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GALACTIC BULGES

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ABSTRACT

We discuss the present observational and theoretical understanding of the stellar populations of bulges and their implications for galaxy formation and evolution. The place of bulges as key to the Hubble Sequence remains secure, but some old paradigms are giving way to new ones as observations develop. Detailed studies of Local Group bulges and haloes provide a basis on which we consider higher redshift data. We present the evidence for and against the currently common preconceptions that bulges are old, above solar metallicity in the mean, and simply scaled-down versions of ellipticals. We conclude life is not so simple: Bulges are diverse and heterogeneous, and although their properties vary systematically, sometimes they are reminiscent of disks, sometimes of ellipticals. The extant observational data are, however, limited. New and future surveys will rectify this, and we discuss the questions those data will address.

1. MOTIVATION AND SCOPE OF REVIEW

1.1 *Introduction*

In his introduction to the report of IAU Symposium #1, *Coordination of Galactic Research*, held near Groningen, June 1953, Blaauw noted, "In the discussion

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the terms ‘halo’, ‘nucleus’ and ‘disk’ are used to indicate different parts of the Galaxy. These general regions are not defined more precisely. Their introduction proved very useful, and one might rather say that their more exact description is one of the problems of galactic research.” This statement provides an excellent example of the limitations of terminology and of the term galactic bulge in that this component continues to lack a clear definition (nucleus? halo?) of either its structure or its relationship to the other stellar components of the Galaxy. This is compounded by the difficulty of observing bulges even once one has decided which part of the galaxy that is.

The common usage of “bulge,” for example in the term bulge-to-disk ratio, allocates all “non-disk” light in any galaxy that has a “disk” into the bulge. That is, the bulge contains any light that is in excess of an inward extrapolation of a constant scale-length exponential disk. Sandage (Sandage & Bedke 1994, *Carnegie Atlas of Galaxies*; panel S11 and p. 45) emphasizes that “one of the three classification criteria along the spiral sequence is the size of the central amorphous bulge, compared with the size of the disk. The bulge size, seen best in nearly edge-on galaxies, decreases progressively,while the current star formation rate and the geometrical entropy of the arm pattern increases, from early Sa to Sd, Sm and Im types.” This is the clearest convenient description of a bulge, namely a centrally concentrated stellar distribution with an amorphous—smooth—appearance. Note that this implicitly excludes gas, dust, and continuing recent star formation by definition, ascribing all such phenomena in the central parts of a galaxy to the central disk, not to the bulge with which it cohabits. Furthermore, for a bulge to be identified at all it must, by selection, have a central stellar surface density that is at least comparable to that of the disk, and/or it must have a (vertical) scale height that is at least not very much smaller than that of the disk. The fact that this working definition can be applied successfully to the extensive classifications in the *Carnegie Atlas of Galaxies* illustrates some fundamental correctness. Bulges are also clearly very much a defining component whose properties underly the Hubble sequence, and hence the reason why we care—understanding how bulges form and evolve is integral to the questions of galaxy formation and evolution.

This review considers the current widespread beliefs and preconceptions about galaxian bulges—for example, that they are old, metal-rich, and related to elliptical galaxies—in the light of modern data. Our aim is to provide an overview of interesting and topical questions and to emphasize recent and future observations that pertain to the understanding of the formation and evolutionary status of bulges. We begin by considering some common preconceptions.

1.2 *Preconception Number 1: Bulges Are Old*

The expectation of “old age” arose, as far as we can ascertain, from the interpretation of the observed correlation between stellar kinematics and metallicity for local stars in the Milky Way by Eggen et al (1962). These authors proposed a model of Galaxy formation by collapse of a galaxy-sized density perturbation, generalized to models wherein the spheroidal components of galaxies—including the entire stellar mass of an elliptical galaxy—formed stars *prior* to the dissipational settling to a disk and so contained the oldest stars (e.g. review of Gott 1977). The high central surface brightnesses of bulges (and of ellipticals), assuming they correspond to high mass densities, also imply a higher redshift of formation, for a fixed collapse factor of the protogalaxy, because at higher redshift the background density was higher (Peebles 1989).

An older component in the central regions of the Milky Way Galaxy clearly exists. The first real work on the bulge (or "nucleus" as it was called at the time) used classical "halo" tracers, such as globular clusters, RR Lyrae, and planetary nebulae. Of course, one must remember that "older" is used here in the sense that the term was used until very recently, which meant much older than the local disk, which contains ongoing star formation. That is, "old" means "there is no obvious AF star population." The Baade-era concept of "old" meant a turnoff in the F-region, which is of course old only for a very metal-poor system (see Sandage 1986, and the *Carnegie Atlas* for thorough reviews of Baade's Population concept). Furthermore, the very idea of discriminating between ages of 10 Gyr and 15 Gyr is a recent concept, in spite of the large fractional difference between the two.

Constraints on the redshift of formation of bulges can be obtained by direct observations of high-redshift galaxies, for which morphological information may be obtained with the Hubble Space Telescope (HST) (see Section 4). In general, disentangling the effects of age and metallicity on stellar colors is difficult, even when the stars are resolved and color-magnitude diagrams may be examined. The state-of-the-art mean age determinations for lower redshift bulges and disks are discussed in Section 3, and the interpretations of color-magnitude diagrams are discussed in Section 2. Much ambiguity and uncertainty remains.

Implicit in the Eggen et al (1962) scenario was the hypothesis that the Galactic bulge was simply the central region of the stellar halo, traced at the solar neighborhood by the high-velocity subdwarfs. These stars are old by anyone's definition. Stellar haloes can be studied easily only in the Local Group, and we discuss the stellar populations in those galaxies in Section 2 below.

1.3 *Preconception Number 2: The Galactic Bulge Is Super-Solar Metallicity*

This belief was strongly supported by study of late M-giants in Baade's Window (cf Frogel 1988), motivated by the Whitford (1978) paper that compared the spectrum of the Milky Way bulge to that of the integrated light of the central regions of external bulges and giant elliptical galaxies (see Whitford 1986 for a personal interpretation of his research). Whitford's investigation aimed to determine whether or not the bulge of our galaxy was "normal," i.e. the same as others. Whitford was apparently influenced, as were most people at that time, by the interpretation of the color-magnitude relation of Faber (1973) to assume that bulges and ellipticals were differentiated only by luminosity, which determined the metallicity, and that ages were invariant and *old*, with a turnoff mass of $\sim$1 $M_\odot$ (Faber 1973), at least for the dominant population. In this case, the most metal-rich stars in a lower luminosity bulge, like that of the Milky Way, could be used as a template for the *typical* star in a giant elliptical.

Whitford (1978) concluded from his data that indeed "the strengths of the spectral features in the sampled areas of the nuclear bulge of the Galaxy are very close to those expected from measures on similar areas of comparable galaxies." However, Whitford's data were, by current standards, of low spectral resolution and were limited to the following: spectra, with a resolution of 32 Å in the blue and 64 Å in the red, for three regions in Baade's Window and for the central regions of five edge-on spirals of type Sa to Sb; lower spectral resolution data for the central regions of M 31; partial data—blue wavelengths only—for one elliptical (NGC3379, E1); and full wavelength coverage spectra for one other elliptical (NGC4976, E4), which he emphasized did not match the Milky Way and was anomalous. Furthermore, the data for Baade's Window in the blue wavelength region—where direct comparison with a "normal" elliptical galaxy was possible—were emphasized to be very uncertain, owing to the large corrections for reddening and foreground (disk) emission. Thus, while the Whitford paper was deservedly influential in motivating comparison between stars in the Milky Way bulge and the integrated population of external galaxies, its detailed conclusions rest on rather poor foundations.

The results of Rich (1988), based on his low-resolution spectra, that the mean metallicity of K/M giants in Baade's Window was twice the solar value, was very influential and widely accepted; however, it is now apparent that line-blending and elemental abundance variations contributed to a calibration error. We discuss below the current status of the metallicity-luminosity relation for bulges and for ellipticals and the detailed chemical abundance distribution for stars in the bulge of the Milky Way. Although super–metal-rich stars clearly exist in the bulge of the Milky Way, they are a minority, and their relationship to the majority population (are they the same age?) remains unknown.

1.4 *Preconception Number 3: Bulges Are Similar to Elliptical Galaxies*

Bulges and ellipticals have traditionally been fit by the same surface brightness profiles, the de Vaucouleurs $R^{1/4}$ law; for simplicity, one is tempted to assume that bulges are simply scaled-down ellipticals and that they formed the same way. N-body simulations (e.g. van Albada 1982), together with analytic considerations of "maximum entropy" end states (Tremaine et al 1986), suggested that this was through violent relaxation of a dissipationless, perhaps lumpy, system. These ideas incorporate the proposition (e.g. Toomre 1977, Barnes & Hernquist 1992) that equal-mass mergers destroy preexisting stellar disks and form bulges and ellipticals, of which these latter two are distinguished only by mass.

Furthermore, the stellar kinematics of ellipticals and bulges of the same luminosity are similar, in that each rotates approximately as rapidly as predicted by isotropic oblate models (Davies et al 1983). However, the two general categories of "bulges" and "ellipticals" are becoming clear to be somewhat heterogeneous and may cover systems that formed in a variety of ways.

The above preconceptions may be tested against modern data. We proceed with the systems for which the most detailed data may be obtained, the galaxies in the Local Group, and then outward in distance.

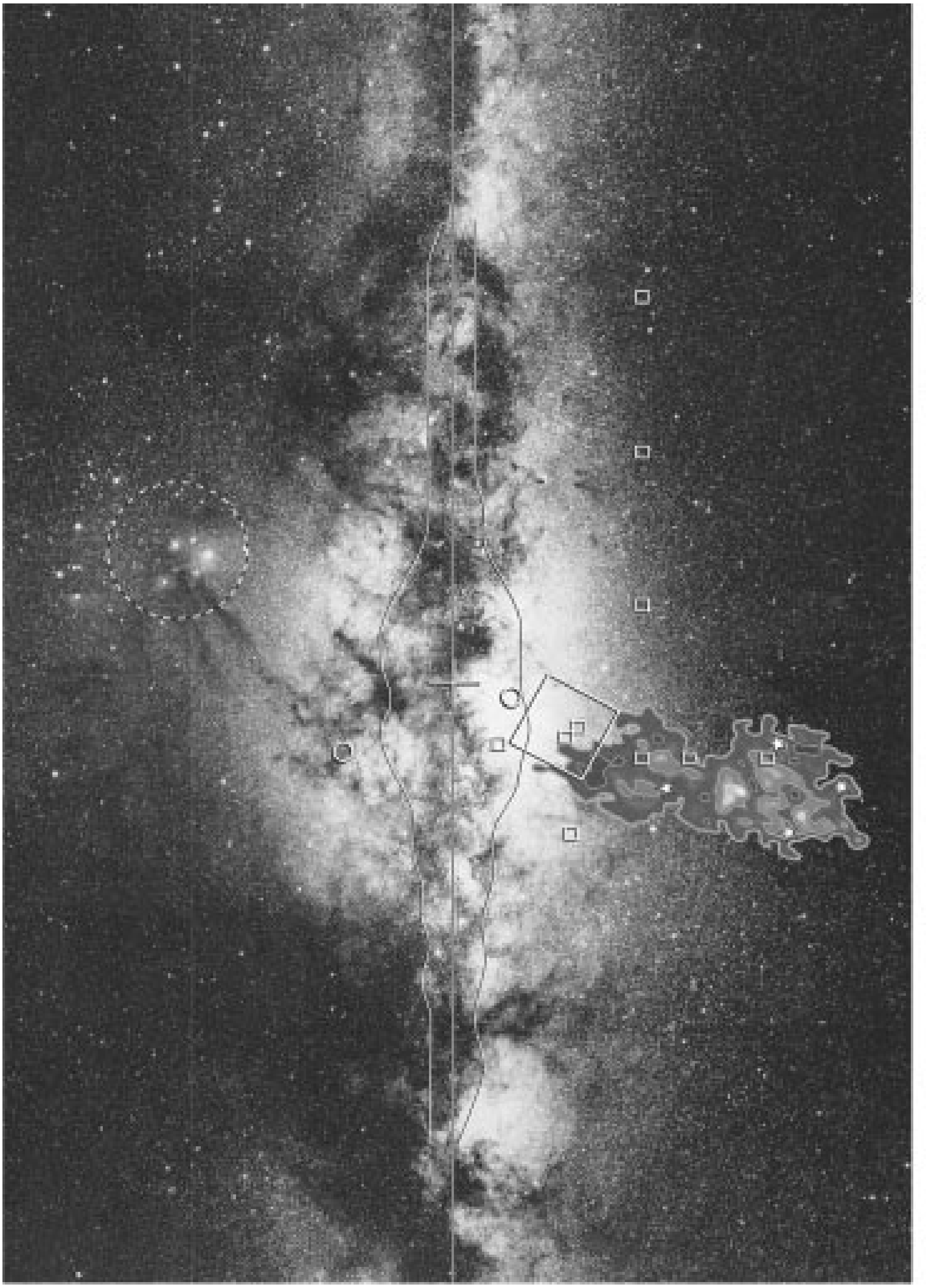
2. RESOLVED BULGES—LOCAL GROUP GALAXIES

The Local Group provides a sample of bulges in which one can determine the stellar distribution functions on a star-by-star basis, which allows a more detailed analysis than is possible based on the integrated properties of more distant bulges/haloes. In this comparison, one must be careful to isolate the essential features because there is much confusing detail, both observational and theoretical, specific to individual galaxies.

Obvious questions that can be addressed most efficiently locally include possible differences, similarities, or smooth(?) gradients in properties—kinematics, chemical abundance distribution, age distribution, scale-lengths, profiles, etc—from inner bulges to outer haloes, and from bulges to inner disks. Different tracers can be used that allow comparisons between, for example, globular clusters and field stars.

