POPULATION STATISTICS OF FAINT STELLAR AND NON-STELLAR OBJECTS

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"You can't say more than you see."
Thoreau

ABSTRACT

1. A disc and halo population model is constructed to fit star counts and color data down to V ∿ 23 at |b| = 90°. This model is used to predict star counts and colors down to V ∿ 30. Deviations from these extrapolated relationships might provide constraints on the number of faint quasars and "black dwarf" stars.

2. The model shows that extra-galactic globular clusters start contributing significantly to "star" counts at V ∿ 25 and are more numerous than stars for V > 31.

3. Morphological studies of galaxies with z ∿ 0.5, which are feasible with the Space Telescope, could provide significant constraints on theoretical models that describe the evolution of clusters of galaxies.

4. It is argued that the Space Telescope reduces the need for super-expensive earth-bound telescopes of heroic dimensions. Ground-based observations should, instead, exploit the advantage of low-cost photons that could be collected by mass produced ∿3m thin mirror "people's telescopes".

I. DEEP EXPLORATION OF "SELECTED AREAS"

The galactic nuclear bulge

Progress in galactic astronomy can be made by complete mapping of relatively bright nearby objects and by deep exploration of a small number of carefully chosen "selected areas". Baade's (1951) study of the galactic nuclear bulge in the low-absorption window surrounding NGC 6522 is a classic example of the latter approach. Unfortunately crowding effects, resulting from the exceedingly high density of stars

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in "Baade's window" have made it difficult to follow up this initial breakthrough. Future progress in this particular area will, no doubt, depend heavily on the improved resolving power of the Space Telescope and on the use of advanced panoramic detectors that will allow the deconvolution of partially overlapping images. Since the nuclear bulge has a distance modulus $(m-M)_V = 16.4$ (van den Bergh 1971) the Space Telescope should be able to study the luminosity function down to $M_V \sim +10$. Such observations might place significant constraints on the possible relationship between environment and the mass-spectrum of star formation.

The galactic halo

A promising beginning has recently been made on the deep exploration of the galactic halo by a group in Berkeley working under the direction of Ivan King. In Selected Area 57, which is located close to the north galactic pole, Kron (1978) has done photometry to very faint limits and Chiu (1979) has performed proper motion studies. This work is supplemented by the high-latitude star counts of Peterson et al. (1979) and Tyson and Jarvis (1979). These investigations provide significant new information on both the stellar density distribution in the halo and, to a lesser extent, on the luminosity function of Population II stars. The main difficulty in the analysis of these data is that the density distribution $\rho(Z)$ and the stellar luminosity function $\phi(M_V)$ have to be determined simultaneously from star counts and color data. The main value of such work, as far as the present conference is concerned, is that it allows one to extrapolate $N(V, B-V)$ to the range $25 \lesssim V \lesssim 30$, which is of interest to Space Telescope observers. Hopefully deviations from these predictions will provide information on (a) very faint quasi-stellar objects, (b) distant young galaxies and (c) the hypothetical "black dwarfs" that might account for the missing mass that appears to be present in the outer regions of many galaxies (Bosma 1978, Ostriker and Peebles 1973, Rubin, Ford and Thonnard 1978). Furthermore, additional observations at intermediate latitudes will allow one to determine the shape of the galactic halo.

II. A GALACTIC DENSITY MODEL

To a first approximation (see de Vaucouleurs 1959, Freeman 1975) the distribution of light in spiral galaxies can be represented by two component models in which a spheroidal core is embedded within an exponential disc. Pritchet and van den Bergh (1980) have therefore attempted to fit star counts to a density law of the form

$$\frac{\rho}{\rho_\odot} = (1 - f)e^{-|r \sin b|/\beta} + f\frac{(a_o^n + \tilde{\omega}_\odot^n)}{a_o^n + a^n} \qquad (1)$$

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In this equation the first term represents a disc of scale-height β and the second term describes a spheroidal population component (Chiu 1979), which accounts for a fraction f (by number) of the stars near the Sun. A point specified by r, ℓ, and b lies on a spheroid with semi-major axis a. The value of a is given by

$$a^2 = r^2\cos^2 b - 2\tilde{\omega}_\odot r \cos b \cos \ell + \tilde{\omega}_\odot^2 + r^2 h^{-2}\sin^2 b, \qquad (2)$$

in which h = c/a is the axial ratio of the spheroidal population. For $(a_0/a)^n \ll 1$ eqn (1) reduces to

$$\frac{\rho}{\rho_\odot} = (1 - f)e^{-|r\sin b|/\beta} + f\left(1 + \frac{r^2}{h^2\tilde{\omega}_\odot^2}\right)^{-n/2} \qquad (3)$$

at $b = \pm 90°$. Clearly observations of N(V, B-V) at the pole, such as those of Kron (1978), can not give a unique solution for the 4 parameters f, β, $\tilde{\omega}_\odot h$ and n.

