

# Where do we stand?

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I review the understanding of bulges that emerged from the lively discussions and presentations during the meeting, and emphasize areas for future work. The evidence is for a diversity of ‘bulges’, and of formation mechanisms.

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## 1. What is a bulge?

Classical bulges are centrally-concentrated, high surface density, three-dimensional stellar systems. Their high density could arise either because significant gaseous dissipation occurred during their formation, or could simply reflect formation at very high redshift (or some combination of these two, depending on the density). For illustration, equating the mean mass density within the luminous parts of a galaxy (assumed to have circular velocity  $v_c$  and radius  $r_c$ ) with the cosmic mean mass density at a given redshift,  $z_f$ , gives (e.g. Peebles 1989)

$$z_f \sim 30 \frac{1}{f_c \Omega^{1/3}} \left( \frac{v_c}{250 \text{ km/s}} \right)^{2/3} \left( \frac{10 \text{ kpc}}{r_c} \right)^{2/3},$$

where  $f_c$  is the collapse factor of the proto-galaxy, being at least the factor 2 of dissipationless collapse, and probably higher so that bulges, as observed, are self-gravitating, meaning that they have collapsed relative to their dark haloes.

The majority view at the meeting, consistent with the observations, is that indeed proto-bulges radiated away binding energy, but also at least their stars formed at relatively high redshift. One must always be careful to distinguish between the epoch at which the stars now in a bulge formed, and the epoch of formation of the bulge system itself (as emphasized by Pfenniger, this volume). Of course if the bulge formed with significant dissipation, meaning gas physics dominated, then the star formation and bulge formation probably occurred together.

The small length-scale of bulges, combined with their modest rotation velocity, leads to a low value of their angular momentum per unit mass. Indeed, in the Milky Way Galaxy, the angular momentum distribution of the bulge is similar to that of the slowly-rotating stellar halo, and different from that of the disk, strongly suggestive of a bulge–halo connection, perhaps via gas ejection from halo star-forming regions (e.g. Wyse & Gilmore 1992). One can appeal to bulges forming from the low angular momentum regions of the proto-galaxy, a variant on the Eggen, Lynden-Bell & Sandage (1967) ‘monolithic collapse’ scenario, explored further by van den Bosch (1998 and this volume). Or one can posit angular momentum transport prior to the formation of the bulge, taking angular momentum away from the central regions, and depositing it in the outer regions. Such transport of angular momentum could perhaps occur during hierarchical merging, by dynamical friction and gravitational torques, although one must be careful not to end up with too small a disk due to over-efficient angular momentum re-arrangement (e.g. Zurek, Quinn & Salmon 1988; Navarro & Benz 1991; Navarro & Steinmetz 1997). More modest amounts of angular momentum transport may be achieved by some viscosity in the early disk (e.g. Zhang & Wyse 1999).

A recurring theme of the meeting was that large bulges (of early-type disk galaxies?)

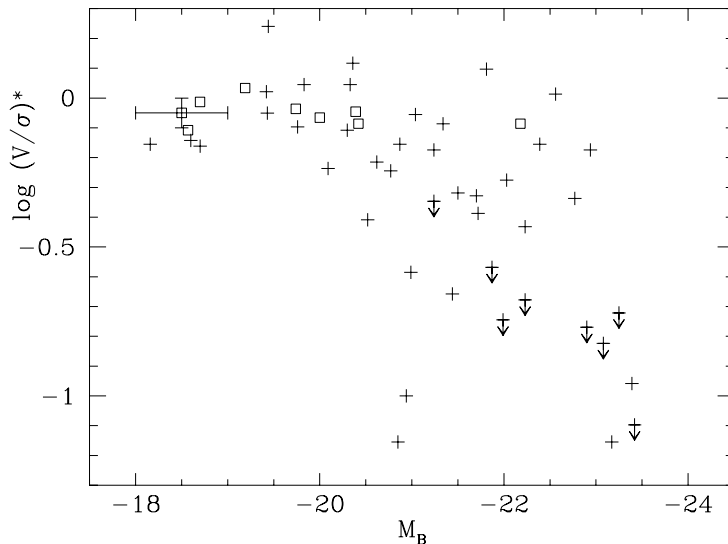


FIGURE 1. The level of rotational support as measured by  $(V/\sigma)^*$ , which has the value unity for an isotropic oblate rotator, against absolute magnitude for elliptical galaxies (plus symbols) and bulges of early-type spirals (open squares); data from Davies *et al.* 1983. The bulge of the Milky Way, with kinematic quantities and flattening estimated in a similar manner as for the external galaxies, is indicated by the point with error bars.

are related to ellipticals while small bulges (intermediate–late-type disk galaxies?) are more closely allied to disks. We need to be very clear about the observational selection criteria used in the definition of samples, and how this could bias our conclusions. As we will see below, the Milky Way bulge shows characteristics of *both* early- and late-type bulges, and will feature in *both* bulge–elliptical connections and bulge–disk connections.

