The Symmetry, Color and Morphology of Galaxies in the Hubble Deep Field

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Abstract.
We present a new method of utilizing the color and asymmetry values for galaxies in the Hubble Deep Field to determine both their morphological features and physical parameters. By using a color-asymmetry diagram, we show that various types of star-forming galaxies (e.g. irregular versus interacting, peculiar galaxies) can be distinguished in local samples. We apply the same methods to the F814W images of the Hubble Deep Field, and show preliminary results indicating that galaxy mergers and interactions are the dominate process responsible for creating asymmetries in the HDF galaxies.

INTRODUCTION

One of the main purposes of the *Hubble Deep Field* (HDF) is to provide an unprecedented opportunity to examine the morphologies of distant galaxies. However, for a large fraction of the galaxies in the HDF (40%), no meaningful morphological indicator of type can be assigned. A problem coupled with the morphology of HDF galaxies is the question of whether the "peculiar" galaxies are merging systems, or if these galaxies are just undergoing an intense episode of star-formation. In this paper, we present a method for determining the morphologies of galaxies in the HDF based on both galaxy asymmetry and rest-frame UBV colors. We use a nearby galaxy sample to simulate the appearance of HDF galaxies, as well as to develop methods that insure reliable comparisons can be made between nearby galaxies and the more distant HDF sample. Our preliminary results indicate that a large portion of the 'peculiar' galaxies in the HDF are probably undergoing a merger or interaction, based on their asymmetry and color values.

MORPHOLOGY USING ASYMMETRY

The first uses of asymmetry for distant galaxy classification [1], [2] used asymmetry as a rough morphological parameter, with image concentration as a second classification parameter [2]. Asymmetry and concentration, while useful for segregating irregular or 'peculiar' galaxies, do not alone distinguish between irregular morphology due to interactions, or simply non-uniform star formation in turbulent environments (e.g. gas rich, dwarf irregulars). Conselice [3] tested the use of asymmetry as a general morphological parameter for nearby galaxies, finding a strong correlation between asymmetry and color.

Here we reformulate earlier methods ([2], [3]) to derive a consistent approach of measuring galaxy asymmetry applicable at both high and low redshifts. Simulations of nearby galaxies degraded in resolution and S/N show significant changes in the asymmetry. It is therefore necessary to correct for these effects, which are common in high-redshift galaxy images. In this preliminary presentation we have corrected for noise, but not for image degradation. Another critical facet of our new formulation concerns finding a self-consistent center about which to rotate the galaxy image. Both [2] and [3] defined the center of rotation by the brightest pixel centroid value. This is not a reliable method for finding the center: galaxy images have brightest pixels which change considerably with image degradation, yet very small changes in the center pixel values change the measured asymmetry considerably. To avoid this problem, we compute the asymmetry for a grid of rotation points centered on an initial best guess. We search for the center yielding the minimum asymmetry value, and iterate the search as necessary until a true minimum is found. This allows a robust method of finding the asymmetry to be computed which is fairly insensitive (in this regard) to resolution.

For galaxies in the HDF with high S/N $>$ (50) in I_{814} which span the redshift range from ($0<z<4.5$) we compute the asymmetry parameter using the corrections mentioned above. We also compute rest frame B and V colors for each galaxy based on either spectroscopic redshifts, or from photometric ones based on F300W, F414W, F606W, F814W, J,H, and K magnitudes [5]. The k-corrections are computed in the empirical and interpolative manner as described in [6]. As such, the rest-frame UBVI colors at higher redshifts, while accurate, have lower precision because they rely increasingly on the near-infrared observed bands which are at lower S/N than the optical data. This should improve with the addition of photometry from deep NICMOS imaging of the HDF.

COLOR-ASYMMETRY DIAGRAM AT $Z = 0$

The color-asymmetry diagram can give a good morphological and physical indication of the present physical state of a galaxy. For the nearby sample of Frei et. al. [4] there is a strong correlation between the asymmetry of a galaxy and the color index for non-interacting face-on systems (Figure 1, left panel). The trend is, as might be expected: blue galaxies are asymmetric while red galaxies are symmetric. However, if we plot the entire Frei sample, which contains galaxies considered 'irregular' or 'peculiar' as well as edge-on disk galaxy systems, we obtain features which do not lie along the normal color-asymmetry sequence (Figure 1, labeled sources in left panel). The fact that these objects do not coincide with the face-on normal galaxies gives a method for deciphering these objects from normal face-on high-surface brightness galaxies at high-redshift. In contrast, the objects at the bluest-asymmetric end of the normal galaxy sequence are true irregulars – that is: the asymmetries are caused by star-formation, and not from projection effects (inclination), or from interactions.

By simply plotting asymmetry and color for a sample of galaxies, one cannot immediately disentangle which galaxies falling outside the normal sequence are inclined or interacting. This requires additional morphological information obtained by direct image inspection. Since, for the most part, inclined systems have a high axis ratio, they can be distinguished easily from interacting systems.