The best external evidence is available on β and n whereas only rather weak constraints can presently be given on f and h. Available data (Allen 1973, Hill, Hilditch and Barnes 1979, Schmidt 1975a) suggest $300 \lesssim \beta \lesssim 400$. From a study of globular clusters in the galactic halo Harris (1976) obtains $n = 3.5 \pm 0.5$. This value is consistent with the data on galactic RR Lyrae stars that have been analysed by Oort and Plaut (1975).

Values of f quoted by Harris (1976) fall into the range $2 \times 10^{-4} \lesssim f \lesssim 7 \times 10^{-3}$. Perhaps the best value (even though it is based on small-number statistics) is $f = 1.15 \times 10^{-3}$, which Schmidt (1975b) derives from application of the V/V_m test to high velocity stars near the Sun.

According to Chiu (1979) $0.7 \lesssim h \lesssim 1.0$. Van den Bergh (1979) finds $h \sim 0.5$ for globulars near the center of the galaxy and $h \sim 1.0$ for halo clusters. Significant constraints on the value of h for halo stars could be obtained from counts at different galactic latitudes.

As a first approximation we have fit the N(V, B-V) data from Kron (1978) at $V \sim 21$ to a density model described by the following parameters:

$$\begin{aligned} \beta &= 350 \text{ pc} \\ f &= 1.25 \times 10^{-3} \\ \tilde{\omega}_\odot h &= 9 \text{ kpc} \\ n &= 3.5 \end{aligned}$$

The luminosity function for main sequence stars was taken from Luyten (1968). For values of n in the range $3 < n < 4$ evolved stars above the main sequence turnoff make a negligible contribution to the counts at $V \gtrsim 19$.

The contribution of white dwarfs to the counts was estimated from the luminosity function and M_V versus B-V relation of Sion and Liebert (1977). For V $\lesssim$ 22 white dwarfs are found to contribute < 1% to the counts of stellar objects. The white dwarf luminosity function of Sion and Liebert gives a local white dwarf density that is $\sim$3 times lower than that of Chiu (1978) and of Green (1978). The numbers of blue stars in our model might therefore have to be multiplied by a similar factor.

The calculated distribution of star counts in V, J and B is given in Table I. The color distribution of stars at different magnitude levels is shown in Figure 1. At V $\sim$ 20 the major contributors are seen to be G dwarfs with B-V $\sim$ 0.6 located at Z $\sim$ 10 kpc and middle M dwarfs with B-V $\sim$ 1.5 at Z $\sim$ 600 pc. At V $\sim$ 25 the relative contribution of G dwarfs to the counts drops whereas the contribution of K dwarfs with B-V $\sim$ 1.1 and Z $\sim$ 40 kpc rises. Finally at V $\sim$ 30 the major contribution to the counts is provided by middle and late M stars at Z $\sim$ 50 kpc.

Inspection of the model predictions shows that β is most strongly constrained by counts of M stars whereas f is primarily determined by the observed counts of the (much more luminous and hence more distant) G stars. Counts of N(V, B-V) in the range 15 < V < 20 would greatly

TABLE I

PREDICTED NUMBERS OF STARS

Mag	log N(V)*	log N(V)†	log N(J)†	log N(B)†
16.5	1.97	2.02	1.88	1.84
17.5	2.11	2.17	2.04	1.99
18.5	2.34	2.36	2.23	2.18
19.5	2.58	2.56	2.44	2.40
20.5	2.78	2.76	2.64	2.59
21.5	2.94	2.93	2.81	2.76
22.5	3.05	3.07	2.95	2.91
23.5	3.14	3.18	3.07	3.03
24.5	3.22	3.27	3.17	3.13
25.5	3.30	3.35	3.25	3.21
26.5	3.40	3.43	3.32	3.29
27.5	3.50	3.51	3.41	3.35
28.5	3.59	3.59	3.50	3.45
29.5	3.64	3.64	3.57	3.53
30.5	3.66	3.66	3.63	3.59

*No stars per magnitude per square degree at |b| = 90° predicted from Wielen's (1974) function luminosity.

†Same as above but for Luyten's (1968) luminosity function.

