Chapter 5

How Did the Milky Way Form?

THE AGE STRUCTURE OF THE OLDER PARTS OF THE GALAXY

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1. Introduction

The history of the Galaxy is encoded in the kinematic, chemical and age profiles of its various populations, and their inter-relationships. Of these, the age structure has proved to be the most problematic. The aim of the present paper is to discuss our understanding of the ages of the various components and to seek to understand the chronology of the system, highlighting along the way some of the unsolved problems.

For the purposes of discussion it is useful to identify the major components. We live in a disk galaxy with a prominent bulge. As we have heard at this meeting the bulge appears to encompass a bar like configuration: indeed, the bulge may be a bar. The masses of disk and bulge appear to be $6\ 10^{10} M_\odot$ and $1\ 10^{10} M_\odot$, respectively, and both are embedded in a much more tenuous, luminous, halo, the mass of which is 1 - $3\ 10^9 M_\odot$ (Bahcall 1986). The inter-relationship of halo and disk has been one of the driving challenges of the study of stellar populations since their identification by Baade. More recently we have come to appreciate that all of this luminous material is enshrouded in a vast unseen mass of dark matter which will be referred to here, following Schmidt (1985) in an effort to avoid ambiguity, as the dark corona. Many refer to it as the dark matter halo. The mass and extent of this component is not well defined, but current estimates suggest that it extends out to at least 50 kpc from the Galactic center at which point the interior mass is $5\ 10^{11} M_\odot$ - $1\ 10^{12} M_\odot$.

In what follows we shall discuss each of these components in turn, returning to their inter-relationships in the final sections.

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2. Dark Corona

No direct age determination of the dark corona exists. Current wisdom holds that the luminous parts of galaxies form within the potential wells of large aggregates of dark material which were the initial irregularities in the expanding Universe. As such they would be the oldest structures in the Universe. What remains unclear is how long after the existence of the deep potential well of the dark matter the luminous components first emerged.

Discussion of the formation of the luminous parts of galaxies has centered around two dominant themes. The first postulates a central gravitational contraction or collapse as suggested most persuasively in the context of the Milky Way system by Eggen, Lynden-Bell, & Sandage (1962, hereafter ELS) : "The oldest stars formed out of gas falling towards the galactic center in the radial direction and collapsing from the halo onto the plane. The collapse was very rapid and only a few times 10^8 years were required for the gas to attain circular orbits in equilibrium." The second questions the primacy of the central collapse in determining the observed structures, and postulates that the merging of fragments of material (both gaseous and astrated) plays a large role. Searle & Zinn (1978, hereafter Searle & Zinn) established the counterpoint to ELS with their suggestion for the origin of the halo: "the loosely bound clusters of the outer ... halo originated in transient protogalactic fragments that continued to fall into dynamical equilibrium with the Galaxy for some time after the collapse of its central regions had been completed". The timescale envisaged by Searle & Zinn was a few billion years.

These two themes have been rehearsed and expanded extensively during the past decades. The central collapse, with dissipation, has been modeled by many workers, beginning with Larson (1969) who first addressed the possible lumpy nature of the Galaxy, through to the recent works of Burkert, Truran, & Hensler (1992) who postulate an initial two phase situation involving clouds and intercloud medium, and Katz (1992) who follows the evolution of a disk galaxy in a lumpy medium of dark material. The role of merging of fragments with an already existing disklike Milky Way system is also the center of intense theoretical activity. As well as providing a possible explanation of the outer halo, it had been shown that accretion of fragments will heat an existing disk. The capture of a satellite of mass $0.1M_{disk}$ might be expected to heat the disk to a vertical velocity dispersion of $\sim$ 40 km/s (Quinn, Hernquist, & Fullagar 1993). Accretion of satellites may drive gas from the disk into the central region and trigger starbursts, with implications for the formation and/or modification of the bulge component (Mihos & Hernquist 1994).

What remains to be established is the relative importance of these two phenomena. Sandage (1990) expresses the opinion "Searle and Zinn is ELS plus noise, all of which is staged within a play by Zurek, Quinn and Salmon, which is on a theme of Larson, after Toomre". Other recent views on the relative importance of the two effects may be found, for example, in Zinn (1993), van den Bergh (1993), and Norris (1994).

