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CHEMICAL EVOLUTION OF BULGES AND HALOS*

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The chemical properties of elliptical galaxies and the bulges of spiral galaxies are reviewed. The mass-metallicity relation for ellipticals appears to span the full range of these galaxies from dwarf spheroidal to gE. Explanations seem possible in terms of galaxy formation models with dissipation and mass loss, but other solutions such as variable yield are discussed. The properties of globular cluster systems and their "parent" galaxies are compared.

Key words: galaxies—clusters: globular

I. Introduction

A generation of astronomers that has seen the basic problems of stellar evolution tamed naturally turns to the evolution of galaxies as the next hunting ground. To the observer the problem looks similar. There is the same zoo of luminous objects out there, awaiting rational classification and physical sequencing. There are two basic approaches available. One approach is (in a different metaphor) to examine the fossil record: to investigate the characteristic stellar population left behind through the aeons of star formation in galaxies. The other is to look back directly at younger galaxies. The latter technique holds great promise. Perhaps we shall see morphological differences in high-redshift galaxies with Space Telescope, or spectroscopic differences with the TMT or NNTT. But there has been no unequivocal detection of galaxy evolution with look-back time up to now (Kron 1984). We examine the former technique in this review.

II. The Simple Model

Galaxies turn gas into stars, and stars enrich the interstellar medium. The seminal paper in which these processes were parameterized and examined for their consequences is that of Schmidt (1963). Here we adopt the notation of Pagel and Patchett (1975). We imagine a closed system with an initial unit mass of gas. The mass of gas in the interstellar medium at any time is μ, and s is the total mass of stars ever made. A fraction α of these consists of long-lived stars. The remainder die essentially when they are born, releasing a mass fraction $p\alpha$ of their original light elements as heavy elements. The quantity p is known as the yield. As shown by Searle and Sargent (1972), the heavy-element fraction of the interstellar medium is then

$$Z = p \ln\mu^{-1} \quad . \tag{1}$$

By integrating from $\mu = 1$ *to* μ approaching zero, it is easy to show that the mean stellar abundance in a population where that process has gone to completion is

$$\langle Z \rangle = p \quad . \tag{2}$$

It was clear from its inception that the simple model failed to reproduce the metallicity distribution in the solar neighborhood. As our horizons expand, we note that it also fails to allow any range in $\langle Z \rangle$ in the halos and bulges of our Galaxy and others. Although detailed models are required to make realistic predictions for comparison with observations, it is worth pursuing the technique of parameterizing the physical processes at least as a guide to the possibilities.

III. The Simple Model with Bells and Whistles

The assumptions of the simple model beg to be modi-

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fied. Perhaps the most urgent is the assumption that the system is closed. There are obvious physical processes which cause material to flow into galaxies. These include the accretion of gas-rich dwarfs, which dominate the luminosity function of galaxies. Particularly in the first few billion years after formation, we should expect material which has just turned around from the Hubble expansion to fall in from large distances. Dark matter in the galactic halo may also be a source of gas. There are also processes of the opposite sign which cause outflow of material from the volume under study, including dissipation, ejection in supernova-driven winds, and the influence of a dense or hot intergalactic medium.

Following Edmunds and Pagel (1983) we parameterize the inflow rate as $\gamma ds/dt$, assuming, to mix cause and effect a little, a proportionality to the star formation rate. The outflow rate is similarly taken to be $\lambda ds/dt$. The basic conservation equation becomes

$$\begin{aligned} \mu &= 1 - \alpha s + \gamma s - \lambda s \\ &= \mathfrak{m} - \alpha s \quad , \end{aligned} \tag{3}$$

where $\mathfrak{m}$ is the mass at time t. Under these circumstances it is easy to show that