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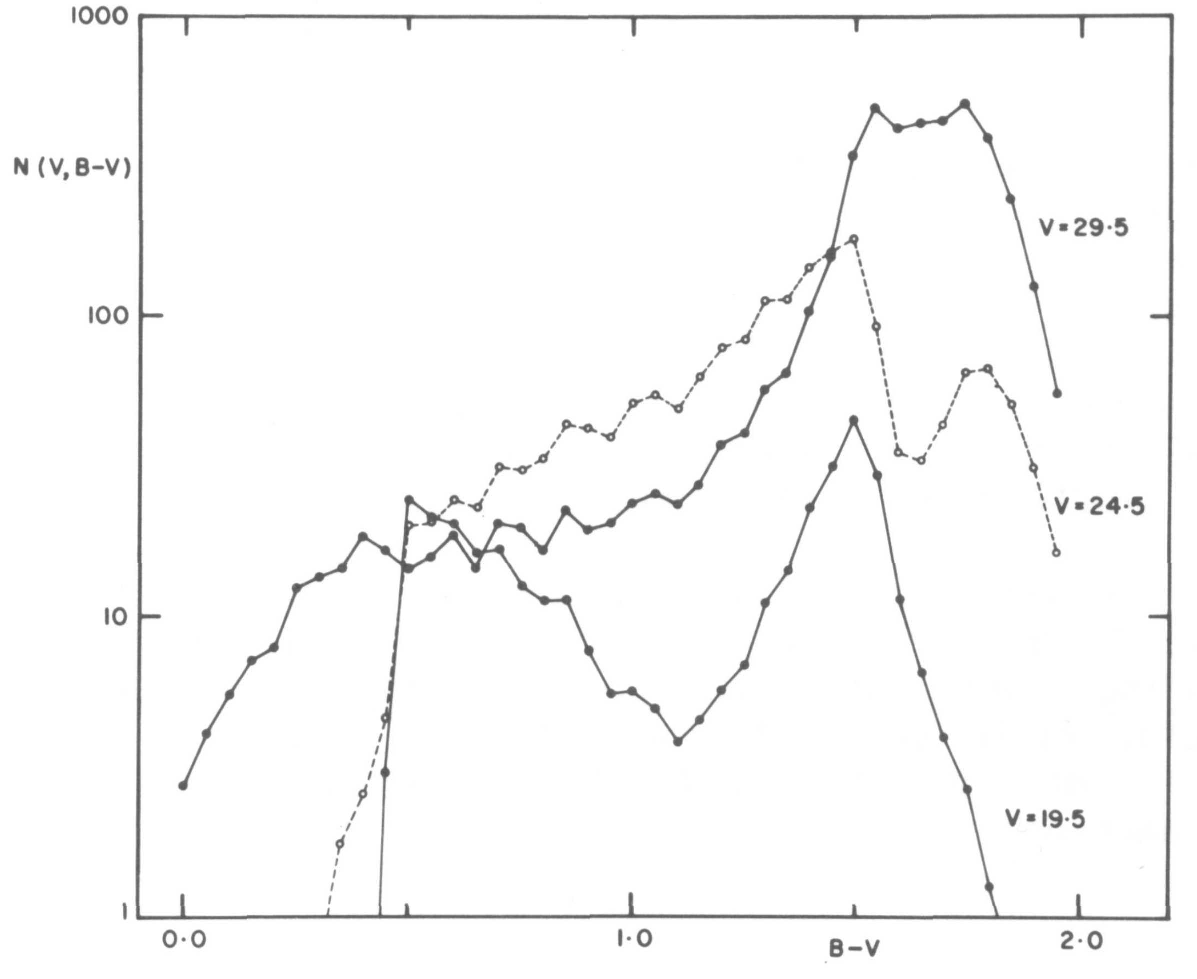

Figure 1. Calculated distribution of B-V colors for stars at V = 19.5, V = 24.5 and V = 29.5

strengthen the determination of β. The data in Table I show that the Luyten (1968) and Wielen (1974) luminosity functions yield rather similar predicted counts. This agreement is not surprising because the Luyten and Wielen luminosity functions for main sequence stars are so similar.

The slope of the faint end of the luminosity function, which is of critical importance for the "missing mass" problem is most strongly constrained by observations of stars in the range $25 \lesssim V \lesssim 30$, which can be explored with the Space Telescope. A proper motion study of a field centered on M87 by Prociuk (1976) shows that "black dwarfs" with $M_V > +15$ contribute $\lesssim 1\%$ to the star counts at $V \sim 22$.