3. Halo

The reader will recall the basic parameters of the halo of the Galaxy: it is spatially extended with density decreasing radially as $R_G^{-3.5}$; is kinematically hot ($\sigma_{total} \sim 200$ km/s) with little systemic rotation ($V_{rot} \sim 30$ km/s); and is metal poor ($-4 <$ [Fe/H] < -0.5). Most important for the present discussion, it is old, with 12 Gyr $\leq$ age $\leq$ 18 Gyr.

The determination of the ages of halo material centers almost entirely on the interpretation of the color-magnitude diagrams of globular clusters, and to a lesser extent on Strömgren photometry of near main sequence metal poor and high velocity stars. As is well known, increasing age leads to fainter turnoffs and bluer horizontal branches, and it is these dependencies which have been utilized to determine the age profile of the halo.

3.1. HORIZONTAL BRANCH AGE CONSTRAINTS

The most powerful claims concerning the age structure of the halo come from consideration of the horizontal branch (HB) morphology of the globular clusters. Searle & Zinn (their Figure 10) demonstrated very clearly that HB morphology is a function of Galactocentric distance, and more recently the subject has been closely re-examined by Lee, Demarque, & Zinn (1994, their Figure 7). Inside the solar circle there exists a tight relationship between HB type and [Fe/H] which may be readily explained solely in terms of a range in [Fe/H], while outside, the dependence of HB type on abundance becomes much looser and at a given [Fe/H] the horizontal branches are redder. While HB morphology depends on several parameters, Searle & Zinn put forward the hypothesis that the data were well explained in terms of age variations. They suggested that there was little age spread inside the solar circle (< 1 Gyr) but that outside the sun the clusters were on average younger by a few Gyr and showed an age spread of a similar amount. The synthetic horizontal branch calculations of Lee *et al.* (1994) confirm that the observations can be explained by age differences of order 2-4 Gyr.

The question that has exercised the minds of many workers over the past 15 years is whether age variations provide the only explanation of these observations. What seems clear is that age is not the only parameter affecting HB morphology in the globular cluster system. The classic example of this is NGC 2808 with its very bimodal horizontal branch (see Byun

& Lee 1991, and references therein). There is now, however, fairly convincing evidence that age differences of order 2-4 Gyr exist in the system, based on considerations of the main sequence turnoff. Several independent investigations of the critical pair NGC 288/NGC 362 all conclude that NGC 362 is younger than NGC 288 by 2-3 Gyr as might be expected from their HB morphologies (Bolte 1989; Green & Norris 1989; Sarajedini & Demarque 1990; VandenBerg, Bolte, & Stetson 1990). And while evidence is growing that the bulk of the clusters may be coeval to within 2-3 Gyr (see e.g. Figure 3 of Buonnano *et al.* 1994) there are currently four distant clusters with ages some 4 Gyr below average : Pal 12 (Stetson *et al.* 1989), Ru 106 (Buonnano *et al.* 1990), and Arp 2 and Terzan 7 (Buonanno *et al.* 1994).

The basic question for the hypothesis of Searle & Zinn, at least in the view of the present author, is not whether age is the only parameter affecting HB morphology. Rather, the question is this: is age the parameter which dominates the behavior of HB morphology as a function of Galactocentric distance. There are two independent pieces of evidence which support the contention that it is. The first is the result of Chaboyer, Sarajedini, & Demarque (1992, their Figure 3) who determine ages based on the luminosity of the main sequence turnoffs of globular clusters and find that on average clusters inside the solar circle are younger than those outside this limit, by some 2 Gyr. They also demonstrate (their Figure 5) that in the range $-1.75 \leq [Fe/H] \leq -1.25$ HB type is a function of age. The second point is that Marquez & Schuster (1994), using ages determined from Strömgren photometry of metal poor near turnoff stars, demonstrate that when age is plotted as a function of apogalactic distance, material with apogalacticon outside 10 kpc is younger on average by $\sim$ 2 Gyr than that inside this value.

