THE STELLAR POPULATION OF THE GALACTIC BULGE

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ABSTRACT. The central kiloparsec of the Milky Way contains a distinct stellar population that resembles distant ellipticals and bulges. An abundance range from 1/10 to nearly 10 times the solar metal abundance produces evolved stars ranging from RR Lyraes to late M giants, OH/IR stars, and Miras. I describe the kinematics, structure, chemical evolution and possible age range of the galactic bulge. Infrared imaging of the M31 bulge reveals a population of luminous AGB stars that may have progenitors younger than 15 Gyr. It is important to measure the age of bulge populations relative to the old globular clusters, and to consider a range of formation scenarios.

1. Introduction

It is especially appropriate to discuss the galactic bulge at a meeting on stellar populations, since Baade's (1944) study of the bulge populations in M31 and the Galaxy helped to found the subject. Giants at a luminosity of $M_v = -3$ were discovered in the bulge of M31; shortly thereafter, Baade (1951) also discovered the RR Lyrae population in the galactic bulge, proving the bulge's existence. It was logical to unify the properties of spheroidal populations with the globular clusters: old, and metal poor. The impact of Baade's advance was such that descriptions of the Milky Way bulge as being old and metal poor persist to this day.

There were a few voices crying in the wilderness that, based on the strong Fe and Na lines in its integrated spectrum, the bulge must be more metal rich. Morgan had obtained spectra of the bulge's integrated light in the 1950's (Morgan & Osterbrock, 1969) and found it strong-lined, and comparable to that of the M31 bulge. Baum (1959) also noted that ellipticals were much redder than globular clusters and therefore could not contain the same stellar population.

Bulge fields are crowded and reddened, and the unresolved turnoff population creates a high background light that must be subtracted. Consequently, spectroscopy of large samples of bulge occurred only after large aperture telescopes and linear detectors were operating in the Southern Hemisphere.

Nassau & Blanco (1958) discovered the key stellar tracer of the bulge population, luminous late M giants. In the following landmark grism surveys using the CTIO 4 m (Blanco, 1988 and references therein) these stars were used to trace the structure of the bulge. In fact, the late M giants present in the bulge in such large numbers are not present in the globular clusters. In principle, one could now make a firm link between these stars, and the cool, luminous giants that Johnson's (1966) IR photometry concluded must be an important component of giant elliptical galaxies. In fact, the presence of M giants evolved from stars of high metallicity with RR Lyraes evolved from stars of low metallicity is *prima facie* evidence of the bulge's wide range in abundance. Arp's (1965) photometry, though hampered by severe crowding, also supported a wide abundance range.

The bulge has been most intensively studied along the minor axis. The region surrounding NGC 6522 ($b = -4°$) known as Baade's Window, has been specially targeted, but one can work over a wide region, even as close as $-2.5°$ from the nucleus (Baade, 1963). For $R_0 = 8$kpc, a field 8 degrees from the nucleus has an impact parameter of 1 kpc.

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Modern spectroscopy by Whitford & Rich (1983) and Rich (1988) confirms both the wide abundance range and the presence of some very metal rich stars. The initial picture of the old, metal poor bulge is now shown to be incorrect. The bulge may even have an age range as well. Continuing study of the bulge is inspired by the resemblance of its stellar population to that of unresolved bulges and ellipticals (Fig. 1)

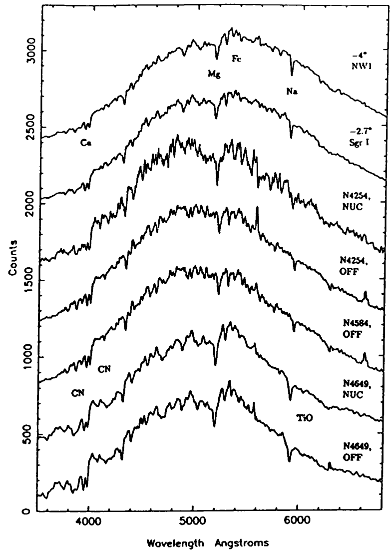

Fig. 1. Integrated spectra of patches of the galactic bulge near Baade's Window ($b = -4°$) and near Sgr I ($b = -2.6°$); these compared with the integrated spectra of other galaxies. Notice that the line strength does not change between the two latitudes in the inner bulge. $H\beta$ is strong in the bulge fields, but CN and the HK break are noticeably weak relative to the nuclei.

