GALAXY COUNTS

J. A. Tyson
Bell Laboratories

ABSTRACT

Counts of faint galaxies should reveal any evidence of galaxy luminosity or color evolution, as well as new information on the faint end of the galaxy luminosity function. The FOCAS automated detection and classification software is reviewed, and results of the deep 4m PF photographic survey to 24^{th} magnitude in 23 fields covering 9 sq. degrees are presented. Color-magnitude plots for stars and galaxies are shown, and galaxy color evolution is discussed. Evidence is found for a faint galaxy blue trend at 22-24 J mag. However, the k-correction becomes so severe at redshift $\sim$1 that the intrinsically fainter galaxies are emphasized in any magnitude-limited survey. No unambiguous evidence is found for evolution. New 4m limit CCD multi-color data are shown and discussed. The limiting magnitude for detection is 27^{th} J magnitude in 2 hours integration. The data exclude evolution starting at any one epoch for z<10.

1. INTRODUCTION

Hubble recognized the advantage of galaxy counts, as opposed to redshift surveys, as a means of obtaining statistically complete samples of high redshift galaxies, to test for cosmological and evolution effects. In recent years, the limiting magnitude for galaxy count studies has been increased from 19 to 27 B mag. Schmidt telescopes survey large regions but are limited to $B \lesssim 22$ mag for reasonable integration times. Large, low f/number reflectors have pushed beyond this limit into a range of apparent magnitudes dominated by cosmological and evolutionary effects and the faint tail of the luminosity function. Departures of galaxy counts from that expected for a nonexpanding homogeneous euclidean universe ($N \sim dex 0.6m$) are dominated by the effect of expansion: the k-correction. Figure 1 shows that the k-correction begins to affect the galaxy counts already at J=17 mag (J≡IIIaJ+GG385), and are dominant by J=21 mag. Plotted are counts from some early surveys, along with early results of our FOCAS (Faint Object Classification and Detection System) 4m PF survey.

M. Capaccioli (ed.), Astronomy with Schmidt-Type Telescopes, 489–498.

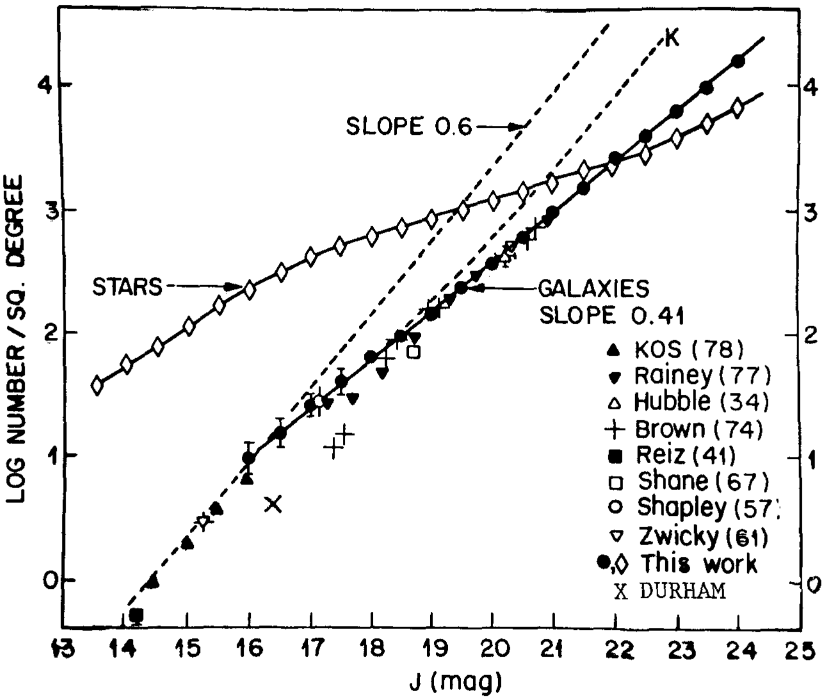

Fig. 1. Galaxy and star counts per square degree to limiting magnitude J, scaled to the north galactic pole. The theoretical curve of slope 0.6 corresponds to the oversimplifications of homogeneity (local density everywhere), flat space-time, and no color-redshift (K) effects. The curve marked K results from making reverse K- and cosmological corrections on the data. Adapted from Tyson and Jarvis (1979).

