PART I.

STELLAR CLUSTER, STAR FORMATION

1. Galactic Bulges

THE GALACTIC BUGLE

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Abstract.

I review current work on the Galactic bulge, with emphasis on issues that may connect to the environment of the Galactic Center. There is growing evidence that the field population of the bulge at $R_{GC} > 500pc$ is as old as the metal rich Galactic center globular clusters, and that field and clusters have the same spatial and metallicity distribution. We suggest that by analogy, extragalactic metal rich cluster systems, which also tend to follow the spheroid light, are old. On the other hand, there has been long standing evidence for an age gradient toward the Galactic center, and recent observations confirm without doubt that there is active star formation there. If a long-lived bar has been funneling gas (and inducing star formtion) in the central 100 pc, the star formation history there will be complicated and interesting.

1. Introduction

There has been a long standing distinction between astronomers who work on the Galactic Center at non-optical wavelengths and focus on the non-thermal activity, and those who work on the Galactic bulge at optical wavelengths and hope to constrain the bulge's formation history. In joining the two groups of astronomers at this meeting, the organizers correctly sense that the subjects are closely connected. Perhaps more importantly, infrared technology has advanced so dramatically that it is feasible to undertake in these heavily extincted fields the kinds of observations once relegated to "optical" methods– crowded field photometry and high resolution spectroscopy for abundance measurement. Also of great importance in the coming years will be the NICMOS instrument on board HST, which will image

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stellar populations in the vicinity of the Galactic Center. Finally, there is the growing awareness that the bulge is actually organized into a bar structure which may help to feed gas into the nuclear region.

Stellar populations can be characterized by age, abundance, kinematics, and structure. Because of the reddening and spatial depth of the density distribution, there has been lively debate about the age of the bulge field population relative to that of the old halo. As discussed in §2 below, there is strong evidence favoring an old (globular cluster-like) age for the bulge. In the central tens of pc, there is much evidence for very recent star formation with activity traceable over the last Gyr (cf. Genzel et al. 1994 review). There is now established that the bulge is a bar (Blitz & Spergel 1991) although the exact shape and pattern speed remain a matter of debate (Zhao 1996; Zhao, Rich, & Spergel 1996; Binney, Gerhard & Spergel 1997). The values of Binney et al. (1997) derived from deprojection of the *COBE* are a pattern speed of 60-70 $\mathrm{kms}^{-1}\mathrm{kpc}^{-1}$ for the bar, axis ratios of 1:0.6:0.4 with a major axis of 2kpc, and an angle betwen the major axis and Sun-center line of 20^o . Armed with the bulge shape, microlensing data, and a dynamical model, one may calculate the mass. Most models give $\approx 1 - 20 \times 10^2 M_\odot$ for the total mass enclosed, although opinion differs as to how it should be allocated between disk and bulge (Bissantz et al. 1997). The self-consistent dynamical model of Zhao (1996) predicts kinematics as a function of position. Finally, in characterizing the bulge, there is the abundance range and chemistry. The 1 dex range in [Fe/H] is observed in the K giants (Rich 1990) and is reflected in the presence of RR Lyrae stars and M giants in the same volume. There is increasing evidence for enhancement of Mg and Ti at high spectral resolution (McWilliam & Rich 1994) and low resolution (Sadler, Rich, & Terndrup 1996). An enhancement in Mg (as is seen in the integrated light of elliptical galaxies) probably explains why the Rich (1988) abundance scale is 0.3 dex higher in [Fe/H] than the McWilliam & Rich (1994) abundance scale: The Rich measurements used a sum of Mg and Fe lines to get better S/N on the equivalent widths. However, the mean [Fe/H] in the bulge is now below Solar. It is difficult to understand why there should be an abundance gradient in the disk, yet the bulge has a lower [Fe/H] (Detailed discussion of the abundance scale is in Rich 1997a,b)

One outstanding issue is whether there are aundance/kinematics correlations, particularly in the bar. Kinematic studies in bulge fields more distant that 1 kpc from the nucleus suffer from disk contamination, as the bulge light declines sharply (note that the steep central density concentration of the bulge is one of its defining characteristics). Combining low resolution abundances (Sadler, Rich, & Terndrup 1996) with astrometry (Spaenhauer, Jones, & Whitford 1992) in Baade's Window ($l = 1^o, b = -4^o$) we find a sharp break in abundance between the barred and non-barred pop-