Following this section, we consider the age, abundance, kinematics, and structure of the bulge population. Looking beyond these dominant descriptive parameters, §3 considers the bulge's chemical and dynamical evolution as tracing its history of formation. We turn in §4 to the study of other bulge populations, and conclude in §5 by posing problems in the study of the bulge.

Recent reviews discussing the bulge population include that of Frogel (1988) and the proceedings of the first ESO/CTIO conference on Galactic Bulges, held in 1990. In 1992, IAU Symposium 153 will be devoted to the subject of galactic bulges.

2. Description of the Stellar Population

The wide range of abundance in bulge stars gives rise to a rich variety of evolved progeny, including late M giants, OH/IR stars, RR Lyrae stars, red and blue horizontal branch stars (Fig. 2). It is noteworthy that Ortolani (1990 and this meeting) finds a red horizontal branch clump in metal rich globular clusters such as NGC 6553. It is likely that UV-bright stars responsible for the far-UV rising flux in external galaxies are also present. The wide abundance range is the key factor responsible for the bulge's diversity. The bulge may contain an age spread as well, giving rise to the 800 day Miras and OH/IR stars (see §2.3 below). Blanco's surveys of giants in the bulge and Magellanic Clouds find that luminous carbon stars must comprise $< 10^{-3}$ of the bulge AGB stars, by far lower than the clouds or solar neighborhood. The lack of carbon stars is generally ascribed to the high metal abundance of the stars (see Rich, 1988 for other implications).

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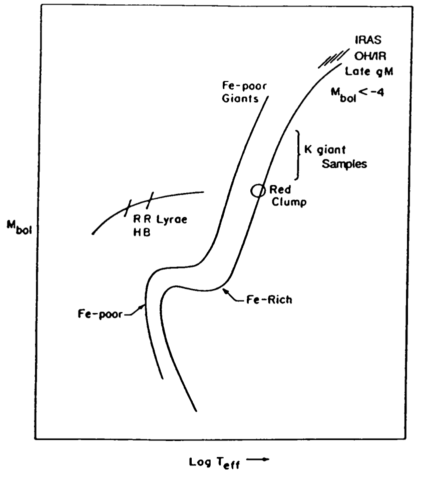

Fig. 2. The wide abundance range in the galactic bulge causes an unusual mix of evolved stars. The progenitors of the late M giants, Miras, OH/IR and IRAS stars are metal rich. On the other hand, the RR Lyraes and HB stars are evolved from the metal poor population (certain to be very old). The red "clump" giants are evolved from the metal rich population.

The disk globular cluster system is also found in the same volume as the bulge. By and large, these clusters are of solar abundance and lower (Armandroff, 1989); direct comparison of bulge field and cluster member spectra show that the bulge field is much more metal rich than the clusters.

2.1. ABUNDANCES

Ideally, one wants to measure the abundance distribution of long-lived stars, but this is not possible because the bulge turnoff is too faint for spectroscopy. Instead, we must search among the more luminous evolved stars for a population unbiased with respect to abundance. The K giants offer such a population. Virtually every star must evolve through the K giant phase; M giants have metal rich progenitors while the progenitors of RR Lyraes are metal poor. These other populations give good insight into the stellar evolution process, but are not suitable for the study of chemical evolution.

Modern digital spectroscopy shows that K giants in Baade's Window (500 pc from the nucleus) range in abundance from 1/10 to nearly 7 times the Solar abundance (Figure 3; Rich, 1988), with a mean of twice solar. Geisler & Friel (1990) employ CCD imaging and Washington photometry to confirm this result, and enlarged the original 88 K giant sample to a few hundred. In collaboration with A. McWilliam and R. Luck, I have begun to study bulge giants at high resolution.

One expects the RR Lyrae stars to be generally metal poor. Walker & Terndrup (1991) find that the Baade's window RR Lyrae stars peak in abundance at −1 dex; RR Lyraes of solar metallicity, commonly found in the solar neighborhood, are absent.

Turning to the M giants, it was long expected that the most luminous M giants would be extremely metal rich. Frogel & Whitford (1987) proposed that high metallicity might extend the lifetimes of turnoff stars, permitting massive progenitors to live long enough to be the source of the brightest M giants (Renzini & Greggio, 1990 calculate that a 15 Gyr old population could be as high as $1.1M_{\odot}$ at the turnoff).

Surprisingly, it has instead been found that even the most luminous M giants are not extremely metal rich (Sharples *et al.*, 1990; Terndrup *et al.*, 1991), with abundances of 2-3 times solar. It is of great importance to measure even crude abundances for the most metal rich late M giants; V.