### 1.1. *The elliptical–bulge connection*

There has been remarkably little new kinematic data for representative samples of bulges (as opposed to detailed study of particular individual bulges, chosen for their unusual characteristics) since the pioneering work of the 1970s and 1980s. As demonstrated by Davies *et al.* (1983), the bulges of early-type spirals are like ellipticals of equal luminosity in terms of rotational support, and are consistent with being isotropic oblate rotators i.e. with having an isotropic stellar velocity dispersion tensor, and being flattened by rotation about their minor axis. This sample was biased towards early-type spirals to facilitate bulge–disk decomposition, by observing edge-on systems with a prominent bulge. The bulge of the Milky Way Galaxy can be observed to match the techniques employed in the study of the bulges of external galaxies and, also then has stellar kinematics consistent with being an isotropic rotator (Ibata & Gilmore 1995a,b; Minniti 1996), as shown in Figure 1 here.

The trend apparent in Figure 1, and discussed more fully in Davies *et al.* (1983), is that the level of rotational support in ellipticals increases as the luminosity of the elliptical decreases. The surface brightness of ellipticals also increases with decreasing luminosity, at least down to the luminosity of M32 (the dwarf spheroidal galaxies are another matter), as noted by Kormendy (1977), Wirth & Gallagher (1984) and many subsequent papers. These two relations are consistent with an increasing level of importance of dissipation in ellipticals with decreasing galaxy luminosity (Wyse & Jones 1984).

Further, the bulges of S0-Sc disk galaxies follow the general trend of the Kormendy (1977) relations, in that smaller bulges are denser (de Jong 1996; Carlberg, this volume; see Figure 3 below for details). Thus one interpretation of Figure 1 is then that (some) bulges too formed with significant dissipation.

As discussed by several speakers, the bulges of S0-Sc disk galaxies have approximately the same Mg2 – velocity dispersion relation as do ellipticals (Jablonka *et al.* 1996; Idiart *et al.* 1997; see Renzini this volume), although the actual physics behind this correlation is not uniquely constrained. The properties of line-strength gradients in ellipticals of a range of luminosities are consistent with lower luminosity ellipticals forming with more dissipation than the more luminous ellipticals (Carollo, Danziger & Buson 1993). Again these results are suggestive that bulges are similar to low-luminosity ellipticals, and that gas dissipation was important.

The detailed interpretation of the line-strength data in terms of the actual age and metallicity distributions of the stars is extremely complex and as yet no definitive statements can be made. There is a clear need for more data, including radial gradients, and for more models (see Trager, this volume). The broad-band colors of (some) bulges are consistent with those of the stellar populations in early-type galaxies in the Coma cluster (Peletier & Davies, this volume). We still need better models to interpret even broad-band colors.

### 1.2. *The disk–bulge connection*

The surface-brightness profiles of bulges in later-type disk galaxies are better fit by an exponential law than by the steeper de Vaucouleurs profile, which in turn is a better fit for the bulges of early-type disk galaxies (Andredakis, Peletier & Balcells 1995; de Jong 1996). The sizes of bulges are statistically related to those of the disks in which they are embedded, and indeed the (exponential) scale-lengths of bulges are around one-tenth that of their disk; this correlation is better for late-type spirals than for early types (Courteau, de Jong & Broeils 1996). The projected starlight of the bulge of the Milky Way can be reasonably well-approximated by exponentials (vertically and in the plane); the Milky Way then fits within the scatter of the correlation of the external galaxies.

The optical colors of bulges are approximately the same as those of the inner disk, for the range of Hubble types S0-Sd (Balcells & Peletier 1994; de Jong 1996), but as ever the decomposition of the light curves is difficult, as is correction for dust. This correlation implies similar stellar populations in bulges and their disks, as may be expected if bulges form from their disks (see Pfenniger, this volume). Thus, should there be a variation of mean stellar age from disk to disk, as may be expected from the range of colors observed, and indeed from observations of gas fraction etc., together with models of star formation in disks, one would expect a corresponding range in the mean stellar age of the different bulges. However, Peletier & Davies (this volume) find only a narrow range in bulge ages for their sample, based on optical–IR colors. More data are clearly needed.

