Galaxy Form and Spectral-Type: A Physical Framework for Measuring Evolution

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Abstract.
I outline a quantitative method for characterizing galaxies both by photometric 'form' and indices of spectral-type, applicable to both nearby and distant galaxies. Such a characterization provides insight on galaxy evolution because there are physical connections between galaxies' stellar populations and their light distribution. "Normal" galaxies' form-parameters (surface-brightness, image concentration and asymmetry) correlate well with spectral-index (color), which in turn correlates only weakly with scale (size or luminosity). Deviations from these normal relations also offer clues to the physical modes of galaxy formation and evolution. As an example, I contrast a puzzling, distant population of compact, but luminous, blue, star-forming galaxies to nearby samples. These distant sources appear to be associated with the bulk of the luminosity increase since $z < 1$. They have structural properties comparable to low-redshift populations, and photometric properties within the norm for nearby, actively star-forming galaxies. When combined, however, their photometric and structural properties appear to be highly unusual.

Keywords: galaxies, classification, morphology, spectral type

1. Classification and Evolution

While great strides recently have been made in identifying galaxies out to very large look-back times (e.g. Steidel *et al.* 1999), when galaxies form and how they evolve is still an issue of debate. The primary physical processes determining a galaxy's appearance are the aggregation of matter and the ensuing star-formation, stellar evolution and chemical enrichment – all within the dynamical development of a gravitating system. It is possible and compelling to model these processes and predict how galaxies appear *a priori* (e.g. Contardo *et al.* 1998). Our limited understanding of the feed-back mechanisms associated with, and controlling star formation make such simulations challenging. In a complementary approach, the specific form and time-scales of these physical processes (e.g. monolithic collapse vs. merging of bound systems, dissipation vs. violent relaxation, and monotonic vs. stochastic star-formation histories) may be differentiable within an observational framework. Sandage (1986) outlined how the Hubble sequence today can be interpreted in terms of different monolithic collapse and star-formation histories. The interpretation, however, is not unique; in hierarchical structure-formation scenarios different inferences are drawn for how disks and spheroids form (e.g. van den Bausch 1998). With a multiplicity of evolutionary paths to a single, current galaxy type, an observational approach to differentiating between these paths is desirable. *Since the ability to measure change relies on making a comparison between galaxies at disparate distances, classification is a cornerstone of galaxy evolution studies.*

To proceed observationally, a framework is needed which takes advantage of current knowledge. For example, there is a *fundamental* connection between stellar populations and local galaxies' structure, known since Baade's study of on our own galaxy and the bulge of M31. Simply interpreted, bulges are spatially compact, nearly spherical, dynamically warm ($V_{rot}/\sigma \sim 1$) systems composed of old, cool stars; disks are dynamically cold ($V_{rot}/\sigma \gg 1$), more diffuse, and the sites of recent, massive star-formation. This simple picture belies a much more complex entanglement of stellar populations (e.g. King, 1971), and more varied dynamical and structural properties of disks and bulges. Nonetheless, large galaxies today have discernibly different spatial and dynamical distributions of stellar populations. These differences are evolutionary clues which can be exploited.

Here we consider the following physically motivated classification scheme, to be applied to galaxies over a range of look-back times: The amount of dissipation in bound, luminous matter is inferred directly by measuring image concentration and surface-brightness. Time-scales for star formation and matter aggregation are assessed independently via characterization of stellar populations, gradients, changes in galaxy scales, and asymmetry. Concentration, surface-brightness, asymmetry, color, and luminosity (or size), then, compose at least part of a critical subset of the classification tools necessary for studying galaxy evolution. Together they are sensitive to the temporal change in the spatial distribution of star-formation.