3.2. MAIN SEQUENCE TURNOFF AGE DETERMINATIONS

There are several approaches to age determination from main sequence globular cluster photometry. One involves the fitting of the full turnoff region to stellar evolution isochrones. See, for example, the study of 47 Tuc by Hesser *et al.* (1987). A second, differential, method (Sarajedini & Demarque 1990; VandenBerg *et al.* 1990) involves comparison of the color difference between main sequence turnoff and subgiant branch at fixed abundance with model calculations. The third, and perhaps most widely used, method involves determination of the luminosity difference between the horizontal branch and main sequence turnoff, and assumptions about the luminosity of the horizontal branch in order to derive the luminosity of the turnoff which, from a theoretical viewpoint, is the best indicator of age. In what follows I shall refer mainly to the results of the second and third approaches, referred to as the $\Delta(B-V)_{TO,RGB}$ and ΔV(TO-HB) methods, respectively.

3.2.1. *Results from the $\Delta V(TO\text{-}HB)$ Method*

There is currently little concensus on the ages of the globular clusters determined with the ΔV(TO-HB) method, driven by disagreement on the dependence of the luminosity of RR Lyrae variables on metal abundance. Sandage (1993) favors a value of $dM_v(RR)/d[Fe/H] = 0.30$, and determines the same age, 14 Gyr, for all clusters. In contrast, Chaboyer *et al.* (1992) and Carney, Storm, & Jones (1992), who adopt $dM_v(RR)/d[Fe/H] \sim 0.20$, find an age, metallicity relation among the clusters, with the most metal poor objects being 2-4 Gyr older than the most metal rich. At [Fe/H] = -1.5, Chaboyer *et al.* report an age of 14 Gyr, while Carney *et al.* report values of 15 and 17 Gyr, depending on which of two assumptions they make regarding the value of [O/Fe]. Not all of the news, however, is bleak. This is a tractable problem. With the determination of horizontal branch magnitudes for globular clusters of different abundance in the Andromeda galaxy with HST much of this uncertainty will be resolved.

Uncertainty in the values of other physical parameters propagates into age uncertainties. Table 1 shows very roughly some of the effects. Given our understanding of the various parameters, it seems reasonable to suggest that our knowledge of cluster ages is uncertain at the 2-3 Gyr level.

TABLE 1. Sensitivity of Ages based on ΔV(TO-HB) (Age ~ 14 Gyr, [Fe/H] ~ -1.3)

Parameter	Δ(Parameter)	Δ(Age)
$[Fe/H]$	+0.2	-0.7
ΔV(TO-HB)	+0.1	+1.5
$[O/Fe]$	+0.3	-1.0
$[\alpha/Fe]$ (includes O)	+0.3	-1.5
Diffusion	On	-0.3
Rotation	On	Unimportant
Y	+0.03	-0.4

3.2.2. *Results from the $\Delta(B-V)_{TO,RGB}$ Color Method*

The color method has also yielded important results. VandenBerg *et al.* (1990) have presented evidence that at [Fe/H] = -2.1 the age spread appears to be less than 0.5 Gyr. They also report that there is a scatter in age which increases with increasing metallicity: at [Fe/H] = -1.3 they find a real spread of ~ 2 Gyr. The importance of this clue cannot be overemphasized. We comment on one possible interpretation in §7.

3.3. ROLE OF ACCRETION/MERGERS

Given that the age spread is real, what does this tell us about the evolution of the Galaxy. There now seem to be many workers offering support for the general concept of accretion as advocated by Searle & Zinn, albeit to different degrees. Lin & Richer (1992) argue that Ru 106 may have been captured from the Large Magellanic Cloud. Zinn (1993) has presented a case for subsystems of old and young globular clusters, while van den Bergh (1993) has also identified subgroups in the halo cluster system, and suggested a past merger with a small galaxy to explain the systematics of the situation. Other observations consistent with the concept of relatively recent merger events are the young, blue metal poor stars discovered by Preston, Beers, & Shectman (1994), and the recently discovered dwarf spheroidal galaxy in Sagittarius reported by Ibata, Gilmore & Irwin (1994), which appears currently to be experiencing the merging process.

