The Age of the Galactic Bulge

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Abstract. The dominant stellar population of the central bulge of the Milky Way is old, with roughly solar metallicity. The age is very similar to that of the old metal rich bulge globular clusters and to 47 Tucanae, which has an age of 13 Gyr. Stellar composition measurements from Keck/HIRES confirm that bulge stars are enhanced in Mg and Ti. New HST/NICMOS data are consistent with an old stellar population dominating the central 100 pc of the Milky Way.

New infrared photometry has been reported for the bulge of M 31. Although bright asymptotic giant branch stars are observed in the infrared, the data are most consistent with an old stellar population.

1. Introduction

Our description of galaxy evolution relies on a balance of data from high redshift, and detailed population studies of the fossil record. Ages, composition, kinematics, and structure of stars preserve evolution in the greatest detail, but are available only for the nearest galaxies. The advent of 8–10m class telescopes and HST marks one of those rare periods where technology conspires to deliver dramatic advances at high redshift. At such times, attention naturally turns away from study of the fossil record, despite the dramatically tighter constraints such work provides. When uncertainties mount in the high-redshift work (as they often do) observers return to the fossil record to resolve the ambiguity. Detailed population studies can give relative ages to accuracies of 1–2 Gyr, and detailed composition measurements that are impossible using integrated light.

1.1. What is the Bulge?

The central bulge of the Milky Way has not easily won recognition as a distinct stellar population. Until the dramatic images obtained by the COBE satellite, showing a clear bulge in the infrared, the possibility could not be ruled out that our central population is instead an extension of the thick disk, inner halo, or

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perhaps even an intermediate age bar. From the infrared imagery, microlensing studies, and stellar dynamics, we now have good constraints on the total mass of the bulge, of order $2 \times 10^{10} M_\odot$ and a self-consistent dynamical model (Zhao, Rich, & Spergel 1996). The typical velocity dispersion of the stars is $\sim 110 \text{ km sec}^{-1}$; the mean abundance of the bulge is $\sim -0.3 \text{ dex}$ (McWilliam & Rich 1994) and the abundance distribution function is consistent with the closed box chemical evolution model (Rich 1990).

The evolved stars in the bulge are quite different from those found in the typical globular cluster. The well known RR Lyrae stars first identified by Baade are present and represent the metal-poor population. However, the bulge has a range in abundance and the most metal rich giants in the bulge exceed the solar abundance. The horizontal branch in the field color–magnitude diagram (CMD) is dominated by red horizontal branch (HB) (clump) stars, not by the bluer RR Lyrae stars, and in optical colors, the tip of the red giant branch is observed to descend fainter than the red clump luminosity due to blanketing in the M giants (Rich et al. 1998). The asymptotic giant branch (second ascent) stars are late M giants and can reach $M_{\text{bol}} = -5$. The presence of such luminous stars in the bulge fueled well-justified speculation that a widespread intermediate age population must be present there. We now know that stars in the 13 Gyr globular cluster age range can reach that luminosity, if they are metal rich (Guarnieri, Renzini, & Ortolani 1997).

Challenged by heavy and variable reddening, extreme image crowding, the spatial depth of the population, and the broad range of metallicity, observers have found it challenging to measure the age. Arp (1965) produced a color–magnitude diagram for the giants in Baade’s Window from photographic $BV$ photometry. Van den Bergh (1972) refined further reddening and distance estimates, and argued for a metal-rich giant branch in his photometry of Baade’s Window. Blanco’s $RI$ photographic plates on the newly commissioned 4m telescope at CTIO led to a breakthrough: for the first time the giant branch was clearly defined, permitting a sample of K giants to be selected for spectroscopy (Whitford & Rich 1983). Van den Bergh & Herbst (1974) developed some age constraints for the Plaut field ($8^\circS$) of the nucleus. Terndrup (1988) attained an old main sequence turnoff in this field, but could not resolve the metal rich bulge population deep in Baade’s Window. The debate concerning the age range in the bulge remains active to this day.

Related to the age is the formation time scale (review in Rich 1999). The time scale for the bulk of star formation can be constrained by modeling the turnoff. One would like to use the asymptotic giant branch (AGB) to constrain residual star formation on Gyr time scales, but the lack of useful correlation between age and tip luminosity for metal rich stars poses a problem. Composition (see Section 3, below) offers some interesting constraint on the formation time scale. To date, the best constraints argue that the bulge is globular cluster age, and formed in $< 1$ Gyr.