$$\langle Z \rangle = p/(1+\lambda/\alpha) \tag{4}$$

as μ goes to zero; i.e., the mean stellar abundance can be reduced to an arbitrarily low level, if we postulate sufficient loss of gas from the system during formation. This possibility has been known for a long time (Sandage 1958), and remains the basis of our understanding of the metallicity distribution of the Galactic halo (Hartwick 1976) and of the chemical composition of dwarf galaxies such as Draco (Zinn 1978; Smith 1984). It is sometimes objected that the removal of a large fraction of the gas of a galaxy will disrupt it. Detailed modeling is required to study the relative importance of gas flows due to dissipative collapse and gas outflow due to expulsion (which presumably is disruptive), all in the context of a massive preexisting dark halo. Models of this sort by Carlberg (1984*a*) appear to be viable. It is also possible that some sort of disruption is involved in the formation of dwarf galaxies like Draco (Gerola, Salpeter, and Carnevali 1983). With a little algebra it can be shown that the metallicity dispersion in a galaxy, σ_z is given by

$$\sigma_z/\langle Z \rangle = (\alpha+\lambda-\gamma)^{0.5}/(\alpha+\lambda+\gamma)^{0.5} \quad . \tag{5}$$

IV. The Mass-Metallicity Relation

The existence of a color-magnitude relation in photometry of early-type galaxies can be traced to the work of Baum (1959). Spectrophotometry by Faber (1973) suggested this should be seen as a metallicity dependence, and the assumption of constant $\mathfrak{M}/L$ in galaxies allows one to speak of a mass-metallicity relation. This relation extends over more than three orders of magnitude in mass according to observations in the Virgo cluster by Caldwell (1983). The step from galaxy color to metallicity is a model dependent one, of course, and it is possible that the ultraviolet colors of ellipticals are affected by recent bursts of star formation. In this context it is interesting to note that a color-magnitude relation is seen in the infrared colors of Virgo dwarfs, which are almost unaffected by recent star formation (Bothun et al. 1984*a*). Figure 1, which shows this, was constructed from observations by Bothun et al. (1984*b*), Bothun and Caldwell (1984), and Persson, Frogel, and Aaronson (1979).

Given the model dependence of the color-metallicity transformation in ellipticals, it is difficult to be sure of the functional form of the mass-metallicity relation. We can go some of the way to removing the model dependence by observing individual stars in nearby ellipticals, either spectroscopically (Kinman, Kraft, and Suntzeff 1980) or photometrically (Mould, Kristian, and Da Costa 1982, 1983). But even with Space Telescope we would expect to fall just short of extending this technique to the giant ellipticals of the Virgo cluster. Figure 2 shows the results of these observations in the mass-metallicity plane together with the inferred super-metal-richness of gE galaxies (Tinsley 1978; Aaronson et al. 1978). The remaining model dependence in this diagram cannot be removed until accurate mass-to-light ratios are measured for giant and dwarf ellipticals. For present purposes $\mathfrak{M}/L$s have been adopted from models which contain no dark matter beyond that predicted for a Salpeter initial mass function extending between 80 and 0.08 $\mathfrak{M}_\odot$. A dependence

$$\langle Z \rangle \sim \mathfrak{M}^{0.4} \tag{6}$$

is a reasonable fit to Figure 2, but this would change if dwarf spheroidals have a higher fraction of dark matter than giants (Aaronson and Cook 1984, cf. Cohen 1984).

Some of the thinking that dEs have massive halos derives from analogy with dIrrs, which Tinsley (1981) argued must be richer in dark matter to balance out the lower $\mathfrak{M}/L$ expected from their bluer colors. However, this may not be the case, if in giant disk galaxies, as distinct from dwarfs, the effective radius for starlight is very much less than the effective radius for matter. (Under this hypothesis the masses of early-type disk galaxies have been underestimated.)

Terlevich et al. (1981) and Efstathiou and Fall (1984) have found that central velocity dispersion is a second parameter in the mass-metallicity relation. The effect is in fact seen in the self-gravitating models of Carlberg (1984*b*).