Figure 1 demonstrated the similarity in their kinematics between bulges and ellipticals of the same luminosity; Figure 2 (taken from Franx 1993) illustrates some of the complexity of bulge kinematics, and emphasizes the need to be aware of the selection criteria – not all bulges are the same. The left-hand panel shows that in terms of the ratio of stellar velocity dispersion to true circular velocity (not the rotational streaming velocity), bulges scatter below ellipticals. Further, the right-hand panel shows that bulges of late-type disk galaxies have values of this ratio similar to that typical of inner disks (from Bottema 1993). The Milky Way bulge in this plot is quite typical ( $\sigma/V_c \sim 0.5$ ,  $B/T \sim 0.25$ ).

Complexity in the relationship between surface brightness and scale-length for bulges

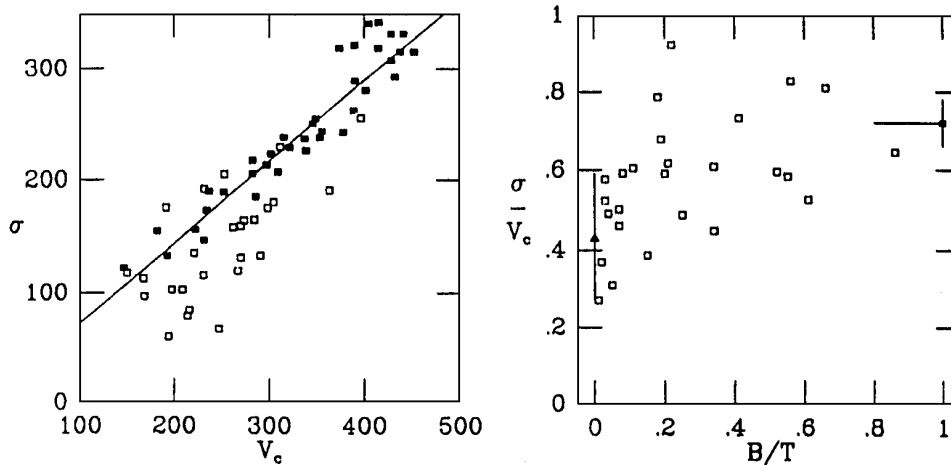


FIGURE 2. *a)* The central velocity dispersion of stellar tracers,  $\sigma$ , against dark halo circular velocity,  $v_c$ . Open symbols represent bulges; closed symbols represent ellipticals. Circular velocities for the ellipticals are derived from models, as described by Franx (1993). *(b)* The ratio of velocity dispersion in the bulge to dark halo circular velocity,  $\sigma/v_c$ , 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.

is illustrated in Figure 3, based on WFPC2 data from Carollo (1999). The plot shows that while the large,  $R^{1/4}$ -law bulges follow the same scaling as ellipticals, the smaller, exponential-profile bulges are offset to lower surface brightnesses and occupy the extension to smaller scalelengths (by about a factor of ten, as noted above) of the locus of late-type disks. This strengthens the disk–bulge connection for these small bulges. However, Carollo (1999) finds both  $R^{1/4}$  and exponential bulges in apparently very similar disks, so some additional parameter is important.

Association of ‘peanut’ bulges with bars, which are essentially a disk phenomenon, was made in several contributions, using both gas and stellar kinematics (Kuijken; Bureau). However, the pronounced ‘peanut’ in the early COBE images of the Milky Way was apparently largely an artefact of patchy dust, and the amplitude of such a morphology in the bulge of the Milky Way is not reliably established (Binney, Gerhard & Spergel 1997). As emphasized by Pfenniger (this volume), the kinematical and dynamical effects of bars are 3-dimensional; they can scatter stars by resonances, and/or themselves go unstable, fatten and dissolve, leading to a bulge. Which process dominates? There is a wealth of fascinating physics to explore. The modellers need to make more contact with observations, including predictions for direct comparison with the stellar kinematics, ages of stars, surface brightness profiles etc.