1.2. Historical Perspective

The importance of the bulge, and the description of bulge populations, was well appreciated by the pioneers in the field, especially Walter Baade. Although the actual Galactic center is obscured by tens of magnitudes of extinction, the cir-
cumstantial evidence for the nucleus lying toward Sagittarius was strong enough that Baade searched for RR Lyrae stars in that direction. His discovery of a sharply peaked magnitude histogram for the RR Lyrae stars marked the discovery of the bulge as a stellar population (Baade 1951).

By the time of the pivotal 1958 Vatican meeting on stellar populations, the present-day view concerning the age and metallicity of the bulge had been developed and was correct. The presence of RR Lyrae stars argued for an old population, but the presence of late-type M giants (discovered in grism surveys by Victor Blanco) argued for high metallicity. In a final table summarizing the characteristics of stellar populations, the Galactic nucleus was classified as old and metal rich, but some lingering doubt was expressed as to whether the nucleus (bulge) population was as old as the globular clusters. This confluence of thinking was summarized in a prescient and sophisticated analysis of the formation history of the M 31 bulge, the template stellar population for Population II (Baade 1963):

“We must conclude, then, in the central region of the Andromeda Nebula we have a metal-poor Population II, which reaches $-3^{m}$ for the brightest stars, and that underlying it there is a very much denser sheet of old stars, probably something like those in M 67 or NGC 6752. We can be certain that these are enriched stars, because the cyanogen bands are strong, and so the metal/hydrogen ratio is very much closer to what we observe in the Sun and in the present interstellar medium than to what is observed for Population II. And the process of enrichment probably has taken very little time. After the first generation of stars has formed, we can hardly speak of a ‘generation’, because the enrichment takes place so soon, and there is probably very little time difference. So the CN giants that contribute most of the light in the nuclear regions of the Nebula must also be called old stars; they are not young.”

High resolution spectroscopy was, of course, lacking, and the realization that some globular clusters are very metal poor, and 1/100 solar abundance, also was absent (witness the mention of M 67 and NGC 6752 in the same breath). But the Vatican conference mentions both large age and high metal abundance for the bulge population. For approximately the next 20 years, the bulge would often be described as metal poor, despite the very clear evidence of a wider abundance range, accumulated prior to that time. Ultimately, the observational definition of the globular cluster abundance scale, combined with new work on the bulge, would modify this erroneous picture.

1.3. The Relationship to High Redshift Studies

Although much can be inferred from the evolution of spiral galaxies as a function of redshift, the well-determined age and age range of one single bulge population (that of the Milky Way) is a powerful constraint.

The classic bulge formation model is that of Eggen, Lynden-Bell, & Sandage (1962) in which bulges form from dissipationless collapse very early on. The widely accepted cold dark matter models have some variations, but basically all concur that elliptical galaxies form from merged disk galaxies (Kauffmann, White, & Guiderdoni 1993; Baugh et al. 1998). At any given redshift, bulges should then be older than ellipticals. Some bulges may be related to bars, which could vertically thicken due to scattering of resonant orbits off of the bar, or due
to the dissolution of bars (Combes 2000, and references therein). Bulges with exponential profiles may be more closely related to disks (Carollo et al. 2001).

The most distant normal star forming galaxies are the Lyman-break galaxies (Steidel et al. 1996) which are strongly clustered (Adelberger et al. 1998; Giavalisco & Dickinson 2001). These galaxies have strong outflows and are evidently metal rich; it is therefore reasonable to suppose that they will evolve into spheroids. The connection between the galaxies at $z \sim 3$ and the population of galaxies that begin to fall in well defined Hubble types by $z \sim 1$ requires much effort and lies ahead of us. By $z \sim 1$ we can begin to classify bulges of spirals, and elliptical and galaxies are well enough resolved to even investigate their star formation histories pixel by pixel. Ellis, Abraham, & Dickinson (2001) studied the evolution of bulges and ellipticals in the Hubble Deep Fields and found that at any given redshift, ellipticals are redder than bulges. Issues such as disk contamination and reddening have rigorously been accounted for. Numerous studies have found evidence for very red ellipticals, and clustering of ellipticals, in the $z \sim 1−1.5$ range (see Stockton’s review, these proceedings). Locally, Peletier et al. (1999) and numerous other studies argue that spiral bulges are as old as present-day Coma ellipticals. In the section that follows, I argue that the stellar populations of the Galactic bulge are consistent with a large age. How do we reconcile these findings with the high redshift studies? Are most bulges subjected to brief starburst events, due to the availability of gas from the disk or environment, or are elliptical galaxies systematically more metal rich? We have to resolve this tension between the high redshift data and the fossil record.

