Photometry Strategies for Distant Clusters

Gregory D. Wirth, David C. Koo, and Matthew A. Bershady
UCO/Lick Observatory, University of California, Santa Cruz

Measuring the shapes and sizes of distant cluster galaxies quantitatively from HST WF/PC-1 images presents some challenging problems, including how to define the galaxy's radius and "total light," and how to quantify the profile shape. We describe an approach that uses circular aperture photometry to obtain a well-defined radius and magnitude, and employs a simple statistic known as the concentration index to describe galaxy profiles. Simulations suggest this method can distinguish between disk- and bulge-dominated galaxies to fairly faint magnitudes. We use this technique to study the morphology of galaxies in the distant cluster 0016+16 at $z = 0.55$ and show that the unusual "E+A" class of galaxies featuring strong Balmer absorption lines is not likely to include normal elliptical galaxies.

Presented at *Quantifying Galaxy Morphology at High Redshift*, a workshop held at the Space Telescope Science Institute, Baltimore MD, April 27–29 1994

1 Crowded-Field Galaxy Photometry

The task of measuring the "structural parameters" (size, shape, surface brightness) for high-redshift galaxies is a job for HST — but not an easy job! Performing galaxy photometry using WFC-1 images of a distant cluster has provided us some insight which we share in this contribution. Special problems in such data include low signal-to-noise ratio (SNR) images, noise amplification that arises from deconvolving the images, and contamination of the galaxy profiles by light from neighboring objects.

To illustrate the difficulty, consider the "simple" task of measuring the brightness of a galaxy. In the ideal case of a large, bright, isolated galaxy, the growth curve (light within a given radius) increases smoothly and monotonically from the center of the galaxy outward, tending toward an asymptotic limit which is the ideal "total light." In contrast, for a typical Cl0016+16 galaxy, the growth curve increases smoothly and monotonically at first, but noise and the presence of neighbors cause the growth curve to begin fluctuating before the total light is determined. There is no asymptotic limit to the growth curve, and thus no well-defined "total magnitude."

Measurements of galaxy size and brightness are closely linked: if the radius of an object is poorly determined, then the total light is not well defined. Our goal is to measure sizes using a method which ideally has the following attributes:

- *Shape independent.* The size measuring technique should not assume a particular profile shape. Since the "effective radius" R_e is a fitting parameter in the $r^{1/4}$ law, it's valid only for measuring elliptical galaxies.
- *Brightness independent.* Galaxies having identical profiles but different magnitudes should have the same radius. This excludes isophotal magnitudes, such as those obtained with the FOCAS photometry software.
- *Redshift independent.* The radius should be the same for identical galaxies at different redshifts. The D_n method requires a redshift-dependent correction for the cosmological dimming of surface brightness, and is thus unacceptable.
- *Total light not required.* Since the total light is hard to determine, the size shouldn't depend on knowing the total light. The half-light radius $r_{0.5}$ fails this criterion.

While it's unlikely that any method could satisfy all of these conditions in practice, we have used a technique that comes close.

We began by measuring the growth curves for galaxies using software written by one of us (M. A. B.). Neighbors are removed by simply masking all pixels lying within $3'$ of other objects, and photometry within circular apertures then provides the profile. To define sizes, we measured the Petrosian metric radius of each galaxy. This Petrosian radius is measured from the "η profile" of the galaxy, defined as $\eta \equiv I(r)/\langle I(r)\rangle$, where $I(r)$ is the brightness profile (surface brightness at r) and $\langle I(r)\rangle$ is the average brightness profile (average surface brightness interior to r). When defined in terms of flux (rather than magnitudes) the η profile has a central value of 1, and decreases toward an asymptotic limit of 0. The radius can then be defined in terms of a value of η: for example, we have defined the "metric radius" of our galaxies as the radius where $\eta(r)$ reaches a value 0.1. Sizes obtained in this manner are (ideally) independent of shape and brightness. In the absence of color gradients they are wavelength- and redshift-independent; furthermore, *global* luminosity evolution will not affect these metric radii. Naturally, they do depend on the noise, seeing, and in the case of circular aperture photometry, galaxy ellipticity.

Given this well-determined metric radius, we can define an analogous "metric light" within this metric radius. For an ideal axisymmetric $r^{1/4}$ profile, 87% of the total light is contained within the $\eta = 0.1$ radius, while exponential disks include 95%.