2.1 *Milky Way Galaxy*

Let us adopt for the moment the working definition of the bulge as the component constituting the amorphous stellar light in the central regions of the Milky Way. Although one might imagine that the Milky Way bulge can be studied in significantly more detail than is possible in other galaxies, our location in the disk restricts our view such that this is true only several kiloparsecs from the Galactic center. Most of the Galactic bulge is obscured by dust and stars associated with the foreground disk. We illustrate the situation in Figure 1 below.



CHEMICAL ABUNDANCES Chemical abundances of K and M giants in the central regions of the Galaxy have been determined by a variety of techniques, ranging from high-resolution spectra that allow elemental abundance analyses to intermediate-band photometry. Application to Baade's Window—approximately 500-pc projected distance from the Galactic center—determined that the metallicity distribution function (calibrated onto a [Fe/H] scale) of K/M giants is broad, with a maximum at ~ -0.2 dex (i.e. ~ 0.6 of the solar iron abundance) and extending down to at least -1 dex and up to at least $+0.5$ dex (e.g. McWilliam & Rich 1994, Sadler et al 1996). It remains unclear to what extent these upper and lower limits are a true representation of the underlying distribution function and to what extent they are observational bias, set by calibration difficulties and/or sensitivities of the techniques. Furthermore, the identification of foreground disk stars remains difficult.

At larger Galactocentric distances, Ibata & Gilmore (1995a,b) utilized fiber spectroscopy down many lines of sight to mimic "long-slit spectroscopy" of the Galactic bulge, in order to facilitate a direct comparison between the Milky Way bulge and those of external spiral galaxies. They obtained spectra of about 2000 stars; star count models, stellar luminosity classifications, and kinematics were used to isolate about 1500 K/M-giants from 700 pc to 3.5 kpc (projected distance) from the Galactic Center. These authors estimated metallicities from the Mg'b' index, calibrated against local field stars; thus there is a possible zero-point offset of up to ~ 0.3 dex, which is dependent on the element ratios of the Bulge stars compared to the local stars. Ibata & Gilmore truncated their distribution function above the solar value, owing to the great similarity

Figure 1 An optical image of the central Galaxy, adapted from that published by Madsen & Laustsen (1986). The field covered is $70^\circ \times 50^\circ$. The Galactic plane is indicated by the horizontal line, and the Galactic center by the cross in the center of the image. Also shown is an outline of the COBE/DIRBE image of the Galactic center (*smooth solid curve*, from Arendt et al 1994), an approximate outline of the Sagittarius dSph galaxy (*complex curve*, from Ibata et al 1997), with the four Sgr dSph globular clusters identified as asterisks; Baade's Window (*heavy circle below the center*); the field of the DUO microlensing survey, which contains some of the other microlensing fields (*solid square*, overlapping the Sgr dSph rectangle; Alard 1996); the four fields for which deep HST color-magnitude data are available (*open squares*, near Baade's Window); and the six fields surveyed for kinematics and metallicity by Ibata & Gilmore (1995a,b: *black/white outline boxes*). The location of Kepler's supernova is indicated as a circle, north of the Galactic plane. Other features of relevance include the extreme extinction, which prevents optical/near-IR low-resolution observations of the bulge within a few degrees of the plane, and the pronounced asymmetry in the apparent bulge farther from the plane. The dust that generates the apparent peanut shape in the COBE/DIRBE image is apparent. The asymmetry at negative longitudes north of the plane, indicated by a large dotted circle, is the Ophiuchus star formation region, some 160 pc from the Sun. The Sagittarius spiral arm contributes significantly at positive longitudes in the plane.

in low-resolution spectra between foreground K dwarfs and such metal-rich K giants, which leads to an inability to identify contamination of the bulge sample by disk stars. They find that the outer bulge metallicity distribution function peaks at ~ -0.3 dex, and continues down beyond -1 dex (see Figure 2 below).

Minniti et al (1995) present the metallicity distribution function for $\sim$250 K/M giants in two fields at projected Galactocentric distances of $R \sim 1.5$ kpc. Their results are calibrated only for stars more metal-poor than ~ -0.5 dex, and one of their fields was selected with a bias against high metallicities. Their data for their unbiased field again shows a broad distribution function, which is approximately flat from -1 to $+0.3$ dex. Minniti et al (1995) also summarize (and list the references to) results from extant photometric chemical abundance determinations (e.g. Morrison & Harding 1993); in general, these agree neither with each other nor with spectroscopic determinations. Further work is clearly needed.

The few large-scale kinematic surveys of the bulge (Ibata & Gilmore 1995a,b, Minniti et al 1995) find no convincing evidence for an abundance-kinematics correlation within the bulge itself, after corrections for halo stars and disk stars (see also Minniti 1996).

The most striking aspects of the bulge K/M giants' metallicity distribution function are its width and the fact that there is little if any radial gradient in its peak (modal) value when one considers only spectroscopic determinations. Further data are required to determine whether or not the wings of the distribution are also invariant. Certainly the very late spectral-type M giants have a significantly smaller scale height than do the K giants (Blanco & Terndrup 1989), a fact that could be a manifestation of either a metallicity gradient in the high-metallicity tail of the distribution function or of an age gradient, with a small scale height, metal-rich, younger population that is concentrated to the Galactic plane. Star formation clearly occurs in the very center of the Galaxy (e.g. Gredel 1996), so that a distinction between inner disk and bulge stellar populations remains problematic, and perhaps semantic, in the inner few hundred parsecs of the Galaxy. External disk galaxies do show color gradients in their bulge components, but the amplitude is luminosity dependent and expected to be small for bulges like that of the Milky Way (Balcells & Peletier 1994).

The little evidence there is concerning the stellar metallicity distribution of older stars in the inner disk is also somewhat confusing. An abundance gradient with the mean rising $\sim$0.1 dex/kpc towards the inner Galaxy, but for data only relevant to Galactocentric distances of 4–11 kpc, has been plausibly established for F/G stars of ages up to 10^{10} years (Edvardsson 1993; their table 14—their few older stars show no evidence for a gradient). A similar amplitude of metallicity gradient is seen in open clusters older than 1 Gyr,

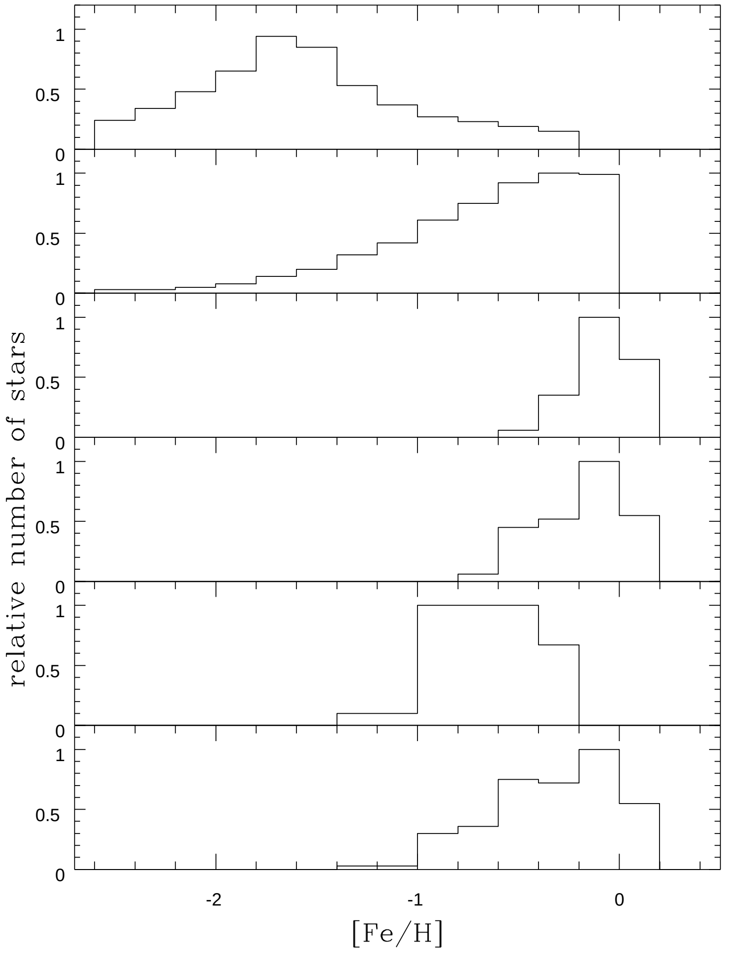


Figure 2 Chemical abundance distribution functions, normalized to unity, derived by Wyse & Gilmore (1995), except where noted. The distributions are, from top to bottom, the solar neighborhood stellar halo (Laird et al 1988); the outer Galactic bulge (Ibata & Gilmore 1995b), truncated at solar metallicity; the younger stars of the solar neighborhood; a volume-complete sample of local long-lived stars; a volume-complete sample of local thick-disk stars; the column integral through the disk abundance distribution for the sum of the long-lived thin disk and the thick disk.

but for clusters that are exterior to the solar circle (e.g. Friel 1995). Earlier data for K giants, however, suggest no radial abundance gradient, with a mean [Fe/H] ~ -0.3 from exterior to the Sun to within 1 kpc of the center (Lewis & Freeman 1989), even though such stars should be no older than the F/G sample. Clearly, however, the abundance range that contains most of the bulge stars overlaps that of the disk, with probable disk gradients that are smaller than the range of the bulge metallicity distribution function. This is of particular interest given the correlations, discussed below, between the colors of bulges and inner disks in external galaxies (de Jong 1996, Peletier & Balcells 1996).

As discussed further below, the mean metallicity of field bulge stars is significantly above that of the globular cluster system of the Milky Way, even if only the inner, more metal-rich "disk" globular clusters with mean metallicity of ~ -0.7 dex (e.g. Armandroff 1989) are considered.

A characterization of the width of the metallicity distribution comes from the fact that the distributions for both Baade's Window (Rich 1990) and for the outer bulge (Ibata & Gilmore 1995b) are consistent with the predictions of the "Simple Closed Box" model of chemical evolution. This is in contrast to the disk of the Milky Way, at least in the solar neighborhood, which has a significantly narrower metallicity distribution and indeed a shortage of low-metallicity stars compared to this model (the "G-Dwarf problem"). This of course does not mean that any or all of the assumptions inherent in the simple closed box model were realized during bulge formation and evolution, but it is rather a way of quantifying the greater width of the observed metallicity distribution in the bulge compared to the disk at the solar neighborhood, two locations that have the same *mean* metallicity.

Elemental abundances provide significantly more information than does metallicity because different elements are synthesized by stars of different masses and hence on different time scales (e.g. Tinsley 1980, McWilliam 1997). Different scenarios for the formation of the bulge could in principle be distinguished by their signatures in the pattern of element ratios (Wyse & Gilmore 1992). The available data are somewhat difficult to interpret, in part owing to small number statistics (e.g. McWilliam & Rich 1994, Sadler et al 1996), but this can be rectified with the coming 8- to 10-m class telescopes.

AGE ESTIMATES RR Lyrae stars, the traditional tracers of an old metal-poor population, are found in significant numbers along bulge lines of sight, at characteristic distances that place them close to the Galactic center (Oort & Plaut 1975). This has been taken as supporting evidence for an old bulge. Indeed, Lee (1992) argued that, for a stellar population of high mean metallicity to produce significant numbers of RR Lyrae stars from the metal-poor tail of the chemical abundance distribution, the population must be older than a metal-poor population with the same RR Lyrae production rate. Lee hence concluded that the bulge contained the oldest stars in the Galaxy, older than the stars in the field halo. But are the observed RR Lyrae stars indeed part of the metal-rich bulge, or of the metal-poor stellar halo, whose density of course also peaks in the inner Galaxy?

The samples of RR Lyrae available for this experiment have been small. However, a side benefit of the recent interest in microlensing surveys of the Galactic bulge (e.g. OGLE, MACHO, DUO) has been well-defined catalogs of variable stars, including RR Lyraes. In an analysis of the projected spatial distribution of DUO RR Lyraes—which have been segregated statistically by metallicity based on periods and fit to density laws of halo, disk, and bulge—Alard (1996) has found that the great majority of RR Lyrae stars in his catalog are not associated with the bulge, but rather with the thick disk and halo. Nonetheless, a detectable fraction of the most metal-rich RR Lyrae variables of the 1400 discovered by DUO do indeed belong to a concentrated bulge population. These stars comprise only about 7% of the whole RR Lyrae sample. Thus, the microlensing surveys have in fact made the first discovery of true bulge RR Lyraes. The intermediate-abundance RR Lyraes are primarily thick disk, whereas the most metal poor are primarily halo, from this analysis.

Analysis of the variable stars detected by the IRAS satellite (mostly Mira variables) implied a significant intermediate-age population (e.g. Harmon & Gilmore 1988), perhaps that traced by the carbon stars (Azzopardi et al 1988, Westerlund 1991) and the strong red clump population (e.g. Pacynski et al 1994a,b).

Renzini (1994, 1995) has emphasized that the relative strength of the red clump and red giant branches is dependent on helium content as well as on age and argues that age is not an important parameter for stellar populations older than 1 Gyr. Thus, should the bulge stars be of high helium content—as expected if they had been found to be super–metal-rich—then the observed red clump would be consistent with an old age. However, the fact that the mean metallicity of the bulge is now established (from unbiased tracers) to be below the solar value, with a correspondingly much-reduced helium abundance, makes this unlikely.