More detailed numerical results will be given in Pitchet and van den Bergh (1980).

III. THE NUMBER OF GLOBULAR CLUSTERS

Contribution to field star counts

Luminous galaxies are embedded within extended halos of globular clusters. Since the number of globulars greatly exceeds the number of galaxies they might begin to contribute significantly to counts of star-like images at very faint magnitude levels. The computation of the number of globular clusters in various magnitude ranges that is

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given below was based on the following simplyfing assumptions:

1. The luminosity function of galaxies is that given by Felten (1977).
2. The number of globular cluster associated with each galaxy is proportional to the luminosity of that galaxy. The constant of proportionality is such that a galaxy of M_B = -20.0 contains 100 globulars. Galaxies fainter than M_V = -13.5 do not contain any globulars.
3. The luminosity function of globular clusters is Gaussian with $\langle M_B \rangle$ = -6.76 and σ = 1.1 mag (Hanes 1977).
4. Globular clusters are distributed uniformly in space.

In Figure 2 the luminosity function of globulars derived from assumptions 1, 2, and 3 is compared to that of galaxies (Felten 1977). The corresponding count - brightness relationship for globular clusters and for galactic field stars at b = ±90° are compared in Table II and Figure 3. In compiling these data H = 50 km $s^{-1}Mpc^{-1}$ was assumed. With this assumption the average space density of globular clusters is 0.41 Mpc^{-3}.

