AUTOMATED FAINT GALAXY COUNTS AND GALACTIC EVOLUTION

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Detection and classification of faint images by eye has traditionally encountered systematic errors faintwards of 20th mag on Schmidt plates and 22nd mag on 4-meter plates. Automated classification of Schmidt plate images has pushed the classification limit to 22 mag (Kibblewhite, et al., 1975). Automated detection and classification of faint 4-meter limit plate images has recently led to statistical studies of galaxy numbers and clustering at redshifts where cosmology and galactic evolution dominate over local effects. Here we report on some aspects of the FOCAS (Faint Object Classification and Analysis System) automated classifier (Tyson and Jarvis, 1979) and compare our results of number counts in SA57 with those of Kron, 1979. Differential galaxy counts in six high latitude fields and evidence for galaxy evolution are briefly discussed.

The interactive feature of FOCAS (Jarvis and Tyson, 1979) allows tests of many classification schemes. We have found that for images fainter than 22 mag more than three measured parameters (or features) are required for reliable classification. The data presented here are based on a 6-dimensional feature space. In designing our detection and classification algorithms we have attempted to obtain reliable operation over as wide a dynamic range of magnitudes and morphologies as possible. Six surface luminosity moments about the centroids of images are used as input to a clustering algorithm operating in the 6-dimensional decision space. Figure 1 shows peak intensity vs. magnitude for a subset of objects. The stars form a tight one-parameter cluster and the division between stars and galaxies can be seen visually down to $\sim$22 mag. First a line is drawn separating these two clusters down to 22 mag, as a zeroth order approximation. This initial line is generally not the optimal separator in other two-dimensional subspaces (see Fig. 2). The classifier then operates in the entire 6-dimensional feature space and evolves a hyperellipsoid decision surface which best separates stars and galaxies. The results of this procedure are checked with duplicate or co-added plates and deep CCD images of parts of the same fields. Classifier thresholds are set on the basis of these checks. Photographic density of sky is well into the linear portion of the gamma curve. Magnitudes are photoelectrically determined through a photoelectric sequence for each area studied.

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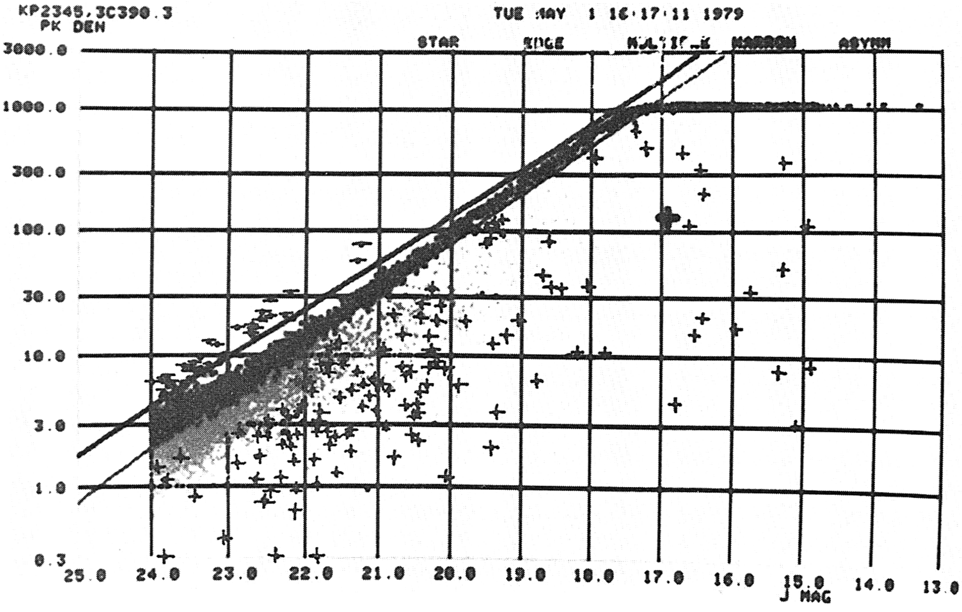

Fig. 1 Peak intensity vs. J. magnitude for a subset of objects. Dark points are stars, points with horiz. bars are noise, light points are galaxies, and crosses are multiple overlapping objects. The lines are the zeroth order intersection of the decision surface. Plate saturation for stars occurs at 17.5 mag.