Understanding the effects of dust along the line of sight to the central regions is crucial. The analysis of infrared (IR) data reduces some of the reddening problems of optical data, but again the interpretation in terms of stellar properties is far from unambiguous. A deep near-IR luminosity function for Baade's window was obtained by Tiede et al (1995). Houdashelt (1996), in a detailed analysis of the available IR photometry and spectroscopy for stars in Baade's Window, concluded that a typical age of perhaps 8 Gyr and mean metallicity of [Fe/H] ~ -0.3 are most consistent.

Optical/near-IR color-magnitude diagrams that extend well below the main sequence turnoff region may be used to make quantitative statements about mean age and age ranges of stellar populations: modulo uncertainties in this case that are due to large and highly variable extinction, to extreme crowding in the inner fields, and to the contribution of foreground stars. In spite of these complications, Ortolani et al (1995) concluded, from a comparison of HST color-magnitude data for the horizontal branch luminosity functions of an inner globular cluster with ground-based data towards Baade's Window, that the stellar population of the bulge is as old as is the globular cluster system and, furthermore, shows negligible age range. This contrasts with earlier conclusions based on prerefurbishment HST color-magnitude data for Baade's Window (Holtzman 1993), which suggests a dominant intermediate-age population. Future improved deep HST color-magnitude data are eagerly awaited.

An example of the information that can be obtained is given in Figure 3, which is a V–I, V color-magnitude diagram from WFPC2 data (planetary camera) obtained as part of the Medium Deep Survey (S Feltzing, private communication).

BULGE STRUCTURE The only single-parameter global fit to the surface brightness of the combined halo plus bulge of the Galaxy that implicitly assumes they are a single entity, is that by de Vaucouleurs & Pence (1978). From their rather limited data on the visual surface brightness profile of the bulge/halo interior to the solar Galactocentric distance, when assuming an $R^{1/4}$-law profile, they derived a projected effective radius of 2.75 kpc, which may be deprojected to a physical half-light radius of 3.75 kpc. As shown by Morrison (1993), the de Vaucouleurs & Pence density profile, extrapolated to the solar neighborhood, is brighter than the observed local surface brightness of the metal-poor halo, which was obtained from star counts, by 2.5 magnitudes. Because the density profile of the outer halo is well described by a power law in density, with index $\rho(r) \propto r^{-3.2}$, and oblate spheroidal axis ratio of about 0.6 (Kinman et al 1966, 1994, Wyse & Gilmore 1989, Larsen & Humphreys 1994), this result actually provides the first, though unappreciated, evidence that the central regions of the galaxy are predominantly bulge light and that the bulge light falls off faster than does the outer halo light. That is, the bulge and halo are not a single structural entity. More generally, because the spatial density distribution of the stellar metal-poor halo is well described by a power law, whereas the inner bulge (see below) is well described by another power law of much smaller scale length, the apparent fit of the single $R^{1/4}$-law profile must be spurious and misleading.

The limiting factors in all studies of the large-scale structure of the stellar Galactic bulge are the reddening, which is extreme and patchy, and severe crowding. The systematic difference between the best pre-HST photometry

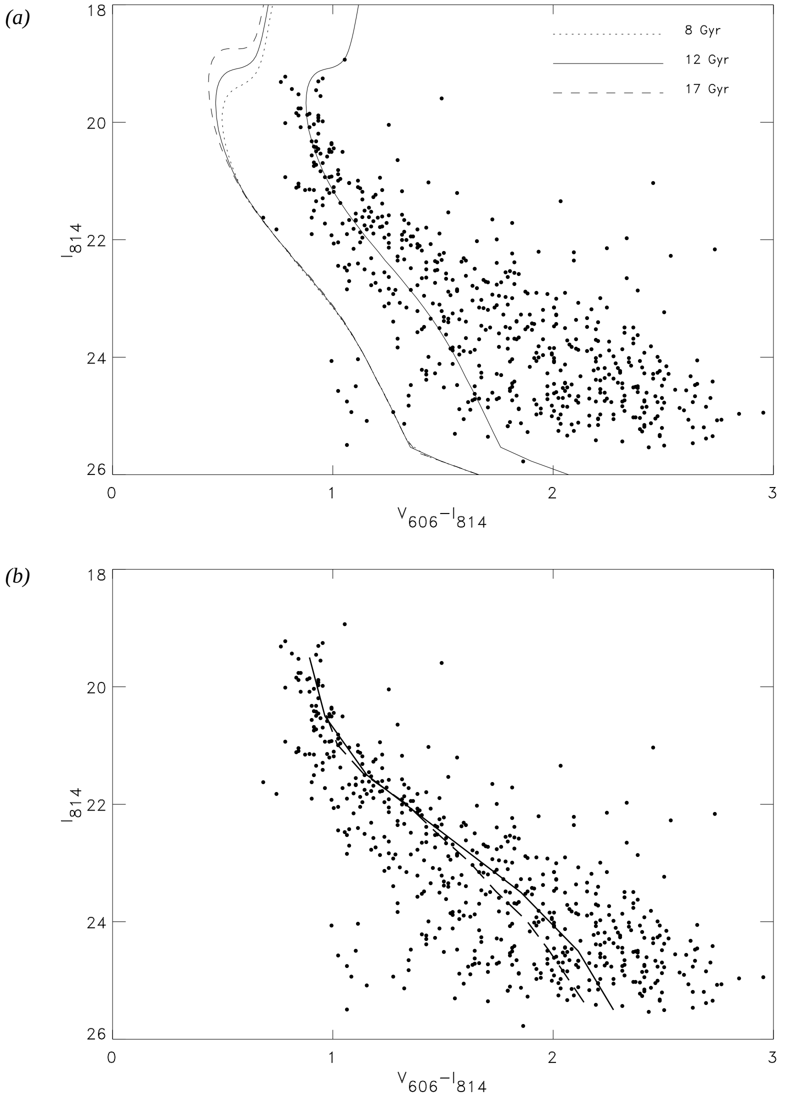


Figure 3 The HST WF/PC2 color-magnitude data for the Galactic bulge, for the field at (l, b) = (3.6, −7) identified in Figure 1, from the Medium Deep Survey. (*a*) The panel shows the data. Overlaid, from a by-eye fit, is a 12-Gyr isochrone for metallicity [Fe/H] = −0.25, from Bertelli et al (1994), together with a range of other ages plotted to one side, to illustrate the precision required and the need for independent determinations of extinction at each point. (*b*) The panel shows the mean line through the data, excluding extreme points, together with the ridge line from similar HST data for the globular cluster 47 Tucanae (Santiago et al 1996), arbitrarily offset to match the mean line.

in crowded regions and the reality, as seen by HST, is now well appreciated after many studies of globular clusters. Near-IR studies within a few degrees of the Galactic plane show optical extinction that has a random variation, on angular scales down to a few arcseconds, of up to $A_V \sim 35$ mag (e.g. Catchpole et al 1990). At southern Galactic latitudes, however, more than a few degrees from the plane, extinction is both low (typically $E_{B-V} \sim 0.2$) and surprisingly uniform, as is evident in the optical bulge image in Figure 1 and as exploited by Baade. Nonetheless, detailed star-count modeling of the inner galaxy (Ibata & Gilmore 1995a,b; M Unavane, private communication) demonstrates that extinction variations are still larger in their photometric effects than are the photometric signatures of different plausible structural models. This sensitivity to extinction, together with the extreme crowding that bedevils ground-based photometry, is well illustrated by the recent history of structural analyses of the inner Milky Way disk by the OGLE microlensing group, based on low spatial-resolution optical data. Their initial analysis of their data suggested that there is no inner disk in the Galaxy, only prominent foreground spiral structure (Paczynski et al 1994a). After more careful consideration of crowding, and of alternative extinction models, this detection of a “hole” in the disk was retracted (Kiraga et al 1997). The true spatial density distribution of the inner disk remains obscure.

There are many analyses of the surface brightness structure of the bulge, which range from straightforward counts of late-type stars perpendicular to the plane along the minor axis (cf Frogel 1988 for references) through extensive two-dimensional analyses (Kent et al 1991), to detailed inversions of photometric maps (e.g. Blitz & Spergel 1991, Binney et al 1997). In all such cases, extreme reddening near the plane precludes reliable use of low spatial resolution data with $|b| < 2$, irrespective of the techniques used. The zero order properties of the photometric structure of the bulge are fairly consistently derived in all such studies and determine ∼350 pc for the minor axis exponential scale height, as well as significant flattening, with minor:major axis ratio of ∼0.5. Together with a disk scale length of around 3 kpc, this result places the Milky Way galaxy within the scatter of late-type disk galaxies on the correlation between disk and bulge scale lengths of Courteau et al (1996).

Considerable efforts have been expended in the last decade to determine the three-dimensional structure of the Galactic bulge. These efforts began at a serious level with analyses of the kinematics of gas in the inner Galaxy, following the prescient work of Liszt & Burton in the 1980s (see Liszt & Burton 1996 and Burton et al 1996 for recent reviews and introductions to the subject), by Gerhard & Vietri (1986) together with much other work reviewed by Combes (1991). A resurgence of interest in bar models has been motivated by (*a*) new dynamical analyses (e.g. Binney et al 1991, Blitz et al 1993), (*b*) the realization that near-IR data might reflect the pronounced molecular gas asymmetry (Blitz & Spergel 1991), (*c*) gravitational microlensing results (Paczynski et al 1994b), and (*d*) the new photometric COBE/DIRBE data (Weiland et al 1994).

It appears that all galaxies in their central regions have non-axisymmetric structures, often multiple structures such as bars within bars (e.g. Shaw et al 1995, Friedli et al 1996). The distinction between inner spiral arms, bars, lenses, local star formation, and the like is perhaps of semantic interest, except in cases where the distortions are of sufficiently large amplitude such as to affect the dynamical evolution. Is the Galaxy like that? The significant question is the existence of a substantial perturbation to the inner density distribution, and gravitational potential, associated with a bar. Secondary questions are the shape of that bar and its relationship to the disk or to the bulge. The extant three-dimensional models of the central regions of the Milky Way derived from the COBE surface photometry depend on systematic asymmetries of the derived "dust-free" surface brightness with longitude of less than 0.4 mag in amplitude, after statistical correction for extinction that is locally some orders of magnitude larger in amplitude (Binney et al 1997). Thus the models are crucially sensitive to reddening corrections made on a scale of 1.5 degrees (the COBE/DIRBE resolution), although reddening varies on much smaller scales (Figure 1).

The models also provide only a smooth description of most of the known foreground disk structure such as can be seen in Figure 1—the Ophiuchus star formation region, the Sagittarius (Sgr) spiral arm, etc—and do not work at low Galactic latitudes. A model of this disk must be subtracted before bulge parameters can be derived. The best available description of the stellar bulge derived this way suggests axis ratios x:y:z $\sim$ 1.0:0.6:0.4 (Binney et al 1997).

It is worth noting that this model, although the best currently available, fails to explain either the high spatial frequency structure in the photometric data or the observed high rate of gravitational microlensing towards the inner Galaxy (Bissantz et al 1997), in addition to having remaining difficulties with the details of the gas kinematics in the inner Galaxy. Little evidence exists for non-axisymmetry in the potential from analyses of stellar kinematics—radial velocity surveys find consistency with an isotropic oblate rotator model (e.g. Ibata & Gilmore 1995, Minniti 1996), though with a mild bar allowed (Blum et al 1995). Although evidence for a bar is seen in proper-motion surveys (Zhao et al 1994, who analyzed proper motions from Spaenhauer et al 1992), this is very dependent on the distances assigned to the stars. Thus it must be emphasized that the best available models for the inner Galaxy remain poor descriptors of the very complex kinematics and spatial distribution of the gas (see Liszt & Burton 1996) and of the complex kinematics of some samples of stars (e.g. Izumiura et al 1995).

Analysis of the photometric structure of the inner galaxy is a very active field of research, which promises major progress in the next few years with the availability of the Infrared Space Observatory (ISO) imaging survey data of the inner galaxy (Perault et al 1996). ISO improves on the $\sim 1^\circ$ spatial resolution of COBE, as it has typically 6-arcsec resolution in surveys. These data provide for the first time a detailed census of individual stars and the ISM in the inner Galaxy, with sufficient resolution and sensitivity to see single stars at the Galactic center, thereby allowing the first ever determination of the true three-dimensional spatial distribution of the inner Galaxy.

We consider the kinematics of the Galactic bulge, the halo, and the disk, and their implications for formation models, below (section 5).

2.2 *M 33 (NGC 598)*

The stellar population of M 33 was reviewed by van den Bergh (1991a), to which the reader is referred for details. We discuss the significant developments since then concerning the existence and nature of the stellar halo and bulge.

M 33 shows photometric evidence for nondisk light, in particular in the central regions. However, the nature of this light remains uncertain, as does whether or not there is a central bulge component that is distinct from the stellar halo.

Attempts to fit optical and IR data for the central regions with an $R^{1/4}$ law generally agree with a "bulge-to-disk" ratio of only $\sim$2%, or $M_{V,bulge}$ fainter than ~ -15 (Bothun 1992, Regan & Vogel 1994). Regan & Vogel emphasize that a single $R^{1/4}$ provided the best fit to their data. Some evidence is given from ground-based H-band imaging (Minnitti et al 1993) and from HST V–I/I CMD data (Mighell & Rich 1995) for asymptotic giant branch (AGB) stars in the central regions in excess of the number predicted by a simple extrapolation from the outer disk; these stars have been ascribed to a rather young centrally concentrated bulge. However, McLean & Liu (1996) contend that their JHK photometry, after removal of crowded regions, shows no resolved bulge population distinct from the smooth continuation of the inner disk.