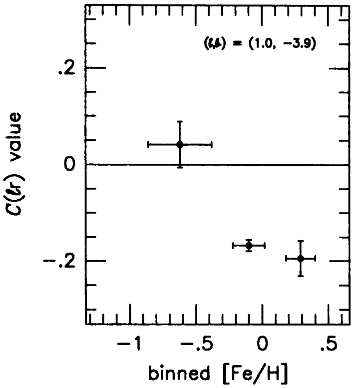

Figure 1. Evidence that the metal rich bulge population has bar-like kinematics (Rich, Terndrup, & Sadler 1998). C_{lr} measures the vertex deviation of v_l vs. v_r velocity ellipsoid for the subsample with the indicated metallicity (see Zhao et al. 1994 for a full description of this statistic). Notice the break at [Fe/H]≈ −0.5, where bar-like kinematics set in.

ulation, but Figure 1 and other analysis finds no strong abundance trends within the bar (Rich, Terndrup, & Sadler 1998).

2. Central Globular clusters

Until recently, the Galaxy's globular clusters were broadly divided into a centrally concentrated, flattened, and metal rich population of disk globular clusters, and a metal poor, much more extended population of halo globular clusters (e.g. Armandroff 1993). It had been suggested by Minniti (1996) that the metal rich disk globular clusters had the kinematics characteristic of the bulge, but Rich (1993) pointed out that the 1000 pc vertical scaleheight of the disk globular clusters was a poor match to the 350 pc scaleheight of the very centrally concentrated light of the bulge. Further, the metallicity distribution of the bulge appeared to extend a full 1 dex more metal rich than the disk globular clusters, which appeared to peak at [Fe/H]=−0.5 (a fact also emphasized by Wyse et al. (1997) in their review). The picture of the bulge globular clusters has changed with the painstaking survey of color-magnitude diagrams to yield reddening and distance measurement, undertaken by Barbuy, Bica, & Ortolani (1998) who find 17 clusters witin $|z| < 500pc$. Consequently, the z distribution of the bulge clusters now follows the spheroid light, a crucial development. Discovery of new metal rich clusters and the lower McWilliam & Rich abundance scale now conspire to bring the abundance distribution of the clusters (Figure 2) into agreement with that of the bulge field stars.

Having established that there are metal rich globular clusters in the bulge, we next want to know their age relative to the halo. HST imaging

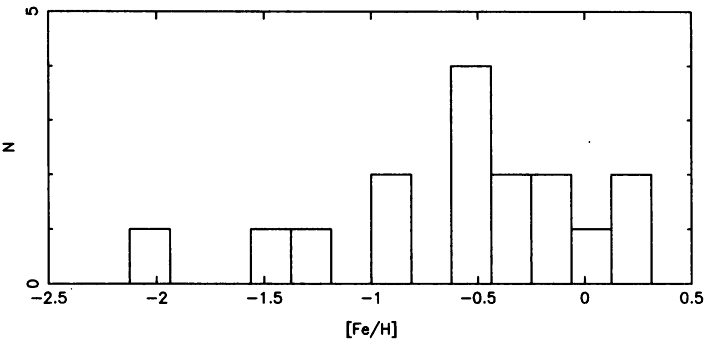

Figure 2. **Abundance distribution of Galactic bulge globular clusters from Barbuy et al. (1998). The mean and range of the metallicity distribution of the clusters now agrees with that of the field star population.**

(Ortolani et al. 1995) overcomes the crowding, field contamination, and extinction for some of the less obscured clusters such as NGC 6553 and 6528, both of which have [Fe/H] ≈ −0.5. The mean line of 47 Tuc overlays precisely the mean lines of these two bulge clusters (Figure 3 below). The age-related parameter $\Delta V_{TO}^{HB} = 3.6$ for these clusters, a typical old halo value. Finally, Ortolani et al. (1995) show that when the horizontal branches of the cluster and field luminosity functions are forced to align (automatically removing reddening and distance differences) the bulge field and the clusters agree in age to within 5%. We conclude that bulge field, metal rich clusters, and the well known cluster 47 Tuc must have the same age.

