THE STELLAR POPULATION OF THE GALACTIC BULGE

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How old is the bulge? Are bulges in general as old as halos? Do bulges form rapidly or slowly? Are they formed from disks via dynamical instabilities, or perhaps by starbursts? In general, do luminous spheroids form at the same time as the oldest stars?

For populations older than 10 Gyr, it is hard even to constrain relative ages (Renzini, 1992). And while there is much current excitement about the prospect of direct lookback studies, imaging of galaxies at a particular redshift give us no information about the evolutionary path of a particular galaxy. These studies tell us about the general state of galaxies at a given epoch and environment, and as the distances become greater, a sample more extreme in properties (activity, intrinsic luminosity) is likely to be selected. While some phases of galaxy formation may be luminous and easily visible (formation of a $2 \times 10^{10} M_{\odot}$ bulge in 10^8 yr) important evolutionary phases might be less readily observed (formation of the first halo stars, or the thick disk). The relative age dating of the oldest stars is still an important project, even with successful direct imaging of high redshift galaxies.

1. The Galactic Bulge

The bulge of the Galaxy is that stellar population which dominates the inner kpc, with approximately Solar metallicity and age > 5 Gyr. The baryonic mass of the bulge is ≈ 10 times that of the stellar halo and $\approx 30\%$ that of the disk. If proto-galaxies and an era of galaxy formation is discovered, we might expect the formation of bulges such as that of our galaxy, at 10-100 $M_{\odot}yr^{-1}$, to be among the more easily observable phases of galaxy formation.

The age of the bulge has been the subject of much recent debate. Observationally, there are a number of reasons to be skeptical that the bulge is as old as the extreme halo. Rich (1992) has emphasized that even if

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one assumes that all the stars > 1 mag brighter than the globular cluster giant branch tips in Frogel & Whitford (1987) can be igored, the large numbers of long period Miras cannot be overlooked. Since Feast's (1963) classic study, it has been known that Miras with $P > 300$ days in the Solar neighborhood have disk kinematics, whereas shorter period Miras look like halo members. Whitelock *et al.* (1991) report a substantial number of Miras with $P > 300$ days in bulge fields 1 kpc from the nucleus, and Glass *et al.* (1995) find approximate half the Miras in the low-latitude Sagittarius field have long periods. Metallicity differences cannot explain this, since the mean metallicity of the bulge is approximately that of the Solar neighborhood (McWilliam & Rich, 1984). Finally, Holtzmann's (1993) *HST* main sequence photometry favors an age < 10 Gyr for the Galactic bulge.

There are other reasons to suspect that the Galactic bulge and perhaps bulges in general may form late or undergo extended periods of star formation. The inner bulge is a bar (Blitz &Spergel, 1991) and has clearly formed as a result of highly dissipative processes. Local group galaxies all have extended giant branches in their spheroids (e.g. Rich & Mighell, 1995). A rapid, violent formation history should leave a clear chemical imprint on the bulge (enhancing the alpha-capture elements, especially oxygen), but no clear evidence of this is found. While McWilliam & Rich (1994) find Mg and Ti enhanced in bulge giants, Ca and Si are found in their Solar abundance ratios. And for bulge giants covering the entire range of Fe metallicity, s-process elements are found in Solar abundance ratios. Since s-process elements are made on the AGB, it is a mystery how an early, violent starburst could leave such a signature. Massive stars are expected to have made large amounts of oxygen. In a careful re-analysis of their data, McWilliam, Tomaney, & Rich (1995) rule out a very high oxygen abundance for the bulge. The chemical evidence (with the current small sample sizes) favors a slower, more extended formation scenario.

1.1. BULGE FORMATION SCENARIOS

A number of plausible scenarios for the formation of the Galactic bulge have been discussed.

Classical: The bulge collapsed on a free-fall timescale. Since $t_{ff} \sim \rho^{-1/2}$, the densest part of the spheroid would be expected to collapse first. Renzini (1992) has emphatically pointed out the logic of this hypothesis and Lee (1992) argues that RR Lyraes in the Galactic bulge are the oldest stars in the Galaxy.

