Galaxy Morphology in the GTO-NICMOS Northern Hubble Deep Field

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Abstract. The increased incidence of morphologically peculiar galaxies at faint magnitudes in the optical could be attributable either to “morphological k-corrections” (the change in appearance when viewing high-z objects at shorter rest-frame wavelengths), or an increase in the incidence of truly irregular systems with redshift. The deep, high-resolution GTO-NICMOS near-IR imaging of a portion of the northern Hubble Deep Field has been combined with the WFPC 2 data and photometric redshift estimates to study the redshift evolution of morphology, comparing galaxy appearance at the same rest-wavelengths (Bunker, Spinrad & Thompson 1999). It appears that morphological k-corrections are only significant in a minority of cases, and that once these are accounted for, evolution is still demanded – galaxies were smaller and more irregular in the past, with some of the peculiarities probably merger-related. This multi-waveband data set also enables a study of the spatially-resolved stellar populations in distant galaxies. A near-infrared analysis of some of the brighter spirals shows more pronounced barred structure than in the optical, indicating that the apparent decline in barred spirals at faint magnitudes in the optical HDF may be due to band-shifting effects at the higher redshifts, rather than intrinsic evolution.

1. Introduction

When coupled with distance estimates such as photometric redshifts, the study of morphology has the potential to probe the dynamical state and evolution of galaxies. However, morphological classification is only reliable to redshifts of a few tenths when hampered by ground-based seeing. The deep, high-resolution WFPC 2 imaging of the Hubble Deep Field (HDF, Williams et al. 1996) dramatically pushed the study of galaxy morphology to faint magnitudes and high redshifts, revealing that by $I_{AB} > 24$, the traditional Hubble sequence no longer provides an adequate description of most galaxies (Abraham et al. 1996).

Some of the faint peculiar galaxies are sub-luminous irregulars at modest redshifts, while others are higher-z. But are they “true peculiar” – the counterparts to local irregulars? Matters are complicated by morphological k-corrections: for single waveband selection, shorter rest wavelengths are sampled in higher-z galaxies. The rest-UV is dominated by sites of recent star formation, and it is known that the appearance of local Hubble-sequence galaxies can be very different in the UV compared to the optical (e.g., O’Connell 1997). This change in apparent morphology, resulting from a dispersion of stellar populations, is well illustrated by some HDF spirals at moderate redshift ($z \approx 1$) which undergo a complete metamorphosis from the observed optical to the near-IR (Fig. 1).

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To address whether the apparent increased incidence of peculiars in the optical at faint magnitudes is attributable to genuine evolution in the fraction of irregular galaxies, or whether it is predominantly due to band-shifting effects, the appearance of galaxies over a variety of redshifts should be compared at the same rest wavelength (Fig. 3).

2. A Study of HDF-North

We have analyzed galaxy morphology to faint magnitudes in HDF-North using the optical & near-IR HST images (Bunker, Spinrad & Thompson 1999). We have studied the GTO-NICMOS data set (Thompson et al. 1999), a 1 arcmin$^2$ area of the HDF imaged for 49 orbits with NIC 3 in both F110W ($\approx J$-band) and F160W ($\approx H$-band). Combined with the four WFPC 2 pass-bands (Fig. 3), this data set provides deep, multi-color, high-resolution imaging extending out to 1.6 $\mu$m – the rest-optical at $z \approx 2$. We use the redshifts of the galaxies to match the rest-wavelengths, determine intrinsic luminosities, and to fit stellar populations/dust reddening to the spectral energy distributions. Where available, we use the spectroscopically-measured redshifts (from Cohen et al. 1996 unless otherwise noted). Where no published spectroscopic redshift exists, we adopt the photometric redshift estimate of Fernández-Soto, Lanzetta & Yahil (1999).

Comparative Morphology: Down to $I_{AB} \approx 26$ (the brightest 100 galaxies in GTO-NICMOS field): only about 1/6 of galaxies change their appearance greatly between the WFPC 2 and NICMOS images – these have large morphological $k$-corrections; about half of the galaxies retain the same morphology in all wavebands (above the redshifted Lyman break) and are “true irregulars”; the remaining third of galaxies are too compact for changes in morphology to be ascertained (the NIC 3 PSF has a FWHM of $\approx 0.25$arcsec); for most cosmologies, the higher-redshift systems are on average more compact.

Spatially-Resolved Stellar Populations: Once we correct for different resolutions of NIC 3 and WFPC 2 (through “PSF matching”), we can use the spatially-resolved colors to study different stellar populations and/or dust-reddening within a galaxy (see Figs. 2 & 3). Some of the galaxies which have the same appearance at all wavelengths fall outside the traditional Hubble tuning-fork diagram, but instead belong to new morphological groups, such as chain galaxies (Fig. 4; Cowie, Hu & Songaila 1995), tadpoles (van den Bergh et al. 1996) and bow-shock systems (Fig. 4).