Such a classification scheme sounds remarkably similar to that proposed over years ago by Morgan & Mayall (1957). They reformulated the concept of galaxy classification set forth by Hubble two decades earlier, and made stellar populations the primary classification parameter. This departure allowed Morgan (1958) to discover that the spectral-type of galaxies' nuclear regions correlated strongly with image concentration. (This is essentially the inverse of Hubble noting that color correlated with morphological type, but here in more physical terms of stellar densities and populations.) Nonetheless, image structure (morphology or "form") remained an essential secondary parameter in Morgan's classification. *This indicates the importance of both form and spectral-type as independent classification axes.*

Form and spectral-indices[1] are now being explored in exquisite detail with modern data-sets; there has been much recent progress in placing galaxy classification on a secure, quantitative footing (e.g. these proceedings and references therein). Most of these explorations, however, have stayed within the context of the Hubble classification scheme, or consider either form or spectral-indices in isolation. Conselice *et al.* (2000) and Jangren *et al.* (1999) recently have demonstrated how modern measures of form and spectral-indices can be used powerfully in concert. Whitmore (1984) long ago pointed the way: His two dominant dimensions are "form" (disk-to-bulge ratio and color) and "scale" (size and color). Whitmore's analysis, based on local, luminous spirals, mixes what we term here as form and spectral parameters. To develop a classification for both nearby and distant samples we deliberately want to separate these parameters from each other and from scale, and then determine how correlations between them evolve.

Indeed, a crucial facet of classification is the ability to incorporate galaxies of all scales (mass, size, and luminosity) in a physically intelligible way. Can late-type galaxies, with neither well-formed disks nor bulges but characteristically low luminosities, be classified sensibly via form and spectral-indices alone? One distinguishing physical parameter here is the ratio of the current to past-average star-formation rate. It should be possible to measure this parameter not only spectroscopically (e.g. color), but via form, through the amplitude of HII regions (flocculence, or high-frequency asymmetry) relative to a smooth, underlying stellar population. Hence there is promise that form and color can be used to distinguish at least between active and quiescent dwarf galaxies, and certainly between the majority of dwarfs and giants observed locally. Determining how such distinctions become distorted at higher redshift gains us insight into how galaxies evolve.

In the balance of this paper I sketch some of the principal dimensions of the classification motivated above, and demonstrate their utility for understanding the nature of compact, luminous galaxies observed at intermediate redshifts.

2. A Modern Revision of Morgan's Classification Scheme

There are numerous ways to define measures of form, spectral-index, and scale. What is presented here is not unique, but the parameters

[1] While Morgan intentionally defined galaxy nuclear spectral-type within the paradigm of classical stellar classification, this may not be suited ideally for a general galaxy classification (e.g. admixtures of hot and cool stellar components must be characterized; nuclear spectra may unobtainable or poorly defined). For clarity, we henceforth refer to other measures of galaxy spectral-type as spectral-indices.

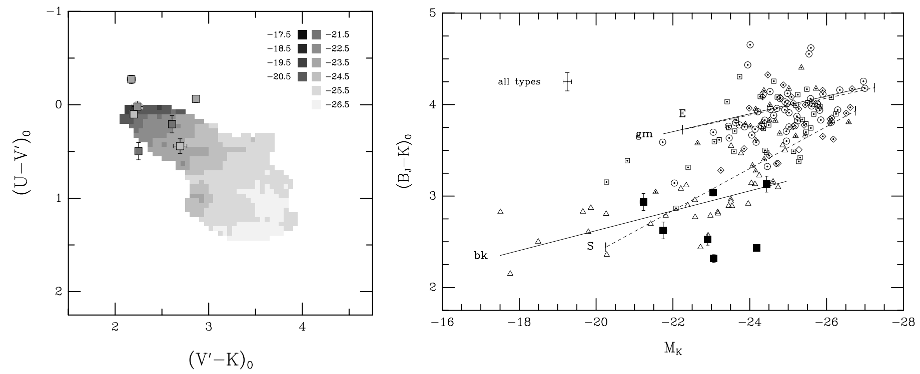

Figure 1. Left: $UV'K$ color-color diagram, showing the mean K-band luminosity of a $B = 20.5$ field galaxy survey as a function of multi-color. Seven LBCGs are superimposed, shaded according to their luminosity. Right: $B_J - K$ vs. M_K color-magnitude diagram for the same field sample, with the seven LBCGs again superimposed (dark symbols). These figures, adapted from Bershady (1995; symbols, coded by broad-band, optical–near-IR spectral-type are identified therein), show that (a) there is a strong correlation in the mean between color and luminosity for all galaxies, but a large range of luminosity for a given color; (b) while LBCGs are among the most luminous galaxies for their luminosity, they are not exceptional *as a class* when compared to a general field population at low redshift.