M33 has neither a bulge nor a bar, but does have a central nucleus, and of course a substantial disk. Such systems need to be discussed in this context. The central nucleus of the Milky Way contains a black hole and star clusters of mass fraction well below the 1% or so estimated to destroy a bar (Norman, Sellwood & Hasan 1996), if we associate all the  $10^{10}M_{\odot}$  of the bulge with the bar. Indeed it is somewhat of a curiosity that the

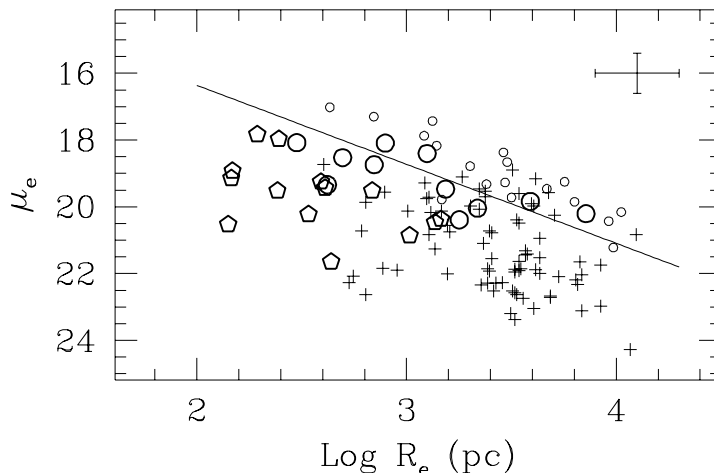


FIGURE 3. The mean  $V$ -band surface brightness  $\mu_e$  within the half-light radius  $R_e$ , as a function of  $\log R_e$  (in pc). The WFPC2 measurements are shown with pentagons for the exponential bulges and large circles for the ‘classical’  $R^{1/4}$ -law bulges. Comparison data from the literature are shown for the  $R^{1/4}$  bulges from Bender *et al.* (1992; small circles) and Scd-Sm disks from Burstein *et al.* (1997; crosses). The solid line is the best fit to the elliptical galaxy sequence (data from Bender *et al.* 1992 and from Burstein *et al.* 1987). The typical  $1\text{-}\sigma$  error bar for the WFPC2 measurements is shown in the upper-right corner.

Milky Way does not fit the relationship between black hole mass and bulge mass found by Magorrian *et al.* (1998).

## 2. When do Bulges form?

The fossil evidence from Local Group galaxies constrains the ages of the stars presently in bulges, which could be rather different from the age of the morphological system.

The overwhelming evidence (contributions by Gilmore, Frogel, Renzini, Rich) for the Milky Way bulge is that its stars are old, except for a very small scaleheight young component – and since all components of the Galaxy have their peak surface brightnesses in the center,† this is as likely to be associated with the disk. Further, as discussed by Rich (this volume) the dominant stellar population even in the nuclear regions is apparently old.

The situation in external bulges in the local universe is more uncertain, but is consistent with stars in large bulges being ‘old’, which means forming perhaps 10Gyr ago.

Direct studies of morphology at high redshift require HST and are at present based on small samples and must be treated with caution if attempting to draw general conclusions. The Hubble Deep Field (HDF) has provided much of the field galaxy sample (as opposed to members of galaxy clusters). Recently, Abraham *et al.* (1999a) analysed the spatially-resolved colors of galaxies of known redshift in the HDF. In contrast to the case of cluster ellipticals discussed by Renzini (this volume), they find that almost half of their (small)

† Some of the decompositions of the COBE data have modelled the disk with a hole in the central regions, which I believe points to continuing uncertainty in the interpretation of those data in terms of the parameterizations of the different components along the line-of-sight.

sample of field ellipticals at intermediate redshift ( $0.4 < z < 1$ ) show evidence for a range of stellar ages. The color gradients in the galaxies for which they could derive a reasonable bulge–disk decomposition are consistent with the mean stellar ages of the bulges being older than those of their disks. These authors argue that this presents difficulties for secular evolution models, but again one must remember the possible selection biases. Abraham *et al.* (1999b) further find a significant deficit of barred galaxies for redshifts above 0.5; as those authors note, more data for a wider range of rest-frame colors and redshifts are needed confirm this result, and then to decide on a robust interpretation. As discussed by Lilly (these proceedings), there is strong evidence from SCUBA data for the existence of compact galaxies with high star-formation rates at high redshift, consistent with proto-spheroids forming in a starburst.