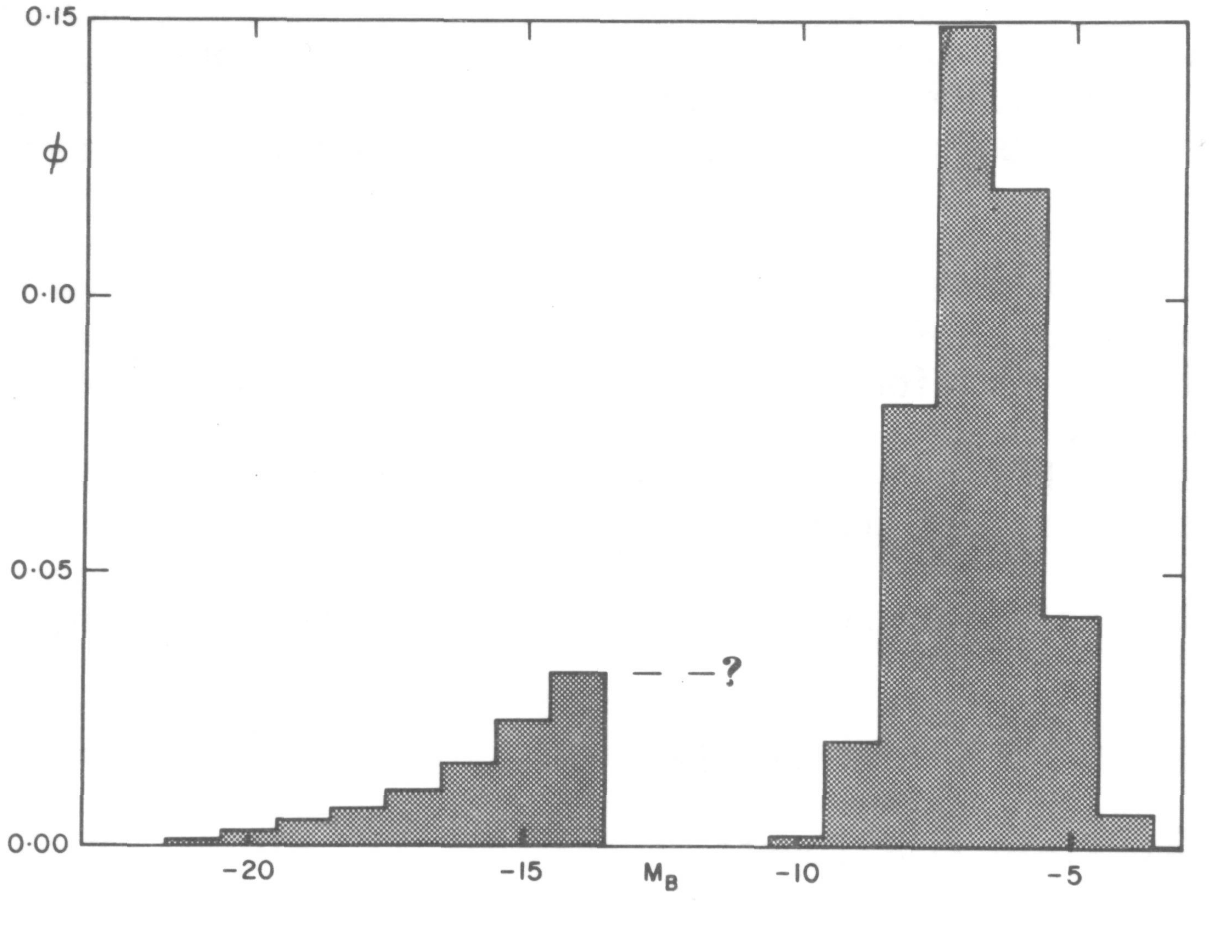

Figure 2. Comparison of the luminosity function of galaxies and globular clusters.

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TABLE II

COMPARISON OF STAR COUNTS AND GLOBULAR CLUSTER COUNTS*

B	log n(clusters)	log n(stars)
24.5	0.16	3.13
25.5	0.76	3.21
26.5	1.36	3.29
27.5	1.96	3.36
28.5	2.56	3.45
29.5	3.16	3.53
30.5	3.76	3.59

*No. per B magnitude per square degree.

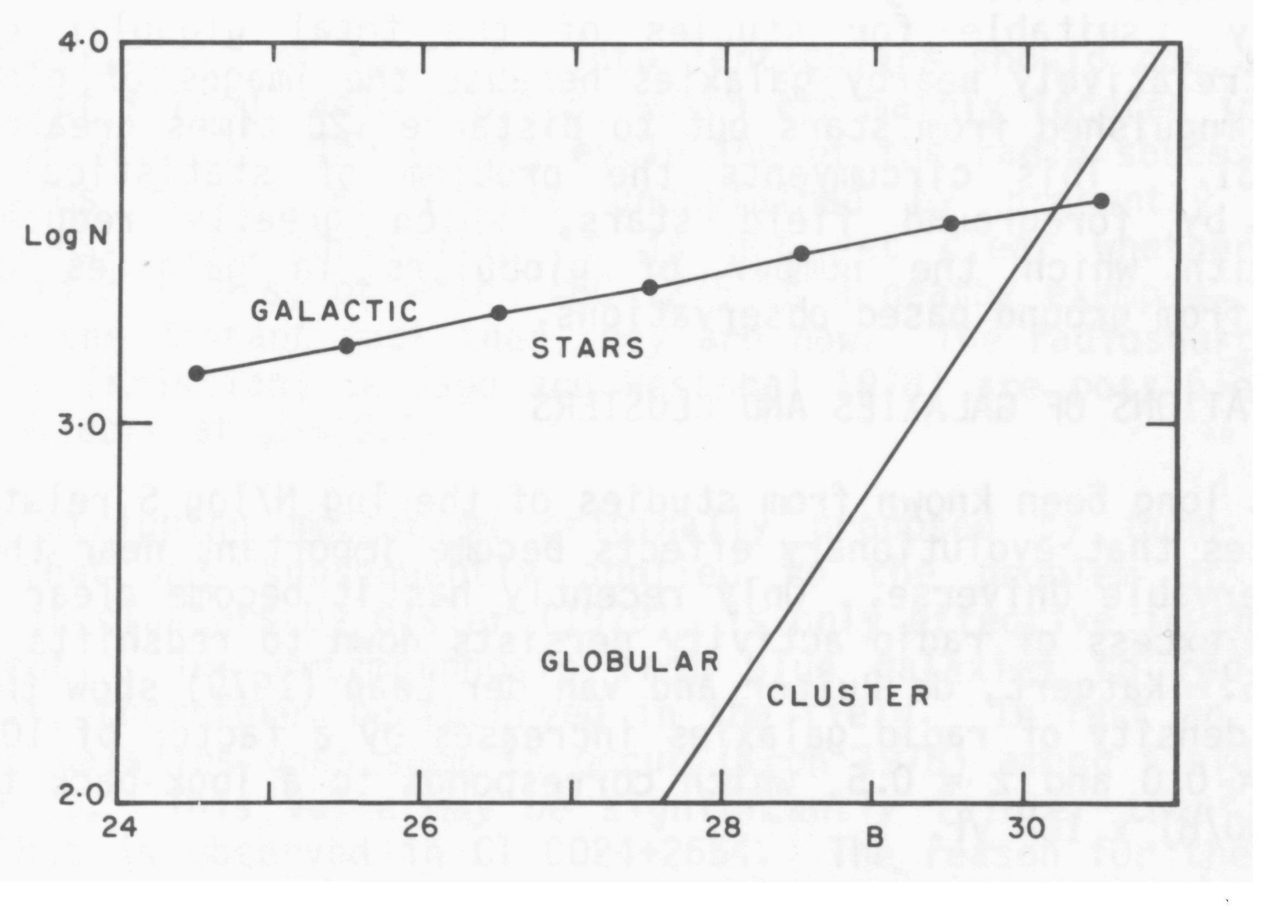

Figure 3. Comparison of predicted numbers of faint stars and globulars. For B > 30 star-like globular cluster images outnumber galactic halo stars.