Stars and galaxies form distinctly separate clusters in the 6-d decision space, as can be seen in Fig. 3 which is a histogram of distances in the 6-d space from the decision surface for a large number of objects. Stars of all magnitudes cluster around the same 6-d point.

Fainter galaxies tend to cluster closer to the star cluster but are reliably distinguished statistically even at 24th magnitude. The majority of galaxies in the range 19-20 mag and many in the range 23-24 mag are off the left boundary of the histogram. Since galaxies greatly outnumber stars at 24th mag, misclassification error will not significantly affect galaxy differential number counts but could adversely affect the star counts at the faint end.

An example of the breakup of multiple or overlapping objects (crosses in Figs. 1 and 2) is shown in Figures 4a,b. (The original display shows color-coded squares for each type of object classified.)

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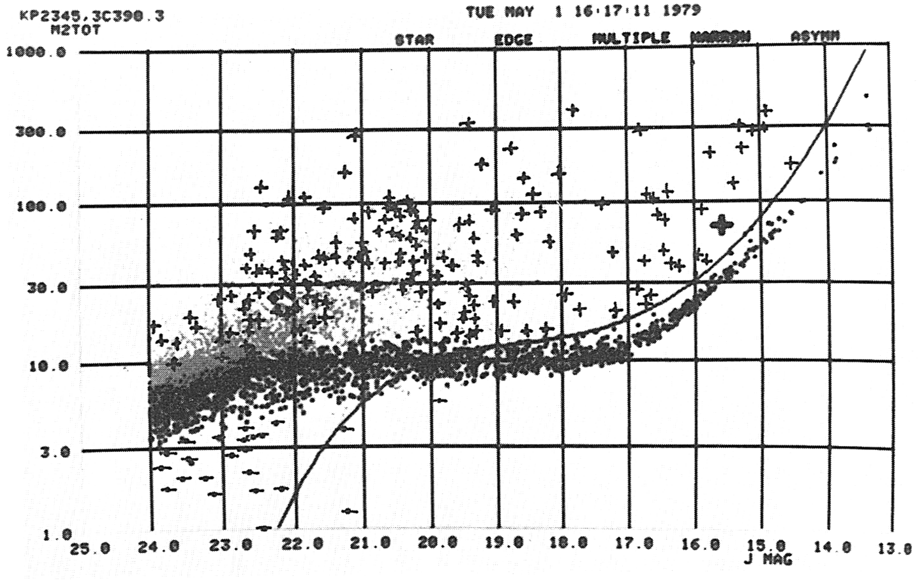

Fig. 2 Second moment M_2 vs. J magnitude for a subset of objects. The line is the intersection of the zeroth order try at a decision surface.

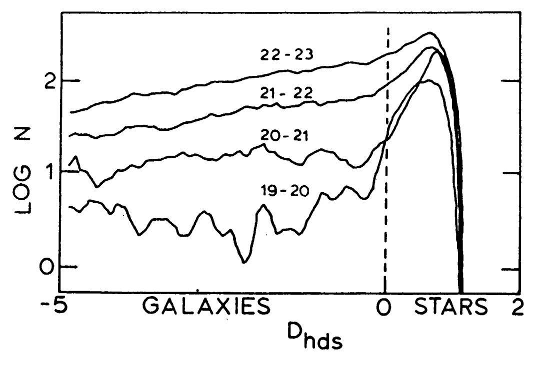

Fig. 3 Clustering in decision space. The region near the decision surface is shown. The number of objects found in several magnitude ranges are plotted vs. their distance from the hyperellipsoid decision surface.

Comparison of Kron's very different technique (Kron, 1978,9) and ours is shown in Fig. 5 where we have analyzed the same raw data plate. Star counts also agree well; this is somewhat surprising since the classification methods are so different, and star counts are expected to be more sensitive to classification error at the faint limit.