Is the $R^{1/4}$ component metal-poor or metal-rich? The giant branch of the HST CMD data is consistent with a broad range of metallicity, ranging from M 15–like to 47 Tuc–like, some 1.5 dex in metallicity. The low end of this metallicity range is consistent with that estimated earlier from ground-based CMD data for fields in the outer "halo," [Fe/H] ~ -2.2 (Mould & Kristian 1986). These outer fields showed a narrow giant branch, which is consistent with a small dispersion in metallicity, and thus the two datasets together are suggestive of a gradient in the mean metallicity and metallicity dispersion. This may be interpreted as evidence for a centrally concentrated more metal-rich component, albeit following the same density profile as the metal-poor stars. Pritchet (1988) reported a preliminary detection of RR Lyrae stars in M 33, again evidence for old, probably metal-poor, stars.

The semistellar nucleus of M 33 has a luminosity similar to that of the brightest Galactic globular clusters, $M_V \sim -10$, and a diameter of $\sim$6 pc. Analysis of its spectrum (Schmidt et al 1990) demonstrated that its blue color reflects the presence of young stars (age less than 1 Gyr) rather than extremely low metallicity; old and intermediate-age stars with metallicity greater than 0.1 of the solar value dominate. The relation of this nucleus to the "bulge," if any, is unclear.

The only kinematic data for nondisk tracers in M 33 are for a subset of its $\sim$200 "large clusters of concentrated morphology" (Christian 1993), of which perhaps 10% have the colors of the classical old globular clusters of the Milky Way. Of these clusters, 14 have kinematics that are suggestive of halo objects, in that they define a system with little net rotation and with a "hot" velocity dispersion of order $1/\sqrt{2}$ times the amplitude of the HI rotation curve (Schommer et al 1991, Schommer 1993). Estimates of the metallicities and ages of the "populous" clusters, based on spectrophotometry, suggest a wide range of each, with even the "globular clusters" spanning perhaps ~ -2 dex to just under solar metallicity (Christian 1993). Improved estimates from better data are possible and desirable. M 33 has a very large number of globular clusters per unit field halo light, but the meaning of this is unclear.

In summary, M 33 has a low luminosity halo, which is at least in part old and metal-poor. There is no convincing evidence for the existence of a bulge in addition to this halo.

2.3 *M 31 (NGC 224)*

The stellar population of M 31 was reviewed by van den Bergh (1991b), and again we restrict discussion to significant subsequent developments.

The field nondisk population has been studied by several groups, following Mould & Kristian (1986; see also Crotts 1986). These authors established, from V and I data that reach several magnitudes down the giant branch, that the bulge/halo of M 31, at 7 kpc from its center, has mean metallicity like the Galactic globular 47 Tuc, [Fe/H] ~ -0.7, and a significant dispersion in metallicity, when assuming an old population, down to ~ -2 dex and up towards solar. Similar conclusions have been reached from HST data for the outer regions of M 31 ($\sim$10 kpc) by Holland et al (1996) and by Rich et al (1996) at $\sim$30 kpc from the center, which limits the amplitude of any chemical abundance gradients, assuming always that one is dealing with an old stellar population.

These HST data also established firmly the scarcity of Blue Horizontal Branch (BHB) stars in the halo of M 31, which confirms the suggestion by Pritchet & van den Bergh (1987, 1988). A few BHB stars were found by Holland et al (1996), who suggest that the horizontal branch (HB) morphology is apparently too red for the derived broad metallicity distribution. If one assumes that the horizontal branch traces a population as old as the Galactic halo globular clusters, then the M 31 field population suffers a severe "second-parameter problem."

Assuming that the derived broad metallicity distribution is well-established, does this lack of a significant BHB population imply a young age for M31? Age can affect HB morphology in that younger populations are redder at a given metallicity, other things being equal (e.g. Lee 1993, who also demonstrates the effects of many other parameters), so that it is of interest to consider this possibility [while recalling that Richer et al (1996) argue quite convincingly, based on relative ages for those Galactic globular clusters with main sequence turn-off photometry, that age is not the dominant "second parameter" of HB morphology, at least in these systems]. Indeed, the presence of bright stars, identified as intermediate-age AGB stars, has been suggested from (prerefurbishment) WF/PC HST VI data at least within the inner 2 kpc of the bulge (Rich & Mighell 1995). Morris et al (1994) argued for a ubiquitous strong luminous AGB component, with a typical age of 5 Gyr, from their ground-based V and I data that reaches the bright giants in various fields of M 31, 16–35 kpc along the major axis of the disk and one probing the halo at 8 kpc down the minor axis (close to the field of Mould & Kristian 1986). Rich et al (1996), and also Holland et al (1996), find no evidence for an extended giant branch in their WF/PC2 HST data for fields in the outer halo, at 10–30 kpc from center, where again the RHB/clump is dominant, with essentially no trace of a BHB. Thus, the data describing possible metallicity/age effects remain unclear.

Large-scale surface photometry of the disk and of the bulge of M 31, in many broadband colors, was obtained and analyzed by Walterbos & Kennicutt (1988). They found that there was no color gradient in the bulge and that the inner disk and the bulge have essentially the same colors, i.e. those of "old, metal-rich stellar populations." This similarity of broadband colors has subsequently been found for a large sample of external disk galaxies, as discussed in Section 3, and clearly must be incorporated into models of the formation and evolution of bulges (see Section 5 below). Walterbos & Kennicutt also derived structural parameters for the disk and bulge that are consistent with the correlation between scale lengths found for the larger sample of more distant disk galaxies by Courteau et al (1996). In terms of total optical light, the bulge-to-disk ratio of M 31 is about 40%.

Pritchet & van den Bergh (1996) emphasize that a single $R^{1/4}$-law provides a good fit to their derived V-band surface photometry (from star counts), with no bulge/halo dichotomy. The $R^{1/4}$ component is significantly flattened, with axial ratio of 0.55, which is similar to the value for the metal-poor halo of the Milky Way (Larsen & Humphreys 1994, Wyse & Gilmore 1989).

In contrast to the metal-poor halo of the Milky Way, which is apparently flattened by anisotropic velocity dispersions, the bulge of M 31 has kinematics consistent with an isotropic oblate rotator, with mean rotational velocity of $\sim$65 km/s and velocity dispersion of $\sim$145 km/s (McElroy 1983), which are typical of external bulges (Kormendy & Illingworth 1982).

Thus, although Baade (1944a,b) identified the "bulge" of M 31 (which we may now define to be field nondisk stars at distances up to 35 kpc from the center of M 31) with Population II (similar to the Milky Way halo), the dominant tracers of the M 31 bulge do not share the characteristics of classical Galactic Population II, as they are neither of low mean metallicity nor have little net rotation (see Wyse & Gilmore 1988 for further development of this point, in the context of thick disks).

There are around 200 confirmed globular clusters associated with M 31 (e.g. Fusi Pecci et al 1993). The distribution of their metallicities has a mean of around -1 dex, which is more metal-poor than the field stars, with a range of perhaps 1 dex on either side (e.g. Huchra et al 1991, Ajhar et al 1996). The inner metal-rich clusters form a rapidly rotating system, whereas the outer metal-poor clusters have more classical "hot" halo kinematics (e.g. Huchra 1993; see also Ashman & Bird 1993 for further discussion of subsystems within the globular clusters). The overall globular cluster system has a projected number density profile that may be fit by a de Vaucouleurs profile (although the central regions fall off less steeply) with an effective radius of $\sim$4–5 kpc (Battistini et al 1993). This is more extended than the $R^{1/4}$ fit to the field stars. Thus, in terms of kinematics, metallicity, and structure, there may be evidence for a bulge/halo dichotomy in M 31 if the halo is traced by the globular clusters and the bulge by field stars. Note that, although there are exceptions, the spatial distributions of globular cluster systems and underlying galaxy light are similar to the first order (Harris 1991).

As seems to be the case for any system studied in sufficient detail, the morphology of the very central regions of M 31 is clearly complicated, with twisted isophotes (Stark 1977), gas kinematics that may trace a bar (e.g. Gerhard 1988), inner spiral arms (e.g. Sofue et al 1994), and two nuclei (Bacon et al 1993) that may indicate a tilted inner disk (Tremaine 1995). These phenomena have been modeled recently by Stark & Binney (1994) by a spherical mass distribution plus a weak prolate bar, with the bar containing one third of the mass within 4 kpc (the corotation radius). The association of the bulge with this bar, which one might be tempted to adopt by analogy with the Milky Way, is unclear.

2.4 *Large Magellanic Cloud*

The Large Magellanic Cloud (LMC) is the nearest barred galaxy, with the bar offset from the kinematic and isophotal center and embedded in an extensive disk. A minor metal-poor old component of the LMC is seen in deep HST color-magnitude data (Elson et al 1997), but its kinematics and spatial distribution are not yet well known. There is a significant amount of new information, from the several microlensing experiments, which will appear in the literature over the next few years concerning the variable star population of the LMC. Of particular relevance are data for the Long Period Variables (LPVs) and the RR Lyrae. The LPVs are believed to have low-mass progenitors and hence trace older stellar populations, while RR Lyrae variables are the traditional tracers of old metal-poor populations. However, most of the information has yet to be analyzed. There has been no kinematical analysis of the LPVs since that of Hughes et al (1991), who found tentative indications of classical hot halo kinematics. The old globular clusters of the LMC, despite prejudice, have kinematics consistent with being in a rotating disk (e.g. Freeman 1993). Thus, little evidence exists for a bulge or halo population in the LMC, except the observation that an old metal-poor stellar population exists.

2.5 *General Properties of the Local Group Disk Galaxies*

The diversity of properties of bulges, haloes, and disks evident in the four largest disk galaxies in the Local Group is striking. The essential properties seem to be the following. The two latest type galaxies (M 33, LMC) have no convincingly detected bulge, but both have at least some evidence for a small population of very old metal-poor stars. Both have old metal-poor globular clusters. The intermediate-type Milky Way galaxy contains what can be termed both a halo (metal-poor, old, extended, narrow abundance distribution, containing globular clusters) and a bulge (metal-rich, mostly, and perhaps exclusively, fairly old, with a very broad metallicity distribution function, and extremely compact in spatial scale). The earlier type M 31 has a prominent and extended bulge, which is both quite metal-rich and fairly old, and has a broad abundance distribution function. The only evidence for a metal-poor old halo in M 31 comes from its globular clusters and its—very few—RR Lyrae stars and BHB stars. In all cases, haloes are supported against gravitational gradients by their velocity dispersion (pressure-supported systems), very unlike disks, though this is perhaps as much a definition as an observation.

Thus, whereas the Local Group Spiral galaxies have a definable halo:disk ratio, which is apparently rather similar for all three, only the two earlier types have a definable bulge-to-disk ratio, which is greater for M 31 than for the Milky Way.

3. LOW-REDSHIFT UNRESOLVED BULGES

3.1 *Bulges and Ellipticals*

In the most simplified picture of galaxies, a galaxy consists of a bulge that follows an $R^{1/4}$ profile and an exponential disk, whereas elliptical galaxies are simply the extension of bulges in the limit of bulge-to-disk ratio tending to infinity.

The picture has been complicated by the discovery that most intermediate luminosity ellipticals (as classified from photographic plates) have significant disks (e.g. Bender et al 1988, Rix & White 1990). These disks can be very difficult to detect, especially when seen face-on. Kormendy & Bender (1996) have recently proposed that ellipticals with “disky” isophotes, which tend to be of lower luminosity than those with “boxy” isophotes, are the natural extension of the Hubble sequence of disk galaxies.

Futhermore, many ellipticals show nuclear disks, either from their kinematics or high-resolution imaging (e.g. review of de Zeeuw & Franx 1991). These disks are very concentrated towards the center and are therefore different from the extended disks in normal spiral galaxies. Sometimes these disks have an angular momentum vector opposite to that of the bulge (e.g. IC 1459, Franx & Illingworth 1988), implying that the gas that formed the disk did not have its genesis in the stars of the bulge but was accreted from elsewhere. Notice, however, that some spiral galaxies also show evidence for these “nuclear disks,” including the Milky Way (Genzel et al 1996) and the Sombrero galaxy (Emsellem et al 1996).

HST observations confirm the similarity in some aspects of low-luminosity ellipticals and bulges. Most of these systems have power-law profiles in their inner parts, with steep profile indexes (e.g. Faber et al 1997). In contrast, most high-luminosity ellipticals show “breaks” in their surface brightness distribution within 1kpc or less from the center, i.e. relatively sudden changes where the intensity profiles flatten. It is not clear yet what formation processes have caused these variations, although it has been suggested that the dynamical effects of massive black holes may be responsible (Faber et al 1997). HST imaging of large samples of spirals is needed to determine better the structure of their bulges. Preliminary results (pre-refurbishment) indicate that a significant fraction of bulges in early-type spirals have power-law profiles in their inner parts, while late-type spirals have shallower inner profiles and often an unresolved nucleus (e.g. Phillips et al 1996).

These results suggest caution in the analysis of other data, as bulges are not necessarily the only important component near the center and as the formation histories of the centers of different galaxies may have been quite different from each other. Indeed, the central 1 kpc or so of most, if not all, galaxies clearly contain something unusual—even without the benefit of detailed HST images (e.g. note NGC 4314 in the Hubble Atlas, which is a barred galaxy that has spiral arms in the center of the bar).

Beyond the very central regions, a systematic variation of surface brightness profile with bulge luminosity has been established, in that bulges in late-type spiral galaxies are better fit by exponential profiles than by the de Vaucouleurs profile, which is appropriate for early-type spirals (e.g. Andredakis et al 1995, de Jong 1995, Courteau et al 1996). HST imaging of late-type spirals is needed to better determine the structure of their bulges. Preliminary results indicate that a significant fraction of bulges in late-type spirals have power-law profiles in their inner parts (e.g. Phillips et al 1996).