3.4. HALO SUMMARY

While there is no universal consensus on the age structure of the halo, the author's view is as follows. (a) The inner halo ($R_G < 8$ kpc) shows little evidence for an age spread (Δ(age) $<$ 1 Gyr). Current best estimates suggest a mean age of 15 ± 2 Gyr. (b) The outer halo shows a real age spread ($\sim$ 2-4 Gyr), and appears to be younger on average than the inner halo by $\sim$ 2 Gyr. (c) There is evidence that the age spread increases with increasing [Fe/H]. (d) A significant part of the halo has been accreted, some at least of which appears to be relatively young.

4. Disk

For the purposes of the present discussion it is useful to recall that the disk density distribution is exponential in both the radial and vertical direction. The disk is kinematically cool and supported by rotation, with metallicity spanning the range $-1.5 <$ [Fe/H] < 0.2, though it should be noted that the lower limit quoted here is still the subject of debate. Stars of all ages, up to that of the halo, are present in the disk. Here we shall consider only material older than a few Gyr.

The large range of properties of the disk has led to the description of its sub-populations in terms of young/old, metal-weak/metal-poor, and thick/thin (e.g. 'the' old disk, 'the' thick disk, metal-poor thick-disk stars). Many workers think in terms of a thick and a thin component, while others think in terms of an extended, continuous, configuration. It terms of the thick/thin description, which provides a useful working model, the relevant parameters in the solar neighborhood are:

TABLE 2. Parameters of the Thin & Thick Disks

Parameter	Thin	Thick
Relative proportion	1	0.02 to 0.10
$[Fe/H]$	-0.4 to +0.2	-1.5 to -0.4
Kinematics	$\sigma_z \sim 20$ km/s	$\sigma_z \sim 45$ km/s
	$V_{rot} \sim 220$ km/s	$V_{rot} \sim 180$ km/s
Scale height	300 pc	900-1300 pc

The relationship between the disk and halo is of considerable interest. Work over the past decade has established fairly convincingly that there is a fairly sharp transition between the metal poor, slowly rotating halo and the metal rich, rapidly rotating disk. See for example Carney, Latham & Laird (1990, Figures 2 and 3) and references therein. With the realization, however, that the halo may contain subcomponents (Zinn 1993; van den Bergh 1993; Norris 1994) one should be alive to the possibility that part of the material traditionally associated with the halo by virtue of its low abundance may in fact be connected in a complicated way with the disk.

Table 3 presents various age estimates for the older material of the disk. The most interesting fact about its age structure is that current estimates suggest that at the solar circle the *bulk* of the disk is significantly younger than the ~15 Gyr of the halo inside the solar circle. Note in particular the values in Table 3, clustering around 10 Gyr, determined from the white dwarf luminosity function, the chromospheric age indicators of local dwarfs, and the oldest open clusters. In some contrast, most results for the metal poorer, kinematically hotter material, which one associates with the thick disk, suggest ages not too different from that of the halo. Note here the disk globular cluster 47 Tuc and the results for the high proper motion stars.

The case of the disk globular clusters needs special emphasis. For 47 Tuc, which has [Fe/H] = -0.7 and R_G = 6 kpc, the results of Carney *et al.* (1992, with [O/Fe] = -0.3), Chaboyer *et al.* (1992) and Sandage (1993) yield an age of 13.9 Gyr, which is only 1.4 Gyr younger than the halo clusters inside the solar circle for which they have also determined ages. While one has to worry a little about possible systematic errors in these estimates, driven by abundance differences, one might hope that the differential result between disk and halo is not greatly in error. Apart from 47 Tuc, little information is available and there is an urgent need for more work on the age profile of the disk globular clusters. One should note the recent work of Fullton & Carney (1994) on NGC 5927, 6352, and 6723, and their intriguing result that the most metal-rich one (NGC 5927) is younger that the others by 3-5

