Morphological Evolution of Galaxies

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Abstract. The morphological evolution of galaxies as a function of redshift is studied using two quantitative structural parameters R_η (galaxy radius) and χ (high spatial frequency power). A direct comparison is made between nearby and distant ($0.2 < z < 1$) galaxies in the Hubble Deep Field (HDF) by following the $4500\mathring{A}$ rest-frame wavelength range.

Few if any of the HDF galaxies are similar in size and in star formation rate to dwarf galaxies such as NGC 4449 and NGC 1569. The majority of HDF galaxies have sizes comparable to local giant galaxies and are slightly more lumpy than *normal* galaxies. Dwarf galaxies undergoing high rates of star formation are unlikely to be local counterparts of the high-redshift population of galaxies. Based exclusively on the structural parameters studied here, giant galaxies undergoing intensive rates of star formation (giant star-burst galaxies) are possible local counterparts of the high-redshift *irregular* galaxies.

Keywords: galaxy morphology, star formation rate

1. Morphological Parameters

The Hubble morphological classification system of galaxies is based on three criteria (Hubble 1926):

1. "Relative size of the unresolved nuclear region"
2. "Extent to which arms are unwound"
3. "Degree of resolution in the arms."

If these criteria have no physical foundation we should leave behind the Hubble system. However, while it is imperative that we upgrade from the qualitative nature of the Hubble system to a quantitative one, it appears that the criteria on which the Hubble system is based are related to physically fundamental quantities. In fact, the first criterion quantified as e.g. the concentration index has been found to be related to the specific angular momentum in galaxies. The second criterion quantified as the pitch angle of the spiral arms at corotation has been found to be correlated to the shear rate of galaxies (see Block, this contribution). In this contribution, I present two novel parameters: (1) the metric radius of the galaxy (R_η) and (2) the power at high spatial frequencies or degree of lumpiness (χ) in the disks of galaxies, both of which quantify the third criterion of the Hubble system. The parameter χ has a simple physical interpretation which is the star formation rate in galaxies. Both parameters R_η and χ are studied in the context of the morphological evolution of galaxies with cosmological time.

A direct comparison is made between nearby ($z \sim 0$) and distant ($0.2 < z < 1$) galaxies by following the $4500\mathring{A}$ wavelength range. The data of the nearby galaxies comprise 136 B-band images of which 23 were obtained with the 0.9-m telescope at Kitt Peak National Observatory and the remainder were selected from the catalog of digital images of Frei *et al* (1996) (113 galaxies). The high redshift sample comprises 94 galaxies ($B_{450} < 25$ mag) from the Hubble Deep Field (HDF) (Williams *et al.* 1997).

The radius R_η is determined from the intensity profile of the galaxy using the formulation of Petrosian (1976). R_η is argued to be a metric radius and more robust than the isophotal radius since it does not depend strongly on angular resolution or limiting surface brightness of the data. On average, the metric radii of nearby and distant galaxies are comparable to each other. The median value of R_η in the local sample is $\langle R_\eta \rangle \sim 5 \pm 1$ kpc and the median R_η in the HDF sample is $\langle R_\eta \rangle \sim 6 \pm 2$ kpc ($q_\circ = 0.5$, $H_\circ = 65\ km/s/Mpc$).

The parameter χ is measured from the residual of the median-filtered image using a box of size approximately equal to the sizes of the star-forming regions (Takamiya 1999). In nearby galaxies, χ is found to trace the star formation rate as it is correlated with optical colors ($B - V$) and the strength of Hα emission lines (see Figure 1).

2. Galaxy Simulations

To assess the reliability of the metric radius and high-frequency power as a useful set of tools to study high redshift sources, simulations of galaxy images at redshifts comparable to the galaxies in the HDF are constructed.

Given that in the HDF 62% of the galaxies that are brighter than $B_{450} = 25$ mag have redshifts in the range $0.2 < z \leq 1$, this study is restricted to the V and I HDF images which sample the $\sim 4500\ \mathring{A}$ rest-frame wavelength range. In this fashion the high and low redshift galaxy comparisons require the least number of ad-hoc assumptions (e.g. knowledge of the shape of the spectral energy distribution in each pixel).