Barred Spirals: Our data can also address the evolution of galactic bars: it has been claimed that at faint magnitudes, the fraction of barred spirals in the optical HDFs declines rapidly (van den Bergh et al. 1996, Abraham et al. 1999). If this is a truly evolutionary effect, then it has great significance for the physics of disk formation: bars are supported by disk self-gravity, so the implication would be either that at high-$z$ the halo mass dominates that of the disk, or there are significant random motions in the stellar orbits (Ostriker & Peebles 1973).

However, when the spirals are imaged in the near-IR, many are revealed to have bars which are absent in the WFPC 2 bands (Fig. 3): the bars have similar colors to the bulges (dominated by older, cooler, redder stars). It appears that morphological $k$-correction effects for the higher-$z$ spirals cause the apparent decline in optically-selected barred spirals at fainter magnitudes. From the small-number statistics of spirals in the GTO-NICMOS field, there is no significant evolution in the incidence of galactic bars.

3. Conclusions

Some Hubble tuning-fork galaxies only reveal their true morphology in near-IR. This is particularly so for galaxies with a large dispersion in stellar ages and spatially-distinct
stellar populations, such as in spiral galaxies. However, such galaxies which undergo a morphological metamorphosis from the WFPC 2 to NIC 3 images are rare; most retain the same appearance in all wavebands, or are too compact for the structural parameters to be determined. Once the morphological k-corrections have been accounted for, it appears that the fraction of true irregulars does increase at faint magnitudes/high-
z. Finally, the deep near-IR data shows that there is no significant evolution in the incidence of barred spirals with redshift: their apparent scarcity in the optical is a band-
shifting effect on the older stellar population of their bars. A more detailed description of this work is given in Bunker, Spinrad & Thompson (1999).

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Figure 1. Spiral galaxies at $z \approx 1$, showing the great change in apparent morphology going from the optical (the rest-UV, where the appearance is irregular) to the near-IR, where their true spiral nature is revealed. In the case of HDF 4-474 (left), the WFPC 2 images are dominated by a star forming knot, and for HDF 4-378 (right) the older/redder population of the bulge is only visible at IR wavelengths.

Figure 2. Stellar population fits to two spatially resolved areas of the $z \approx 1$ spiral HDF 4-474 (see Fig. 1), using the latest version of the Bruzual & Charlot (1993) models. The bulge (left panel) is clearly very much older than the star-forming H$_\text{II}$ region in one of the spiral arms (right panel).
Figure 3. A montage of galaxies down to $I_{AB} < 26.0$ which lie within the GTO-NICMOS Hubble Deep Field, ranked in order of redshift. Each galaxy is displayed in the waveband which most closely matches the rest-frame $B$-band, from the WFPC2 images (F450W–’$B$’, F606W–’V’, F814W–’I’) and the NIC3 data (F110W–’J’, F160W–’H’). Each box is 2 arcsec across. At higher redshifts, the incidence of the familiar Hubble-sequence galaxies declines greatly. The identification numbers come from the catalog of Williams et al. (1996), and the photometric redshifts are taken from Fernández-Soto, Lanzetta & Yahil (1999). Those denoted by ‘z(sp)’ have spectroscopically-determined redshifts.
Figure 4. Examples of a bow-shock interacting system (left) and a chain galaxy (right). Note the bow-shock area itself is comparatively blue, implying a young stellar population with star formation presumably triggered by the shock front, whereas the redder (older) core of the galaxy is more prominent in the near-IR. The chain galaxy (the two-component U-drop called “the Hot Dog”; Steidel et al. 1996, Bunker et al. 1998) appears the same at all wavelengths and is blue, implying a relatively homogeneous, young population (a primæval galaxy candidate?).

Figure 5. Spatially-resolved colors of the northern and southern components of the chain galaxy called “the Hot Dog” (HDF 4-555.1; Fig. 4). The northern and southern components exhibit subtly different colors, attributable to either different stellar populations or non-uniform dust extinction. Adopting the approach of Abraham (1997), we also plot the evolution in the $(V - I)$ and $(J - H)$ colors with time for a Salpeter IMF and an exponentially-decaying star formation rate, with e-folding times ranging from 0.1 Gyr to 1 Gyr. At $z = 2.8$, $(J - H)$ straddles the age-sensitive 4000 Å break.
Figure 6. The left panel shows the only optically-selected barred spiral in HDF-North (van den Bergh et al. 1996), and this seems to be through chance alignment of a swath of young stars with the approximate axis of the true bar. The galactic bar in the spiral displayed in the right panel is only recognizable at infrared-wavelengths – at its redshift of $z \approx 1$, the optical wavebands only sample the rest-UV, where the older & redder bulge/bar stellar populations are not prominent, with the light of young stars (e.g., the HII regions) dominating.