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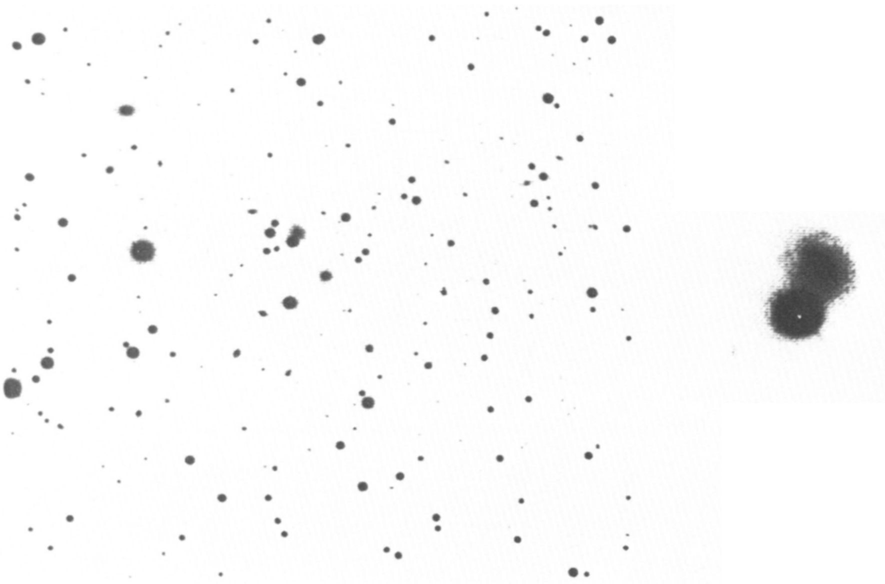
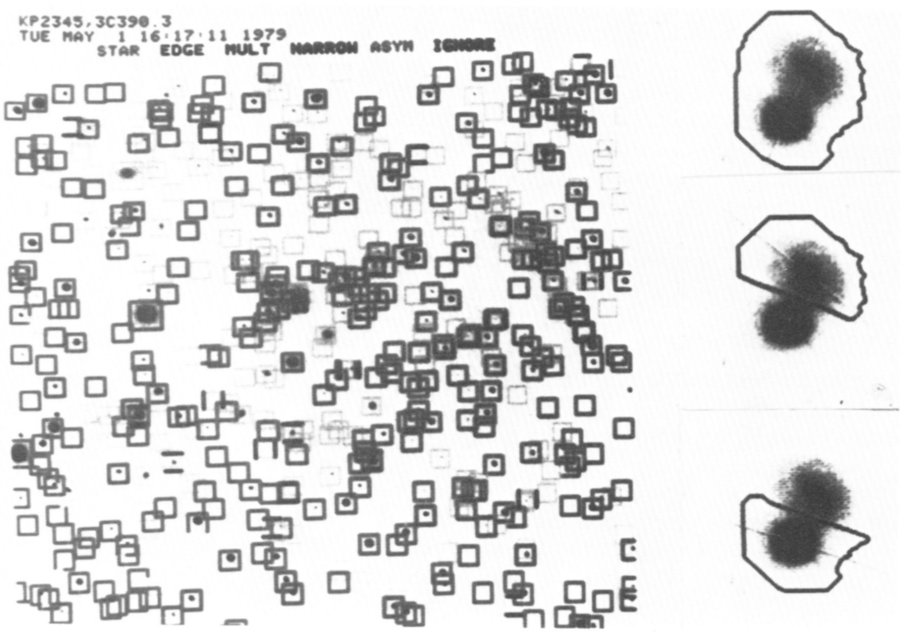


Fig. 4a,b Above (4a) is shown a part of one digitized plate 12 arc min across containing a multiple object shown at full resolution on the right. In Fig. 4b (below) is shown the breakup of the multiple into a final classification of a galaxy and star.