2.1. IMPLICATIONS FOR EXTRAGALACTIC GLOBULAR CLUSTER SYSTEMS

Globular cluster systems in elliptical galaxies frequently have a distinct bimodal color distribution which is interpreted as due to two peaks in metallicity (e.g. Forbes, Brodie, & Grillmair 1997). An important breakthrough was achieved by Geisler, Lee, & Kim (1996) in their study of NGC 4472. The red clusters follow the spheroid light, while the blue (metal poor) clusters are spatially extended. The theory of Ashman & Zepf (1992) has been proposed to explain these bimodal distributions. The Milky Way may now be considered to have a bimodal cluster distribution in this sense, with a red cluster system following the spheroid light, and an extended metal poor cluster system linked with the pop II halo. As we have shown that at least some of the Milky Way's metal rich clusters are old, the merger hypothesis does not work well for the bulge. While it is true that the Sgr dwarf galaxy is disintigrating (Ibata et al. 1997) wide scale surveys of the bulge

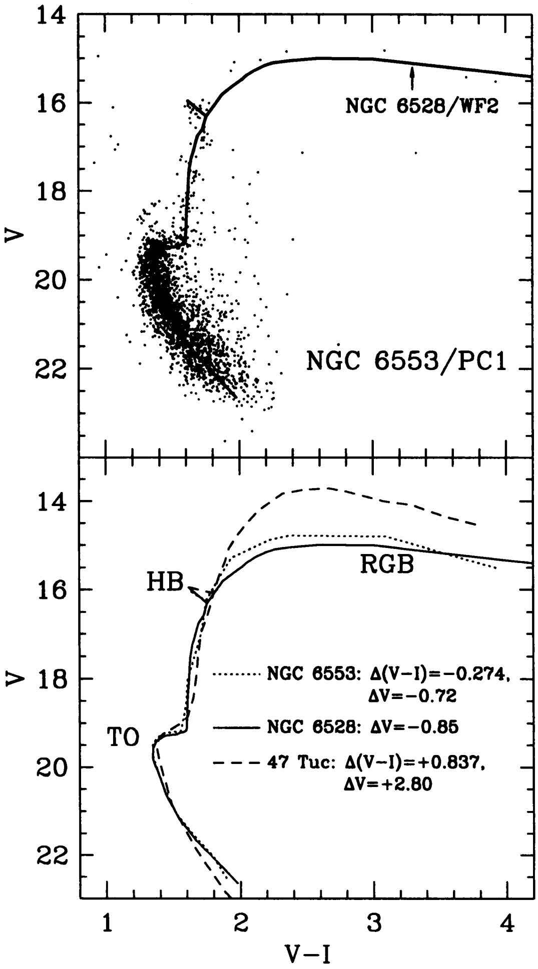

Figure 3. The color-magnitude diagram for the metal rich bulge globular cluster NGC 6553, from F555W (V) and F814W (I) images obtained using the Planetary Camera on board HST (Ortolani et al. 1995). The locus of NGC 6528 (derived using the same setup) has been shifted to overlay the data of NGC 6553. In the panel below, notice the agreement between 47 Tuc and the two cluster loci. We conclude that these bulge clusters have the same age (within observational uncertainties) as 47 Tuc.

by Azzopardi and Blanco have found only low-luminosity R-type carbon stars, and the metallicity of the Sgr field is still too low to match the bulge. [As an aside, the author strongly disagrees with the view of Ng (1997) that the bulge carbon stars (Westerlund et al. 1991) belong to the Sgr dwarf galaxy. The bulge C stars have the spectral characteristics and luminosities of early R stars and they have the kinematics and abundance gradients characteristic of the bulge (Tyson & Rich 1991).]