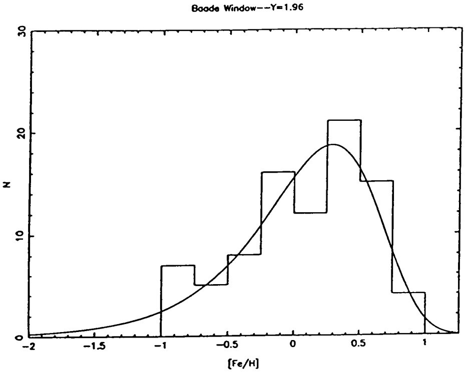

Fig. 3. Abundance distribution for 88 K giants in Baade's Window from Rich (1988). Theoretical curve represents the simple model of chemical evolution with $y = 2.0$ (see text). If the evolution were dominated by infall, there would be fewer metal poor stars. If wind outflow dominated the evolution, the theoretical curve would be the same but shifted to lower abundance. If the wind catastrophically terminated evolution, the metal rich end would be sharply cut off.

Smith is analyzing echelle spectra of a relatively clean continuum point in the M giant spectra near 7400Å.

If the bulge's abundance picture were not already complex enough, the planetary nebulae present a further contradictory picture. Ratag (1991) finds that bulge planetaries have normal (disk) N O, Ne, and Ar abundances, but are enhanced in He. These data appear to conflict with McWilliam & Rich's (1991) finding that the bulge giants are enhanced in alpha-capture elements.

In collaboration with N. Tyson I am investigating the abundance distribution and abundance gradient (first seen by van den Bergh 1971) in the galactic bulge. Figure 4 gives the preliminary result, that the bulge's abundance is constant within 1 kpc, declining quickly beyond that. It is not clear whether there is a gradient or population transition. Blanco (1988) finds a remarkable drop in the number count of M giants. Gradients are seen in the M giants using CO (Frogel *et al.* 1990) and in TiO (Terndrup *et al.* 1990). It will be of great interest to determine if Fe and and α-capture elements (Si,Mg, and Ca) show differing gradients in abundance.

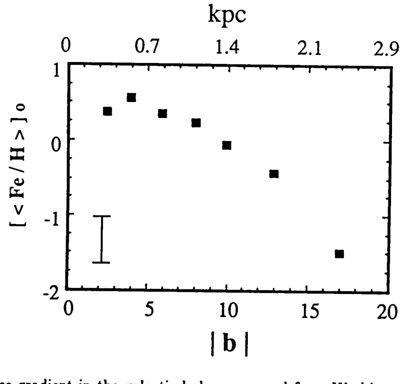

Fig. 4. Abundance gradient in the galactic bulge measured from Washington photometry of the giants (Tyson, 1991). The zero-point of the abundance scale has been set by requiring Baade's Window to have an abundance of $\langle[\mathrm{Fe/H}]\rangle = +0.3$, in agreement with Rich's (1988) spectroscopy.

The contradictory abundance picture derived from the evolved stars in the bulge is of sufficient concern that it will be worthwhile to measure abundances of the last unbiased stellar sample–the bulge main sequence.

2.2. KINEMATICS

The $10^{10}M_\odot$ of the bulge dominates the inner kpc, supporting the galactic rotation curve there (Bahcall *et al.* 1983). While less massive than the disk, the bulge is 5-10 times as massive as the stellar halo. Dramatic progress can be expected soon in defining the global kinematics of the bulge. It also appears that kinematics depend on metal abundance, though this question remains plagued by small number statistics. If we believe that Rich's (1988) K giant sample is representative of the bulge, then stars more metal rich than −0.5dex comprise more than 80% of the bulge's mass.

The metal rich stellar population of the bulge appears to rotate at about 100 km/sec. Efforts by Feast *et al.* (1990) find rotation of 10 km/sec/deg in late M giants and IRAS sources in the bulge; the OH/IR stars (te Lintel Hekkert 1990) and planetary nebulae (Kinman *et al.*, 1989) follow the general rotation field.

