriminate among various types of starburst and active galaxies. Most of the compacts with $[OIII]/H\beta$ measurements lie in the moderate to high excitation regime populated by HII galaxies and CNELGs. These objects also have $SFR/M$ characteristic of HII galaxies. A second group of distant compacts have $[OIII]/H\beta$ and $SFR/M$ similar to those of more evolved disk starbursts such as local DANS and SBNs. Based on this, we have classified the sample into HII-like and disk starburst-like galaxies, depending on their $SFR/M$ (see Figure 3b). With this simple criterion, we find that $\sim$60% of distant compact galaxies have stellar and structural properties consistent with those of nearby HII galaxies, while the remaining 40% are similar to more evolved disk starbursts.

Two other major results can be drawn from the analysis of the $M - SFR/M$ diagram. First, the highest values of the $SFR/M$ exhibited by compact galaxies are similar to those of local HII galaxies. Thus we do not find evidence for an increase in the peak of the $SFR/M$ activity with redshift in our sample. Second, compact galaxies at $z > 0.7$ are, on average, $\sim$10 times more massive than their counterparts with similar $SFR/M$ at $z < 0.7$. Although selection effects may account for the lack of low-mass compact objects at high-$z$, they cannot explain why the massive star-forming systems are not present in the intermediate-$z$ sample. This is not the result of a volume-richness effect either, since the volumes mapped in both samples differ by only a factor $\sim 1.5$. The apparent lack of massive starbursts in the intermediate-$z$ sample suggests a steep evolution of the global SFR with redshift, although this result should be taken
Fig. 2. (a): $S_B$ vs. $M_B$. Dotted lines indicate the general regions occupied by different classes of local galaxies; the arrow (F) represents the direction of fading. (b): $R_e$ vs. $\sigma$. Dashed lines represent constant mass-lines in $M_\odot$; the arrows represent the effect of dissipation (D), mergers (M), stripping (S) and winds (W) on $R_e$ and $\sigma$. We adopt $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.05$.

Fig. 3. (a): $M_B$ vs. $[OIII]/H\beta$. Local galaxy sample is from Gallego et al. (1997); DANS: Dwarf Amorphous Nuclear Starbursts; SBN: Starburst Nuclei; Sy2: Seyfert 2 galaxies; III: III galaxies. Dashed lines represent the approximate location of spiral galaxies. (b): $M$ vs. $SFR/M$. The dotted line represents the division between III-like and disk starburst-like galaxies adopted in our classification.
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with caution given the small number of galaxies involved in this analysis.

4 Discussion

Distant compact emission-line galaxies are young, low-mass star-forming systems. Unless reignited by new star formation, they should fade within a few Gyrs. The issue of fading and transformation of one galaxy class to another is quite complex. Perhaps one of the most useful tools we have to study how distant young galaxies relate to nearby evolved stellar systems is the $R_e - \sigma$ diagram, since neither $R_e$ nor $\sigma$ depend strongly on the fading of the stellar population. Although there are several physical processes that may modify these parameters during galaxy evolution (see Figure 2b), we find no evidence against the idea that HII-like compact galaxies (most of those with $M < 10^{10} M_\odot$) are related structurally and kinematically to the nearby population of Sph and Irr galaxies. Their evolution into one galaxy class or another may depend critically on their ability to retain part of their interstellar medium in the likely event of starburst-driven galactic winds. The extremely low mass-to-light ratios of HII-like compacts (i.e., $M/L \sim 0.3$ solar) suggest that the kinetic energy supplied by the current starburst is large enough, compared to their binding energy, to blow out most of the gas, thus preventing future star formation. Without additional star formation, galaxy evolution models predict that these low-mass starbursts will fade enough to match the low luminosities and surface brightnesses of Sph galaxies (see Figure 2a). We thus conclude that a class of HII-like, faint blue galaxies may actually be among the progenitors of today’s spheroidals.

The compact galaxy sample is also useful to investigate the role of low-mass starbursts on the evolution of the SFR density at redshifts $z < 1$. In Figure 4, we show a current overall picture of the evolution of the SFR density with redshift. The interpretation of this figure should be approached with caution, given the likely differences in the calibrations for the various SFR tracers, incompleteness of the data sets, and uncertainties in the models. Despite these caveats, most of the results summarized in this figure imply that the total SFR density of the universe decreased by a factor of $\sim 10$ from $z \sim 1$ to the present-day. Assuming our sample is representative of the general population of compact galaxies, we estimate that the total SFR densities associated to this class are: $0.004 M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ at $z=0.55$, and $0.008 M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ at $z=0.85$. These values, when compared to a similar sample of local galaxies, support a similar decline in the SFR density in the last $\sim 8$ Gyrs. From the comparison with the SFR densities derived by Cowie et al. (1995), we conclude that compact emission-line galaxies, though only $\sim 20\%$ of the general field population, may contribute as much as $\sim 45\%$ to the global SFR of the universe at $0.4 < z < 1$.

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Fig. 4. SFR density vs. redshift. Filled circles are the estimates for compact galaxies. These values should be compared to the open circles labelled “Interm-z” and “High-z”, which represent the values for similar samples of nearby compact galaxies. Dotted lines represent Pei & Fall’s models (1995). The dashed line represents the fiducial value. We adopt $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$.

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