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Spectral Classification, Morphology, and Detection of Distant Galaxies[1]

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ABSTRACT. We describe a framework for utilizing both colors and morphology to test for evolution in deep samples of field galaxies. Spectral classification, as a first step, provides a well-defined referent when comparing galaxy morphology at different redshifts, because unlike morphology, colors can be measured consistently regardless of image resolution. We examine the dependence of size and surface brightness on spectral type and demonstrate the importance of these morphological quantities in determining survey completeness in the B_J and K bands. By these criteria, the deepest published K band counts should be complete to $z<0.6$ for all galaxies found in our sample. Bright, optical surveys may miss nearby, faint blue galaxies.

1. INTRODUCTION

The photometric and morphological properties of distant galaxies form a complimentary set of observables that can be used as tracers of galaxy evolution and cosmology. To utilize such information in deep imaging and spectroscopic surveys it is necessary to (i) determine a survey's selection function as well as to (ii) have means by which to compare intrinsically similar galaxies at different redshifts. These two requisites are necessarily intertwined because the visibility of a galaxy at a given redshift is fundamentally a measure of its apparent signal-to-noise (S/N). For imaging surveys S/N depends on galaxy color, size, surface brightness, and shape, or image concentration (Pritchet and Kline 1981; Tyson 1984; King and Ellis 1985; Weedman and Williams 1987; Kron 1989; Phillips et al. 1990). We refer to surface brightness and concentration here as "morphology." Hence both the photometric and morphological properties of galaxies form a *necessary* set of observables in order to interpret any survey of distant galaxies.

In order to compare intrinsically similar galaxies at disparate redshifts a classification scheme is needed that is objective, well defined over a large range of redshifts, and well correlated with observables describing the selection function, as discussed above. The traditional Hubble classification is somewhat subjective and dependent on the apparent resolution, and hence redshift of the sample. Although quantifiable morphological measures correlate with Hubble type (e.g., Kent 1985), such quantities will still depend on resolution. Dressler (1992) has demonstrated that it is possible with the *Hubble Space Telescope (HST)* to do a Hubble-like morphological classification of galaxies at $z=0.4$. However, such spatial information does not exist for galaxies in the proposed high-redshift cluster in the same frames (Dressler et al. 1993). Therefore, these galaxies remain unclassifiable within their scheme, as will the vast fraction of all galaxies at the limits of deep surveys which are either too faint or too small for adequate image restoration, and all surveys without space-based observations.

In contrast, galaxies can be objectively classified on the basis of spectral type using broad-band colors, as we will discuss, in analogy to Morgan's spectroscopic classification (Morgan and Mayall 1957). Galaxies are classifiable in such a scheme to survey photometric limits, regardless of image resolution, if adequate k corrections exist. Morphological characteristics salient for the determination of the visibility of galaxies, namely surface brightness and concentration, are known to correlate at least as strongly, if not better, with Morgan's spectroscopic type as with Hubble type (Kent 1985). Indeed, one of the motivations of Morgan's classification was the broad and overlapping range in central light concentration in Hubble types Sa and Sb, which Morgan found correlated with spectral type (Morgan 1970).

To illustrate the approach of spectral classification for the study of distant galaxies we present some preliminary results from our program to determine the multivariate distribution of spectral type, luminosity, and morphology in the optical and near infrared from a well-defined, moderately distant galaxy sample. These data will be utilized in the future to interpret *apparent* distributions of galaxies observed at higher redshifts in ground-based optical, near-infrared, and *HST* images. After summarizing the current data set and spectral classification (see Bershady 1992), we present the distribution of surface brightness and size as a function of spectral type. We demonstrate the importance of such quantities for determining the visibility of galaxies, and discuss differential effects between B_J and K bands for detecting galaxies of different spectral type. We conclude by commenting on work in progress to determine distributions of distant galaxy profiles using *HST*.