The age distribution of inner disks is of obvious importance for constraining scenarios of disk–bulge formation. Unfortunately, we do not know this well, even in the Milky Way. Indeed, we do not have a good understanding of the star formation history even at the solar neighborhood. We do know that out to a few kpc from the Sun there are stars in the thin and thick disks that are as old as the globular clusters (Edvardsson *et al.* 1993; Gilmore, Wyse & Jones 1995). The stellar color–magnitude data, the chemical abundances and the white dwarf luminosity function data are all broadly consistent with a local (solar neighborhood) star formation rate that has been approximately constant, back to  $\sim 12$ Gyr (e.g. Noh & Scalo 1990; Rocha-Pinto & Maciel 1997). Most models of star formation in disks predict that the central regions should evolve faster, and hence the mean stellar age should be older in the inner disk than in the outer disk. Thus perhaps indeed predominantly-old bulges can be formed recently, from old stars in the central parts of disks. But one really has to be careful to avoid a significant age range in the bulge, reflecting the continuing star formation in the disk up to the time of bulge formation.

Simulations of hierarchical clustering galaxy formation predict ‘bulges’ to form stars at redshift of  $z \sim 2$  (peak) even if assembled later (Frenk, oral presentation this meeting; Baugh, Cole, Frenk & Lacey 1998). In these scenarios, bulges (and ellipticals) form from mergers between pre-existing disk galaxies, and consist of a mix of the disk stars, plus, in some versions, new star formation in the central regions resulting from the disk gas being driven there during the merger. Disks are then (re-)accreted around these bulges. Thus bulges in galaxies with relatively big disks (i.e. Scs) should be the oldest bulges, and bulges with small disks should be the youngest (Baugh, Cole & Frenk 1996; Kauffmann 1996). This is not obviously consistent with the observations presented at the meeting.

A preliminary attempt to make detailed predictions and see if the ‘bulges’ in these models fit the observed scaling between size and luminosity was presented at the meeting by Lacey; the models did not include dissipation and failed to produce small enough bulges. This is further evidence that the high phase space densities of bulges require dissipation (cf. Wyse 1998).

### 3. What are the Timescales – duration of bulge formation?

The finest time-resolution in studies of stellar populations is available from study of the patterns of elemental abundances in individual stars, as discussed in this volume by Renzini; the elemental signature of a short duration of star formation is a pattern of enhanced  $\alpha$ -elements as produced by Type II supernovae alone only. The bulge of the Milky Way is surprisingly under-studied and really do need more data for field stars; for the extant small sample, different  $\alpha$ -elements show different patterns (McWilliam & Rich 1994), unexplained within the context of solely Type II supernovae yields (e.g. Worthey

1998) or in comparison with the element ratios of stars in the stellar halo. It is worth noting however that the elemental abundances seen in the bulge field stars and in the bulge (or thick-disk?) globular clusters are consistent with a normal massive-star stellar IMF (cf. Wyse & Gilmore 1992), as also seen via star counts for the lower mass stars in Baade’s window (Holtzman *et al.* 1998).

Color-magnitude diagrams of old populations can only constrain the duration of star formation to be less than many Gyr, due to the crowding of the isochrones (reflecting the long main-sequence lifetimes of low-mass stars). Further, one needs to know the metallicity distributions, and crucially for the Milky Way bulge, the distance distribution, since foreground disk stars are a difficult contaminant.

As mentioned above, hierarchical-clustering and merging scenarios predict a many Gyr spread in ages of bulge stars, but we need a better quantification of ‘many’. And again, a significant age spread is predicted in the simpler secular evolution models, although the restriction to only one early disk–bar–bulge episode would minimise it.

The shortest durations of star formation are predicted by the starburst models wherein pre-assembled gas forms stars on only a few free-fall times, but the physics of the assembly of the gas will also play a role (Carlberg, this volume, who favors wind-regulated accretion of gas-rich satellites; Elmegreen, this volume, who favors unregulated, monolithic collapse). That very high star formation rates happened in some systems at high redshift is supported by the SCUBA observations (Lilly, this volume), but important aspects of the model obviously need to be worked out (e.g. is there or isn’t there a dominant supernova-driven wind?)

## 4. Constraints from Physical Properties

### 4.1. *Angular momentum distributions*

The hierarchical-clustering and merging scenario predicts misalignment in the angular momentum vector of different shells of material around a peak. This may be expected to translate into some persistent misalignment between disk and bulge, and even counter-rotating components. While examples of such systems exist (see Bertola *et al.* this volume), these would appear to be the exception rather than the rule (see Kuijken, this volume).