have been chosen to be robust to changes in signal-to-noise and image resolution, and are cost-effective in terms of the required telescopic observations relative to delivered information. Specifically, we use:

1. A spatially-integrated spectral-index, or stellar population parameter: ideally measured via optical and near-infrared multi-colors or spectra, but rest-frame $B - V$ can be used as a low-cost surrogate.

2. Form parameters: concentration (C), surface-brightness (μ), and asymmetry (A), as measured in a single, rest-frame band.

3. Scale parameters: size (r), and luminosity (L) – these should not be viewed as identical since there is a range of surface-brightness at any given r or L. Ideally, a kinematic measure of mass would be added as a third, independent scale parameter.

Figures 1-3 illustrate selected correlations between the above parameters for two samples that we use to form a reference-set of nearby galaxies: (i) the Frei *et al.* (1996) sample, as studied by Conselice *et al.* (2000) and Jangren *et al.* (1999); and (ii) the somewhat more distant ($z \sim 0.13$) photometric sample from Bershady (1995). The latter contains a substantial number of low-redshift, low-luminosity, actively star-forming systems, but has no measured form-parameters.

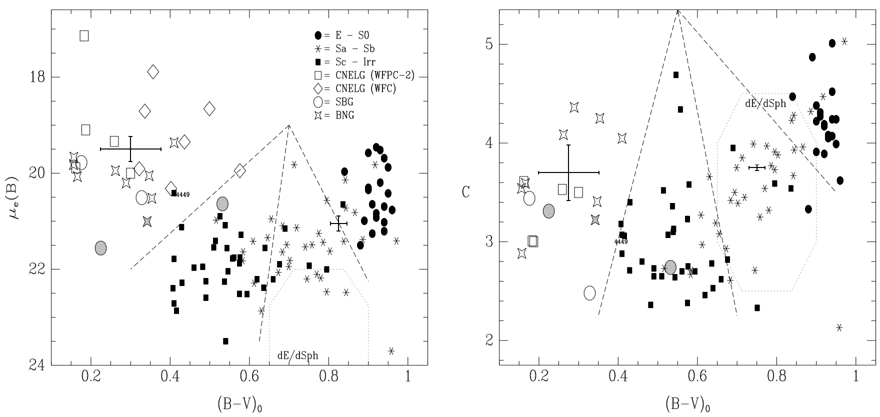

Figure 2. Left: B-band half-light surface-brightness vs. $B-V$. Right: B-band concentration vs. $B-V$. Dashed lines are heuristic classification boundaries, analogous to Abraham *et al.* (1996) for A vs C. Adapted from Jangren *et al.* (1999).

The Frei *et al.* sample, like most – if not all – bright galaxy samples, is unrepresentative of the number and variety of low-luminosity and small systems. Consequently, the reference distribution of form-parameters, based here only on the Frei *et al.* sample, should be viewed as preliminary. To amend this, we are in the process of measuring form-parameters for other samples containing nearby, star-forming dwarfs. Here, we schematically indicate the locus of dwarf ellipticals/spheroidals in Figures 2 and 3 as compiled by Jangren *et al.* (1999) and references therein. Finally, we have included an intermediate redshift sample of what we will term "luminous, blue compact galaxies," (LBCGs).