2. k-CORRECTION DOMINANT

The k-correction dominates all other cosmological or evolutionary effects for all types of galaxies. For example, in figure 2 I show the effects of k-correction on a giant elliptical galaxy. The observed V surface brightness is plotted vs. isophotal radius of the galaxy image, for various redshifts. A photographic surface brightness detection limit of 26 V mag/arcsec^2 implies a nearly stellar image by redshift 1.5, whereas the much lower limit of a CCD detector suggests a 4 arcsec dia resolved image at z=1.5.

I will show some recent CCD data which Pat Seitzer and I have obtained on the CTIO 4m telescope. Although some of the faint galaxies at 26 J mag are probably high redshift, I will argue that it is likely that many are subluminous galaxies at much lower redshift which do not suffer a large k-correction.

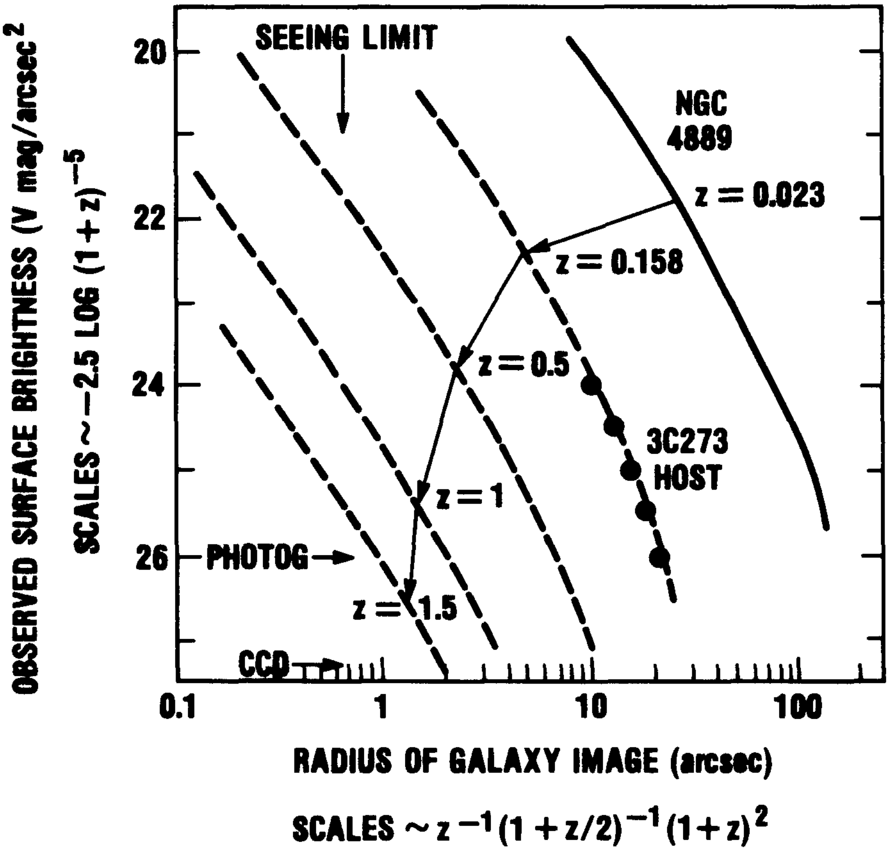

Fig. 2. k-correction dominates the detection limit of even giant elliptical galaxies, suggesting a practical limit of z=1.5 for 1-hour CCD exposure.

Figure 2 is for an unfiltered CCD exposure. If there is a broadband filter or if the detector is a photographic plate then the surface brightness scales like $(1+z)^{-6}$. If one then introduces luminosity evolution $E \sim (1+z)$, then the same scaling as in Fig. 2 is obtained. Thus, considerable evolution cannot prevent a deficit in number counts of these galaxies beyond $z \sim 1$.