Quantification of the specific angular momentum distributions of disks and bulges is obviously desirable, but the observational determinations are dependent on not only detailed kinematic data, but also the decomposition of the light profile (and M/L). Note that in the Milky Way the determination of the kinematic properties of the bulge – and in particular any gradients – requires very careful treatment of contamination by the disk (see Ibata & Gilmore 1995a,b; Tiede & Terndrup 1997 for details). The extant theoretical predictions of angular momentum distributions of bulge and of disk are also not sufficient.

### 4.2. *Central star clusters and bars*

‘Secular evolution’ models for forming bulges from inner disks naively predict an anti-correlation between significant central mass concentrations and bars, since in these models the clusters destroy the bar. There is a particular need to determine how many cycles of bar formation/dissolution are expected theoretically, and how many are allowed by the observations. The uniform old age of bulges, including that of the Milky Way, suggested by most of the evidence presented at this meeting (but again remember possible selection effects) argues strongly for only one such episode, and as noted by Gilmore (this volume), the disk must still continue into the central regions. The relative frequency of

bars, exponential versus  $R^{1/4}$  bulges, central star clusters etc. is as yet poorly quantified. The initial results of an HST WFPC2 and NICMOS imaging survey of nearby spiral galaxies (Carollo 1999) have revealed some of the complexity of the inner regions of these systems, finding a high fraction of photometrically-distinct compact sources sitting at the galactic centers. These ‘nuclei’ have surface brightnesses and radii ranging from those typical of the old Milky Way globular clusters to those of the young star-clusters found in interacting galaxies (e.g. Whitmore *et al.* 1993; Whitmore & Schweizer 1995), with typical half-light radii of a few pc up to  $\approx 20$ pc. Many of the nuclei are embedded in bulge-less disks or in bulge-like structures whose light distribution is too dusty/star-forming to be meaningfully modelled. Every exponential bulge was found to contain a nucleus, and further the luminosity of the nucleus was consistent with its being sufficiently massive to have destroyed a bar of the same mass as the (exponential) bulge. Are these nuclei the central mass concentrations of the models?

The V – H color distribution of the exponential bulges is rather broad, and peaks at  $V - H \sim 0.96$ , significantly bluer, by about 0.4 mag, than the value typical of the  $R^{1/4}$  bulges (Carollo *et al.* 1999). If this bluer color can be ascribed to a younger age, this would indicate that exponential bulges are the preferred mode, for bulges forming more recently. The relatively massive central clusters found in these exponential bulges could theoretically prevent subsequent bar formation, and removing the possibility of successive cycles of bar formation – gas inflow – formation of central object – bar dissolution mechanism (as was discussed also by Rix in his oral presentation at this meeting).

#### 4.3. *Chemical abundance distributions*

The K-giants in the Milky Way bulge have a very broad metallicity distribution, both in Baade’s window (at a projected Galactocentric distance of around 500pc; Rich 1988) and at projected distances of several kpc (Ibata & Gilmore 1995a,b). The breadth of the metallicity distribution in the bulge contrasts with that narrow distribution observed in the disk at the solar neighborhood. The lack of metal-poor stars in the local disk conflicts with predictions of the ‘simple model’ of chemical evolution, and is the famous ‘G-dwarf problem’. One hastens to add that the fact the Milky Way bulge has a broad distribution, and indeed fits the predictions of the ‘simple model’ of chemical evolution, does not mean that any or all of the many assumptions of the ‘simple model’ are valid; another example of a stellar system with a metallicity distribution that is well-fit by the simple model (albeit with a reduced yield) is the stellar halo of the Milky Way. The G-dwarf problems has many solutions, the most popular of which is to postulate gas inflows (e.g. Tinsley 1980). The width of a metallicity distribution is related to the ratio of inflow time to star formation time, and perhaps the wider metallicity distribution in the bulge can be interpreted in terms of very rapid star formation, occurring too fast for inflow to affect the metallicity structure.

The M-giants studied by Frogel (this volume) in the inner 100pc or so of the bulge do appear to have a narrow metallicity distribution, but this may reflect the bias inherent in the sample selection by such a late spectral type; data for K-giants are desirable, both because they are a more representative evolutionary phase of low-mass stars, and because their spectra are easier to interpret and use to determine metallicities, than are M-giants.