Using 36 nearby normal and irregular type galaxies, I simulated images of distant galaxies at three redshifts: 0.35, 0.5, and 0.9 as illustrated in Figure 2. At $z = 0.35$ and $z = 0.50$ the simulations are

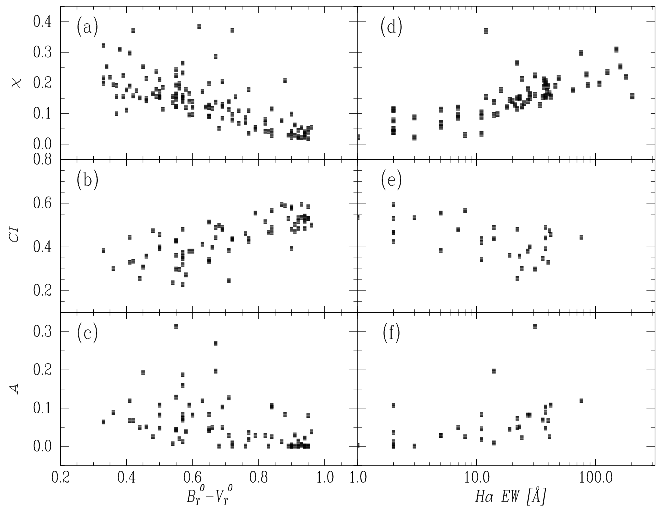

Figure 1. The parameter χ and the parameters introduced by Abraham *et al.* (1996): asymmetry and concentration index are compared to the extinction corrected and total $B-V$ color and Hα equivalent width.

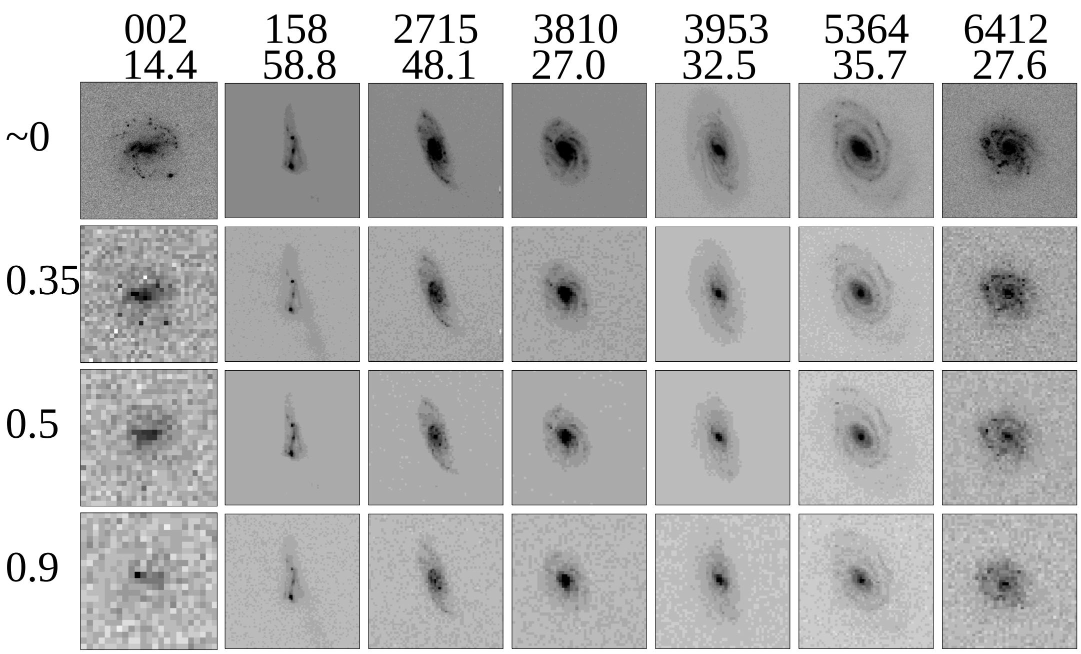

Figure 2. Illustration of simulated galaxy images. Each column shows a different galaxy as indicated at the top. Each row represents a different redshift that increases downwards (Arp 002, Arp 158, NGC 2715, NGC 3810, NGC 3953, NGC 5364, and NGC 6412). For each galaxy, the field of view covered in kpc is indicated underneath the galaxy number. The intensity levels are 4 standard deviations above the median (black) and 5 standard deviations below the median (white).

of images in the WFPC2/$F606W$ filter for a total integration time of 30.3 hours, and at $z = 0.90$ they correspond to the WFPC2/$F814W$ filter in 34.3 hours. The simulations show a decrease in signal-to-noise ratio and angular resolution with the most conspicuous features being the cores of the galaxies. Consequently, with decreasing signal-to-noise galaxies are identified and classified with regards to the significance of their cores. All galaxies retain their shapes which can be recognized with their original forms except for small galaxies like Arp 002 (as well as NGC 4449 and NGC 1569). At large redshifts small galaxies ($R_\eta < 3$kpc) remain largely undetected while giant galaxies (both normal and irregular) are detectable in the WFPC2/HDF data.