TABLE 3. Age Estimates of the Disk

Method/Sample	Age	Comment
Globular cluster 47 Tuc	14 Gyr	$R_G = 6$ kpc
White Dwarf Luminosity Function (Winget *et al.* 1987, Wood 1992)	9.3 ± 2 Gyr	Bulk of disk locally
Chromospheric Ages (Barry 1988)	$\leq$ 11 Gyr	Bulk of disk locally; calibrated with age(NGC 188) = 8 Gyr
Old open clusters (Demarque *et al.* 1992)	$\leq$ 9 Gyr	Age(NGC 6791) = 9 Gyr caveat: clusters easily destroyed
Th/Nd ratio in stars (Butcher 1987)	$\leq$ 10-12 Gyr	Beware Co I contamination. Lawler *et al.* (1990) find 15-20 Gyr
Red giants at z = 1-3 kpc (Norris & Green 1989)	< Age(47 Tuc) by several Gyr	Solar vicinity, no kinematic bias
High proper motion stars (Carney *et al.* 1989)	$\geq$ Age(47 Tuc) to within 3 Gyr	Kinematically biased sample
Strömgren Photometry:		
(Edvardsson *et al.* 1993a,b)	Relatively few stars older than 10-12 Gyr formed in solar nbd. Small component with 12 < Age < 18 Gyr	Sample biased on abundance Ages accurate to 20%
(Marquez & Schuster 1994)	Thick disk stars younger than halo by 1-2 Gyr	Beware systematic differences driven by [Fe/H] difference

Gyr. This problem should be solved soon (at least from the point of view of obtaining the necessary high quality data) by observations with HST.

The results of recent Strömgren photometry based age investigations are also of considerable importance. While the Edvardsson *et al.* (1993a,b) sample of solar neighborhood dwarfs contains stars which appear to be as old as the halo clusters, they conclude that when one considers where the stars originated and the metallicity bias of the sample there are very few old stars in the sample and that "one might wonder whether disk stars formed this far from the galactic center more than 10-12 Gyr ago". A second particularly important result for the age chronology of the disk is their finding that [α/Fe] as a function of [Fe/H] depends on the place of origin of stars in their sample: at [Fe/H] = -0.8 to -0.4 they report that stars which formed closer to the Galactic center appear more enriched in the α elements, suggesting that star formation and chemical enrichment occurred over a shorter period towards the center and proceeded more sedately further out.

The reader should note also that the question of the relative ages of thick disk and halo remains unresolved. Differences of 0-3 Gyr (in the sense of the thick disk being younger) appear not inconsistent with the observations, but it seems unlikely that the difference can be greater than this.

4.1. DISK SUMMARY

Inside the solar circle there appears to be only a small age difference between the oldest disk material and the halo. Thick disk material may be younger by $\sim$ 1-3 Gyr at most. On the other hand, the bulk of the material in the solar neighborhood appears younger than the halo by 4-5 Gyr. This is surely suggestive of an hiatus between an early epoch of star formation and the bulk of star formation in the solar neighborhood.

5. Bulge

The Galactic bulge is an agglomeration of populations with an extremely complicated age structure, which is not yet understood. As well as being the intersection of the halo and disk, there is now evidence that the center of the Galaxy contains a bar, and indeed perhaps what we refer to the bulge is really a bar. For a description of the bulge and its properties the reader is referred to Dejonghe & Habing (1993), and Rich in these proceedings. Here I shall say only a few words on some age determinations.

The existence of RR Lyrae stars at the Galactic center demonstrates that at least part of the bulge is old. Indeed, Lee (1992) has argued from the abundance distribution of the RR Lyraes in the bulge, in comparison with their distributions at larger Galactocentric distances, that they are older than the inner halo globular clusters by 1.3 Gyr. This has led him to support an inside-out chronology for the formation of the Galaxy.

Studies of K giants in the Galactic center, which presumably are representative of a significant amount of material there, suggest that the bulk of the bulge may be quite young. The work of McWilliam and Rich (1994) is particularly important in this regard. From a high resolution abundance analysis of 11 bulge giants they have recalibrated the abundance distribution of the bulge, and readdressed the significance of the relative blueness of its the color-magnitude diagram. They report: "use of our abundance scale ... suggests that the Frogel and Whitford (1987) infrared H-R diagram requires that the mean mass of the Baade's window giants can be no less than about $1.1M_\odot$". From such a large mass one infers a significantly younger age than that of the disk globular clusters of similar metal abundance - presumably by several Gyr.