2. SAMPLE COMPLETENESS

The galaxy sample discussed here consists of two subsets of the Koo–Kron redshift survey for which we have

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obtained K band images to accompany the existing U,B_J,R_F,I_N band areal photometry (Kron 1980; Koo 1986; Koo and Kron 1988): (1) A magnitude limited sample to $B_J \leqslant 20$ with high spectroscopic completeness; (2) a color-redshift selected sample to $z=0.3$ limited in magnitude by $R_F \leqslant 20.5$. Both subsamples should be extremely complete in terms of catalog detection for nearly all galaxy types because the 50% detection for a typical galaxy is >3–4 mag fainter. This completeness can be expressed in terms of S/N as a function of surface brightness and size, since at radius r in the background limited regime,

$$\mathrm{S/N}(r) = \sqrt{\pi} r 10^{-0.4(\langle\mu\rangle_r - \sigma_{\mathrm{sky}})}, \tag{1}$$

where $\langle\mu\rangle_r$ is the average surface brightness interior to radius r, and σ_{sky} is the noise due to the sky background, in magnitudes per square arcsecond. For our photographic J and F plates, $\sigma_{\mathrm{sky}} \sim 26.5$ and 25.4, respectively. At $B_J=20.5$, the S/N at a radius including nearly all of a galaxy's light ($r=2r_1$, Kron 1980) is in the range 53 ± 16; at $R_F=20.5$, $\mathrm{S/N}(2r_1)=28\pm6$. The full range of *observed* S/N at these magnitude limits, which correlates with size (or surface brightness), stays well above detection thresholds.

The situation for detection in principle is better than presented above since the optimum S/N is at $r<2r_1$. For galaxies with a given profile shape, the maximum S/N is uniquely related to $\mathrm{S/N}(2r_1)$ by a constant factor. For Gaussian, exponential, and $r^{1/4}$ light distributions these factors are, respectively, 1.2, 2.1, and 3.9. A distinguishing characteristic of these three types of profiles that is *independent* of surface brightness and size, is their degree of central light concentration. Hence mean surface brightness, size, and concentration provide most of the needed input to describe a survey selection function for object detection. The remaining key ingredients are color and azimuthal asymmetry. The latter is required to determine optimum apertures which in general are not circular.

3. SPECTRAL CLASSIFICATION

Our spectral classification scheme is based on a simple two-star population synthesis model, constrained by the five observed broad-band magnitudes (Bershady 1992). We have found that only five distinct stellar pairs were selected as best fits to our sample. These pairs, denoted bk, bm, am, fm, gm, have become the five spectral classes (where, e.g., F5 and F0 become f). We have shown that the simplicity of this model is justifiable in terms of the information content in broad-band colors.

There are several important results of this classification pertinent to galaxy visibility: (1) The distribution of the spectral types in $U-V$ vs. $V-K$ is similar to the Hubble sequence (Aaronson 1978; Bershady 1992). Hence morphological characteristics should correlate with spectral type. (2) Luminosity correlates with both optical and near-infrared color in a similar way for all spectral types. (3) k corrections are highly correlated with galaxy type, by definition. For example, the galaxy distribution in $U-V'$ vs. $V'-K$ has a knee at approximately $U-V'=0.7$ and $V'-K=3.3$, centered between the average colors of bm, am, and fm galaxies, or Hubble-type Sbc. [$V' \equiv (B_J+R_F)/2$.] Galaxies redder in $U-V'$ have nearly the same $V'-K$ color; galaxies bluer in $U-V'$ rapidly become bluer in $V'-K$. These bluest galaxies, bk type, are intrinsically the faintest, particularly in the near infrared, but have the smallest optical k corrections of all galaxy types. One would expect that these objects have typically lower surface brightness (as we will show) and are less concentrated than the redder spectral types.