V. Gas Loss in Protogalaxies

If the primary cause of gas outflow in ellipticals and bulges during formation is the energy released in supernovae, we can equate this energy to the binding energy

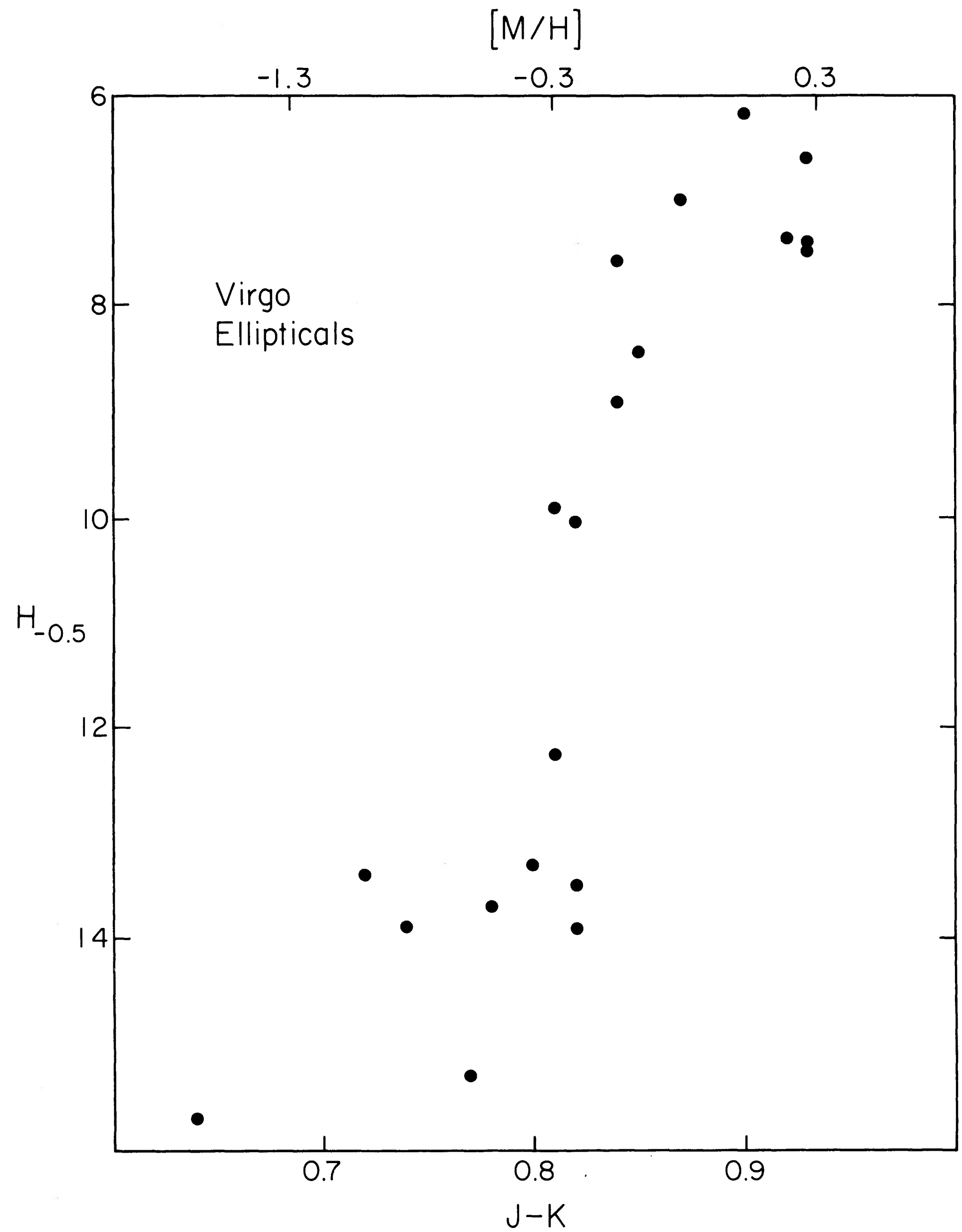

FIG. 1—An infrared color-magnitude relation for elliptical galaxies in the Virgo cluster.