Like the halo, the bulge has a large radial velocity dispersion. Sharples *et al.* 1990 report radial velocities for over 300 of Blanco's M giants (in Baade's Window), finding a non-gaussian velocity distribution, but confirming Mould's (1983) dispersion of 113 km/sec. Rich (1990b) finds K giants in Baade's Window to have σ = 104km/sec, confirmed in the Sadler *et al.* (1992) 500 K giant sample. A key question is whether the 1/10 solar stars have a higher dispersion than the metal rich stars (as suggested by the small sample of Rich 1990b). Rich *et al.* (1992) finds that 33 bulge RR Lyraes have a dispersion of 127 km/sec, in agreement with the metal poor bulge K giants. Minnitti (these proceedings) also finds this effect, and further suggests that metal poor K giants have less rotation support. The bulge's velocity dispersion declines with increasing galactocentric distance (Tyson & Rich, 1991) and this can be used to show that the bulge has no missing mass (Kent *et al.* , 1991).

Recently, it has become possible to measure proper motions from plates obtained in the 1950s. Spaenhauer *et al.* (1991) find that the w velocity dispersion is 66 km/sec, compared with a radial velocity dispersion of 110 km/sec (as one might expect looking at the *COBE* image). They also find that low abundance stars have a larger w velocity dispersion, though this is only a 2σ result (the 500 K giant sample mentioned above consists of these proper motion stars and should clarify the issue).

Several recent lines of evidence suggest that the bulge may be a bar (see §2.4 below); measurement of bulge minor axis rotation may confirm or refute this idea. The possibility that the bulge may be a bar also bears on the interpretation of proper motion data, which frequently is analyzed under the assumption that velocities in the plane are isotropic.

2.3. AGE

The discovery of RR Lyrae stars shows that at least part of the bulge is very old; Lee (these proceedings) suggests that the bulge may be the oldest stellar population in the Galaxy. The situation is complicated by the presence of very luminous evolved stars.

Bolometric measurements of Blanco's latest bulge M giants reveal the extremely luminous termination of the bulge AGB, fully 1.5 mag brighter than the He core flash (Frogel & Whitford, 1982). Wood & Bessell (1983) derive large formal pulsation masses for bulge Miras, suggesting a progenitor population as young as 1-2 Gyr.

Presently, there is a clear conflict between Frogel *et al.*'s assertion that the distribution function of M_{bol} for bulge LPV's is identical to that of the globular cluster LPV's. If we take the Mira P-L relationship of Whitelock (1990) and the bulge IRAS Mira period distribution of Whitelock *et al.* 1990, we find that most bulge LPV's must be brighter than $M_{bol} = -5.0$, given that the majority of bulge LPV's exceed 400 days in period. The longest period Miras (770 days) must be as bright as $M_{bol} = -5.4$ (coincidentally, the brightest M31 bulge giants are also -5.4). Given that extinction and the bulge's spatial thickness potentially render the measurement of absolute magnitude of an individual star impossible, it becomes attractive to compare the period distributions of the bulge and cluster LPV's. In this case, the very long periods (high luminosities) of the bulge stars stand out.

Revision of the bulge distance to 8.1 kpc by Walker & Terndrup (1991) and others requires that the Frogel & Whitford (1987) bulge luminosity function of M giants from the Blanco grism surveys be brightened by 0.31 magnitudes. One is now placed in the uncomfortable position of explaining how old low mass stars can ascend to $M_{bol} = -4.7$, yet also exhibit vigorous mass loss (OH/IR and IRAS phases) that should terminate this evolution at fainter magnitudes. This mass loss is estimated by Whitelock (1990) to be as high as $10^{-4} M_{\odot} yr^{-1}$. Van der Veen (1989) proposes that low mass Miras evolve toward longer periods without increasing in luminosity: low mass stars could have long periods, but the P-L relationship would be invalid.

Direct application of Iben & Renzini's (1983) theory requires a $1.5 M_{\odot}$ progenitor mass for stars at $M_{bol} \approx -5$. Greggio & Renzini offer two explanations. First, the metallicities may be greatly enhanced, allowing massive stars to live 15 Gyr. As discussed in §2.1, the M giant abundances are not high enough to extend the lifetimes, and if $\Delta Y/\Delta Z > 0$, then we are almost forced to conclude that the progenitors must be younger than the globular clusters (Renzini & Greggio, 1990). Blue straggler progeny may be present, but probably cannot account for the rank and file 400 day bulge Mira that attains $M_{bol} = -5$.

We can look to the color-magnitude diagrams of bulge fields and easily conclude that the very young (1-2 Gyr) progenitors of Wood & Bessell (1983) are not present (Rich, 1985). If the modulus is now 14.57, however, the CMD's of Rich (1985) and Terndrup (1988) cannot rule out the presence of a substantial population of intermediate age stars; note that Terndrup's isochrones must be faded by 0.31 mag.