Much recent research into the properties of elliptical galaxies has demonstrated the existence of a "fundamental plane" that characterizes their dynamical state (e.g. review of Kormendy & Djorgovski 1989, Bender et al 1993). The bulges of disk galaxies in the range S0–Sc (T0–T5) have also recently been demonstrated to occupy the same general locus in this plane (Jablonka et al 1996). Furthermore, these bulges have a similar Mg2 line strength–velocity dispersion relationship to that of ellipticals, but the bulges are offset slightly to lower line strengths. This offset may be due to bulges having lower metallicity or lower age. Contamination by disk light can produce a similar effect. Jablonka et al argue in favor of a close connection between ellipticals and bulges. Balcells & Peletier (1994) find that bulges follow a color-magnitude relationship similar to that of ellipticals but that bulges have a larger scatter. Furthermore, they find that bulges and ellipticals of the same luminosity do not have the same colors and that bulges are bluer. The offset is similar to that seen by Jablonka et al in the strength of the magnesium index, but Balcells & Peletier interpret it as indicating a real, though complex, difference between bulges and ellipticals. In addition to the data noted above on the central parts of bulges, Balcells & Peletier (1994) find that the amplitude of radial color gradients also varies systematically with bulge luminosity. They interpret their results as consistent with bright bulges ($M_R < -20$) being similar to ellipticals (despite the color zero-point offset), whereas faint bulges are perhaps associated with disks.

The potential well of the outer regions of disk galaxies is clearly dominated by dark matter, whereas the properties of dark matter haloes around elliptical galaxies are less well known (e.g. de Zeeuw 1995). How do properties of bulges scale with dark haloes? Figure 4 shows the ratio of bulge dispersion divided by the circular velocity of the halo (derived from rotation of tracers in the disk) against bulge-to-disk ratios. The square on the right represents elliptical galaxies, derived from models by Franx (1993), which assume a flat rotation curve. The triangle on the left corresponds to the inner regions of pure disks, as derived for a sample of Sa–Sc galaxies by Bottema (1993) (it should be noted that the inner regions of disks are not cold, but warm). Bulges may be seen to lie on a rather smooth sequence between these two extreme points. This suggests that the bulges in galaxies with low bulge-to-disk ratios may have been formed at the same time as the disk, whereas bulges in galaxies with large bulge-to-disk ratios are so much hotter than the disk that it is more likely that they formed separately. More and better data would be valuable to improve the diagram.

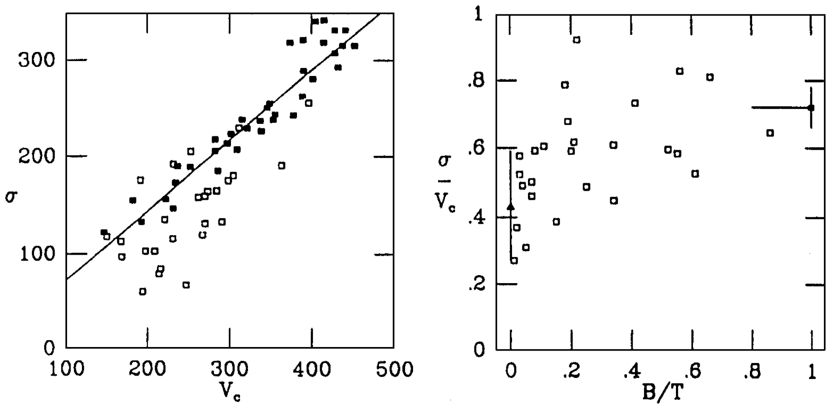


Figure 4 (*a*) The central velocity dispersion of stellar tracers, σ, against dark halo circular velocity, V_c. Open symbols are bulges; closed symbols are ellipticals. Circular velocities for the ellipticals are derived from models, as described by Franx (1993). (*b*) The ratio of velocity dispersion in the bulge to dark halo circular velocity, σ/V_c, taken from Franx (1993), plotted as a function of bulge-to-total luminosity (B/T) ratio, for the entire range of Hubble Type. The triangle at left is valid for the inner regions of pure disks, the square at right for ellipticals. Note that systems with low B/T have kinematics almost equal to those of inner disks.

3.2 *Bulges and Disks*

Astronomical gospel declares that bulges are red and disks are blue. This is generally presumed to be derived from studies of nearby bulges. Unfortunately, there are very few data on which these rather strong statements are based. The observations were difficult to make before the advent of CCD cameras and have been lacking since then until very recently—perhaps because the problem was considered to be solved. Full two-dimensional imaging is needed for accurate bulge/disk decomposition and for exclusion of dusty areas, and large surveys with multicolor information are still rare. Notable exceptions are the recent studies of the colors of “normal” spiral galaxies by de Jong (1995, 1996) and by Balcells & Peletier (1994, Peletier & Balcells 1996).

A relationship between bulges and disks is seen clearly in their colors. We show in Figure 5 the correlation between bulge color and the color of the disk of the same galaxy, for the data of Peletier & Balcells (1996), taken from their table 1. The disk color is measured at two major axis scale lengths, and the bulge color at half an effective radius, or at 5 arcsec, whichever is the larger. Note that bulges are more like their disk than they are like each other, and the very wide range of colors evident. This sample consists of luminous ($M_R \lesssim -21$) nearby disk galaxies that span the range S0–Sbc.

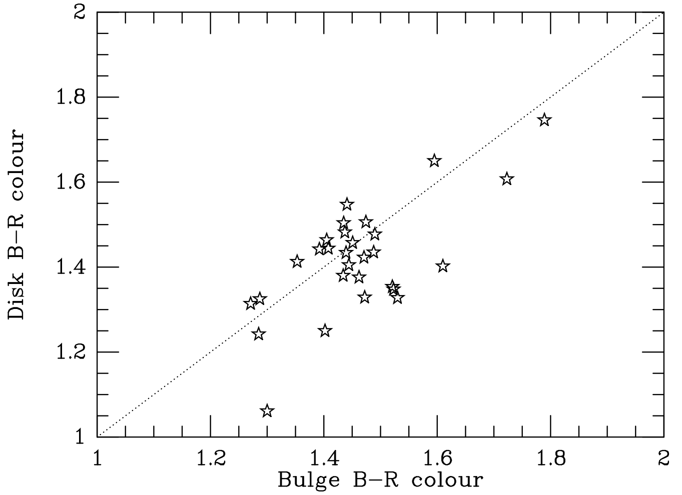


Figure 5 The correlation between bulge color and the color of the disk of the same galaxy, for the data of Peletier & Balcells (1996), taken from their table 1. The disk color is measured at two major axis scale lengths, and the bulge color at half an effective radius, or at 5 arcsec, whichever is the larger. Note that bulges are more like their disk than they are like each other, and the very wide range of colors evident.

The color range for the bulges is noticeably large—almost as large as is the range of colors for the disks. Furthermore, although some bulges are quite red, blue bulges clearly exist, as do red disks. The sample of de Jong (1996) includes the later morphological types of disk galaxies (Sc and Sd) and shows a similar relationship between the colors of bulge and inner disks. These data show that there is little support for sweeping statements such as "bulges are red, and disks are blue." Color data for the "hidden" disks in elliptical galaxies would be very interesting.

Furthermore, the similarity in color between inner disk and bulge has been interpreted as implying similar ages and metallicities for these two components and an implicit evolutionary connection (de Jong 1996, Peletier & Balcells 1996). Given the difficulties of disentangling the effects of age and metallicity even with resolved bulges, any quantification of "similar" must be treated with caution (see Peletier & Balcells 1996, who derive an age difference of less than 30%, assuming old populations with identical metallicities). We notice in passing that the ages of ellipticals have not been determined yet to high accuracy. Measurements of various absorption line strengths have been interpreted to indicate a wide range of ages of the central regions of ellipticals, with no correlation between age and luminosity (Faber et al 1995), but this is far from rigorously established because of the coupling of age and metallicity in their effects on line strengths.

A close association between bulges and disks has been suggested by Courteau et al (1996), on the strength of a correlation between the scale lengths of the bulge and disk; they find that bulges have about one-tenth the scale length of disks. This correlation shows considerable scatter, especially for earlier galaxies of type Sa, and relies upon an ability to measure reliably bulge scale lengths that are a small fraction of the seeing. More and better data are anticipated.

3.3 *Bulges in Formation at $z < 0.1$?*

A few local exceptional systems are candidates for young bulges. Gravitational torques during interactions can act to drive gas to the central regions (e.g. Mihos & Hernquist 1994), where it may form stars, and which may, depending on the duration of star formation and of the interaction, be heated into a bulge. Schweizer (1990) discusses local disk galaxies with blue bulges, presenting them as evidence for recent bulge-building in this manner. These galaxies include (the dwarf) NGC 5102, an S0 galaxy with a bluer bulge than disk and strong Balmer absorption lines in its central regions. Classic merger remnants such as NGC 7252 are forming disks in their central parts, which may imply that these galaxies perhaps have evolved into S0s, or early type spirals (e.g. Whitmore et al 1993).

A more dramatic example of gas-rich mergers is Arp 230, which shows classical shells in the bulge component and a young disk rich in gas, as displayed in Figure 6 (D Schiminovich & J van Gorkom, private communication and in preparation).

4. HIGH-REDSHIFT BULGES

Direct searches for the progenitors of local bulges may be made by the combination of statistically complete redshift surveys of the field galaxy population, combined with photometric and especially with morphological data. As an example, the I-band–selected CFHT redshift survey contains galaxies out to redshifts of order unity, and these galaxies may be analyzed in terms of the evolution of the luminosity function of galaxies of different colors, presumed to correlate with morphological type (Lilly et al 1995). The data are consistent with very little evolution in the luminosity function of the red galaxies, over the entire redshift range $0 < z < 1$, and substantial evolution in the blue galaxies' luminosity function, with the color cut dividing the sample into blue and red taken as the rest-frame color of an unevolving Sbc galaxy. This lack of evolution for red galaxies may be interpreted as showing that the stars of

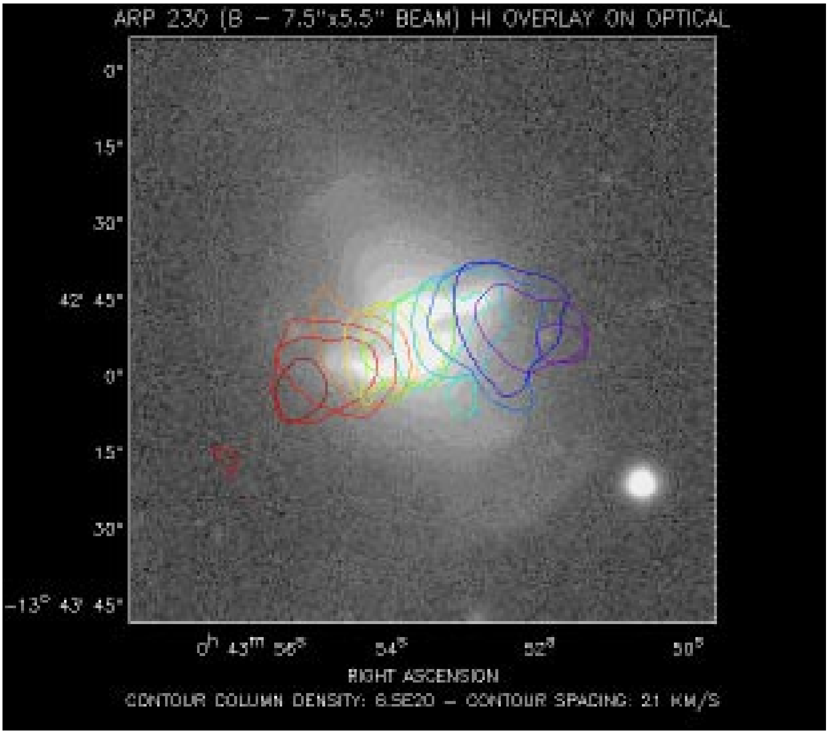


Figure 6 An optical image of Arp 230, with overlaid HI contours. This galaxy shows evidence for shells in its outer bulge, which indicates a recent substantial accretion event, and also has a young gas-rich disk (D Schiminovich & J van Gorkom, private communication).

bulge-dominated systems—the red galaxies—were already formed at redshifts greater than unity, corresponding to a look-back time of greater than half of the age of the universe, or 5–10 Gyr (depending on cosmological parameters).

The high spatial resolution of the HST allows collection of morphological information. Schade et al (1995) obtained HST images for a subset (32 galaxies in total) of the CFHT redshift survey, mostly blue galaxies with $z > 0.5$. They found, in addition to the "normal" blue galaxies with exponential disks and spiral arms and red bulge-dominated galaxies, a significant population of high luminosity ($M_B < -20$) "blue nucleated galaxies" (BNG), with large bulge-to-disk ratio (B/T $\gtrsim$ 0.5)—could these be bulges in formation, at look-back times of $\sim$5 Gyr? Small number statistics notwithstanding, most of the blue nucleated galaxies are asymmetric and show some suggestions of interactions. Schade et al (1996) found similar results for a larger sample, using just CFHT images for morphological classification, and confirmed that red galaxies tend to have high bulge-to-disk ratios.