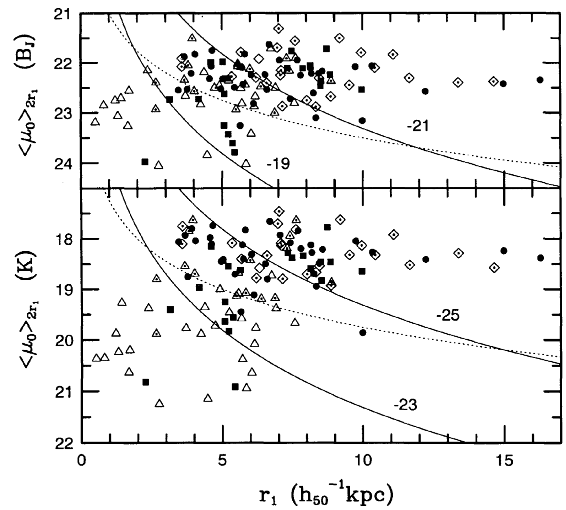

FIG. 1—Rest-frame average surface brightness within $r=2r_1$ (magnitudes per square arcsecond) in the B_J (top panel) and K (bottom panel) bands vs r_1 in kpc ($q_0=0.1, H_0=50$) measured in the K band for galaxies in our survey (see the text). Symbols denote spectral type: open triangles (bk), dotted triangles (bm), diamonds (am), filled squares (fm), circles (gm). Characteristics errors: 0.07% (bm–gm) and 15% (bk) for r_1; 0.15 mag (bm–gm) and 0.3 mag (bk) for both $\langle\mu_0\rangle_{B_J}$ and $\langle\mu_0\rangle_K$. Solid lines are at labeled, constant absolute magnitude. Dashed lines are at constant (arbitrary) S/N, assuming the model described by Eq. (1). For reference, r_1 is equivalent to $\sqrt{\pi/2}\sigma$ for a Gaussian profile, 2β for an exponential profile of scale length β, and 2.289 r_e for a $r^{1/4}$ profile with effective radius r_e.

Finally we note that this classification is well defined but not unique. However, it has the advantage of being simple while at the same time fully utilizing the available color information and highlighting the correlation of color with luminosity. Because the deepest galaxy images will always be in broad bands, this classification scheme is suited for the study of distant galaxies.

4. REST-FRAME SURFACE BRIGHTNESS AND SIZE

In Fig. 1 we have plotted the distributions of the B_J and K band *rest-frame* average surface brightness within $r=2r_1$ vs r_1 in kpc ($q_0=0.1, H_0=50$ km s^{-1} Mpc^{-1}) for all spectral types. Both galaxy subsamples have been included, but we have eliminated objects with $r_{1,\mathrm{gal}}/r_{1,\mathrm{psf}} < 1.4$(13% of the sample), where $r_{1,\mathrm{gal}}$ and $r_{1,\mathrm{psf}}$ are the measured r_1 of the galaxy and point-spread function. Below this limit seeing effects appreciably distort the intrinsic $r_{1,\mathrm{gal}}$ (e.g., greater than 15% distortion for exponential profiles). The characteristic surface brightness and size of each spectral type in the two subsamples are the same within the measured dispersion. The adopted resolution threshold preferentially eliminates objects at the highest and lowest redshifts of our sample. The latter have small metric sizes and high B_J surface brightness, but are very blue.

The striking feature of the K band distribution is that the bluest galaxies, bk-type, have the smallest sizes and lowest surface brightness, whereas the surface brightness contrast in B_J is considerably smaller between spectral types. This difference is a reflection of the change in color between the objects and the fact that the apparent r_1 sizes are the same in the optical and near-infrared (Bershady 1992). Note that the largest galaxy is the central galaxy in the rich cluster II ZW 1305.4+2941 at $z=0.24$ (Koo et al. 1986); the third largest is an ultra-luminous disturbed system, also at $z=0.24$ (Majewski 1988); the outlying object with $r_1 \sim 10h_{50}^{-1}$ kpc but low surface brightness indeed appears exceptionally diffuse in both K and B_J images. The top panel of this figure (B_J) compares qualitatively to Figs. 10 and 12 in van der Kruit (1987) of central disk surface brightness and scale length, keeping in mind that our measures are of average surface brightness and characteristic, size, include all galaxy components (e.g., disk and bulge), and contain no correction for orientation.