2. Age Constraints From the Turnoff

Because of the high reddening, uncertainty in the distance modulus, and presence of foreground stars, one cannot constrain the age of the bulge with confidence by placing isochrones on the CMD. The foreground main sequence disk stars have proven a vexing population, as they overlay the old main sequence turnoff point precisely and appear as an intermediate age population. To increase the contrast between the bulge population and the foreground, one needs to study fields close to the Galactic center, where reddening and crowding become serious. Estimates from modeling and direct starcounts place the foreground contamination at 10–15% (see the CMDs by Feltzing & Gilmore 2000).

The strongest arguments in favor of an intermediate age population in the bulge were based on the presence of luminous AGB stars. An empirical correlation between AGB star luminosity and intermediate populations was established using Magellanic Clouds clusters (Aaronson & Mould 1985). The $\sim 1$ mag extension at the turnoff point prevented a convincing resolution of the problem.

Ortolani et al. (1995) found a solution to the problem. Both the reddening and distance modulus uncertainties could be eliminated if a differential comparison is made between the bulge luminosity function and that of an old globular cluster of comparable metallicity. The crucial technique is to force fit the bulge field luminosity to the globular cluster luminosity function at the point of the red clump, and to examine the agreement at the turnoff point in detail. Red clump stars are fueled by helium core burning, and the core mass (hence luminosity) has almost no dependence on age and little dependence on metallicity.
The bulge is concentrated spatially and consequently there is little distance dispersion. Therefore, when the red clumps are force fit, it is easily seen that the turnoff rise of bulge and NGC 6553 are identical. Therefore, using the well established $\Delta V_{HB}$ method of age determination, we are able to show that the bulge and NGC 6553 have identical ages.

The next question is, how old is NGC 6553? The metallicity of the cluster is in some debate right now. Barbuy et al. (1999) find $[\text{Fe/H}] = -0.5$ and alpha elements up by +0.5 dex relative to scaled solar. Cohen et al. (1999) use Keck/HIRES spectroscopy to find $[\text{Fe/H}] = -0.16$ and alpha elements up by +0.3 dex. R. M. Rich, L. Origlia, & S. M. Castro (in preparation) use infrared spectroscopy to find $[\text{Fe/H}] = -0.3$ and alpha elements up by +0.3 dex. Regardless of which value one adopts, NGC 6553 is a good match for the field population of the bulge, and only 0.4–0.5 dex more metal rich than 47 Tuc.

We have determined a white dwarf distance for 47 Tuc (Zoccali et al. 2001) one of the nearest of the metal rich disk globular clusters. The distance modulus translates into a turnoff age of $13 \pm 2.5$ Gyr. Given the close correspondence between NGC 6553 and 47 Tuc, I adopt an identical age for the Galactic bulge. This makes the bulge of order the age of the halo. There has been recent work that solidifies this large age, and additionally places limits on the time scale of bulge formation. Feltzing & Gilmore (2000) show quantitatively that all of the stars lying slightly brighter than the old main sequence turnoff in the bulge fields belong to the foreground. This is also being confirmed in proper motion surveys based on HST data (K. Kuijken & R. M. Rich, in preparation).

### 2.1. Implications for Red Globular Cluster Systems

As a final side note, in many elliptical galaxies with globular cluster systems, the globular clusters are bimodal in their color distribution. The bluer clusters tend to be spatially extended, while the red clusters follow the spheroid, just as is the case in the Milky Way (the bulge clusters follow the bulge). It is widely accepted (Ashman & Zepf 1992) that the red cluster systems are connected with late mergers. In the Milky Way bulge, we have shown (one example) that the red clusters are old, like those in the halo. However, I would propose that the red clusters in ellipticals should be considered to have the age of the old spheroidal stars, unless proof to the contrary can be developed.

### 3. Time Scale Constraints From Abundances

Considering that this is a meeting that discusses both ages and time scales, we should address the time scale of formation of the bulge. Strong constraints have been attained from the photometry discussed in the last section. The compositions of stars also have the potential to constrain the time scale for chemical enrichment. Massive star supernovae which explode on $10^6$ yr time scales have ejecta rich in alpha-capture elements (O, Mg, Si, etc.), the products of nucleosynthesis in their hydrostatic burning shells. Type Ia SNe experience a deflagration in their explosions, and contribute more iron (but on time scales of $\sim 1$ Gyr) than the massive star (core detonation) supernovae. The general trend is that the alpha/iron ratio declines with increasing $[\text{Fe/H}]$ with the more recently formed stars approaching solar composition. The more rapid the enrichment, the higher
the iron abundance of stars that maintain an alpha-enhanced composition. This paradigm, fully described in (cf. McWilliam 1997) permits us to make relative comparisons of enrichment time scales in stellar populations. Figure 1 shows the abundance trends for bulge giants measured from spectroscopy on Keck, using the HIRES echelle (Vogt et al. 1994). A more detailed discussion of recent Keck results on bulge giants is given in Rich & McWilliam (2000).