The large ages of the bulge metal rich clusters and the proven similarity of the cluster abundance and spatial distribution with those of the spheroid (Barbuy et al. 1998) agree better with the early formation scenario of Forbes et al. In the case of the Milky Way, we suggest that the extended halo may have formed during an early period of frustrated star formation, with metallicity insufficient to cool the gas quickly. As metals built up, cooling finally became efficient and the gas cooled to the much denser configuration of the proto-bulge, with a significant starburst. A disklike configuration might have been unstable to bar formation, although this would require a very long-lived bar (an issue that is currently a matter of much debate). While it is early to draw vast conclusions, I believe that the work of Barbuy et al. (1997) and Ortolani et al. (1995) now securely place the metal rich disk/bulge system of globular clusters in a secure extragalactic context.

3. Importance of the Central Star Formation History

The central population which is the focus of this meeting was once thought to be old and quiescent, like that of the M31 nucleus (Becklin & Neugebauer 1968). It is now known that massive star formation is in progress on scales from 0.1 to 100 pc, fueled by $10^8 M_\odot$ of molecular gas (Morris & Serabyn 1996; review) with at least 12 hot, helium emission line stars in the infrared cluster itself (Krabbe et al. 1991, Eckart et al. 1995). An extended AGB population present in the central pc is evidence for another burst some 10^8 yr ago (Haller & Rieke 1989; Blum et al. 1996) and now there also appear to be a number of SiO masers in the central cluster (Izumiura et al. 1997). The star formation on large scales includes several interesting star clusters and the extremely luminous "Pistol Star" (Figer, McLean, & Morris 1995; Figer et al. 1998).

The precise star formation history of the central 200 pc remains an important unsolved problem, because of the marked central concentration (on 100 pc scales) of bright giants (Catchpole et al. 1990), luminous OH/IR with rapid rotation kinematics (Lindqvist et al. 1992), and long period Miras (Glass et al. 1995). These may be strong indications of an intermediate-age population, or they may reflect AGB evolution of very old, metal rich stars (Frogel & Whitelock 1998). IRAS Miras (Whitelock et al. 1991) and SiO masers (Izumiura et al. 1994) $>$ 1 kpc from the nucleus are luminous enough to be considered intermediate-age progeny, yet there is no evidence for a correspondingly young turnoff population. Infrared photometry of our old cluster NGC 6553 (Guarnieri, Renzini, & Ortolani 1997) finds AGB stars as luminous as $M_{bol} \approx -5$. Metallicity rather than age might make such bright AGB stars, continuing the trend established for lower metallicity by Frogel & Elias (1988). Within the central 200 pc, the central concentration of these AGB stars supports the notion of an intermediate age population, yet in the outer bulge similar AGB stars appear to be old. This confusing problem will frustrate attempts to derive ages based on AGB stars for distant resolved populations.

In view of the ongoing star formation (something not observed in M31, for example), the striking central concentration mapped by Catchpole et al. 1990, and the nuclear cusp (Serabyn & Morris 1995), there is clear motivation to explore in depth the star formation history of the central 100 pc. The nuclear cusp in the central $5' = 10$ pc is a stellar population distinct from the nuclear star cluster, and is deserves precision age measurement from turnoff photometry. There is strong evidence that the bar is long-lived, and therefore gas has been channeled to the center for many Gyr, and we would expect a more or less continuous star formation history (or bursts perhaps) over that time. The extent and amount of massive star formation in the Galactic center region is striking, and sets the Galaxy apart from other Local Group members.

4. Conclusion

HST imaging of UV-dropout galaxies finds a population of star-forming nucleated galaxies at $z \sim 3$ (Giavalisco et al. 1996) One point in favor of a much higher formation redshift is the correlation between black hole mass and luminous spheroid mass in nearby galaxies with non-AGN black holes (Kormendy & Richstone 1995). This connection hints at bulge formation being extremely early. The correlation of inner disk and bulge colors (Balcells & Peletier 1994) hints an even larger proportion of the typical galaxy's mass formed early. We think the metal rich clusters also formed early. There are dissipative merger scenarios with starbursts that could do this, and also deliver gas to the nuclear regions reaching very high densities – with formation of a bulge, and perhaps a black hole, resulting from the merger or infall event. But constraints are now pushing that hypothetical merger back to a time so early that it must be considered part of the bulge formation process. We may yet hope that the ancient populations of the globular clusters (and bulge field stars) point toward a yet to be observed population of proto-massive galaxies at very high redshift.

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