Focusing first on "nearby" samples, the following correlations are apparent. Spectral-index and luminosity are well correlated (Figure 1), but there is a substantial range in luminosity for a given type (color). The form parameters correlate strongly with spectral-index (Figure 2), moderately well with each other (Figure 3), but very weakly with scale (*N.B.* only large r and L probed here). To complete this suite of figures, see e.g. Okamura *et al.* (1984), or Kent (1985) for μ vs. c; Conselice *et al.* (2000), for A vs. $B-V$; and Jangren *et al.* (1999), for form vs. scale. While form and spectral-index together distinguish well between normal Hubble types, form-parameters alone are not as good – particularly for separating intermediate and late Hubble types. In other words, the dominant difference between intermediate and late types, as defined by the Hubble sequence, is color.

We note that while we are considering μ to be a form parameter, it contains a hidden luminosity scale. This scale becomes evident if, for example, the time-scales for size evolution is much larger than for changes in the characteristic M/L a galaxy's stellar population. Asym-

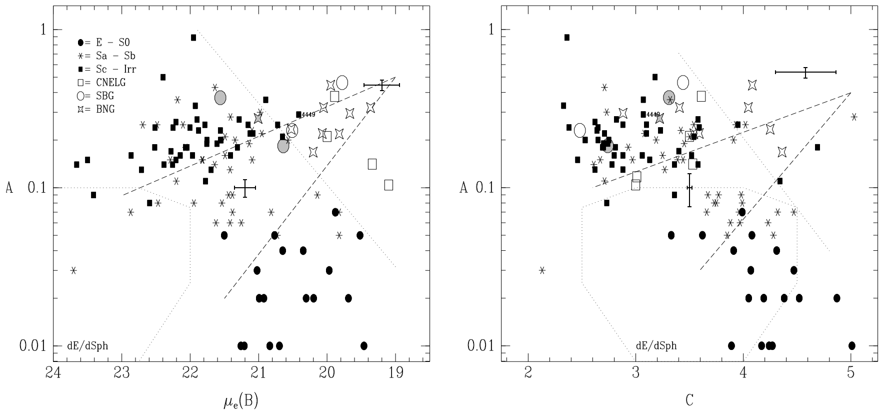

Figure 3. Left: B-band rotational asymmetry vs. half-light surface-brightness. Right: B-band rotational asymmetry vs. concentration. Dashed lines are heuristic classification boundaries, analogous to Abraham *et al.* (1996) for A vs C. Adapted from Jangren *et al.* (1999).

metry and image concentration may also be affected by evolution, but only by dynamical changes or spatially-dependent variations in star-formation; μ is guaranteed to evolve even in a dynamically relaxed and uniform stellar system. Hence it is important to keep in mind that evolution may drive different changes in A, c and μ.

3. Luminous Blue Compact Galaxies

A particularly intriguing distant population consists of small, but luminous, blue, star-forming galaxies, found in a number of deep redshift surveys. What we define as LBCGs (Jangren *et al.* 1999) contain the smallest galaxies for their observed luminosity (e.g. Koo et al. 1994). Guzmán *et al.* (1997) and Lilly *et al.* (1998) have argued that these sources appear to be the most rapidly evolving in terms of space-density, and hence are likely to be associated with (if not a key component of) the observed increase in star-formation between $0 < z < 1$. How do they fit in to the above classification scheme?

As seen in Figure 2, the LBCGs lie off the reference sequence when viewed by form *and* spectral-index. However, their optical–near-IR colors and luminosities are within the upper bounds established for nearby field samples (Figure 1). In terms of form-parameters alone (Figure 3), the LBCGs are extreme in A vs. μ, but not in terms of A vs. c.