A further smoking gun is the lack of metal rich RR Lyrae stars in the bulge. These stars are found in large numbers in the much more metal poor solar neighborhood. Is the bulge too young to make RR Lyrae stars? One compromise is that the metal rich bulge is slightly yonger than the globular clusters.

We can collect the problems with age into a set of questions.

1. How can the bulge be older than the globular clusters, yet have an AGB that terminates at M_{bol} =-5 and contain Miras in excess of 700 days (along with very luminous OH/IR stars)? How can the AGB attain such high luminosities and have large mass loss, yet also be evolved from a 15 Gyr old population?
2. If the He abundance is normal (or likely enhanced, if $\Delta Y/\Delta Z > 0$), stars of high metallicity may have *decreased* lifetimes, if H is no longer the majority element. If the luminous M giants have only 2-3 times the solar metals, the lifetimes will not be so extended, anyway.
3. The IR colors of the bulge giant branch are similar to those of 47 Tuc, despite the high derived metal abundances for the stars.
4. Metal rich ([Fe/H] > -0.3) RR Lyraes comprise approximately 1/3 of the known RR Lyraes in the solar neighborhood (and are thought to be members of the thick disk). Why are they absent from the bulge?

2.4. Structure

If pictures are worth a thousand words, the recent image of the bulge obtained with the COBE satellite would qualify. Seen in the 1 μm light of K giants which trace the mass, the bulge is revealed to be a compact, peanut-shaped system contained within 1 kpc. Not surprisingly, Blanco (1988) finds the M giants dramatically concentrated to the plane, and the highest abundances are found within 1kpc as well. The flattened nature of the bulge is quantitatively illustrated by Kent's

(1991) measurement of a (350pc=2.5°) scale height at 2 μm . The M giant counts of Blanco and Terndrup (1989) also hint at a flattened, box-shaped structure (as does Harmon & Gilmore's (1989) image constructed from IRAS sources). One feature conclusively evident from the *COBE* map is that bulge is not smoothly connected to the $R^{-3.5}$ spheroid. Whitelock *et al.* (1990) use Mira luminosities from the P-L relation to show that the bulge is too deep in the line of sight to fit the $R^{-3.65}$ power law for M giants found by Blanco & Terndrup (1989). This conflict may be resolved if the bulge is in fact triaxial (or even a bar).

Recently, several lines of evidence independently support the idea that the bulge is in fact a bar, pointing toward $b > 0$ (Blitz & Spergel, 1991); Weinberg, 1991; Whitelock, 1991). At this meeting, Whitelock showed that the bulge Miras appear to be more numerous and closer at positive galactic latitudes; there is evidence that the bulge Miras have a wide spatial distribution as well. While the above authors concur on the issue of triaxiality, they suggest that there may be triaxial components in addition to the bulge (bar) that may be connected with the thick disk, and they are not all in agreement on the size and orientation of these additional components. The problem arises as to what an edge-on bar should look like. It has been suggested (Pfenniger & Norman, 1990) that peanut-shaped bulges might actually be edge-on bars.

A central bar may scatter bulge stars into the solar vicinity, thus providing an explanation for the enigmatic high velocity metal rich stars found in the solar neighborhood by Grenon (1989). Barbuy & Grenon (1990) report these stars to have high O abundances as would be expected for bulge members (Matteuci & Brocato, 1990).

Searches for minor axis rotation and quantitative analysis of the *COBE* data should resolve the question of the bulge's geometry.

Massive molecular clouds of CO reside near the nucleus (Bally *et al.* , 1988). Presumably, these clouds survive the hot gas ejected by Type I SNe, and are probably a source of the star formation known to occur in the nuclear region. They may be a source of secular acceleration, propelling stars into orbits above the plane on timescales of a few Gyr.

3. Chemical Evolution of the Bulge

The early history of the bulge's formation is written in the ages and abundances of its stars. The compact appearance of the bulge suggests that it may satisfy the requirements of the simple model of chemical evolution–no significant infall or outflow, effectively instantaneous reclycling, and have largely formed in a free-fall time. Indeed, Rich (1990a,b) finds that the abundance distribution is fit by the simple model with a yield of twice solar (See Figure 3). Tyson's (1991) survey using Washington Photometry finds that the bulge's mean abundance remains constant within 750 pc; perhaps the evolution of this volume closely satisfied the requirements of the simple model.