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It should, perhaps, be emphasized that the data in Table II over estimate the true number of globular clusters that will actually be observed by a factor of say 2 to 4. This is so because the present calculations do not take in to account the fact that clusters projected on the main body of their parent galaxy will in general, be unobservable.

Inspection of the data in Table II, which are plotted in Figure 3 shows that $\sim$0.1% of the star-like objects at B $\sim$ 25 are globulars. This rises to $\sim$50% at B $\sim$ 30. Due to the clumpy distribution of galaxies in space N(clusters)/N(galaxies) will, at a given magnitude level, show large variations over the sky. Below thirtieth magnitude globular clusters, which show much less "K-dimming" than do galaxies, will outnumber galactic halo stars.

Globular clusters in nearby galaxies

New observations of NGC 5128 (=Cen A) by van den Bergh (1978) show that this peculiar giant elliptical galaxy contains $\sim 10^2$ times fewer globular clusters per unit luminosity than does M87. Possibly this difference is related to the fact that NGC 5128 is a field galaxy whereas M87 is located near the center of the rich Virgo Cluster. Other factors that could correlate with the frequency with which globular clusters occur in galaxies might be flattening, intrinsic color and halo color gradient. The Space Telescope will be particularly suitable for studies of the total globular cluster content of relatively nearby galaxies because the images of globulars can be distinguished from stars out to distance $\sim$20 times greater than that to M31. This circumvents the problem of statistical noise introduced by foreground field stars, which greatly reduces the accuracy with which the number of globulars in galaxies can be determined from ground based observations.

IV. OBSERVATIONS OF GALAXIES AND CLUSTERS

It has long been known from studies of the log N/log S relation of radio sources that evolutionary effects become important near the edge of the observable Universe. Only recently has it become clear that a significant excess of radio activity persists down to redshifts as low as z $\sim$ 0.25. Katgert, de Ruiter and van der Laan (1979) show that the population density of radio galaxies increases by a factor of 10 to 30 between z = 0.0 and z = 0.5, which corresponds to a look-back time of only $\sim 3(100/H) \times 10^9$ yr.

Most strong radio sources are of morphological types E and cD. Such objects are strongly concentrated in clusters of galaxes. Are the strong evolutionary effects that are observed in radio galaxies a function of time-dependent changes in the cluster environment, or do they result primarily from changes within the galaxies themselves? These are questions that can be attacked directly by morphological studies of

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galaxies with the Space Telescope. A galaxy with a diameter of 10 kpc and a redshift z = 0.5 will have an apparent diameter of 3".5 in a Universe with H = 75 km $s^{-1}Mpc^{-1}$ and q_0 = 0. The image of such a galaxy contains ~10 resolution elements for ground based and up to ~10^3 resolution elements for Space Telescope observations. The latter value is marginally sufficient for accurate morphological classification. Since the appearance of galaxies is strongly dependent on wavelength it is vitally important that nearby galaxies photographed in blue light be compared to distant ones at λ ~ 4200 (1+z)Å. It would be particularly important to see how the relative numbers of elliptical, lenticular, anemic, and spiral galaxies in distant clusters differ from those in nearby clusters of comparable richness.

Some insight into the kinds of effects that might be found in such studies is provided by the color observations of cluster galaxies that have recently been published by Butcher and Oemler (1978). These authors find that some distant clusters contain quite blue galaxies. In Cl 0024+1625 (with z = 0.39) these blue objects first appear ~2 mag below the brightest cluster galaxy. The fact that the luminosity function of nearby S0 galaxies peaks well below that of ellipticals (van den Bergh and McClure 1979) suggests that these blue objects are spiral or anemic galaxies that have not yet been completely stripped of gas (Gisler 1979). Additional support for this speculation is provided by the observation that the blue galaxies in Cl 0024+1625 are less concentrated to the cluster core than are the red galaxies.