2 Concentration Index as Shape Parameter

We'd like to accomplish more than just measuring the sizes and surface brightnesses of these distant galaxies. For studying early-type galaxies, it's useful to know which galaxies in a sample are likely to be ellipticals and which are probably not; thus, we desire a simple quantitative parameter to distinguish between disk and bulge morphology. A first step would be to analyze the galaxy profiles, but in reality the profiles are quite noisy. Instead, consider the growth curves of the galaxies: as integrated versions of the surface brightness profile, these are inherently more stable. How can we use the growth curves to distinguish different profile shapes?

Figure 1 shows the idealized growth curves for the $r^{1/4}$ profile typical of an elliptical galaxy and the exponential disk used to describe spiral galaxies. Notice how much steeper the exponential disk growth curve becomes at the half-light radius, compared to the $r^{1/4}$ law. Although you might choose to fit a line to this part of the growth curve to obtain a measure of the steepness, the same thing can be done by using the separation (in log space) of the radii enclosing 20% and 80% of the total light. This is essentially the concentration index (C) which has been used previously, defined by $C \equiv 5\log(r_{0.8}/r_{0.2})$, where r_N encloses a fraction N of the total light. The quantity C measures the profile *shape* independent of the *size*.

As belabored above, we don't know the total light for these galaxies; however, the metric light is close to the total light, and so we define a concentration index for which r_N measures a fraction of the *metric* light, rather than of the *total* light. This changes the profile shape slightly, so that we expect ideal $r^{1/4}$ profiles to have $C = 4.6$ instead of 5.3, while disks give 2.7 (vs. 2.8 using total light). For comparison, a Gaussian profile which normally has $C = 2.2$ would yield 2.1 by our metric method.

3 Theory Confronts Reality

So much for the theoretical discussion of the concentration index and the Petrosian radius — how well do these parameters work in reality? We used the techniques described above

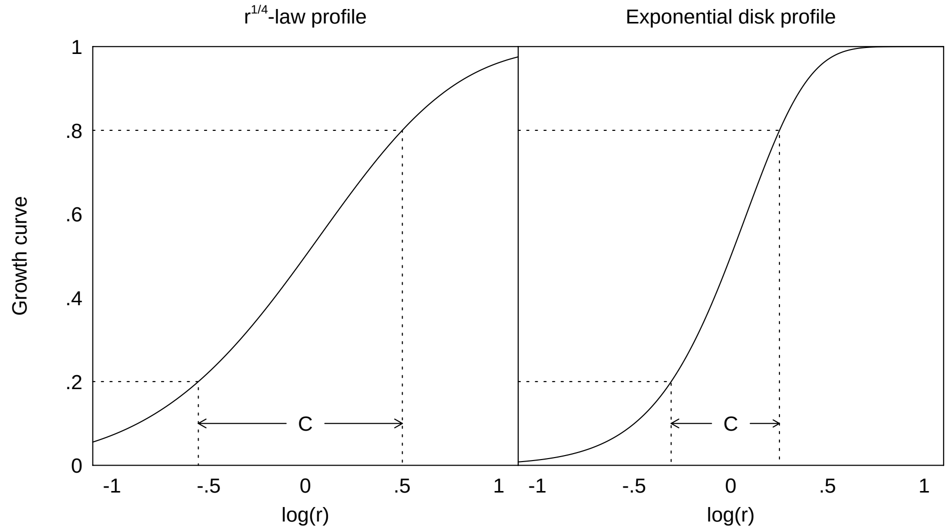

Figure 1: Comparison of the growth curves for ideal $r^{1/4}$ and exponential disk profiles. The concentration index basically measures the distance marked as C.

to analyze deconvolved HST WFC-1 images of the distant cluster 0016+16, a particularly rich and red group of galaxies at redshift $z = 0.55$. We expect that in these real data several factors will conspire to muddle the clear picture implied by the above discussion: spherical aberration degrades the resolution; pixellation of the images causes further loss of spatial information; and noise results in a breakdown of our ability to distinguish profile shapes at some magnitude limit.