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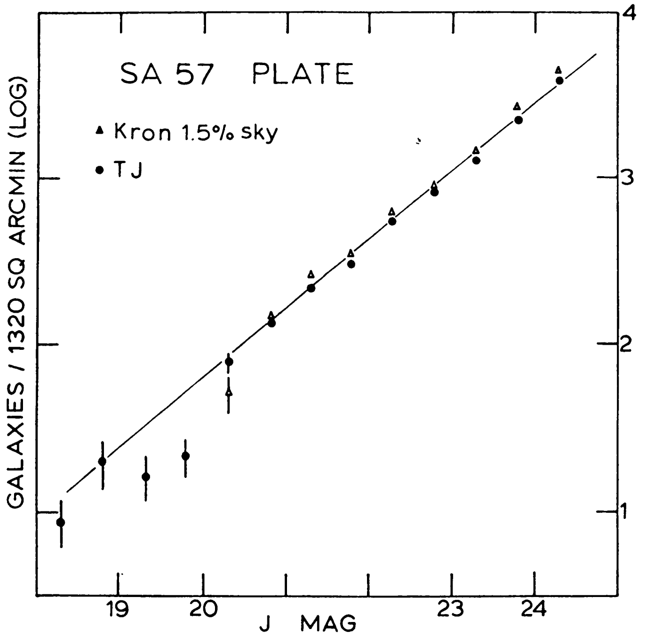

Fig. 5 Differential numbers of galaxies per half-magnitude bin counted on the same plate of SA57 by Tyson-Jarvis (filled circles) and Kron (triangles). A re-binning correction (Kron 1979, Fig. 6) has been applied to Kron's data to convert it to magnitudes integrated out to 1.5% of night sky surface luminosity. The line has slope 0.41.

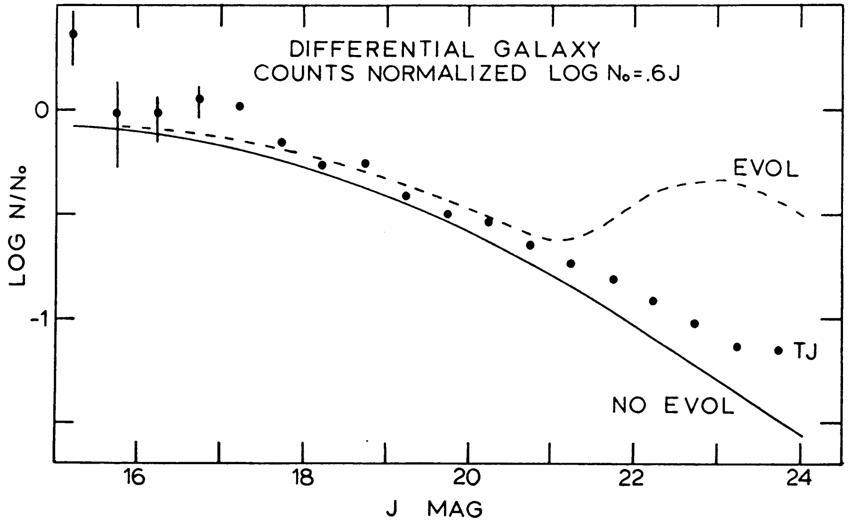

Fig. 6 Observed and theoretical differential galaxy counts. TJ are our data from the average of six high north latitude fields. Errors are smaller than the size of the points, except for the four brighter than 17th mag. The two model curves are from Tinsley, 1979. N (J) has been normalized by the Euclidean $N_o(J)$ where Log N_o = 0.6 J - 9.

We have examined eleven fields in the north with the FOCAS classifier so far, resulting in the classification of approximately 60,000 galaxies in these fields down to J = 24 mag. Although data down to J = 24.5 mag is kept and classified, we currently trust number counts for magnitudes brighter than 24th. Fig. 6 shows the sum of 6 high north galactic latitude fields. A total of 34,241 galaxies are found in these 6 fields to J = 24 mag. At high latitude we find 17,100 ± 800 galaxies per square degree to 24th mag. The dispersion in this number between individual high-latitude fields is 2500 per square degree. This is more than 10 times larger than the expected errors, due to high latitude clumped extinction. Local clustering effects are also seen, mostly around J = 17th mag. It appears that the "local" supercluster is considerably larger than we had thought. None of our fields are near any known rich clusters brighter than 18 mag per galaxy.