Metamorphosis of spirals into lenticulars should not affect the frequency of strong radio sources, which are mainly located in galaxies of types E and cD. The strong evolution of the radio souces in E and cD galaxies therefore remains unexplained by presently available observations. In particular it is not yet clear whether blue cD galaxies in clusters, of which NGC 1275 is a nearby example, were more common in the distant past than they are now. The radiosources 3C 299 and 3C 330 (Kristian, Sandage and Westphal 1978) are possible examples of such objects at z ~ 0.5.

The stripping mechanism originally proposed by Gunn and Gott (1972), that was subsequently applied to the problem of the blue galaxies in clusters by Gisler (1979), is only effective in the cluster environment. The metamorphosis from blue galaxies to red galaxies should not, therefore, be observed in the field. In fact an excess of very blue galaxies does seem to occur (Kron 1978) among field galaxies with V > 22. This value may be significantly fainter than the value V ≳ 21 that is observed in Cl 0024+2654. The reason for the observed color change in field galaxies is still obscure. Possibly it is simply due to the fact that young spirals form stars more vigorously than do older ones. Taken at face value the observation that faint, distant and hence presumabley young, galaxies are blue tends to support scenarios incorporating strong evolutionary effects. A problem with this interpretation is, however, that it predicts that galaxies were much more luminous in the past that they are at the present time.

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Counts of very faint extended objects, such as those reported by Peterson et al. (1979) and by Tyson and Jarvis (1979), do not show the dramatic increase in the number of galaxies with V > 21 that are predicted by models (Tinsley 1977a,b) which incorporate strong evolutionary effects. It follows that either (1) star formation does not start with a bang (Tinsley 1978), (2) the initital burst of star formation in early-type galaxies is shrouded in dust or (3) newly forming galaxies are mis(?)classified as quasi-stellar objects. Hopefully observations with the Space Telescope will enable us to make a choice between these alternatives.

V. THE SPACE TELSCOPE AND THE FUTURE OF GROUND-BASED ASTRONOMY

When we go to the marketplace we expect to pay dearly for exotic wares from far away places. By the same token astronomers are willing to pay a stiff premium for photons that either a) have wavelengths that do not allow them to penetrate the earth's atmosphere or b) come from very faint distant objects.

Until recently it was necessary to build ever larger ground-based telescopes to expand the astronomical horizons towards the edge of the observable Universe. With the advent of the Space Telescope, which can study objects fainter than those visible from Earth, this situation has changed dramatically. This development leaves Earth-bound astronomy free to exploit its ability to gather photons at relatively low cost. Furthermore the recent advent of thin-mirror telescopes has, I feel, shifted the advantage of wholesale photon collecting even more decisively towards earth-bound observatories. In my view ground-based astronomy must face this new development squarely by vigorously exploiting its cost effectiveness.

This suggests that we should not aim to build super-expensive Earth-bound telescopes of heroic dimensions. Although detailed engineering studies of this subject have not yet been made I strongly suspect that thin-mirror alt-azimuth telescopes with apertures of $\sim$3m of standardized design and produced in large numbers will turn out to be the most cost-effective photon collectors.

If past history is a reliable guide, these Earth-based "people's 3m telescopes" will be kept very busy studying the plethora of fascinating objects discovered by orbiting observatories.

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DISCUSSION

King (Discussion leader): Since Dr. van den Bergh based parts of his discussion on Berkeley work that has not yet appeared in print, I should like to begin with a brief description of that work. The basic material is colors, magnitudes, and proper motions of stars down to V = 21 or 22 in three high-latitude fields. It is important that we have 3 fields at different latitudes and longitudes, because our ability to discriminate between disc and halo stars depends on the contrast between these 3 directions.

Two Ph.D. theses have involved this material. Kate Brooks' thesis project consists of the fitting of models of density distributions and luminosity functions, for both Populations I and II. The density functions are very like those that Dr. van den Bergh quoted. George Chiu's proper motions are of unusually high accuracy, and practically every star has a measured motion. With these motions he can make a fairly good population classification of individual stars. Interestingly, he seems to find a gradual transition between the two populations, not just in their relative proportions, but in the metal abundances and velocity dispersions of the stars themselves. Also, both studies seem to require a rather strongly flattened halo, although there is some possibility that this is really a manifestation of the population transition that I just mentioned.

With regard to Richard Kron's thesis, the data paper is in press (Ap. J. Suppl.). The interpretation paper will be written jointly with Bruzual, since Bruzual models of early galaxy evolution are intimately involved. The problems of faint galaxies continue to be actively pursued at Berkeley.

