COUNTS AND COLORS OF FAINT GALAXIES

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The color distribution of faint galaxies is an observational dimension which has not yet been fully exploited, despite the important constraints obtainable for galaxy evolution and cosmology. Number-magnitude counts alone contain very diluted information about the state of things because galaxies from a wide range in redshift contribute to the counts at each magnitude. The most-frequently-seen type of galaxy depends on the luminosity function and the relative proportions of galaxies of different spectral classes. The addition of color as a measured quantity can thus considerably sharpen the interpretation of galaxy counts since the apparent color depends on the redshift and rest-frame spectrum. To a first approximation two colors for a galaxy can determine a redshift and a spectral class, because redshift loci in a color-color diagram run roughly parallel to each other, and roughly perpendicular to the zero-redshift galaxy "main sequence" (Tinsley 1977a, Pence 1976) for small redshift. This game becomes more and more uncertain at higher redshift, because the systematics of galaxy UV spectral energy distributions are not well known, and what is known is not well understood (Code and Welch 1979). Redshifts for some random sample of faint galaxies is required to pin down the color-redshift relations; steps in this direction have already been taken by E. Turner. The reason for stressing colors, as opposed to redshifts, is that colors can be obtained relatively easily for large samples of faint galaxies if panoramic detectors are used: indeed, colors are not much more difficult to obtain than magnitudes.

Granting, however optimistically, that colors can be used as statistical redshift indicators, galaxies could then be counted to successive limits in redshift, rather than magnitude, which would sample the volume element directly. A full discussion of the use of colors as a

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test for cosmological models and as a test for evolution will be found in Bruzual and Kron (1979).

Besides the broader context of the color distribution of a complete sample of galaxies, there are the specific applications of using colors to isolate particular classes of objects. For instance, galaxies at very high redshift, $z \gtrsim 4$, would appear to be very red and might perhaps be identified by this property alone (Davis and Wilkinson 1974). Very blue galaxies, on the other hand, are presumably galaxies at lower redshift with active star formation. Studying the characteristics of these objects as a function of redshift might reveal important aspects of the history of star formation in galaxies. For example, a natural extension of the work of Butcher and Oemler (1978) would be to look at the distribution of galaxies in remote clusters in a color-color diagram, and see whether deductions about the star formation history can be made, à la Larson and Tinsley (1978) and Huchra (1977). The colors of radio galaxies probably relate both to recent star formation (van den Bergh 1978) and to the existence of a non-thermal (evolving?) contribution to the light (Smith 1977, Yee and Oke 1978). Many of these topics will be examined in detail later in the symposium and so will not be discussed here.

Figure 1 displays some examples of empirical determinations of the color distribution of faint galaxies. Figure 1a gives the photoelectric data used by Kron and Shane (1974) to calibrate the depth of the Shane and Wirtanen galaxy count survey; the galaxies should be representative of the survey limit. Figure 1b shows a section of Rainey's (1977) photographic data for Selected Area 57, chosen here to correspond roughly in magnitude with the Kron and Shane photometry. Finally, Figure 1c reproduces Butcher and Oemler's (1978) faint ISIT photometry of a region $\sim$100 arc sec away from 3C 295, which is taken to represent the field.

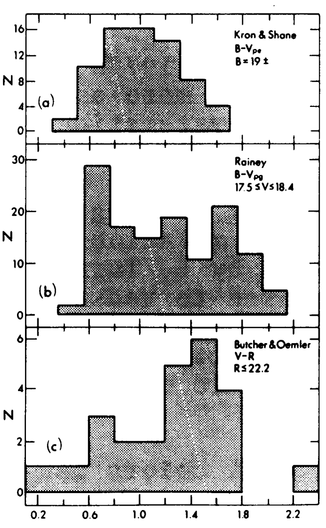

Fig. 1 - Color distributions for faint galaxies.