Our data for $18 < J < 24$ mag are approximated by the relation $\text{Log Ntot} = 0.41\ (\pm .004)\ J - 5.63$. The differential galaxy number counts shown in Fig. 6 (TJ) are compared with theoretical models of Tinsley (1979) for no evolution and for somewhat conservative evolution. These models are constrained to give present galaxy colors. The EVOL model has galaxy formation taking place at a redshift of 5. Although the data show evidence for some evolution, it is clear that there has been considerably less evolution over the look-back times involved in a magnitude-limited sample at J = 24.5 than had been suspected. Although the theory contains several adjustable parameters, perhaps the simplest is to move galaxy formation to earlier epochs. A redshift of formation greater than 10 would give agreement with the data. A larger sample of data will be discussed in greater detail in an article in preparation. In brief:

1. The bright flash of initial stellar burning in E's and S0's is not seen, either because galaxies formed earlier than $Z \gtrsim 10$ or perhaps because gas and dust then surrounding the galaxies prevents us from seeing this flash.

2. High latitude clumped extinction averaging ~0.4 mag exists.

3. There is some evidence for a local supercluster to the north, containing galaxies at $J \gtrsim 17$ mag.

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DISCUSSION

Fong: In your star/galaxy separation plots, there is a clear separation between stars and galaxies down to $20^m_.0$ or $21^m_.0$, but, going fainter, the objects overlap and become just a uniform spread. How do you decide which are stars and which are galaxies?

Tyson: On scatter plots which are not saturated by thousands of points, there is a clear separation down to 22 mag-23 mag. However, several (we currently use 8) classifier features are necessary in order to separate stars and galaxies to 24th mag. In the resulting multi-dimensional feature space, clustering is well-defined down to our faint limit. Fainter than 24th mag, the clusters which define stars and galaxies merge. This can be seen in our histogram of numer as a function of distance from the decision surface in the feature space. Obviously, such a procedure must be checked: we use CCD deep exposures to examine and verify our classifier decisions for a small subset of the data.

Baum: Could you comment further on the models with which your galaxy counts are being compared? In particular, if a substantially different luminosity function were considered, could you disentangle the effect of the luminosity from the effect of evolution?

Tyson: If the luminosity function had an enhanced faint tail, you might expect to see an excess of faint objects locally. This is not seen. Accordingly, Tinsley has used the Schechter Luminosity function in constructing her models. The dashed line EVOL shows Tinsley's estimated number counts for a formation redshift of 5 in a model constrained to give present epoch colors and in which star formation in spirals decays exponentially without a bright early burst, and ellipticals and S0's form stars up to 10^9 yr. There are many model adjustable parameters which could be modified to fit the data. Early formation redshift is the simplest but not the only possibility.

Hawkins: How secure is your magnitude scale at the faint end, and what comparison do you have between photoelectric magnitudes? Do C.C.D. magnitudes have systematic errors?

Tyson: After field flattening there is no evidence for systematic error in C.C.D. magnitudes -- the C.C.D.'s have a very large dynamic range. (R. Lynds recently found nonlinearity in the edge of the field in the JPL C.C.D. due to post-C.C.D. electronics.) In addition to spot C.C.D. tests of our FOCAS-assigned faint magnitudes, we have obtained photoelectric sequences well into the linear portion of the γ-curve of our plates for each of our fields. It is crucial to obtain accurate sky subtraction at the faint end, since any systematic error changes the N(J) slope htere. In that sense, the algorithm for sky determination is what is being tested by various photoelectric tests.

Tarenghi: What do you mean by "supercluster," the local supercluster or a more distant one?

Tyson: In addition to the excess counts to 16th mag in the north recently observed by Kirshner, Oemler, and Schechter, we find a significant excess in the form of two clumps centered at 15.5 mag and 17 mag. We have checked the PSS plates for clusters and we are near none. If this "local" superclustering is all part of one cluster, its size is probably larger than 500 Mpc.