Extending these results to even higher redshifts, and hence studies of progenitors of older present-day bulges, has been achieved by the identification of a sample of galaxies with $z \gtrsim 3$ based on a simple color criterion that selects systems with a Lyman-continuum break, superposed on an otherwise flat spectrum, redshifted into the optical (e.g. Steidel et al 1996a,b). Ground-based spectroscopy of 23 high-redshift candidates provided 16 galaxies at $z > 3$ (Steidel et al 1996b). The observed optical spectra probe the rest-frame 1400- to 1900-Å UV and provide a reasonable estimate of the reddening, and hence dust content, and of the star formation rate. The systems are inferred to be relatively dust-free, with the extinction at ∼1600 Å typically ∼1.7 mag, which corresponds to an optical reddening in the galaxies' rest-frame of $E(B - V) \sim 0.3$ mag. Whether the low dust content is a selection effect, perhaps due to fortuitous observational line of sight, or is a general feature of these high-redshift galaxies is not clear. The comoving space density of these systems is large—on the order of half that of bright ($L > L^*$, with L^* the knee of the Schecter luminosity function) galaxies locally, which suggests that not too many of them can be hidden. The star formation rates, assuming a solar neighborhood IMF, are typically $\sim$10 $M_\odot$/year. There are interstellar absorption lines due to various chemical species; these lines may be interpreted as indicative of gas motions in a gravitational potential of characteristic velocity dispersion of ∼200 km/s, which is typical of normal galaxies today.

Morphological information from optical HST images (Giavalisco et al 1996) for 19 Lyman-break candidates, of which 6 have confirmed redshifts, show that in the rest-frame UV (1400–1900 Å) these systems are mostly rather similar, in contrast to the wide range of morphological types seen at lower redshifts, $z \sim 1$, discussed above. Furthermore, the typical $z \sim 3$ galaxy selected this way is compact, at least in the UV, and has a half-light radius of ∼2 kpc, which is reminiscent of present-day bulges in the optical. Some of these galaxies show faint surrounding emission that could be interpreted as "disks." The star formation rates inferred from the spectra build the equivalent of a bulge—say 10^{10} $M_\odot$—over a few billion years, which spans the redshift range from $1 \sim z \sim 4$. Similar results are obtained from $z > 3$ samples derived from the HST Deep Field (Steidel et al 1996a) and for one galaxy at a redshift of $z = 3.43$, the central regions of which do, in fact, fit a de Vaucouleurs profile (Giavalisco et al 1995).

Thus, there is strong evidence that some (parts of some) bulges are formed at $z \gtrsim 3$. However, it is hard to draw definite conclusions about all bulges on the basis of these results because the observations at these redshifts can be biased. If, for example, half of all bulges form at $z \lesssim 0.5$, then we would simply not observe those at higher redshifts. At higher and higher redshifts, we would simply be selecting older and older bulges. Our conclusions would become strongly biased. This is very similar to the bias for early-type galaxies discussed by van Dokkum & Franx (1996).

5. FORMATION SCENARIOS

5.1 *Are Bulges Related to Their Haloes?*

Analyses of globular cluster systems in external galaxies conclude that they are more metal-poor in the mean than the underlying stellar light, at all radii in all galaxies (Harris 1991). It is worth noting that the Milky Way is sometimes considered an anomaly here, in that the metallicity distribution function for the (metal-poor, also known as halo) globular cluster system is not very different from that of field halo stars, with differences restricted to the wings of the distributions (e.g. Ryan & Norris 1991). It is important to note, however, that this comparison is done in the Milky Way at equivalent halo surface brightness levels well below those achievable in external galaxies. The higher surface brightness part of the Milky Way, that part which is appropriate to compare to similar studies in other galaxies, is the inner bulge. As discussed above, the metallicity there is well above that of the globular clusters. The Milky Way is typical. More importantly, this (single) test suggests the possibility that *all* spiral galaxies that have globular cluster systems have a corresponding field halo, which in turn is systematically more metal-poor and extended than is the more metal-rich observable bulge.

If this is true, the Local Group galaxies are typical, and the concept of "stellar halo" must be distinguished from that of "stellar bulge." In addition, although haloes seem ubiquitous, they are always of low luminosity and seem generally more extended than bulges. Bulges are not ubiquitous, as they are only found in earlier type galaxies, and cover a very wide range of luminosities. This is, in fact, clearly seen in the Hubble classification criteria from Sa to Sc types.

What is the evolutionary relationship, if any, between bulges and haloes? The Milky Way is an ideal case to study this because it has both bulge and halo. We noted above that the bulge is more metal-rich and possibly younger than the halo, contrary to the argument of Lee (1992). What of its dynamics?

In the Milky Way, the bulge stars do show significant net rotation (e.g. Ibata & Gilmore 1995b, Minniti et al 1995), but the very concentrated spatial distribution of these stars leads to low angular momentum orbits. Indeed, the angular momentum (per unit mass) distribution of the bulge is very similar to that of the stellar halo and very different from that of the disk (Wyse & Gilmore 1992, Ibata & Gilmore 1995b); see Figure 7. As discussed below, this is suggestive of the Eggen et al (1962) scenario, with the bulge as the central region of the

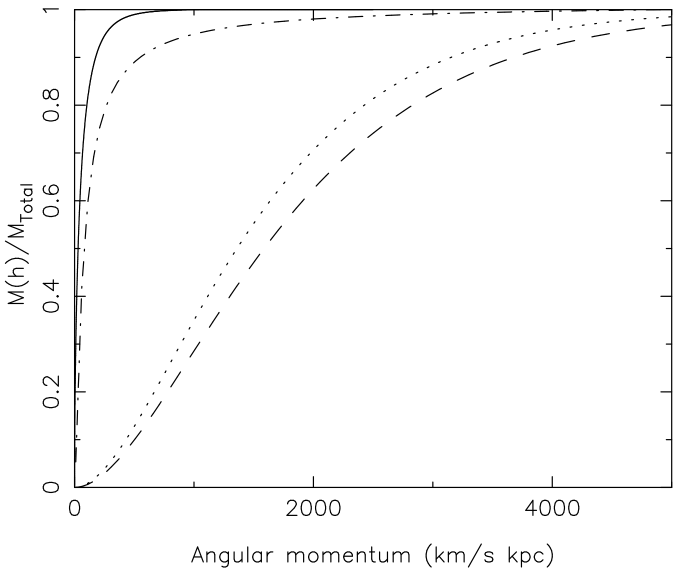


Figure 7 Cumulative distribution functions of specific angular momentum for the four major Galactic stellar populations. The solid curve is the distribution for the bulge, from Ibata & Gilmore (1995b). The other curves are taken from Wyse & Gilmore (1992): The dashed-dotted curve represents the halo, the dotted curve represents the thick disk, and the dashed curve represents the thin disk. It is clear that the halo and bulge are more like each other than they are like the disk components.

halo but formed with significantly more dissipation. Furthermore, the available estimates of the masses of the stellar halo and bulge give a ratio of ∼1:10, which is (coincidentally?) about the ratio predicted by models in which the bulge is built up by gas loss from star-forming regions in the halo (e.g. Carney et al 1990, Wyse 1995). The real test of this model is determination of the *rate* of formation and chemical enrichment of the stars in each of the halo and bulge. This is feasible and only requires good data on element ratios (e.g. Wyse & Gilmore 1992).

5.2 *Accretion/Merging*

DESTRUCTION OF DISKS BY MERGERS The current paradigm of structure formation in the universe is the hierarchical clustering of dominant dissipationless dark matter; galaxies as we see them form by the dissipation of gas into the potential wells of the dark matter, with subsequent star formation (e.g. Silk & Wyse 1993). The first objects to collapse under self-gravity are the highest density perturbations on scales which are characteristic of dwarf galaxies, and globular clusters, though globular clusters seem, on chemical evolution grounds, not to be the first objects to have formed. Large galaxies form by the merging of many smaller systems. The merging rate of the dissipationless dark haloes is reasonably straightforward to calculate (e.g. Lacey & Cole 1993). Unfortunately, many badly understood parameters are involved in the physics of gaseous heating/cooling and star formation, which determine how the baryonic components evolve. In the absence of understanding, the naive separation of different stellar components of galaxies is achieved by the following prescription (Baugh et al 1996, Kauffmann 1996): Star formation occurs in disks, which are destroyed during a merger with a significantly larger companion, with "significant" meaning a free parameter to be set by comparison with observations. In such a merger, all the extant "disk" stars are reassigned to the "bulge," the cold gas present is assumed to be driven to the center and fuel a burst of star formation, and a new disk is assumed to grow through accretion of intergalactic gas. Ellipticals are simply bare bulges, which are more likely in environments that prevent the subsequent reaccretion of a new disk—environments such as clusters of galaxies (e.g. Gunn & Gott 1972). One consequence (see Kauffmann 1996) of this prescription is that late-type spirals, which have a large disk-to-bulge ratio, should have older bulges than do early-type spirals, since to have a larger disk the galaxy must have been undisturbed and able to accrete gas for a longer time. This does not appear compatible with the observations discussed above. Bulge formation is highly likely to be more complex than this simple prescription.

ACCRETION OF DENSE STELLAR SATELLITES The central regions of galaxies are obvious repositories of accreted systems, as they are the bottom of the local potential well, provided that the accreted systems are sufficiently dense to survive tidal disruption while sinking to the center (e.g. Tremaine et al 1975). Should the accreted systems be predominately gaseous, then the situation is simply that described by Eggen et al (1962), with the chemical evolution modified to include late continuing infall. [It is worth noting that late infall of gas *narrows* resulting chemical abundance distribution functions (e.g. Edmunds 1990), and at least the Milky Way bulge has an observed very broad distribution.] We now consider models of bulge formation by accretion of small stellar systems.

As discussed above, the mean metallicity of the Galactic bulge is now reasonably well established at [Fe/H] ~ -0.3 dex (McWilliam & Rich 1994, Ibata & Gilmore 1995b, McWilliam 1997), with a significant spread below -1 dex and above solar. Thus, satellite galaxies that could have contributed significantly to the bulge are restricted to those of high metallicity. Given the fairly well-established correlation between mean metallicity and galaxy luminosity/velocity dispersion (e.g. Bender et al 1993, Lee et al 1993, Zaritsky et al

1994), only galaxies of luminosity comparable to the bulge can have been responsible. That is, one is immediately forced to a degenerate model, in which most of the stellar population of the bulge was accreted in one or a few mergers of objects like the Magellanic Clouds or the *most* luminous dwarf spheroidals (dSph). Because the metallicity distribution of the bulge is very broad, significantly broader than that of the solar neighborhood, a compromise model is viable, in which only the metal-poor tail of the bulge abundance distribution function has been augmented by accretion of lower luminosity satellite galaxies. Quantification of this statement awaits more robust measurement of the tails of the bulge metallicity distribution function and of appropriate element ratios.

Limits on the fraction of the bulge that has been accreted can be derived from stellar population analyses, following the approach utilized by Unavane et al (1996) concerning the merger history of the Galactic halo.

The Sagittarius dSph galaxy was discovered (Ibata et al 1994) through spectroscopy of a sample of stars selected purely on the basis of color and magnitude to contain predominantly K giants in the Galactic bulge. After rejection of foreground dwarf stars, the radial velocities isolated the Sagittarius dwarf galaxy member stars from the foreground bulge giants. The technique (serendipity) used to discover the Sagittarius dSph allows a real comparison between its stellar population and that of the bulge. Not only the radial velocities distinguish the dwarf galaxy, but also its stellar population—as seen in Figure 8 (taken from Ibata et al 1994), *all* giant stars redder than $B_J - R \gtrsim 2.25$ have kinematics that place them in the low velocity-dispersion component, i.e. in the Sagittarius dwarf. This is a real quantifiable difference between the *bulge* field population and this, the most metal-rich of the Galactic satellite dSph galaxies.

Furthermore, the carbon star population of the bulge can be compared with those of typical extant satellites. In this case, there is a clear discrepancy between the bulge and the Magellanic Clouds and dSph (Azzopardi & Lequeux 1992), in that the bulge has a significantly lower frequency of carbon stars.

Thus, although accretion may have played a role in the evolution of the bulge of the Milky Way, satellite galaxies like those we see around us now cannot have dominated. However, accretion is the best explanation for at least one external bulge—that of the apparently normal Sb galaxy NGC 7331, which is counter-rotating with respect to its disk (Prada et al 1996). It should also be noted that for S0 galaxies—those disk galaxies that at least in some models have suffered the most merging—Kuijken et al (1996) have completed a survey for counter-rotating components in the disks and found that only 1% of S0 galaxies contain a significant population of counter-rotating disk stars. This is a surprisingly low fraction and suggests some caution prior to adopting late merger models as a common origin of early-type systems.

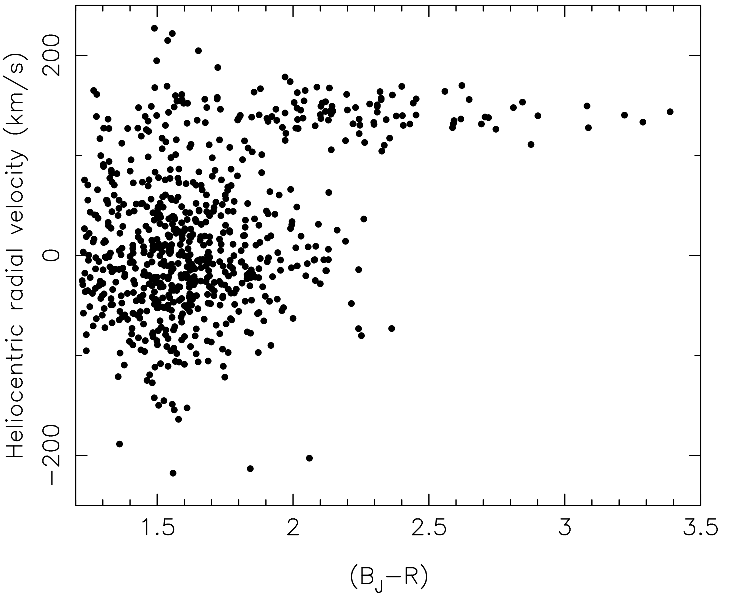


Figure 8 Heliocentric radial velocities of the sample of stars observed by Ibata et al (1994), towards $\ell = -5°$, $b = -12°$, $-15°$, and $-20°$. The stars with velocities less than about 120 km/s are predominately bulge K giants. Those with velocities between about 120 and 180 km/s are members of the Sagittarius (Sgr) dSph galaxy, which was discovered from this figure. Note the real difference between the color distributions of bulge and Sgr members. Thus, the bulge cannot be built up by merger of several galaxies like the Sgr dwarf.