This result is supported by the work of Holtzman *et al.* (1993), who have analyzed HST based color-magnitude and luminosity function data which reach to below the bulge main-sequence turnoff for a region in Baade's Window. While these authors were commendably cautious in view of problems associated with the spatial distribution, photometric zero-points, abundance, and reddening of the material they were sampling, they were forced to the conclusion: "The location of the break in the luminosity function suggests that there are a significant number of intermediate age ($<$ 10 Gyr) stars in the Galactic bulge."

The work of McWilliam and Rich (1994) is important in a second area. As emphasized by Matteucci and Brocato (1990), the dependence of $[\alpha/\mathrm{Fe}]$ on [Fe/H] depends strongly on the rate and duration of star formation. If, for example, star formation in the bulge was an efficient and very rapid process one might expect relatively higher values of $[\alpha/\mathrm{Fe}]$ (say 0.5) for [Fe/H] >-0.5 compared with values $[\alpha/\mathrm{Fe}] < 0.1$ found in the solar neighborhood. Unfortunately the data of McWilliam & Rich (their Figure 20) on the α elements is inconclusive on this point: for whereas Mg and Ti are suggestive of such a phenomenon, Si and Ca are not. Nevertheless, with more data for a considerably larger sample, strong constraints on the timescale for the formation of the bulge should be possible.

6. Order of Events

The observational data discussed in the preceding sections suggest the following chronology.

The bulk of the halo inside the solar circle, and part of the bulge, formed relatively quickly some 15 Gyr ago. This seems to have happened within 1 Gyr, and may have occurred as envisaged by ELS. The bulk of the outer halo assembled a little later, by $\sim$ 1-2 Gyr, over a longer time, $\sim$ 2-4 Gyr. Accretion of fragments played an important role in the outer halo, and continues to the present time, as shown by the capture of the Sagittarius dwarf spheroidal galaxy, apparently currently under way. A large part of the outer halo probably assembled as suggested by Searle & Zinn. The halo contained $\sim$ 1/30 of the mass to which the disk would grow.

A disk with <[Fe/H]> $\sim$ -0.6 existed inside the solar circle within 1-2 Gyr of the formation of the inner halo. (Witness the disk globular cluster population and the thick disk in the solar neighborhood. More work is, however, urgently needed on the age profile of the disk globular cluster population.) The disk at this stage contained $\sim$ 1/10 of the mass to which it would eventually grow.

At the solar circle the bulk of the disk formed 4-5 Gyr after the inner halo and the oldest disk stars. The work of Edvardsson *et al.* (1993a) on [α/Fe] versus [Fe/H] indicates that the disk formed from the inside out.

The bulge remains a challenge. It contains material as old as, and probably older by $\sim$ 1 Gyr, than the inner halo. Current best estimates (by no means definitive) suggest that a large fraction of the bulge is relatively young ($\sim$ 10 Gyr), but much work is needed to place this on a firm footing.

7. Cosmogony

If the above chronology is correct, it suggests that some marriage of central contraction (ELS) and later accretion (Searle & Zinn) will explain the halo and disk observations. Some interesting questions, however, remain. What happens to the enriched gas (several times the mass of the stars which have formed [see eg Hartwick 1976]) and the supernova energy which escaped the star forming regions of the halo and thick disk. Carney *et al.* (1990) and Wyse & Gilmore (1992) suggest that the halo ejecta go to form the bulge, and similarly that the thick disk ejecta form the thin disk. An important possibility which has its origins with Berman & Suchkov (1991) and Burkert *et al.* (1992) is that the energy output during this phase completely ionized the remainder of the protogalaxy, precluding further star formation for a few Gyr. In the Burkert *et al.* two phase model (clouds, intercloud medium) the ionized material is heated to 2 10^{6}°K and is chemically enhanced to [Fe/H] = -1.5. If more globular clusters form in the second epoch of star formation this could contribute to an age, metallicity relation in the halo (as claimed by Chaboyer *et al.* 1992, and Carney *et al.* 1992), and to an age dispersion, metallicity relation similar to that reported by VandenBerg *et al.* (1990). Note that we now have two processes competing to explain the age spread in the halo - successive generations and accretion.