of the gas, following Tinsley (1980):

$$G\mathfrak{M}\lambda s/r_e \sim Es \quad , \tag{7}$$

where E is the energy produced in supernovae per unit mass of stars made, and r_e is the effective radius of the galaxy. Where λ is large, equation (4) predicts for dwarf galaxies

$$\langle Z \rangle \sim \lambda^{-1} \sim \mathfrak{M}/r_e \sim \mathfrak{M}^{0.5} \tag{8}$$

for constant surface brightness galaxies. For λ small:

$$\langle Z \rangle \sim pk\mathfrak{M}^{0.5}/(1+k\mathfrak{M}^{0.5}) \quad , \tag{9}$$

which approaches p for large $\mathfrak{M}$. This predicts a flattening of the mass-metallicity relation toward the yield in giant elliptical galaxies. Bingelli, Sandage, and Tarenghi (1984) have shown that constant surface brightness is a zeroth-order approximation for elliptical galaxies. A better approximation for r_e steepens to $\mathfrak{M}^{0.75}$ in giants and flattens to $\mathfrak{M}^{0.25}$ in dwarfs.

VI. Variable Yield

The yield depends upon the physics of nucleosynthesis in massive stars and the proportions of stars that are involved in these processes. It is not necessarily constant, and one could in principle obtain a mass-metallicity relation by demanding that the yield be some function of galactic mass, presumably though some unspecified local physical variable. In their analysis of the bulge of the

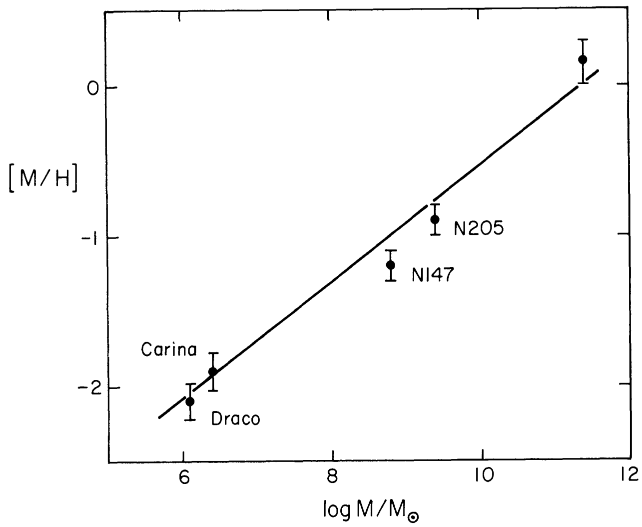

FIG. 2—A mass-metallicity relation for elliptical galaxies. The unlabeled point shows the metallicity inferred for the brightest ellipticals from integrated light models.

galaxy NGC 7814, van der Kruit and Searle (1982) trace the inverse relationship between metallicity and $\mathfrak{M}/L$. They speculate that changes with radius in α, the fraction of matter locked up in low-mass stars and particularly black dwarfs, could be responsible for this effect. One could achieve a similar result by hypothesizing a Z dependence of the slope of the initial mass function (IMF). To test these notions we need unequivocable measurements of $\mathfrak{M}/L$ in dwarf spheroidals and a determination of the IMF slope in the Galactic nuclear bulge.