Number counts, however, are dominated by spiral galaxies. Assuming Freeman's law we can write the surface luminosity as $B_o \exp(-r/r_o) = (1+z)^4\ \alpha\ \sigma_s/k(z)E(z)$, where σ_s is the night sky surface brightness, α is the fraction of night sky for the outer detection isophote, and k'and E are k-correction and luminosity evolution, respectively. This leads to a total "zero-redshift" magnitude correction $K\ (\alpha, q_o, z)$ given by $K = K_\sigma + K_q$ where $K_\sigma = -2.5 \text{ Log } \{1-(\alpha\ \sigma_s/B_o)[1-\ln(\alpha\ \sigma_s/B_o)$
$-6\ \ln(1+z)](1+z)^6\}$ and
$K_q = 5 \text{ Log } q_o^{-2}\ \{q_o+(q_o-1)z^{-1}[(1+2q_o z)^{1/2}-1]\}$. Figure 3 shows $K(\alpha, q_o, z)$

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plotted vs. redshift z for 2 values of α(1% and 0.4% night sky) and 3 values of q_0(.01,.03,.3). Clearly, aperture or detection isophote effects dominate at the limiting redshifts. However, it is easy to suffer a 3-4 magnitude k-correction for modest redshifts.

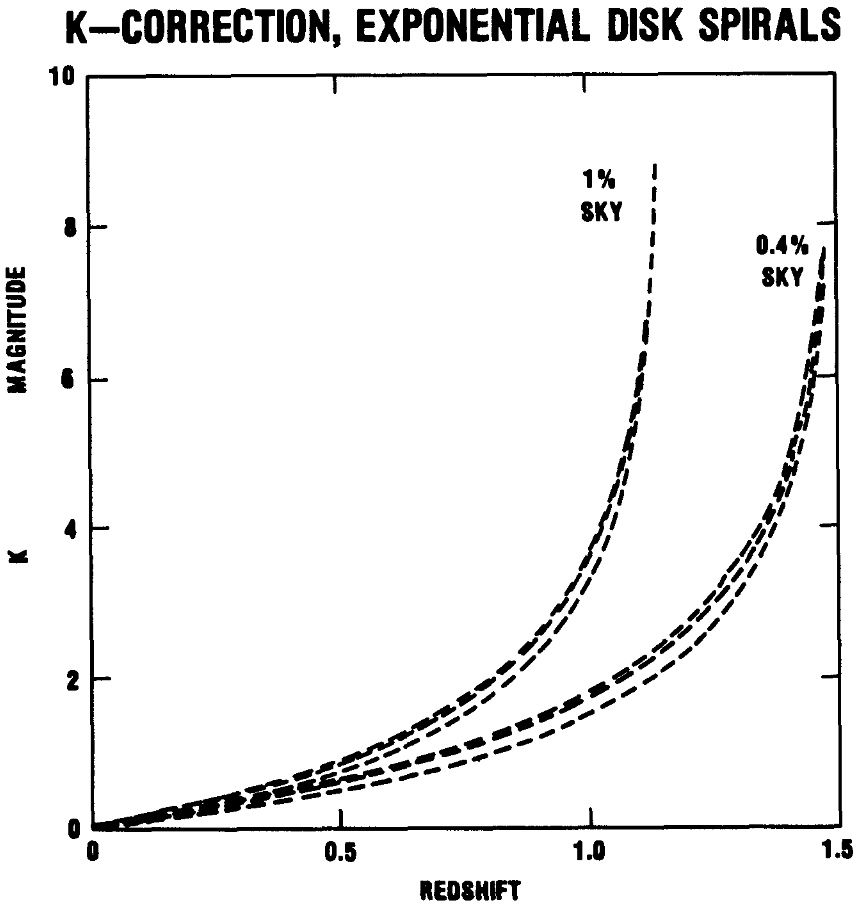

Fig. 3. k-correction to J magnitude for two values of detection limit isophote and three values of q_0 (see text), for spiral galaxies.

3. COUNTS OF BRIGHT GALAXIES

Schmidt telescopes play an important role in the detection of evolutionary effects by tying down the galaxy counts at the bright end. For example, the local supercluster may contribute to the counts at J$\approx$14-16 mag (see fig. 1), and wide-field surveys going to J$\simeq$19 mag in other direction are needed. Preliminary data from the Durham group (Ellis 1981) from five UKST fields are shown as a cross in figure 1. Clearly, any model of galaxy counts will predict significantly different counts at 24th magnitude depending on which 15th mag count it is normalized to. More complete surveys of 12-19th mag are needed, particularly in the south. Automated reduction classification of the ESO blue and red Schmidt surveys will be very helpful.

