The Size Evolution of High-Redshift Galaxies

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Abstract. It is appropriate in a conference on the growth of galaxies to examine what we know about the evolution of galaxy sizes. Quantifying galaxy size evolution is challenging because most high-redshift galaxies are only barely resolved from the ground. The Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) has greatly improved our ability to measure the spatial structure of distant galaxies. We briefly review previous HST measurements of size evolution and present early results from analysis of the first three-fifths of the Great Observatories Origins Deep Survey (GOODS) ACS data. The observed size evolution appears to follow the basic trends expected from hierarchical models.

1 Introduction

Observations from HST over the past several years have provided us with clear evidence for the evolution in galaxy morphology and size. The challenge now, with larger and deeper samples, is to quantify that evolution to an accuracy useful for testing theoretical models. We focus here on galaxy sizes, which are perhaps the simplest morphological quantity to measure and interpret.

The basic framework of galaxy formation within the hierarchical Cold-Dark-Matter (CDM) cosmology was set out by White & Rees[25], and has been refined by numerous N-body and semi-analytical studies [24,10,4,20]. Most studies follow the basic framework of Fall & Efstathiou [8], in which dark halos acquire their angular momenta via tidal torques, the angular momentum per unit mass of the baryons and the dark matter are initially the same, and angular momentum is conserved as the baryons collapse and cool to form a disk. With these simplifying assumptions the baryons typically collapse by factors of ~ 10 and the resulting disks have rotation curves, surface-density profiles, and scale radii similar to those observed locally. Further analytical studies have calculated the distribution function of disk-galaxy sizes and the disk-galaxy size-redshift relation [5,13]. Meanwhile cosmological N-body + hydrodynamical simulations have formed disks that appear similar to spiral galaxies, but that tend to be too small to match present-day galaxies ([14]; but see [7]). It is not yet known whether the source of this discrepancy lies in baryonic, dark-matter physics, or numerical issues in the simulations.

If the general Fall & Efstathiou view of disk formation is correct, there are two rather robust expectations that are worth exploring through the observations of high-redshift galaxies. (1) The sizes of galactic disks forming at a redshift z should be a fixed fraction of the size of the dark-matter halo, and therefore scale

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with redshift as $R_s \propto H^{-1}(z)$ at fixed circular velocity, or $R_s \propto H^{-2/3}(z)$ at fixed mass. (2) If governed primarily by the angular momenta of their halos, the sizes of disk galaxies should should show a log-normal distribution.

The theory described above is specific to disk galaxies. However, it is not unlikely that, at least at early times, the scaling with redshift is similar for early-type galaxies (i.e. that the characteristic radii of the luminous parts of these non-rotationally supported galaxies are directly proportional to the virial radii of the dark-matter halos). For both types of galaxies there are likely to be a variety of effects, only partially included in theoretical models, that may influence the size distribution or scaling with redshift. Merging, adiabatic contraction, the sensitivity of star-formation thresholds to the the metagalactic background and chemical evolution, are all likely to be relevant. Furthermore, one should differentiate between galaxy radii at the "formation epoch", with the expected simple redshift scaling discussed above and galaxy radii at some later epoch. This distinction may become quite important for understanding trends at redshifts $z < 1$. In any case, it is certainly worth measuring the trends, even if there is not a rock-solid set of predictions. We adopt the cosmology defined by $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ throughout this paper.

2 Previous Observations

Redshift $z \sim 1.3$ provides a natural dividing line for studying size evolution. At lower redshifts it is possible to work at rest-frame optical wavelengths and it is interesting and sensible to restrict the comparisons to specific Hubble types. At higher redshifts, the dearth of high-resolution near-IR data forces us to work in the rest-frame ultraviolet and the morphological connection to present-day Hubble types becomes more tenuous. The evolution of disk galaxies to $z \sim 1$ has been explored previously via the magnitude–size ($M_B - r_e$) relation [17,11,16,18,2] and the Tully-Fisher ($M_B - V_c$) relation [23]. Based on *HST* imaging, most studies found evidence for a significant increase ($\sim$ 1–1.3 magnitude) in the rest–frame B-band surface brightness of disk galaxies to $z = 1$, while Simard et al. [18] found no evidence for surface brightness evolution once the selection effects of the survey were taken into account. The luminosity–size evolution of disks remains a controversial issue and the interpretation of any observed evolution with redshift depends crucially on accounting for the selection biases of the survey [18,6,2]. Lilly et al. [11] reported that the abundance and size distribution remains constant out to $z \sim 1$, for the large disks with scalelengths greater than ~ 5 kpc, for which their sample is fairly complete. The space densities at different look-back times provides a key observable to help determine how and when large galaxies like the Milky Way were formed.

At higher redshifts early results from the Hubble Deep Field (HDF) indicated that Lyman-break galaxies were in general smaller than local early-type galaxies [12]. Bouwens et al. [1] have done pioneering work quantifying the selection biases, using the technique of "cloning" dropouts from lower redshifts. They find a trend from redshift $z \sim 3$ to $z \sim 5$ that is consistent with $r(z) \propto (1+z)^{-1}$