As for observations of faint stars with ST, it is worth noting that much of this work can be done on serendipity exposures made with the WFC. To do it properly, however, requires a little more, because it is important to determine colors and proper motions. ST will be directed, under control of other instruments, to the same primary field again; but in order to get the same secondary field again we will have to specify that the ST roll angle be the same. This makes the repeated observations "secondary observations," according to the scheme in which Ed Groth classifies things.

ST proper motions should be measurable over a short time interval. Whereas the best ground-based astrometry can get relative positions of stars to ± 0.010 arcsec, ST pictures should have little difficulty achieving ± 0.002 arcsec and can even aspire to ± 0.001 arcsec. With this sort of accuracy we can even contemplate doing parallaxes of the stars in random field exposures!

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Finally, I would like to make some remarks on the faint end of the luminosity function. Such stars are very rare in a magnitude-limited sample, and in indiscriminate surveys they tend to be lost among the more numerous stars in the medium-faint-luminosity range. From the ground they will best be studied by pre-screening the faint stars through large-proper-motion surveys like those of Giclas and particularly of Luyten.

ST offers an interesting opportunity to study the luminosity function directly, however. If we find an opaque dark nebula at 500 pc distance (and such can be found), then a WFC field in this direction will include a volume of 25 cubic parsecs, and a picture will record all stars in this volume down to absolute magnitude +17. A few such fields, with colors, proper motions, and possibly some crude parallaxes, will go a long way toward determining the faint luminosity function with a single blow.

Bahcall: Ray Soneira and I have constructed a detailed model for the disk and spheroid components of the Galaxy. The stellar luminosity functions and scale heights were determined from observations in the Solar neighborhood. The global distribution of matter was assumed to be an exponential disk plus a de Vaucouleurs spheroid. All of the available data on star counts for the observationally well-studied range of $4 \lesssim m_V \lesssim 21$ are consistent with the derived model over the observed five orders of magnitude variation in the projected star density at the Galactic pole. The calculated latitudinal and longitudinal dependences of the star counts are also in good agreement with existing observations. The computed M/L ratios for the disk and spheroid are in agreement with observations of other galaxies.

Further ground-based observations at attainable faint magnitudes ($m_V \leq 23^m$) would be important. The predicted strong longitudinal dependence of the spheroid star counts would permit a more accurate determination of the spheroid star density and axial ratio if the appropriate measurements were made. Our knowledge of the scale length of the disk could also be improved by star counts with ground-based telescopes.

The Galaxy model of the disk and spheroid is used to predict the star densities (in B and V) that may be observable with the aid of the Space Telescope down to very faint magnitudes. The stellar density to $m_V = 28$ from the disk and spheroid is predicted to be 10^4 stars per square degree. The predicted star counts are insensitive to many of the model parameters, although drastic changes in the shape of the luminosity function outside the presently determined magnitude range could produce measurable departures from the predicted star counts at faint magnitudes. The rotation curve computed solely from the disk and spheroid components decreases beyond about 10 kpc from the center of the Galaxy. A halo with even a relatively small mass density in the Solar neighborhood

(ρ_H(Sun) = 0.01 $M_\odot$ pc^{-3}) can give rise to a flat rotation curve. The stellar content of such a halo would be revealed by observations with Space Telescope cameras if the halo consists of main sequence stars with $M_V^{MS} \lesssim 19.0^m$ (existing observations imply $M_V^{MS} \gtrsim 12.5^m$) or faint white dwarfs with $M_V^{WD} \lesssim 17.5^m$ (existing observations imply $M_V^{WD} \gtrsim 11.5^m$). Existing data imply $(M/L)_{HALO} > 250$ (Solar Visual units).

This work has been submitted for publication to the Astrophysical Journal with the title "The Universe at Faint Magnitudes: I Models for the Galaxy and the predicted Star Counts."

Rubin: There is now no evidence that the rotation curve of our Galaxy is falling at the position of the Sun. Classically, the evidence for a falling curve came from values of Oort's constants A and B with $A > -B$, i.e.,values of A of 15 and B of -10, each with uncertainty ± 3 or so. The recent publication of Fricke and colleagues shows that $A \approx -B \approx$ 13 km s^{-1} kpc^{-1} for early type stars at 2 kpc distance. This evidence that $A = -B$ means that the rotation curve of our Galaxy is flat in the vicinity of the Sun.

Gunn: By studying the neutral hydrogen velocity distribution, Knapp, Tremaine and I found the same result from techniques very different from the classical one. There is other direct evidence as well from the velocities and distances of distant HII regions that the rotation curve is sensibly flat out to at least 25 kpc.