VII. Formation Through Mergers

One might suppose that the existence of a mass-metallicity relation would be a thorn in the side of the theory that ellipticals and bulges were formed through mergers of smaller galaxies. However, this is not necessarily the case, if coalescence of gas-rich systems is involved. Suppose, following Tinsley and Larson (1979), that the efficiency of star formation (mass of stars formed divided by mass of gas present) is some positive power of the current mass of the galaxy, i.e.,

$$ds/d\mathfrak{m} \sim \mathfrak{m}^n \quad . \tag{10}$$

It is easy to show that

$$s/\mathfrak{m} \sim s^{n/(n+1)} \quad . \tag{11}$$

In an accreting system with

$$\mu = \mathfrak{m} - \alpha s \quad , \tag{12}$$

as before, the equivalent of equation (1) is:

$$Z = p\, ln\, \mathfrak{m}/\mu \tag{13}$$

for which

$$\langle Z \rangle = p\alpha s/\mathfrak{m} \tag{14}$$

for small s. We obtain

$$\langle Z \rangle \sim s^{n/(n+1)} \quad , \tag{15}$$

which gives the appropriate dependence for n approximately a half. This theory seems a trifle ad hoc. The merging process is restricted to a rather distant epoch when very gas-rich galaxies were common.

VIII. Color Gradients in Halos

Color gradients arise naturally in a dissipative collapse phase of bulges and halos. Observations of color gradients are therefore an important test of galaxy formation models. At this point, however, the observational data on this subject are in a far from definitive state (Boroson, Shectman, and Thompson 1984). Strom and Strom (1979) carried out an extensive program of photographic surface photometry in cluster ellipticals. They reported that only 20% exhibited observable halo color gradients, these tending to be the more massive galaxies. Wirth (1981) has published a single-channel photometry of a sample of spheroidal systems, and finds relatively small color gradients in early-type galaxies, but progressively larger color gradients in the bulges of later-type spirals. These data did not permit deconvolution of disk and bulge, but, unless the disk light were highly reddened, it is not clear that this would have compromised his result. It is interesting to combine this correlation with what we know about the kinematics of ellipticals and spiral bulges (Illingworth 1980). Since rotation plays a role in supporting spiral bulges, which it does not in ellipticals, it would seem more than a coincidence that spiral bulges have large color gradients. The situation may be simply that protogalactic gas clouds of larger angular momentum experience more generations of star formation and enrichment, before the z-component is finally dissipated and the disk is formed. Further high-quality data are needed to test the correlation found by Wirth. Deep surface photometry and deconvolution of the Sab galaxy NGC 7814 by van der Kruit and Searle (1982) shows a large color gradient. CCD surface photometry of ellipticals by Davis et al. (1984) seems to be showing larger color gradients than the ellipticals studied by Wirth and Strom.

IX. Metallicity Distribution in Galaxies with Color Gradients

Provided that the metallicity dispersion in a spheroidal shell δr is small

$$\sigma_Z \ll (dZ/dr)\delta r \quad , \tag{16}$$

it is possible to learn something about the relative amounts of metal-rich and metal-poor material. Figure 3 shows the distribution by light in NGC 7814 from the analysis by van der Kruit and Searle and the calibration of $(U-V)$ as a metallicity indicator by Aaronson et al.