5.3 *Disk–Bars–Bulges, Etc*

Recall that the broadband color distributions of disk galaxies show smooth continuity across the transition between disk and bulge. In the mean, there is approximate equality between the colors of the inner disk and the bulge in any one galaxy (de Jong 1996, Peletier & Balcells 1996). These data may be interpreted as showing similar mean age and metallicity for inner disk and bulge (de Jong 1996, Peletier & Balcells 1996), but the degeneracy of age and of metallicity on the colors of stellar populations cause uncertainties (see, for example, Peletier & Balcells 1996). Courteau et al (1996) find further that the scale lengths of disk and bulge are correlated. They argue that this relationship implies that the bulge formed via secular evolution of the disk. In principle this is possible if disks are bar-unstable and bars are themselves unstable, and if significant angular-momentum transport is feasible.

The secular evolution of collisionless stellar disks has been studied in some detail recently, in particular through three-dimensional N-body simulations (Combes et al 1990, Raha et al 1991; see Combes 1994 and Pfenniger 1993 for interesting reviews). These simulations demonstrated that not only are thin disks often unstable to bar formation, but bars themselves can be unstable, in particular to deformations out of the plane of the disk, perhaps leading to peanut-shaped bulges. The kinematics of stars in "peanut bulges" lend some observational support for the association of peanut bulges with bars (Kuijken & Merrifield 1995). Thus stars initially in the inner disk end up in the bulge, which provides a natural explanation for the continuity observed in the properties of the stellar populations in disks and in bulges.

Merritt & Sellwood (1994; see also Merrifield 1996) provided a detailed description of the physics of instabilities of stellar disks. They demonstrated that the buckling instability of the stellar bar that produces a peanut bulge (Combes et al 1990, Raha et al 1991) is a collective phenomenon, similar to a forced harmonic oscillator. Thus the instability involves the bar in general, not only stars on special resonant orbits, as had been earlier proposed (e.g. Combes et al 1990). Not all instabilities form peanuts, which is just as well for this class of model for bulge formation, because, although box/peanut bulges are perhaps fairly common, comprising 20% of galaxies (Shaw 1987), the subset of these that rotate on cylinders is small (e.g. Shaw 1993 and references therein). Relevant photometric studies show that the light in a peanut bulge is additional to that in a smooth underlying disk, not subtracted from it (e.g. Shaw et al 1990, Shaw 1993), which rather weakens the case for these models.

The extant simulations of bar instabilities also find that a very small mass concentration at the center of the galaxy can destroy a bar. Such a mass concentration is very likely, since inflow, driven by gravitational torques, is probable after a bar is formed. Hasan & Norman (1990) suggested that a sufficiently large central mass concentration could eventually destroy the bar. Norman et al (1996) used three-dimensional N-body simulations to follow the evolution of a bar-unstable disk galaxy and attempted to incorporate the effects of gas inflow by allowing the growth of a very centrally concentrated component. Indeed, in time the fraction of material in this central component is sufficient to destroy the bar, fattening it into a "bulge-like" component. Bulges may be built up by successive cycles of disk instability–bar formation–bar dissolution (Hasan et al 1993). The time scales and duty cycles are not clear. Some simulations (e.g. Friedli 1994) find that as little as 1% of the mass in a central component is sufficient to dissolve a bar. This is a potential problem, as Miller (1996) points out, since the fact that one observes bars in around 50% of disk galaxies means that bars cannot be too fragile. A numerical example supporting Miller's important point is provided by Dehnen (1996), who finds that his bar is stable even with a cuspy density profile in the underlying disk. The simulations are clearly not yet mature.

A further potential problem with the general applicability of this scenario of bulge formation is the different light profiles of bars in galaxies of different bulge-to-disk ratio—early-type disk galaxies have bars with flat surface density profiles (e.g. Noguchi 1996, Elmegreen et al 1996), whereas late-type galaxies have bars with steeper surface brightness profiles than their disks. The Courteau et al correlation, that bulge scale lengths are around one-eighth that of disks, was found for a sample of late-type galaxies. In this scenario, the color of a bar should also be the same color as its surrounding disk, so that the subsequent bulge is the same color as the disk. While colors of bars are complicated by dust lanes and associated star formation, barred structures are often identified by means of color maps (e.g. Quillen et al 1996), suggesting problems for this class of model.

Specific counter-examples to models where the bulge forms through secular evolution of the inner disk are the high-luminosity but low surface brightness disk galaxies, such as Malin 1 (McGaugh et al 1995), which have apparently "normal" bulges (e.g. surface brightnesses and scale lengths typical of galaxies with high surface brightness disks) that clearly could not have formed by a disk instability.

Dissipationless formation of bulges from disks suffers yet a further problem, in that the phase space density of bulges is too high (Ostriker 1990, Wyse 1997). This also manifests itself in the fact that the spatial densities of bulges are higher than those of inner disks. Thus one must appeal to dissipational processes to form bulges, such as gas flows. The presence of color gradients in some external bulges would support a dissipative collapse with accompanying star formation (e.g. Balcells & Peletier 1994). Indeed, Kormendy (1993) has argued that many bulges are actually inner extensions of disks, formed through gas inflow from the disk, with later in situ star formation. This complicates the interpretation of the similarity between the colors of bulges and inner disks, which was a natural product of a stellar instability to form bulges from disk stars. One should note also that should bulges indeed not be formed at high redshift, then dissipation is also implicated in the production of the high spatial densities of their central regions.

It is also important to note that the term bar is used no less generically than is the term bulge. There is a fundamental, and rarely clarified, difference between a detectable perturbation to the luminosity distribution and a substantial $m = 2$ perturbation to the galactic gravitational potential. Inspection of the delightful pictures in the *Carnegie Atlas of Galaxies* (Sandage & Bedke 1994) suggests a continuum of structures, with all degrees of symmetry and asymmetry (i.e. $m =$

1, 2, . . .) and relative amplitudes. When is a bar fundamentally more than the region where spiral arms meet the center? More important for the continuing debate about the center of the Milky Way, is it true that all these structures are seen in the cold disks only? Is there such a thing as a bar-bulge?

6. CONCLUSIONS

In the Local Group, all spiral galaxies, and probably all disk galaxies, have an old metal-poor spatially extended stellar population that we define to be a stellar halo. These seem to be the first stars formed in what would later become the galactic potential, though the possibility of later accretion of a *minor* fraction remains viable. The bulges of Local Group spiral galaxies are more diverse in properties, ranging from the very luminous, intermediate metallicity and very spatially extended bulge of M 31 through the intermediate luminosity, centrally concentrated bulge of the Milky Way, to no firm detection of a bulge in M 33.

In general, well-studied bulges are reasonably old, have a near-solar mean abundance, though with a very wide abundance distribution function, which is of importance, and are consistent with isotropic oblate rotator models for their kinematics, in which the basic support is provided by random motions and the flattening is consistent with additional rotational effects. Given these properties, bulges are most simply seen as the more dissipated descendents of their haloes.

However, diversity is apparent. All bulges of disk galaxies are not old, super–metal-rich, and simply small elliptical galaxies. This is not to say that such systems do not exist, but rather that bulges are heterogeneous. Higher luminosity bulges seem to have a closer affinity to ellipticals, whereas lower luminosity bulges prefer disks. But even this statement does not apply to all the properties of the stellar populations of bulges.

This diversity, together with the surprisingly limited database available concerning the photometric, structural, and kinematic properties of bulges, precludes firm conclusions. Much new and much needed data are about to become available, with the advent of 6- to 10-m class telescopes, with their exceptionally efficient spectrographs, and wide field array imaging systems on smaller telescopes. It will be interesting to see if the next review on bulges will be entitled “Disks and Ellipticals.”

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Literature Cited

Ajhar A, Grillmair C, Lauer T, Baum W, Faber S, et al. 1996. *Astron. J.* 111:1110–27
Alard C. 1996. PhD thesis. Univ. Paris VI
Andredakis YC, Peletier RF, Balcells M. 1995. *MNRAS* 275:874–88
Armandroff T. 1989. *Astron. J.* 97:375–89
Ashman K, Bird C. 1993. *Astron. J.* 106:2281–90
Azzopardi M, Lequeux J. 1992. In *The Stellar Populations of Galaxies, IAU Symp. 149,* ed. B Barbuy, A Renzini, pp. 201–6. Dordrecht: Kluwer
Azzopardi M, Lequeux J, Rebeirot E. 1988. *Astron. Astrophys.* 202:L27– L29
Baade W. 1944. *Ap. J.* 100:137–46
Bacon R, Emsellem E, Monnet G, Nieto J-L. 1994. *Astron. Astrophys.* 281:691–717
Balcells M, Peletier R. 1994. *Astron. J.* 107:135–52
Barnes J, Hernquist L. 1992. *Annu. Rev. Astron. Astrophys.* 30:705–42
Battistini P, Bonoli F, Casavecchia M, Ciotti L, Frederici L, Fusi-Pecci F. 1993. *Astron. Astrophys.* 272:77–97
Baugh CM, Cole S, Frenk CS. 1996. *MNRAS* 283:1361–78
Bender R, Burstein D, Faber S. 1993. *Ap. J.* 411:153–69
Bender R, Doebereiner S, Moellenhoff C. 1988. *Astron. Astrophys. Suppl.* 74:385–426
Bertelli G, Bressan N, Chiosi C, Fogatto F, Nasi E. 1994. *Astron. Astrophys. Suppl.* 106:275–302
Binney J, Gerhard O, Spergel D. 1997. *MNRAS* In press
Binney JJ, Gerhard O, Stark AA, Bally J, Uchida KI. 1991. *MNRAS* 252:210–18
Bissantz N, Englmaier P, Binney J, Gerhard O. 1997. *MNRAS* In press
Blanco V, Tendrup D. 1989. *Astron. J.* 98:843–52
Blitz L, Binney J, Lo KY, Bally J, Ho PTP. 1993. *Nature* 361:417–24
Blitz L, Spergel DN. 1991. *Ap. J.* 379:631–38
Blitz L, Teuben P, eds. 1996. In *Unsolved Problems of the Milky Way, IAU Symp. 169.* Dordrecht: Kluwer
Bothun G. 1992. *Astron. J.* 103:104–9
Bottema R. 1993. *Astron. Astrophys.* 275:16–36
Burton W, Hartmann D, West S. 1996. See Blitz & Teuben 1996, pp. 447–68
Buta R, Elmegreen BG, Crocker DA, eds. 1996. *Barred Galaxies, IAU Colloq. 157, ASP Conf. Ser. 91.* San Francisco: Astron. Soc. Pac.
Carney B, Latham D, Laird J. 1990. In *Bulges of Galaxies,* ed. B Jarvis, D Terndrup, pp. 127–35. Garching: Eur. Space Obs.
Catchpole R, Whitelock P, Glass I. 1990. *MNRAS* 247:479–90
Christian C. 1993. See Smith & Brodie 1993, pp. 448–57
Combes F. 1991. *Annu. Rev. Astron. Astrophys.* 29:195–238
Combes F. 1994. In *The Formation and Evolution of Galaxies,* ed. C Munoz-Turon, F Sanchez, pp. 317–98. Cambridge: Cambridge Univ. Press
Combes F, Debbasch F, Friedli D, Pfenniger D. 1990. *Astron. Astrophys.* 233:82–95
Courteau S, de Jong R, Broeils A. 1996. *Ap. J. Lett* . 457:L73–L76
Crotts A. 1986. *Astron. J.* 92:292–301
Davies RL, Efstathiou GP, Fall SM, Illingworth G, Schechter P. 1983. *Ap. J.* 266:41–57
Dehnen M. 1996. In *New Light on Galaxy Evolution,* ed. R Bender, RL Davies, p. 359. Dordrecht: Kluwer
de Jong R. 1995. PhD thesis. Univ. Groningen
de Jong R. 1996. *Astron. Astrophys.* 313:45–64
Dejonghe H, Habing H, eds. 1993. In *Galactic Bulges, IAU Symp. 153.* Dordrecht: Kluwer
de Vaucouleurs G, Pence W. 1978. *Astron. J.* 83:1163–74
de Zeeuw PT. 1995. See van der Kruit & Gilmore 1995, pp. 215–26
de Zeeuw PT, Franx M. 1991. *Annu. Rev. Astron. Astrophys.* 29:239–74
Edmunds M. 1990. *MNRAS* 246:678–87
Edvardsson B, Andersen J, Gustafsson B, Lambert DL, Nissen P, Tomkin J. 1993. *Astron. Astrophys.* 275:101–52
Eggen O, Lynden-Bell D, Sandage A. 1962. *Ap. J.* 136:748–66
Elmegreen B, Elmegreen D, Chromey F, Hasselbacher D, Bissell B. 1996. *Astron. J.* 111:2233–37
Elson R, Gilmore G, Santiago B. 1997. *MNRAS* In press