4. GALAXY/STAR CLASSIFICATION

Automated classification faint galaxy count surveys are now an international enterprise, although most groups currently report results for only one or two fields. Because of the known clustering of faint galaxies on 1° scales and the open possibility of high-latitude clumped extinction, it is necessary to study tens of fields spaced over the sky. There has also been a trend towards classifiers based only on a few (2 or 3) moments of the intensity. Such classifiers have limited dynamic range, and fail systematically as galaxy brightness approaches sky. Recent faint galaxy count surveys have been reported by Kron (1978,1980), Tyson and Jarvis (1979), Peterson et al. (1979), and Karachentsev (1980). There are several currently in progress, and I will report here on the results of our survey to date. Theoretical predictions incorporating various evolutionary scenarios have been made by Brown and Tinsley (1974), Tinsley (1977,78,80), Bruzual and Kron (1980), Bruzual (1981) and Koo (1981). All the credit for developing luminosity evolution models suitable for direct comparison with observation must go to Beatrice Tinsley. Her schematic models have been an incentive for more extensive galaxy count studies at both bright and fainter limits.

The 7-moment parametric star/galaxy classifier (FOCAS, Jarvis and Tyson 1981) has a range of 17-23 J mag for accurate classification on 1-hour 4m PF J limit plates. An improved version of FOCAS, allowing an additional magnitude of classification at the faint end (Valdes, 1982) has been applied to 23 of our FOCAS photographic fields and two new CCD fields. This new classifier is based on successive convolutions of an ensemble of stellar + various broadened stellar images with every detected object. Goodness of fit is then related to a classification based on the amount of broadening and fraction of broadened image required. A price in computer run-time is paid for this 'infinite-moment' resolution classifier: whereas the 7-moment cluster algorithm classifier takes about 6 hours on a VAX 11/780 for a 4×10^7 pixel 4m PF photographic field to 24th J mag, the new classifier takes 20-30 hours for the same data, and .5-10 hours on a 10^5 pixel CCD image to 26th J mag, depending on field crowding and the number of other users. Figure 4 shows the results for 23 4m limit photographic fields and two recent 4m CCD fields.

5. FAINT GALAXY COUNTS

The best fit to the average of the 23 FOCAS fields for $21 < J < 23$ mag is $\log N \sim .432J$. The dotted lines in figure 4 are the 1σ bounds for field-to-field variations in the photographic data. The two squares are FOCAS galaxy counts based on two 4m PF CCD fields obtained recently by Pat Seitzer at CTIO in a total of 4 hours of integration in J. The limiting magnitude for object detection (50% completeness) is 27 J mag,

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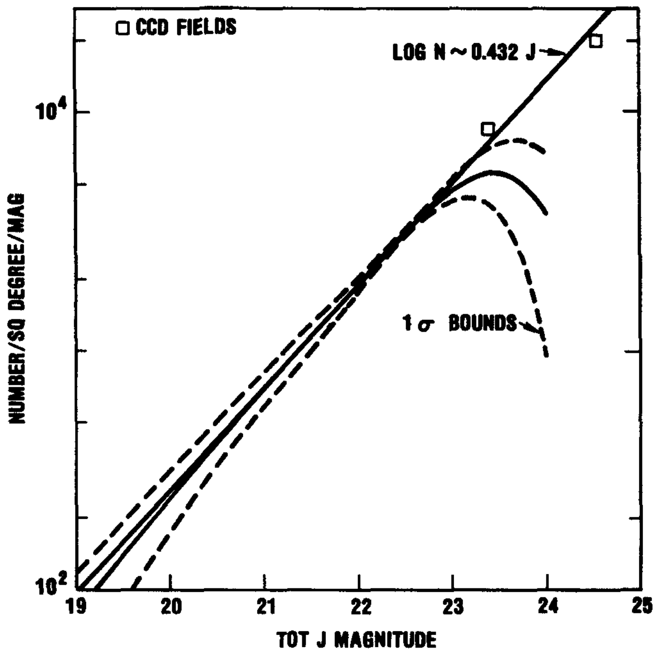

Fig. 4. Differential galaxy counts from 19-25 J mag.

and for photometry and classification 26 J mag. Nearly all objects are found to be blue galaxies. These preliminary CCD data for two fields at 60° galactic latitude are consistent with the continuation of the logN∿.43 J relation to 25 mag and beyond.