5. SIGNAL-TO-NOISE AND DETECTION

Assuming the model described by Eq. (1), which ignores differences in profile shape, we have drawn a line of constant (but arbitrary) S/N in each panel of Fig. 1. Lines of constant absolute magnitude, also plotted, have different logarithmic behavior in this plane. Because the latter curves map into constant apparent magnitude in the observed frame, the two sets of curves represent the difference between a magnitude and S/N limited sample. The curves of constant S/N assume that the detection aperture is tailored to—i.e., optimized for—the size of each galaxy. In practice, typically an aperture of constant size is used. A fixed aperture will make the S/N curve flatter for galaxies apparently larger than the aperture (flux is missed), and steeper for apparently smaller galaxies (more sky noise at same total flux). In total, the situation for detection becomes worse in this case for all but the galaxies of the apparent size of the detection aperture. This behavior will depend on both the metric size and redshift of galaxies.

Considering the optimum case for detection, blue galaxies (e.g., bk type) will be much harder to detect in K than in B_J compared to redder galaxies (e.g., am, gm type) because the relative change in their surface-brightness distribution between bands separates the bk type from the am, gm types in a direction nearly perpendicular to lines of constant S/N. This discussion so far, however, has not considered the effects of redshift in the form of k corrections. We have used our broad-band data, interpolated with the two-star models to calculate k corrections to $z=0.65$ and 6.75 for the B_J and K bands, respectively, to simulate the distributions in Fig. 1 at different redshifts.

At moderate redshifts $0.3<z<1$, k corrections in the K band are reasonably independent of spectral type (0.3 mag dispersion at $z=1$), and the relative distribution in the lower panel of Fig. 1 is largely unchanged. The curve of constant S/N is equivalent to a five-sigma detection limit in the K band for $\sigma_{\rm sky} \sim 20$, 21, and 22 mag per square arcsecat $z=0.3$, 0.6, and 1, respectively. We have assumed a detection aperture of radius 1.25 arcsec to match what was used by Cowie et al. (1990) for their deepest K band field with $\sigma_{\rm sky}=24$ mag per square arcsec. The metric r_1 that is optimally detected at these redshifts is 10, 12 and 14 h_{50}^{-1} kpc for the above apparent aperture, and assuming exponential profiles. Since curves of constant S/N will shift with $\sigma_{\rm sky}$, Cowie et al.'s sky noise in principle allows them to detect all the galaxies in our survey out to $z=0.6$.

For the B_J band, since k corrections are much larger for the redder types (fm and gm), these galaxies move vertically to fainter surface brightness (and apparent magnitudes) relative to bluer types. The result is that the intermediate types bm and am become the most visible galaxies at $z=0.65$ in a blue selected sample. At $z=0.3$, the five-sigma detection threshold for bk-type galaxies for our plates lies ~ 1.6 mag below the drawn line of constant S/N. (In our survey these galaxies are mostly at $z<0.2$.) Most bk-type galaxies would not be visible even at $z=0.03$ if $\sigma_{\rm sky}$ were about 3 mag brighter, namely, ~ 23.5 mag per square arcsec. Brighter surveys may therefore have missed this local population.

6. CONCLUDING REMARKS

As we have already mentioned, a more realistic model for the S/N must include image concentration to account for differences in profile shape. Because we expect redder galaxies to be more compact, this makes bluer galaxies relatively harder to detect. Future work will focus on investigating profile shapes of galaxies over a range of redshift and spectral type utilizing ground-based and *HST* images. Our preliminary results based on surface brightness and size indicate that the deepest K band survey is able to detect to $z \leqslant 0.6$ the bluest galaxies that we can detect to $z<0.2$ in our optically selected survey. These galaxies are classified in our scheme as bk type. Comparison of galaxy counts between our and Cowie et al.'s (1990) surveys therefore will be a critical test of their claim that faint, blue galaxies have undergone rapid evolution since $z \sim 0.3$ (Bershady et al. 1993). This test is particularly important because brighter samples may have missed such a local population, and it is these surveys that have been used to define the zero-redshift universe.

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