Analysis of the simulated images that reproduce HDF galaxies show that the metric radius can be recovered to better than ± 2 kpc (1-4 pixels). The spread is larger with increasing redshift. As for the χ parameter, it is expected that the reduced signal-to-noise ratio, relative increase in background, and cosmological surface brightness dimming tend to accentuate the visibility of high contrast features. The simulations corroborate this expectation showing that in general the values of χ increase slightly with redshift. It is worth emphasizing that these effects will artificially increase the likelihood of identifying high redshift galaxies as irregulars.

3. Conclusions

For a restricted sample of the HDF galaxies ($z < 1$ and $B_{450} = 25$ mag), χ reaches values similar to those of nearby galaxies and to what is expected from simulations of distant galaxy images. Comparisons of nearby galaxies with WFPC2/HDF galaxies at $z > 1$ require *morphological k-correction* and therefore are subject to larger uncertainties than at $z < 1$. Among the HDF galaxies, I find that few if any can be identified with a population of dwarf galaxies with rates of star formation similar to NGC 4449 or NGC 1569. While big HDF galaxies ($R_\eta > 13$kpc) have large values of χ, by and large most HDF galaxies are giant galaxies ($R_\eta > 3$kpc) with χ values similar to that of nearby galaxies (see Figure 3). Based on the parameters R_η and χ it is likely that the true *irregular* HDF galaxies are similar to nearby giant star burst galaxies (possibly similar to Ultra Luminous Infrared Galaxies or Luminous Infrared Galaxies). Most HDF galaxies are similar to nearby normal galaxies, few if any star-bursting dwarf galaxies are detected in the HDF, and $\sim 20\%$ of the HDF galaxies with $z < 1$ are *irregulars* (half of which have large intrinsic sizes).

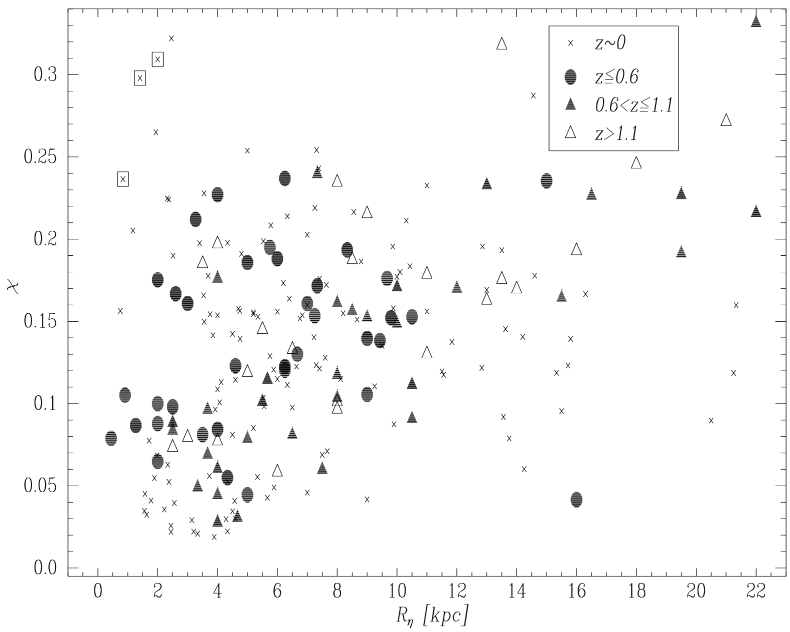

Figure 3. Metric radius (R_η) vs. degree of lumpiness (χ). Small crosses are nearby galaxies, filled circles are HDF galaxies with $z \leq 0.6$, filled triangles are HDF galaxies with $0.6 < z \leq 1.1$, and open triangles are HDF galaxies with $z > 1.1$. Open boxes indicate examples of nearby dwarf galaxies undergoing high star formation rates.

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