6. COMPARISON WITH THEORY

The galaxy count data are compared with theory in figure 5, adapted from Tinsley (1980). Galaxy counts, normalized by logN=0.6 J, are plotted versus total J magnitude. Our original FOCAS results based on 6 high galactic latitude fields are shown as open circles. The results presented in figure 4 are shown as solid circles continuing to J=26 mag. [Our current magnitudes are within 0.2 mag of total due to our low effective surface luminosity threshold of 26.5 mag/sq. arcsec photographic and 28 mag/sq. arcsec CCD]. Tinsley's no-evolution prediction is shown by the solid line intersecting the lower right-hand corner. Other recent no-evolution predictions (based on various mixes of galaxy colors and differing M_J^*'s) by Peterson, et al. (1979), Ellis (1981), and Koo (1981) are shown as dashed lines. Tinsley's three models with evolution are shown as dotted lines (Tinsley 1980). The vertical bar indicates the amount of free adjustment Tinsley estimated between theory and experiment, based on uncertainties at the bright end, problems with magnitudes at the faint end, and allowable range of mixes of galaxy colors input to the theory.

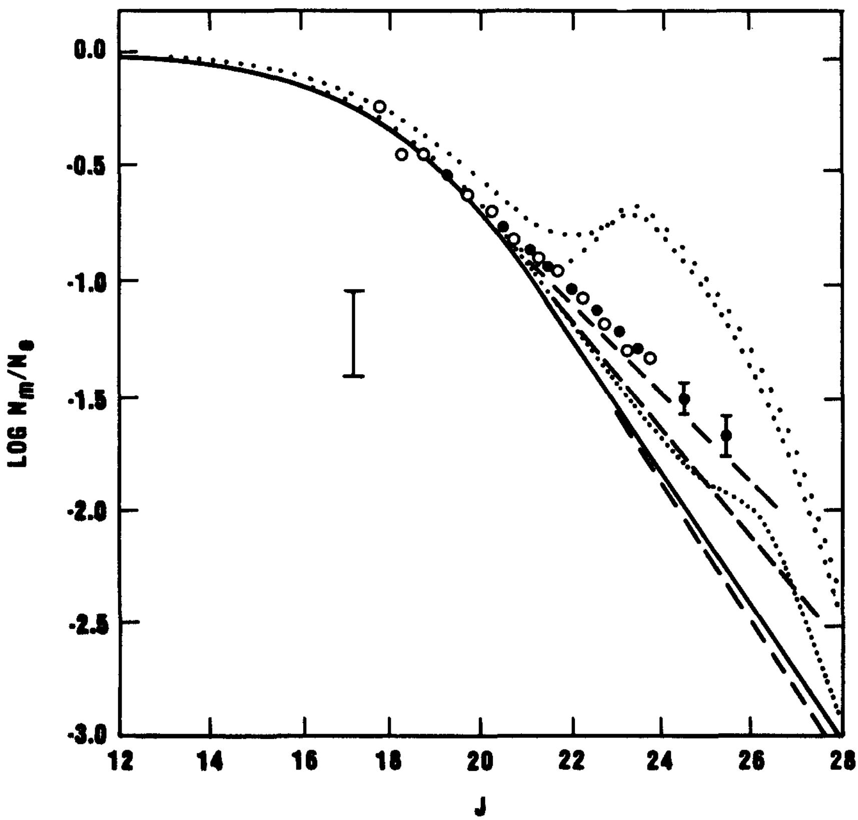

Fig. 5. Observed and predicted number counts normalized to logN∿0.6 J, adapted from Tinsley (1980).

Clearly star-burst evolution models at formation redshifts less than $z \gtrsim 5$-10 are ruled out. Although the data are suggestive of some kind of continuous evolution, the case for evolution is not unambiguous, due to the uncertainties.

7. FAINT GALAXY COLORS

As in faint galaxy counts, the dominant systematic effect in faint galaxy colors is due to the k-correction. M* galaxies at these faint apparent magnitudes have large k-corrections (see fig. 3) and the sample is systematically biased towards intrinsically fainter 'dwarf' galaxies which are relatively nearby and thus do not suffer as great a k-correction. Since dwarf galaxies are about 0.5 mag bluer (see deVaucouleurs et al. 1981) in J-F than the mean color of a complete sample of nearby galaxies, this means that there will be a blue trend in mean galaxy color with apparent magnitudes for $J \gtrsim 22$ mag. Various burst models of galaxy evolution predict an additional blue trend whose

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amplitude depends on the assumed formation redshift.