Asymmetries of the Hubble Deep Field galaxies

To first order the HDF sample *avoids* the trend of asymmetry with color as seen in the local sample of Frei et al. The majority of galaxies in the HDF are either too asymmetric or too symmetric for their colors (compared with the local sample). However, the local sample includes almost entirely bright (~L*) galaxies (presumably as does the HDF for galaxies at the largest redshifts), while for $z < 1$, many of the HDF galaxies are low luminosity (sub-L*). Indeed, the colors of the

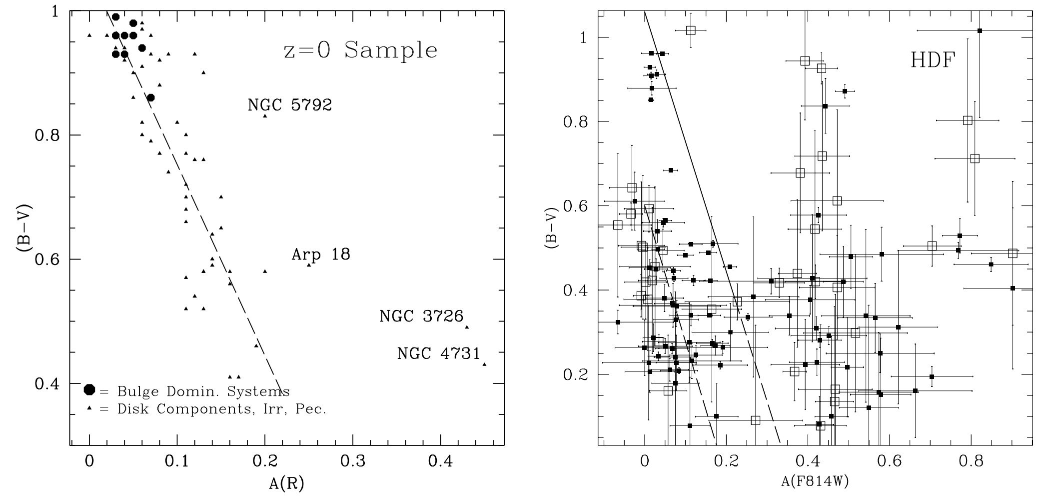

FIGURE 1. Asymmetry-Color diagrams for a local $z = 0$ sample (left panel), as well as for the high S/N galaxies in the HDF (right pabel). A tight correlation between color and asymmetry can be seen in the local sample for most objects with A<0.2 (solid line, both panels). The objects not on this line, labeled with NGC numbers, are galaxies generally regarded as undergoing an interaction or merger. In the HDF sample ($z > 1$, open symbols; $z < 1$, filled symbols), we see a strong bimodal pattern, with most galaxies either very asymmetric or symmetric for their blue colors.

HDF galaxies are blue compared to galaxies in the local Frei et al. sample, with very few galaxies having colors with (B-V) >0.80 (e.g. the colors of un-evolved ellipticals).

It is likely that the highly asymmetric HDF galaxies are the result of interactions. Normal star-formation processes as defined by the local sample would still lead galaxies to lie along the local sequence, albeit at the extreme blue, asymmetric end. Moreover our visual inspection of the asymmetric, blue HDF galaxies (A>0.3) reveals that the majority (80%) are not highly inclined. The asymmetric 'objects' in the HDF cannot be star-bursting regions embedded in a largely hidden galaxy, since in this scenario the bursting region would likely be blue and symmetric.

A class of galaxy not seen in the local sample but present in profusion in the HDF are blue, symmetric objects. These systems might be related to the blue-nucleated objects similar to those found in z $\approx$ 0.5 surveys (e.g. [1]), although Jangren et al. [7] find these specific objects to have A>0.2. The appearance of such a 'new' class of objects could be due either to increased, nucleated (symmetric) star-formation, or to resolution effects – an issue we are exploring. We emphasize, however, that in our asymmetry formulation, resolution effects will only tend to lower A. Hence the highly asymmetric galaxies discussed previously cannot be an artifact of the analysis.

Our preliminary results indicate that a large portion of the galaxies in the HDF, while extremely blue, are not undergoing a burst of star formation in a manner similar to nearby irregular galaxies. For the most part these galaxies do not appear morphologically as thin, highly inclined systems, but appear as 'peculiar' galaxies. Another substantial fraction of HDF galaxies appear to be highly blue and symmetric. If this is not a result of decreased physical resolution, we would surmise these systems have enhanced nuclear starbursts. Roughly 40%, however, appear too asymmetric for their blue color. Such asymmetry is indicative of interactions or mergers which are disturbing the global light distribution. While these results are preliminary, if the deviation from the normal-galaxy color-asymmetry sequence is confirmed to increase with redshift as we have found, this indicates that *merging* is a *critical* process shaping the morphology of high redshift galaxies.

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