The various data have qualitative differences due to (1) different bandpasses;

(2) different depths represented, at least in the case of Butcher and Oemler; (3) different random errors; (4) different selection rules defining the sample; and (5) completely different photometric methods: large-aperture photoelectric photometry, iris photometry, and digital surface photometry, for Figures 1a, 1b, and 1c, respectively. Because of this diversity, any effort to rationalize the various data would be difficult; a better approach would be to build a numerical model for the expected color distribution explicitly for a specific set of bandpasses and magnitude range. One example of such a model (for B-V) has been presented by Pence (1976), which does agree, within the uncertainties in the comparison, with Figure 1a, and to a lesser extent with Figure 1b. The Butcher and Oemler color distribution, Figure 1c, appears to be similar to the distant cluster color distributions. This is particularly interesting because numerical models by several authors (e.g., Pence 1976, Tinsley 1977b, 1978, 1979, Bruzual and Kron 1979) have suggested that the median redshift for field galaxies with $m_R \sim 22$ is about the same as the redshift of 3C 295. The Shane and Wirtanen survey has a depth corresponding to a median redshift near 0.13, so that in terms of the placement of the λ4000 feature with respect to the bandpasses, the Shane and Wirtanen depth viewed with B-V should be similar to the Butcher and Oemler depth viewed with V-R.

Anyway, the main point of Figure 1 is to present what is currently known about the color distribution of faint galaxies and to show that the colors are not really exceptional—there do not appear to be large numbers of blue galaxies or large numbers of very red galaxies, and the colors are not too different from those encountered at z = 0. This stability of color is the result of two competing effects: all types of galaxies, even the bluest, become apparently redder with increasing redshift (Wells 1972); but on the other hand the intrinsically bluer galaxies get dimmer less rapidly with redshift, so that the most-frequently-seen type of galaxy at a given magnitude shifts blueward with increasing redshift (Greenstein 1938). Figure 2 shows how these effects also depend on galaxy evolution and, because of the cosmological sensitivity of the time-redshift relation, on the choice for q_0 and t_0. The curves were computed using a particular galaxy spectral-energy distribution model by Bruzual (1979), which adopts a stellar synthesis for the galaxy light, with standard assumptions about the mass function and the star formation rate. The J and J-F system refer to the photographic IIIaJ and IIIaF emultions. Figure 2a gives the predicted color *vs.* redshift curves for a galaxy type which, with J-F $\sim$ 1.05 at z = 0, corresponds to something like morphological type Sa. The no evolution curves differ from each other because t_0 was chosen to be

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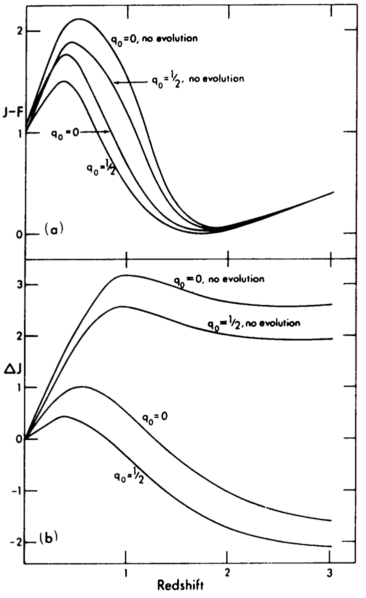

Fig. 2 - Color-redshift and Δ mag-redshift curves for a particular galaxy energy distribution model.

16 b.y. for the $q_0 = 0$ example and 13 b.y. for the $q_0 = 1/2$ example. The curves with evolution differ partly because of this, and also because for each redshift the look-back time is different for the two values of the deceleration parameter (the galaxy spectral evolution model is specified as a function of time, not redshift, because it is based directly on the component stellar evolutionary tracks). The color-redshift curves evidently depend quite strongly on q_0 and t_0, at least for this particular form of the star formation rate. Other energy distribution models, with either redder or bluer present-day colors, generally behave similarly to the particular case which is illustrated, but some galaxy types may not evolve strongly in color, e.g., ellipticals in the recent past (Tinsley 1972). Still, if the star formation rate were known as a function of time, the color-redshift relation would be a cosmological test in its own right, essentially reflecting the time-redshift relation. More to the point, the number of galaxies seen at each color depends on q_0 both via the time-redshift relation and via the volume element.