From the width of the giant branch in color-magnitude diagrams, the M31 bulge is inferred to have a rather broad metallicity distribution in its outer parts, but a narrow metallicity distribution interior to 1kpc (Renzini, this volume; Rich, this volume). Perhaps this variation in width also reflects a variation of the ratio of star-formation rate to gas inflow rate, this time a variation with radius within the bulge. At face value, the



opposite trend – one with a broader metallicity distribution in the inner, more dense parts – may be expected in models where the local star formation rate is determined by a non-linear function of gas density, but the flow rate is given by the inverse of the dynamical time (proportional to the square root of density), so that the ratio of star formation time to flow time decreases with increasing density.

The stellar populations of the resolved bulges in the Local Group are not compatible with their formation via accretion and assimilation of satellites and or globulars like those remaining today – the bulges are too metal-rich, and have too narrow an age distribution. However, perhaps some part of the metal-poor tail in the Milky Way bulge could be due to accretion of the dense, metal-poor and old globular clusters. Note that for stellar satellite systems with a realistic density profile, a significant fraction of the stars will be tidally removed far out in the halo, and only a fraction will make it into the center (Syer and White 1998; see Kuijken, this volume). Kuijken (this volume) notes that the timescale of satellite accretion is rather long, so that any bulge-building by this means should be on-going. This raises a further difficulty, in that the old, metal-rich bulge stars are unlike those in typical satellites. A graphic illustration of the difference in stellar populations between the bulge of the Milky Way and the Sagittarius dwarf, one of the more massive satellite galaxies of the Milky Way, is shown in Figure 4.

#### 4.4. *Chemical Abundance Gradients*

A strong chemical abundance gradient is a signature of slow, dissipative collapse. Such gradients are weakened, but not erased, by any subsequent mergers (e.g. White 1980; Barnes & Hernquist 1992). There are no clear predictions for secular evolution models (but are needed).

Observationally, there are weak or minimal amplitude gradients in mean metallicity in resolved bulges (Milky Way Galaxy – Gilmore, Frogel, this volume; M31 – Frogel, Rich, Renzini, this volume). As mentioned, the interpretation of absorption line-strengths remains ambiguous, and we need more data and models.

## 5. Summary

Bulges are diverse in their properties, and probably in their formation mechanisms, or at least in the dominant physics at the epochs of star formation and/or assembly. Perhaps the differences are just a matter of degree, since, for example, even ‘monolithic collapse’ involves fragmentation, with subsequent star formation in the fragments. A centrally-concentrated profile appears to match ‘maximum entropy’ arguments (Tremaine, Henon & Lynden-Bell 1986) for the end-point of violent relaxation of a cold, clumpy system, independently of the details of the evolution to that end-point.

The overall trends of the observations are that small bulges, of late-type disk galaxies, show a strong connection to their disk, while big bulges, of early-type disk galaxies, are more like the low-luminosity extension of the elliptical galaxy sequence. The bulge of the Milky Way appears to straddle these two generalities, having an affinity for its disk in terms of structure, but having the old, metal-rich population associated with ‘spheroids’.

What does this mean? Even the casual reader should have noted the not-infrequent occurrence of the sentiment ‘more data and models are needed’ in the text above. We are at the stage of requiring robust quantitative results from both theory and observations.

More specifically, for the Milky Way, we require good HST color-magnitude diagrams for more lines-of-sight towards the Milky Way bulge, following the work of Feltzing & Gilmore (1999) in establishing the association of a younger stellar population with foreground disk. We also require good reddening maps and metallicity data to aid the