To check how these factors will affect real galaxies, we ran some simple simulations by generating axisymmetric disks and bulges of different sizes and brightnesses, convolving with the image of a deconvolved star, and inserting these fake galaxies into a Cl0016+16 image. Figure 2(a) shows the resulting distribution of C vs. metric magnitude, and overall the news is encouraging: pure disks can be discriminated from pure bulges past m=21. At the bright end, the disks achieve their ideal value of $C = 2.7$, and the bulges tend toward their target of 4.6 for C. As expected, there is some size dependence, with smaller objects being more difficult to discriminate.

Measurement for actual galaxies in the Cl0016+16 images are shown in Fig. 2(b). Since the simulations assumed round objects that were either pure disks or bulges, and since real galaxies are often elliptical in shape and include both disks and bulges, the scatter in the real observations is higher. The squares mark galaxies with spectra typical of late-type stars, and their location in this graph coincides well with the predicted location of the $r^{1/4}$ profiles;

hence, these are probably ellipticals. Circles denote emission line galaxies, which we might expect to be spirals. Indeed, they generally lie in the bottom of the diagram, in agreement with the exponential disks. Triangles identify a third spectral type in this cluster, "E+A" galaxies which have spectra resembling the combination of a late-type stellar spectrum with strong Balmer absorption lines typical of an A star. The concentration index measurements show that these galaxies are closer in shape to the exponential disks than to the bulge systems, and hence are unlikely to be normal elliptical galaxies.

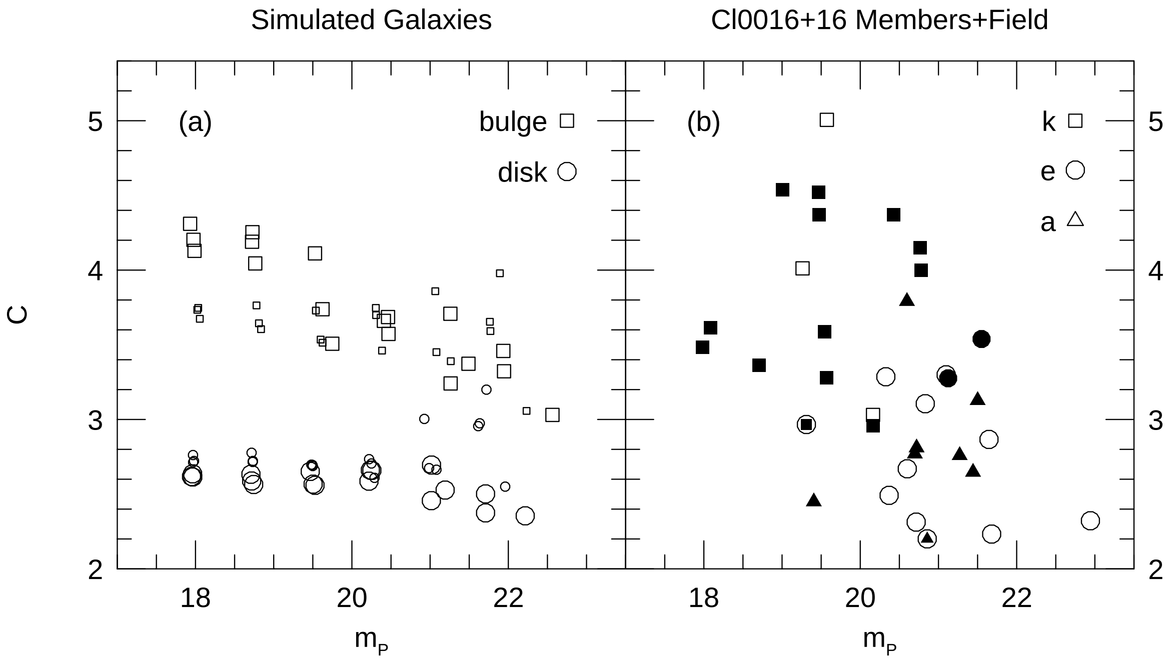

Figure 2: Concentration index vs. metric magnitude in Cl0016+16. (a) Measurement for simulated galaxies; larger symbols denote longer model scale lengths. (b) Values for actual galaxies in Cl0016+16 field, including members (filled symbols) and field galaxies (open symbols) with spectral types as indicated.

Quantifying the morphology of distant galaxies is a difficult undertaking, and using the concentration index to measure profile shapes is but a small first step. Nevertheless, this exercise has shown that even pre-refurbishment HST images of distant galaxy clusters contain valuable morphological information.