The bulge shows a unique pattern of enrichment not shared by any other Galactic stellar population. The alpha element Mg remains enhanced even above the solar iron abundance, as does Ti. Oxygen follows a less striking trend, while exceeding the solar abundance at $-0.3$ dex. Ca and Si are modestly enhanced. This complicated pattern of enhancement is not predicted by supernova models, but is likely consistent with the bulge being rapidly enriched by massive stars. The rapid formation time scale is consistent with the age constraints from the photometry, and with observed large star formation rates at high redshift.

4. The Age of the Nuclear Population

The stellar population of the Galactic nucleus is one of the most active and dramatic star forming regions in the Galaxy (Morris & Serabyn 1996). Massive star formation dominates the energy input, and includes such dramatic examples as the $10^6 L_\odot$ Pistol Star (Figer et al. 1998) and the Arches cluster, with $10^3$ massive O stars and an age of 2 Myr (Figer et al. 1999). Considering the intensity of star formation near the nucleus, one expects to find a stellar population with a wide range of ages, and a present day mass function consistent with a continuous history of star formation. Ground-based imaging of the Galactic Center (Catchpole, Whitelock, & Glass 1990) found evidence for a concentration of the most luminous AGB stars toward the Galactic Center, further strengthening the case that the inner 100 pc of the Galaxy must have a wide age range.
Figure 2. $H$-band luminosity functions of the bulge using HST/NICMOS (R. M. Rich et al., in preparation). The age-sensitive gap between the red clump ($H \sim -1.25$) and the main sequence rise at $H \sim 3$ is very similar for the Galactic Center fields (10–40 pc from the nucleus) and the old metal rich globular cluster NGC 6528 (lower panel). The nucleus is dominated by an old population.

Using the NICMOS infrared imager on board HST, we obtained deep infrared photometry of optically obscured fields near the Galactic center (R. M. Rich et al., in preparation; Figure 2). Much to our surprise, we found a clearly-defined red clump and red giant branch, consistent not with an intermediate age population of ongoing star formation, but rather with an old stellar population. We again use the vertical method of age determination, $\Delta$(mag)$_{HB}$, this time comparing our Galactic Center population to NGC 6553 (Figure 2). We conclude that the bulk of the stellar population in these regions is as old as the globular clusters, just as is the case in the outer bulge. In light of the star formation activity in the nuclear region, this is a surprising finding. The luminosity function and color–magnitude diagram of these fields a mere 40 pc from the Galactic Nucleus appears identical to that of bulge globular clusters observed in the same NICMOS bands. The lack of an intermediate age population is surprising; perhaps conditions in the Galactic Center permit only the formation of massive stars, so that longer-lived low mass stars would not survive.

5. Conclusion

Using the widely accepted vertical method of age determination, the Galactic bulge has approximately the age of the Galactic globular cluster 47 Tuc, $13 \pm 2.5$ Gyr. The vertical method (using infrared luminosity functions) also shows that the population within 10–40 pc of the nucleus is old. The composition of the bulge K giants is consistent with early, rapid formation of the bulge. These age measurements indicate that the Galactic bulge/bar is among the oldest Galactic
stellar populations. If the population formed by the vertical thickening of a massive disk, it must have done so very early in the Galaxy’s formation history.

Local group bulges are also consistent with this picture. The infrared luminosity functions of M 32 (Davidge et al. 2000) and the bulge of M 31 (Stephens et al. 2001) terminate at $M_{bol} = -5$—confirming early ground-based IR imaging by Rich & Mould 1991. While the old globular cluster NGC 6553 has bright AGB stars, the complicated behavior of metal rich stars on the asymptotic giant branch probably makes it difficult to rule out an intermediate age component in these local group bulges. Better age constraints must come from modeling the color and integrated spectral energy distribution, to constrain trace intermediate-age main sequence stars. Our capability to use the old main sequence turnoff point to constrain the age of the bulge is a golden opportunity not available for even the nearest Local Group bulges. In terms of age, the Galactic bulge much more resembles the halo than it does the disk, and all the data point to it being completely in place very early on in the Galaxy’s history.

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