Because our reference sample is incomplete, it is problematic to assess how unusual the LBCGs are in form. Nonetheless, the most luminous and compact LBCGs (a sub-class which we refer to as CNELGs) do appear to be unusual even when compared to their slightly larger counterparts (SBGs) of comparable rest-frame color and redshift ($z \sim 0.4$). Figure 4 reveals color gradients (roughly between rest-frame U and J bands) such that the most compact sources are *bluer* in their centers, indicative of young, centrally concentrated bursts embedded within older, more extended populations. The slightly more extended sources, like nearby, normal galaxies, show the characteristic reddening in their centers due to the increasing relative dominance of the bulge. The most extreme LBCGs, then, show the opposite correlation between form and stellar type exhibited by galaxies along the Hubble sequence – i.e., in opposition to the underlying premise of our classification scheme!

How might these sources individually evolve? Are there local counterparts? To start, the LBCGs' color gradients allow us to conclude that the intermediate-z bursts are not their first. More difficult to ascertain is whether these sources (a) persist in, or oscillate into and out of the luminous, blue phase via recurring bursts, or (b) burst once or twice, and then fade into obscurity. Certainly the stellar fossil record from the local group (Grebel, 1998; Tolstoy, 1998) is consistent with multiple burst phases for dwarfs. However, do the LBCGs have adequate gas to sustain significant future bursts? *This critical question could be answered by identifying comparable systems within redshift range of HI observations* ($z \leq 0.15$). If these sources have no subsequent bursts and simply fade, their image structure will evolve to become less concentrated, lower surface-brightness, and more symmetric. As in previous photometric analysis (Guzmán *et al.* 1998), Jangren *et al.* (1999) find the faded colors *and* form of the LBCGs are still consistent with some of today's spheroidal population (e.g. NGC 205).

Finally, we would like to understand the origin of the centrally-concentrated star-formation in these systems; it appears as if they are forming "outside-in." How was the gas which formed these stars funneled into the central 1-2 kpc? There are tails and wisps in these systems indicative of interactions or merging, but the bursts are large (L^* luminosities), may contain as much as 10% of the total stellar mass, and the total mass appears to be small ($M \leq 10^{10} M_\odot$) based on sizes and narrow line-widths. STIS spectroscopy or high-angular resolution integral-field spectroscopy would be invaluable to determine if the most extreme LBCGs are rotationally supported, truly low mass, dynamically disturbed, or are suffering from super-novae driven winds that may rid them of their ISM and quench future star-formation.

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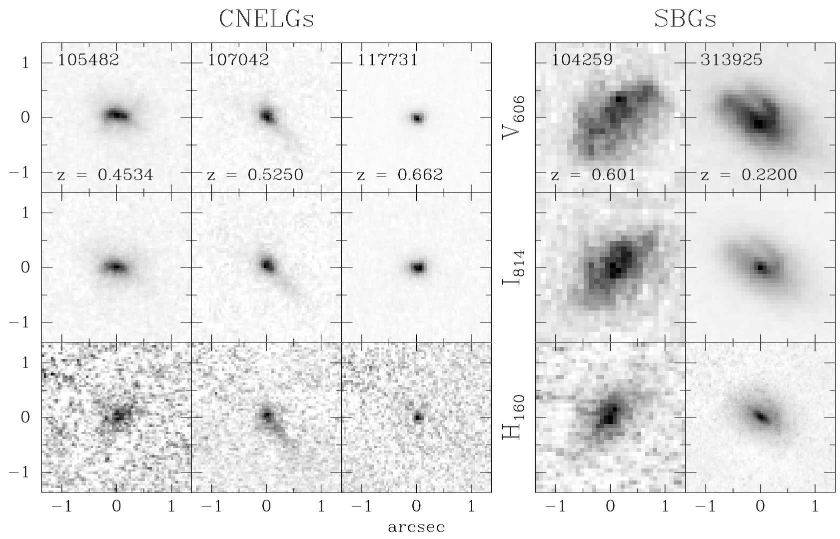

Figure 4. VIH montage of three representative CNELGs and two SBGs (see text) from our on-going HST WFPC-2 / NICMOS imaging programs of LBCGs. Note the distinctly different systematic changes of apparent morpholgy with band-pass between the CNELGs and SBGs: CNELGs are *more* compact at shorter wavelengths.

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