Bulge From Disk: A massive starburst, happening at any time during the life of a galaxy, might have formed a massive inner disk. This disk is unstable to bar modes, which can vertically thicken into a bulge (Pfenniger

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& Norman, 1990; Merrit & Sellwood, 1994). This idea explains the high density of the bulge and the peanut/bar morphology observed for many galaxies. The longevity of the bar may be a problem.

Bulge from Halo: The metal poor halo could have formed early on, perhaps in an early era of "frustrated" star formation. The hot 10^7K gas could cool and dissipate to the center, resulting in either an extended or starburst formation scenario (Larson, 1975; Wyse & Gilmore, 1992).

Bulge from Mergers: The Sgr I dwarf is observed to be in an encounter with the Milky Way (Ibata *et al.* 1995); were there others? If so, such galaxies must not have been rich in carbon stars, since virtually no thermally pulsing carbon stars are known in the bulge (Blanco, 1988).

In principle, measurements of age and age dispersion can distinguish among these scenarios, but differences between a 10 and 14 Gyr old metal rich population are subtle.

2. Ages of Metal Rich Globular Clusters and the Galactic Bulge

Direct measurement of the age of the bulge from turnoff photometry is complicated by reddening, dispersions in age and metallicity, and the depth of the bar, problems that affect both ground and space based photometry. An approach which addresses this problem (and in which I am involved) is to determine secure ages for the metal rich Galactic center globular clusters and to estimate their ages by the parameter ΔV_{TO}^{HB} (Ortolani *et al.* 1995). The bulge can be compared with the clusters by tying both luminosity functions at the red clump, removing reddening and distance uncertainties. The metal rich clusters have the same ΔV_{TO}^{HB} as the old halo clusters (Figure 1). Luminosity functions of the bulge field Baade's Window (500 pc S of the nucleus) and the clusters agree almost perfectly near the turnoff, admitting virtually no age spread in the bulge field population. It is important to repeat this experiment at various locations in the bulge, particularly at lower latitudes—note that Catchpole *et al.* (1990) see a concentration of luminous AGB stars toward the nucleus, with a clear excess in the inner 140 pc.

An absolute age measurement of the bulge is within sight. At the time of this writing, deep *HST* imaging of the old globular cluster 47 Tuc has been obtained (GO6114, A. Renzini PI). Reaching deep enough to solidly measure the white dwarfs, the distance modulus will be obtained by comparison with the white dwarf cooling sequence rather than with the main sequence. Since Ortolani *et al.* (1995) show that the loci of the metal rich clusters overlay those of 47 Tuc nearly exactly, this approach will indirectly give an absolute age for the Galactic bulge. If the initial findings of Ortolani *et al.* (1995) are confirmed and the bulge is found to be old, then it will

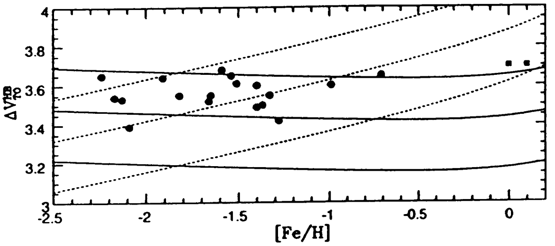

Figure 1. Metal rich globular clusters are probably as old as the oldest halo globular clusters (Ortolani *et al.* 1995). The luminosity difference between the HB and turnoff ΔV_{TO}^{HB} is plotted for a representative set of halo globular clusters (filled circles) and for the metal rich clusters NGC 6528 and NGC 6553 (filled squares). The lines refer to ages of 18, 15, and 12 Gyr (upper, middle, and lower lines) for HB luminosity-metallicity relationship of Sandage &Cacciari, 1990 (solid lines) and Walker, 1992 (dotted lines); see Ortolani *et al.* (1995) for additional discussion.

mean that the Mira period distribution and absolute luminosities will be of little use in the relative age dating of stellar populations, a fact that will complicate our extension of an "age ladder" into the Local Group spheroids and beyond.

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