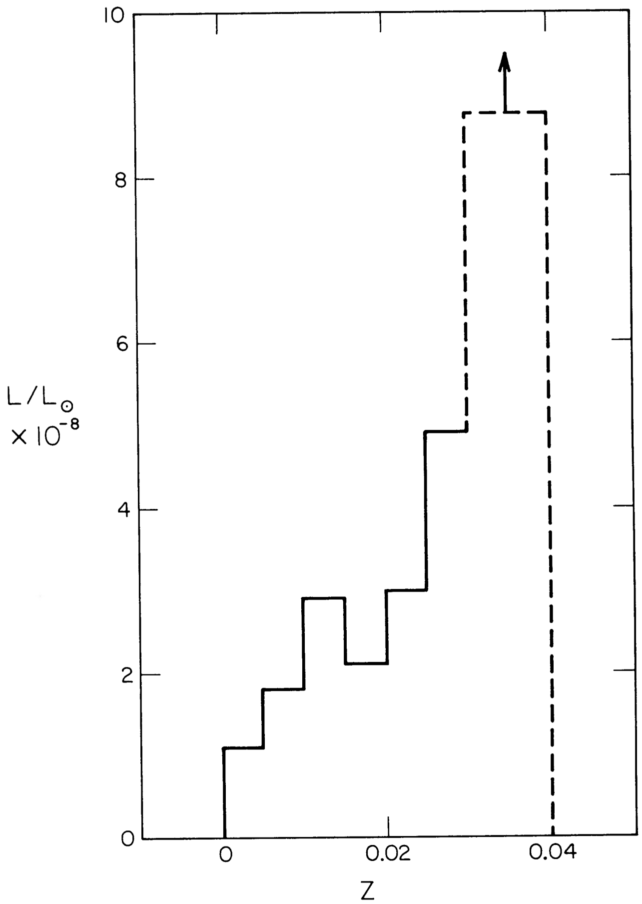

FIG. 3—Metallicity distribution in NGC 7814 inferred from the color distribution outside 3 kpc measured by van der Kruit and Searle (1982). The dashed line is a lower limit to the light contained in the central parts.

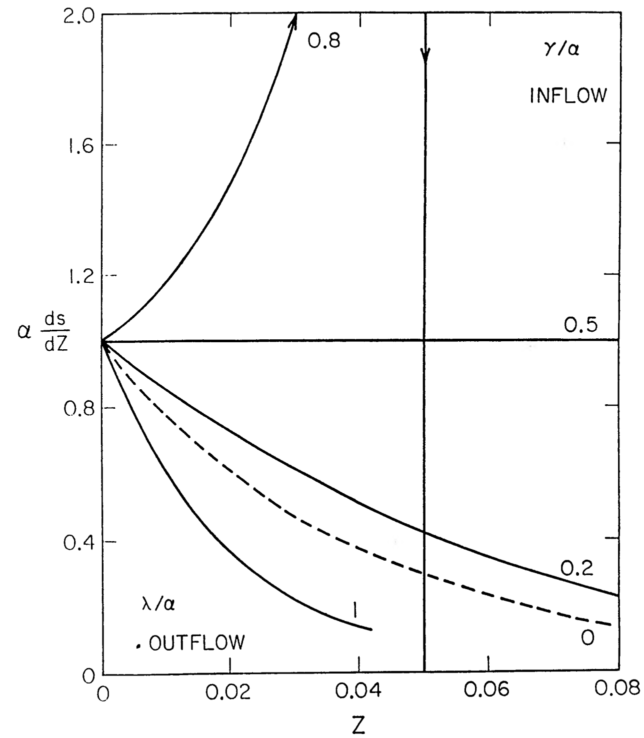

FIG. 4—Metallicity distribution in a model of chemical evolution incorporating gas flow in and out of the system. The curves are for different values of the inflow γ/α and outflow λ/α. The yield assumed was $p = 0.04$. The simple model gives the dashed curve.

(1978). Figure 4 shows predicted distributions for different values of the inflow parameter γ/α and the outflow parameter λ/α. Distributions which are flat or skewed to the metal-rich end like NGC 7814 or the solar neighborhood are indicative of infall.

X. Globular Clusters are a Separate Population

A number of arguments suggest that globular clusters make up a separate stellar population from the stars of the bulges and halos of galaxies. Chemical and kinematic differences are seen; age differences are more difficult to establish.

1. Strom et al. (1981) have shown that the globular clusters in M87 are bluer in integrated light than the galactic halo at the corresponding radius. Both systems show a similar color gradient, but there is an offset.

2. Harris (1983) has pointed out that a similar difference in mean color exists between the colors of the globulars and the integrated light of four dwarf elliptical galaxies.

3. Ratnatunga (1984) has shown that field K giants and horizontal-branch stars (Pier 1984) are kinematically different from the globular cluster system of the Galaxy (Frenk and White 1980).