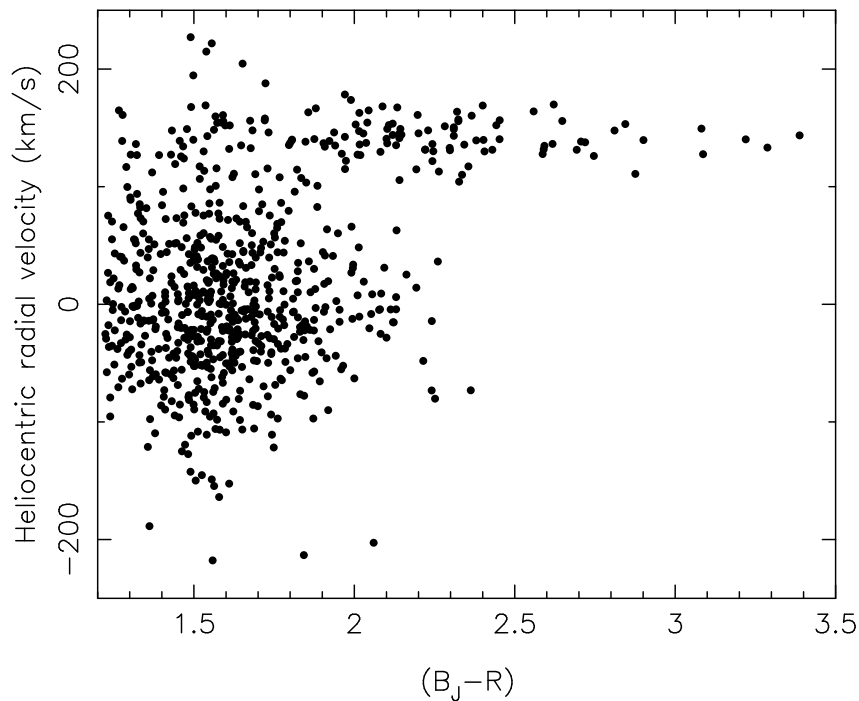


FIGURE 4. Heliocentric radial velocities of the sample of K-giant stars observed by Ibata, Gilmore & Irwin (1994) in lines-of-sight towards the Milky Way bulge ( $\ell = -5^\circ$ ,  $b = -12^\circ, -15^\circ, -20^\circ$ ). Note the narrow velocity-dispersion subsample centered at around 150km/s. These stars are members of the Sagittarius dwarf spheroidal galaxy, which was discovered from these data. The reddest stars are exclusively members of this galaxy, illustrating the real difference in stellar populations between the bulge and this satellite galaxy. The bulge cannot have formed from a simple merger of satellites like the Sagittarius dwarf.

interpretation of these color-magnitude diagrams. The inner disk of the Milky Way is remarkably under-studied, and again age and metallicity distributions – and stellar kinematics – are obviously crucial in determining the similarity or otherwise of inner disk and bulge. Further, we need to understand the relationship between the ‘bulge’ globular clusters and the bulge field population; present models of globular-cluster formation appeal to pre-enrichment to provide the uniform enrichment within a given cluster, so it is not obvious that the enrichment signatures of cluster stars and field stars should be the same. Elemental abundances for statistically-significant samples of unbiased tracers of the field in a variety of lines-of-sight are required to understand the history of star formation.

A combination of HST and ground-based (to probe both small- and large-scale structure) broad-band optical and IR colors, and surface brightness profiles, are still lacking for large samples, including the whole range of spiral Hubble types. These data should allow a robust quantification of the correlations between morphologies. Basic kinematic data, including gradients, should be obtained for a representative sample of bulges and disks. While we may lack the means at present for a unique interpretation of absorp-

tion line-strength data, the straightforward test for continuity in the line strengths from bulges to their disks is meaningful.

The redshift of statistically-significant samples of galaxies is being continually pushed back (at what point will this pose a real problem for CDM?) and HST and the next generation of telescopes should provide robust morphological classifications. We will no doubt see evolution, but need to have the model predictions to be able to distinguish the underlying physics behind the evolution.

‘Secular-evolution’ models are their early stages of development, but several key questions may be posed. While it may be reasonable to comment that a correlation between bulge scale-length and disk scale-length points to a connection between bulge and disk, can the models ‘post’-dict the factor of ten that is observed? Can they predict the frequency with which one should see barred spirals today, even ones with big bulges? Are all bars the same? Are there too many bars and/or central concentrations observed for the models of bar dissolution? Or is the dominant mechanism of bulge-building in this scenario actually scattering of disk stars through resonant coupling, rather than bar dissolution? How can this be compatible with uniformly old bulges? But are exponential bulges (apart from the Milky Way bulge) composed of old stars?

Cold-dark-matter dominated cosmologies gained popularity partially because of their robust predictive power, a requirement for a good theory, in terms of the large-scale structure formed by the dissipationless dark haloes, (e.g. Davis, Efstathiou, Frenk & White 1992). The predictions for the luminous components, the galaxies as we observe them, have not yet achieved the same level of maturity. Advocates of merging and hierarchical clustering should quantify further the ages of stars now in bulges, and the epoch of assembly into bulges. What is predicted for the age spread within a typical bulge like the Milky Way? What fraction of bulges should have angular momentum vector misaligned with their disk? Should colors of bulge and disk be correlated?

If bulges form in a ‘star-burst’, what is the role of a supernova-driven wind? In this context, the X-ray properties of bulges, including the Milky Way, should constrain the ability of the bulge potential well to retain hot gas.

Where do we stand? – inspired to get to work!

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