Color-magnitude plots for stars and for galaxies in a typical FOCAS field are shown in figure 6. The well-known sharp edge to the colors of

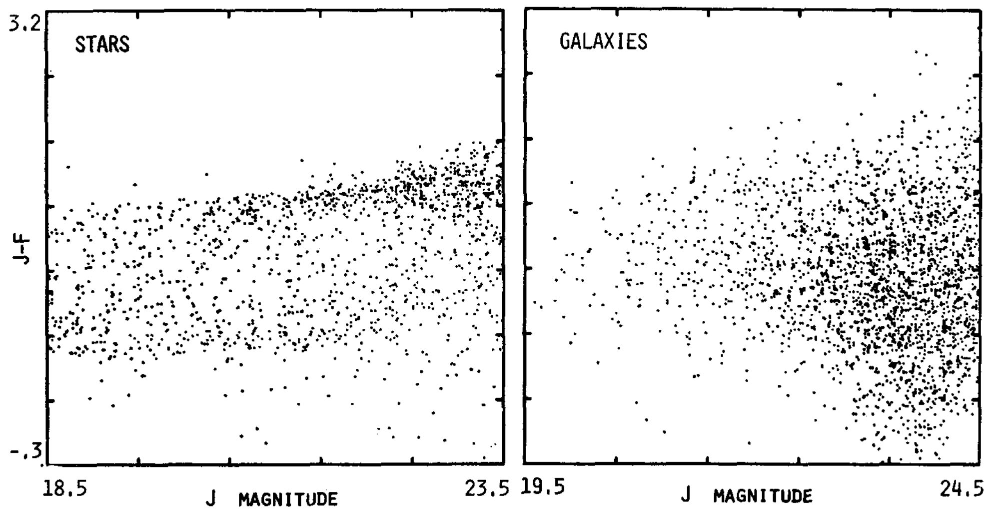

Fig. 6. Color-magnitude diagram for objects classified as stars (left) and galaxies (right) in one FOCAS field.

the m-dwarf stars (upper branch in figure 6, left) can be used as a systematic-error-free calibrator of color: For each half magnitude in each FOCAS field, I measure the difference in J-F color between this red edge to the red dwarf star distribution and the mean of the galaxy colors for the same field. We currently have J,F color data in 12 fields.

The resulting color-magnitude diagram for an average of 12 FOCAS fields and for $20 < J < 24$ mag is shown in figure 7. There is a very significant blue trend in the data, consistent within 2σ with both Tinsley's (error bar) and Bruzual's (dashed curve) mild evolution models. As mentioned above, this is a combination of the k-correction color bias and whatever color evolution may be present. It is easy to account for all of the blue trend with no color evolution, taking the observed luminosity function and a reasonable estimate of the k-correction (1 mag) at J=23.5 mag. Thus, although suggestive, the evidence for evolution in the faint galaxy colors is not unambiguous. What is needed is a redshift for each of these galaxies, an unlikely prospect in the near future.

8. PROBLEMS COMPARING COUNTS WITH THEORY

The problems encountered above in deconvolving any evolutionary effects from galaxy counts and colors divide into three separate areas:

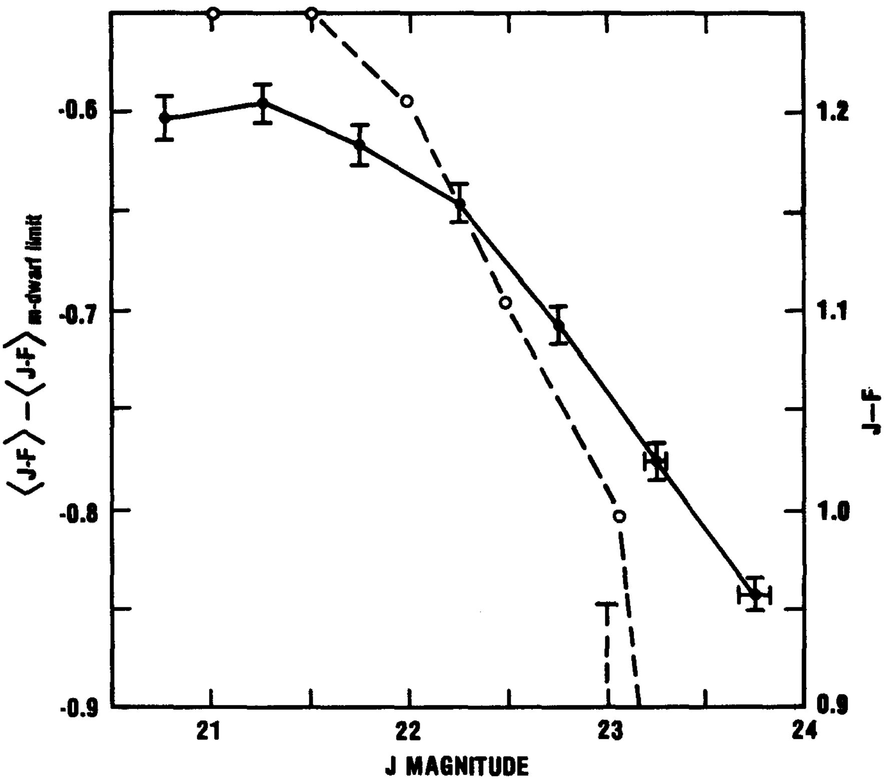

Fig. 7. Color-magnitude diagram for faint galaxies. Some theoretical estimates are also plotted.

8.1. Bright end normalization

Effects of our local superclustering (J$\lesssim$14 mag) generate departures from the true cosmic average galaxy counts in this apparent magnitude range.

8.2. Faint end systematics

Aside from occasionally significant differences in definition of magnitude, star/galaxy classification, and multiple object splitting algorithms, there are two known systematics operating in every case which tend to favor counting dwarf galaxies at the faint end: (1) k-correction bias toward the faint end of the luminosity function. (2) High redshift galaxies are very small and are vulnerable to misclassification as stars.

8.3. Theory

In addition to adopting values for the initial mass function, star formation rate, and galaxy formation redshift, the theory must adopt some mix of galaxy types and colors - which affects in turn the k-correction. Also, the absolute magnitude scale M_J^* in the photometric system (J) used for the counts by most observations is not well known, since it has been obtained by conversion from Johnson colors.

Progress in these areas of difficulty will allow difinitive conclusions regarding the type of evolution allowed by the data. We already see that burst models at formation redshifts <5 are ruled out. The bright end normalization problem will go away when automated counts from Schmidt surveys are available over most of the sky. Progress is already being made on the faint end systematics. A dynamic range for the detector/splitter/classifier of at least 6 magnitudes is crucial. It will be helpful to have F-band counts going as faint as the J-band limit, to cover dwarf galaxies in both bands. In summary, galaxy luminosity evolution, if present, is very mild and continuous.

REFERENCES

Brown, G.S. and Tinsley, B.M.: 1974, Ap.J. 194, p.555.
Bruzual, A.G.: 1981, Ph.D. Thesis, University of California, Berkeley.
Bruzual, A.G., and Kron, R.G.: 1980, Ap.J. 241, p.25.
Ellis, R.: 1981, in VIIth Course of the International School of Cosmology and Gravitation: Erice, May 11-13.
Jarvis, J.F., and Tyson, J.A.: 1980, A.J. 86, p.476.
Karachentsev, I.D.: 1980, Sov. Astron. Lett. 6, p.1.
Koo, D.C.: 1981, Ph.D. Thesis, University of California, Berkeley.
Kron, R.G.: 1978, Ph.D. Thesis, University of California, Berkeley.
Peterson, B.A., Ellis, R.S., Kibblewhite, E.J., Bridgeland, M.T., Hooley, T., and Horne, D.: 1979, Ap.J. 233, p.L109.
Tinsley, B.M.: 1977, Ap.J. 211, p.621; erratum Ap.J. 216, p.349.
____________: 1978, Ap.J. 222, p.14.
____________: 1980, Ap.J. 241, p.41.
Tyson, J.A., and Jarvis, J.F.: 1979, Ap.J. 230, p.L153.
Valdes, F.: 1982, SPIE 331, p.465.
deVaucouleurs, G., deVaucouleurs, A., and Buta, R.: 1981, A.J. 86, p.1429

DISCUSSION

T. SHANKS: It is well known that magnitude limited samples of galaxies are biased toward bright, high redshift galaxies. Why then do you think your blue galaxy counts are dominated by intrinsically faint galaxies?

A. TYSON: This is not true at these very faint magnitudes, where an M* galaxy would have a redshift around 0.5, implying a mean k-correction of perhaps 1 magnitude. At that point, for example, the ratio of subluminous galaxies with M=M*+2 to M* galaxies is near unity in such a faint sample.

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