4. The metallicity distribution of Galactic globulars is skewed toward metal-poor objects (Hartwick 1976), the opposite sense from Figure 3.

5. There are differences between the relative abundances of carbon, nitrogen, oxygen, and iron between globular cluster giants and field halo stars (Kraft and Suntzeff 1982).

Finally, consider Figure 5, which shows the distribution of $(V-K)$ color indices of early-type galaxies and Galactic globular clusters in the sample of Aaronson et al. (1978). Similar populations should have similar distributions, but how appropriate is the comparison? It could be argued that the Galaxy is of modest size, its bulge is only $M_v = -20$ (Edmunds and Phillipps 1984), whereas the early-type galaxy sample has $\langle M_v \rangle = -20.8$ (Hubble constant of 50 km s^{-1} Mpc^{-1}). However, Frogel (1984) maintains there is no evidence that larger galaxies have redder clusters, although some shift is seen in Figure 5 for M31 (Frogel et al. 1978), and the NGC 5128 clusters are clearly exceptional. It could also be argued that the galaxy colors were measured through circular apertures and that a better comparison could be made, say, at the effective radius of the galaxy. Annular color indices can be calculated, however, from available mean growth curves:

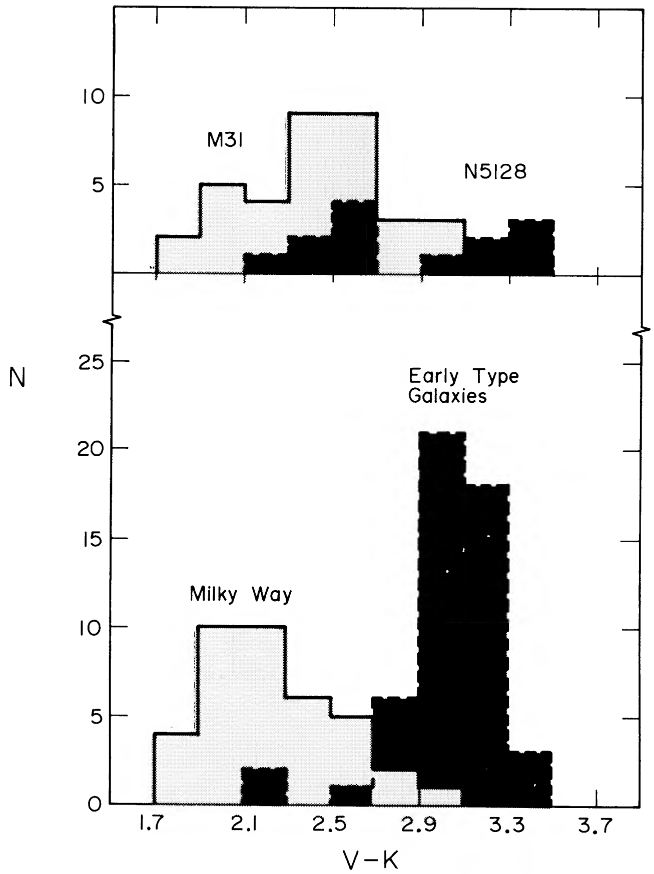

FIG. 5—Color distribution of (lower) Galactic globular clusters, and early-type galaxies and (upper) M31 and NGC 5128 globular clusters. The sources are cited in the text.

$$V - K_{\text{annular}} = V - K_{\text{circular}} - 2.5 \log dV(r)/dK(r) \quad , \tag{17}$$

where $V(r)$ and $K(r)$ are the growth curves. The correction turns out to be small, basically because the color gradients in early-type galaxies are small, and the growth curves at V and K are not very different (Frogel et al. 1978; Sandage 1975).

With these auxiliary arguments Figure 5 lends support to the notion that globular clusters are bluer than galaxy spheroids in which they are found.

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