Figure 2b gives, for the same energy distribution model used in Figure 2a, the redshift dimming ΔJ (positive = fainter) in excess of the bolometric cosmological dimming. For no evolution, ΔJ is just the k correction, with the two top curves differing as before only in the present-day ages which were assumed. When the energy distribution is allowed to evolve, ΔJ incorporates both the k correction and the evolution. The calculation of the number-color relation for this galaxy type would then use Figure 2a, and the volume element as a function of redshift, to compute the number of such galaxies at each color, but would need also Figure 2b to specify the relative contributions brighter than some magnitude limit, which is what is required for a practical application. Note that all of the curves in Figure 2a tend to the same color at high redshift, but whether or not these are actually seen depends strongly on evolution, as evident from Figure 2b. As an extreme example, an elliptical galaxy, or more precisely speaking, a galaxy which has produced few hot stars for the past few times 10^9 years, would become very red with increasing redshift, but would however not be seen (in a blue band) for the same reason: the k correction would be very large. Nevertheless, there must have been some epoch when the star formation rate was highest, and depending on how high this rate was, young ellipticals could have been very luminous and either blue, if $z \lesssim 3$, corresponding to that epoch, or red, if $z \gtrsim 4$.

Any model for the evolution of galaxies must be consistent with the counts as a function of both magnitude and color. Figure 3 gives an example of such a comparison. The model for the color distribution was derived again from Bruzual's synthetic energy distributions, with a standard assumed galaxy luminosity function and a count zero point which agrees with the bright data of Kirshner et al. (1978). The numerical model includes individual evolving energy distributions such as that used in Figure 2, as well as several others with different colors at $z = 0$ so as to reproduce the color distribution of Kirshner et al. The dashed curve in Figure 3a was computed for $q_0 = 1/2$, $t_0 = 13$ b.y., and the solid curve for $q_0 = 0$, $t_0 = 16$ b.y. The lower set of curves in Figure 3a is for the magnitude interval $21 \leq (J+F)/2 < 22$, and the upper set is for the magnitude interval $22 \leq (J+F)/2 < 23$. Figure 3b reproduces the equivalent photographic data from Kron (1978) for Selected Area 57. Note that Figure 3a gives not only the expected color distribution, as in Figure 1, but also the expected counts themselves in the area relevant to Figure 3b. The random errors for the photometry were determined from comparison of pairs of plates, and an analytic approximation to these errors has been included in the model of Figure 3a. The main conclusion here is that

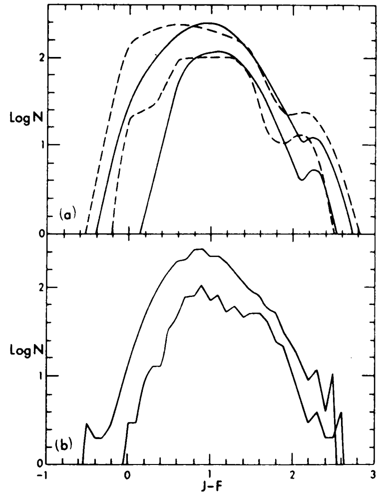

Fig. 3 - Theoretical (top) and observational (bottom) color distributions. Dashed curves computed for $q_0 = 1/2$, solid curves for $q_0 = 0$. Upper and lower sets of curves in each panel refer to $V \sim 22.5$ and $V \sim 21.5$, respectively.

the q_0 = 1/2 model predicts more blue galaxies than are observed, which is reflected in the behavior of the one component to the numerical model that is shown in Figure 2. The next step is to check that the assumed star formation rates are realistic, and this could be done either by getting redshifts for a relatively small sample, or by obtaining more than one color for each galaxy, a program which is currently under way by D. Koo and co-workers and by J. A. Tyson and J. Jarvis.

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DISCUSSION

Hawkins: I think that the method of distinguishing stars from galaxies using the colour/colour plot is a much sounder approach than the image structure approach described by Tyson.

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