Emsellem E, Bacon R, Monnet G, Poulain P. 1996. *Astron. Astrophys.* 312:777–96
Faber SM. 1973. *Ap. J.* 179:731–54
Faber SM, Trager S, Gonzalez J, Worthey G. 1995. See van der Kruit & Gilmore 1995, pp. 249–58
Faber SM, Tremaine S, Ajhar EA, Byun Y-I, Burstein D, et al. 1997. *Ap. J.* In press
Franx M. 1993. See Dejonghe & Habing 1993, pp. 243–62
Franx M, Illingworth G. 1988. *Ap. J.* 327:L55–L59
Freeman KC. 1993. See Smith & Brodie 1993, pp. 27–38
Friedli D. 1994. In *Mass Transfer Induced Activity in Galaxies*, ed. I Shlosman, pp. 268–73. Cambridge: Cambridge Univ. Press
Friedli D, Wozniak H, Rieke M, Martinet L, Bratschi P. 1996. *Astron. Astrophys. Suppl.* 118:461–79
Friel E. 1995. *Annu. Rev. Astron. Astrophys.* 33:381–414
Frogel J. 1988. *Annu. Rev. Astron. Astrophys.* 26:51–92
Fusi-Pecci F, Cacciari C, Federici L, Pasquali A. 1993. See Smith & Brodie 1993, pp. 410–19
Genzel R, Thatte N, Krabbe A, Kroker H, Tacconi-Garman L. 1996. *Ap. J.* 472:153–72
Gerhard OE. 1988. *MNRAS* 232:P13–P20
Gerhard OE, Vietri M. 1986. *MNRAS* 223:377–89
Giavalisco M, Macchetto D, Madau P, Sparks B. 1995. *Ap. J. Lett.* 441:L13–L16
Giavalisco M, Steidel C, Macchetto D. 1996. *Ap. J.* 470:189–94
Gott JR. 1977. *Annu. Rev. Astron. Astrophys.* 15:235–66
Gredel R, ed. 1996. *The Galactic Center. ASP Conf. Ser.*, Vol. 102
Gunn J, Gott JR. 1972. *Ap. J.* 176:1–20
Harmon R, Gilmore G. 1988. *MNRAS* 235:1025–47
Harris W. 1991. *Annu. Rev. Astron. Astrophys.* 29:543–80
Hasan H, Norman C. 1990. *Ap. J.* 361:69–77
Hasan H, Pfenniger D, Norman C. 1993. *Ap. J.* 409:91–109
Holland S, Fahlman G, Richer HB. 1996. *Astron. J.* 112:1035–45
Holtzman JA, Light RM, Baum WA, Worthey G, Faber SM, et al. 1993. *Astron. J.* 106:1826–38
Houdashelt M. 1996. *PASP* 108:828
Huchra J. 1993. See Smith & Brodie 1993, pp. 420–31
Huchra J, Kent S, Brodie J. 1991. *Ap. J.* 370:495–504
Hughes SA, Wood P, Reid IN. 1991. *Astron. J.* 101:1304–23
Ibata R, Gilmore G. 1995a. *MNRAS* 275:591–604
Ibata R, Gilmore G. 1995b. *MNRAS* 275:605–27
Ibata R, Gilmore G, Irwin M. 1994. *Nature* 370:194–96
Izumiura H, Deguchi S, Hashimoto O, Nakada Y, Onaka T, et al. 1995. *Ap. J.* 453:837–63
Jablonka P, Martin P, Arimoto N. 1996. *Astron. J.* 112:1415–22
Kauffmann G. 1996. *MNRAS* 281:487–92
Kent S, Dame TM, Fazio G. 1991. *Ap. J.* 378:131–38
Kinman T, Suntzeff N, Kraft R. 1994. *Astron. J.* 108:1722–72
Kinman T, Wirtanen CA, Janes K. 1966. *Ap. J. Suppl.* 13:379–409
Kiraga M, Paczynski B, Stanek K. 1997. Preprint
Kormendy J. 1993. See Dejonghe & Habing 1993, pp. 209–30
Kormendy J, Bender R. 1996. *Ap. J. Lett* . 464:L119–22
Kormendy J, Djorgovski S. 1989. *Annu. Rev. Astron. Astrophys.* 27:235–78
Kormendy J, Illingworth G. 1982. *Ap. J.* 256: 460–80
Kuijken K, Fisher D, Merrifield M. 1996. *MNRAS* 283:543–50
Kuijken K, Merrifield M. 1995. *Ap. J. Lett.* 443:L13–L16
Lacey C, Cole S. 1993. *MNRAS* 262:627–49
Larsen J, Humphreys R. 1994. *Ap. J. Lett.* 436:L149–52
Lee MG, Freedman W, Mateo M, Thompson I, Rath M, Ruiz M-T. 1993. *Astron. J.* 106:1420–62
Lee Y-W. 1992. *Astron. J.* 104:1780–89
Lee Y-W. 1993. See Smith & Brodie 1993, pp. 142–55
Lewis J, Freeman KC. 1989. *Astron. J.* 97:139–62
Lilly S, Tresse L, Hammer F, Crampton D, Le Fevre O. 1995. *Ap. J.* 455:108–24
Liszt H, Burton WB. 1996. See Blitz & Teuben 1996, pp. 297–310
Madsen C, Laustsen S. 1986. *ESO Messenger* 46:12
McElroy D. 1983. *Ap. J.* 270:485–506
McGaugh S, Schombert J, Bothun G. 1995. *Astron. J.* 109:2019–34
McLean I, Liu T. 1996. *Ap. J.* 456:499–503
McWilliam A. 1997. *Annu. Rev. Astron. Astrophys.* 35:503–56
McWilliam A, Rich M. 1994. *Ap. J. Suppl.* 91:749–91
Merrifield M. 1996. See Buta et al 1996, pp. 179–87
Merritt D, Sellwood J. 1994. *Ap. J.* 425:551–67
Mighell K, Rich RM. 1995. *Astron. J.* 110:1649–64
Mihos JC, Hernquist L. 1994. *Ap. J.* 425:L13–L16

Miller RH. 1996. See Buta et al 1996, pp. 569–74
Minniti D. 1996. *Ap. J.* 459:175–80
Minniti D, Olszewski E, Liebert J, White SDM, Hill JM, Irwin M. 1995. *MNRAS* 277:1293–311
Minniti D, Olszewski E, Rieke M. 1993. *Ap. J. Lett.* 410:L79–L82
Morris PW, Reid IN, Griffiths W, Penny AJ. 1994. *MNRAS* 271:852–74
Morrison H. 1993. *Astron. J.* 106:578–90
Morrison H, Harding P. 1993. See Dejonghe & Habing 1993, pp. 297–98
Mould JR, Kristian J. 1986. *Ap. J.* 305:591–99
Noguchi K. 1996. See Buta et al 1996, pp. 339–48
Norman C, Sellwood J, Hasan H. 1996. *Ap. J.* 462:114–24
Oort J, Plaut L. 1975. *Astron. Astrophys.* 41:71–86
Ortolani S, Renzini A, Gilmozzi R, Marconi G, Barbuy B, et al. 1995. *Nature* 377:701–4
Ostriker JP. 1990. In *Evolution of the Universe of Galaxies, ASP Conf. Ser.*, ed. R Kron, 10:25. San Francisco: Astron. Soc. Pac.
Paczynski B, Stanek KZ, Udalski A, Szymanski M, Kaluzny J, et al. 1994a. *Astron. J.* 107:2060–66
Paczynski B, Stanek KZ, Udalski A, Szymanski M, Kaluzny J, et al. 1994b. *Ap. J. Lett.* 435:L113–16
Peebles PJE. 1989. In *The Epoch of Galaxy Formation*, ed. CS Frenk, R Ellis, T Shanks, A Heavens, J Peacock, pp. 1–14. Dordrecht: Kluwer
Peletier R, Balcells M. 1996. *Astron. J.* 111:2238–42
Perault M, Omont A, Simon G, Seguin P, Ojha D, Blommaert J, et al. 1996. *Astron. Astrophys* . 315:L165–68
Pfenniger D. 1993. See Dejonghe & Habing 1993, pp. 387–90
Phillips A, Illingworth G, Mackenty J, Franx M. 1996. *Astron. J.* 111:1566–74
Prada F, Gutierrez CM, Peletier RF, McKeith CD. 1996. *Ap. J. Lett* . 463:L9–L12
Pritchet CJ. 1988. In *The Extragalactic Distance Scale, ASP Conf. Ser.*, ed. C Pritchet, S van den Bergh, 4:59–68. San Francisco: Astron. Soc. Pac.
Pritchet CJ, van den Bergh S. 1987. *Ap. J.* 316:517–29
Pritchet CJ, van den Bergh S. 1988. *Ap. J.* 331:135–44
Pritchet CJ, van den Bergh S. 1996. See Blitz & Teuben 1996, pp. 39–46
Quillen A, Ramirez S, Frogel J. 1996. *Ap. J.* 470:790–96
Raha A, Sellwood J, James R, Kahn FD. 1991. *Nature* 352:411–12
Regan M, Vogel S. 1994. *Ap. J.* 434:536–45
Renzini A. 1995. See van der Kruit & Gilmore 1995, pp. 325–36
Rich RM. 1988. *Astron. J.* 95:828–65
Rich RM. 1990. *Ap. J.* 362:604–19
Rich RM, Mighell K. 1995. *Ap. J.* 439:145–54
Rich RM, Mighell K, Freedman W, Neill J. 1996. *Astron. J.* 111:768–76
Richer HB, Harris WE, Fahlman GG, Bell RA, Bond HE, et al. 1996. *Ap. J.* 463:602–8
Rix H-W, White SDM. 1990. *Ap. J.* 362:52–58
Ryan S, Norris J. 1991. *Astron. J.* 101:1865–79
Sadler E, Rich RM, Terndrup D. 1996. *Astron. J.* 112:171–85
Sandage A. 1986. *Annu. Rev. Astron. Astrophys.* 24:421–58
Sandage A, Bedke J. 1994. *The Carnegie Atlas of Galaxies.* Carnegie Inst. Wash. Publ. 638. 750 pp.
Santiago B, Elson R, Gilmore G. 1996. *MNRAS* 281:1363–74
Schade D, Lilly S, Crampton D, Hammer F, Lefevre O, Tresse L. 1995. *Ap. J. Lett.* 451:L1–L4
Schade D, Lilly S, Lefevre O, Hammer F, Crampton D. 1996. *Ap. J.* 464:79–91
Schmidt A, Bica E, Alloin D. 1990. *MNRAS* 243:620–28
Schommer RA. 1993. See Smith & Brodie 1993, pp. 458–68
Schommer RA, Cristian C, Caldwell N, Bothun G, Huchra J. 1991. *Astron. J.* 101:873–83
Schweizer F. 1990. In *Dynamics and Interactions of Galaxies*, ed. R Wielen, pp. 60–71. Berlin: Springer-Verlag
Shaw M. 1987. *MNRAS* 229:691–706
Shaw M. 1993. *MNRAS* 261:718–52
Shaw M, Axon D, Probst R, Gately I. 1995. *MNRAS* 274:369–87
Shaw M, Dettmar R, Bartledress A. 1990. *Astron. Astrophys* . 240:36–51
Silk J, Wyse RFG. 1993. *Phys. Rep.* 231:293–67
Smith G, Brodie J, eds. 1993. In *The Globular Cluster – Galaxy Connection.* San Francisco: Astron. Soc. Pac.
Sofue Y, Yoshida S, Aoki T, Soyano T, Tarusawa K, et al. 1994. *PASJ* 46:1–7
Stark AA. 1977. *Ap. J.* 213:368–73
Stark AA, Binney J. 1994. *Ap. J. Lett.* 426:L31–L33
Steidel C, Giavalisco M, Dickinson M, Adelberger KL. 1996a. *Astron. J.* 112:352–58
Steidel C, Giavalisco M, Pettini M, Dickinson M, Adelberger KL. 1996b. *Ap. J. Lett.* 462:L17–L21
Tinsley BM. 1980. *Fundam. Cosmic Phys.* 5:287–388
Toomre A. 1977. In *The Evolution of Galaxies and Stellar Populations*, ed. RB Larson, B

Tinsley, pp. 401–416. New Haven: Yale Univ. Obs.
Tremaine S. 1995. *Astron. J.* 110:628–34
Tremaine S, Henon M, Lynden-Bell D. 1986. *MNRAS* 219:285–97
Tremaine SD, Ostriker JP, Spitzer L. 1975. *Ap. J.* 196:407–11
Unavane M, Wyse RFG, Gilmore G. 1996. *MNRAS* 278:727–36
van Albada T. 1982. *MNRAS* 201:939–55
van den Bergh S. 1991a. *PASP* 103:609–22
van den Bergh S. 1991b. *PASP* 103:1053–68
van der Kruit, Gilmore G, eds. 1995. *Stellar Populations, IAU Symp. 164.* Dordrecht: Kluwer
van Dokkum PG, Franx M. 1996. *MNRAS* 281:985–1000
Walterbos R, Kennicutt R. 1988. *Astron. Astrophys.* 98:61–86
Weiland JL, Arendt RG, Berriman GB, Dwek E, Freundenreich HT, et al. 1994. *Ap. J.* 425:L81–L84
Westerlund B, Lequeux J, Azzopardi M, Rebeirot E. 1991. *Astron. Astrophys.* 244:367–72
Whitford A. 1978. *Ap. J.* 226:777–89
Whitford A. 1986. *Annu. Rev. Astron. Astrophys.* 24:1–22
Whitmore BC, Schweizer F, Leitherer C, Borne K, Robert C. 1993. *Astron. J.* 106:1354–70
Wyse RFG. 1995. See van der Kruit & Gilmore 1995, pp. 133–50
Wyse RFG. 1997. Preprint
Wyse RFG, Gilmore G. 1988. *Astron. J.* 95:1404–14
Wyse RFG, Gilmore G. 1989. *Comments Astrophys.* 8:135–44
Wyse RFG, Gilmore G. 1992. *Astron. J.* 104:144–53
Wyse RFG, Gilmore G. 1995. *Astron. J.* 110:2771–87
Zaritsky D, Kennicutt R, Huchra J. 1994. *Ap. J.* 420:87–109
Zhao H, Spergel DN, Rich RM. 1994. *Astron. J.* 108:2154–63