How seriously should one take the apparent hiatus of 4-5 Gyr between formation of the inner halo, thick disk, old bulge, on the one hand, and the bulk of the disk in the solar neighborhood, on the other. One possibility is that the evolutionary ages of the globular clusters have been overestimated, and their real age is $\sim$ 10 Gyr. While this has a certain attractiveness in the cosmological context, we shall not discuss it further, except to note that if this is the case some revision to basic ideas of stellar evolution will be necessary. Assuming the reality of the age difference we make four comments. First, we refer the reader to the work of Mathews & Schramm (1993) who present a model of the halo forming while the protogalaxy was still expanding as part of the general expansion of the Universe, with disk formation occurring some 4-5 Gyr later after the system had turned around and contracted significantly. The small difference in age ~ 1-2 Gyr discussed here between the thick disk material and the halo may prove difficult for this scenario. Second, it is interesting that the Carina dwarf spheroidal galaxy presents a nice example of a system with two main epochs of star formation at ~ 6 and >10 Gyr (see Smecker-Hane *et al.* 1994). Hiatuses do happen! Third, the ionization concept of Berman & Suchkov (1991) mentioned above leads naturally to periods with little star formation. Fourth, perhaps the observed age difference is just the time that it takes the bulk of the disk to grow outwards, as suggested by models such as those of Larson (1976).

The implications of the age structure of the bulge and its bar are far from clear. By definition, the models of Larson (1976) contain a bulge which forms dissipatively over a period of a few Gyr. In counterpoint to this, as noted in §2, minor mergers provide an interesting way of moving gas from the disk into the bulge (Mihos & Hernquist 1994) and may have contributed to its development, while they also have the propensity to thicken disks. It is then important to note the growing observational evidence that there is no kinematic gradient in the thick disk (Soubiran, 1993; Onja *et al.* 1994), which tends to favor a merger rather than a dissipational origin of the thickening, and to recall the association made between bulges and thick disks by van der Kruit & Searle (1981), who first claimed that one generally accompanies the other. (There seems, however, to be some disagreement about the reality of the connection. On the one hand, Shaw & Gilmore (1990) have presented data which argues against it, while Morrison *et al.* (1994), on the other, implicitly appear not to accept this more recent result.) If bulges and thick disks are causally connected it may be that merger events play a role in the establishment of both.

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DISCUSSION

I. King: I know that it's not fair to blame you for the hypothesis that the disk has been puffed up by mergers, but I wonder how you would reconcile this idea with the fact that the thick disk (as evidenced by 47 Tuc) seems to be older than the thin disk.

Norris: he age results show that the disk is thick only for ages greater than 10 Gyr, so the concept of mergers thickening the disk presumably applies to events which happened early in the life of the Galaxy.

K. Freeman: Are you convinced (regarding the hiatus between thin and thick disk etc.) that Edvardsson *et al* and others are on the same age scale.

Norris: No. Edvardsson *et al* quote an error of 20% for their ages. What does impress me, however, is that the white dwarf luminosity function result has stood the test of time now in spite of many efforts to increase the ages. Also, almost all of the diverse methods of age dating of the bulk of the disk in the solar neighborhood report ~ 10 Gyr. This contrasts quite strongly with the 14 Gyr which stellar evolution methods yield for 47 Tuc.

A. Gould: The ages scale inversely with the adopted RR Lyrae luminosities. Have you accounted for this when comparing relative ages.

Norris: Each of the three groups whose ages I quoted employ a consistent treatment of the RR Lyrae luminosities as a function of [Fe/H]. Without knowing which formulation is correct, it doesn't make much sense to seek to make a correction.

F. Matteucci: If there was a big time interval between the halo and disk formation during which star formation stopped one should expect a signature of that in the abundance ratios. In particular, one should expect a decreasing trend for $[\alpha/\mathrm{Fe}]$ ratios due to the fact that Fe continues to be produced during the absence of star formation whereas the αs are not.

Norris: That's clearly an important test. A comparison of data such as those of Edvardsson *et al.* with the predictions of models of disk formation should be able to constrain the extent of the hiatus.