We can use the abundance distribution to determine if wind outflow affected the bulge's chemical evolution. In the strict simple model of chemical evolution, the abundance distribution is described by a single parameter, the yield. For the case in which gas is removed from the system by outflow, the abundance distribution can vary in two ways. If the outflow is steady, the yield is reduced and the abundance distribution shifts toward lower abundances. If the wind outflow occurrs suddenly (for example, when the thermal energy of the gas exceeds the binding energy of the galaxy) then the abundance distribution is truncated, and lacks the metal rich end (Searle & Zinn, 1978; Rich, 1990a). Using Washington photometry, N. Tyson and I are surveying 8 fields from 250 to 1500 pc on the minor axis. We hope to determine the abundance distribution function in each field and study its changes as one leaves the bulge. We expect to be able to determine if the gradient is really a transition to the halo, or is due to a wind outflow.

3.1. Chemical Abundance Profiles

If we can measure the ratios of Fe, O, r-process, and s-process elements, we may gain insight into the earliest era of the bulge's formation. Short-lived (10^6yr) massive star SNe produce O, α-capture, and r-process elements, but little Fe. Core deflagration SNe (likely linked to white dwarfs, hence a 10^8 yr lifetime) contribute most of the Fe. If we can measure the abundances of O, Fe, and Eu (an r-process element) in individual bulge giants, we can determine the timescale for enrichment. Barbuy (these proceedings) finds that O is enhanced in metal rich stars in the solar neighborhood. A. McWilliam and I have been measuring abundances in stars covering the full abundance range in the bulge. We have found that Mg, Si, and Eu are enhanced relative to Fe. The presence of strong Eu ($\lambda\lambda$6645Å lines in bulge giants with [Fe/H] = +0.5 indicates that massive star SNe remained important in the enrichment well above the solar abundance. The analysis of 4 bulge giants is given in Table 1; all are enhanced in Eu, Mg, and Si. We have not yet measured the O abundance; spectrum synthesis will be required.

TABLE 1. COMPOSITION OF BULGE GIANTS
A. McWilliam, R.M. Rich (1991)

	BW IV - 3	I - 141	I - 194	IV - 25
Fe/H	−1.13	−0.90	−0.16	+0.60
Ca/Fe	+0.30	+.42	+.13	+.14
Si/Fe	+0.23	+.52	+.47	+.25
Mg/Fe	+0.31	+.84	+.64	+.51
Na/Fe	+0.22	+.40	+.44	+.80
Al/Fe	+0.02	+.40	+.41	+.74
Zr/Fe	...	−.78	+.26	+.03
Y/Fe	+0.09	+.12	−.16	+0.10
Ba/Fe	−0.32	−.95	−.26	−0.74:
La/Fe	+0.41	+.33	+.10	+0.18
Eu/Fe	+0.83	+.74	+.63	+0.36

3.2 Formation of the Bulge (Bar?)

The chemical evolution and dynamical data provide support to two broad classes of formation scenarios. In the collapse and spin-up picture, the bulge forms in a free-fall time (the classic ELS picture). Violent star formation enriches the ISM, and gas dissipation causes the latest (most metal rich) stellar generations to be flattened and rotation supported. In this picture, it is difficult to see how the bar forms.

Alternatively, the bulge could have formed from in a violent starburst occurring in gas already in a massive disk near the nucleus (analagous to some luminous IRAS galaxies observed today). If the disk dominated the potential, it would be unstable to bar formation. Acceleration mechanisms of Pfenniger & Norman (1990) could heat the bar to produce today's observed thickness. It seems difficult to understand how the classic collapse and spin-up could produce a bar. If the bulge formed in a free-fall time (the canonical scenario) how was there also sufficient time to enrich Fe (presumably from Type I SNe) to the highest observed values? Was there enough time for the dissipational processes that would be required if successive metal rich populations were "spun up" relative to the first generation of metal poor stars?

4. Extension to Other Galaxies

To what extent does our bulge resemble ellipticals and distant bulges? Morgan & Osterbrock (1969) noted the strong-lined integrated spectrum of Baade's Window and compared it to that of distant galaxies. Whitford (1978) used an early spectrum scanner at the CTIO 1.5 m to quantitatively show that Mg, Na, and Fe were enhanced in the integrated light of Baade's Window as they are in distant galaxies. Figure 1 shows that the integrated light of the bulge has weaker metals than the giant ellipticals; note particularly the weakness of the blue CN bands (also seen by Rich (1988) in individual bulge stars).

In recent years, it has become possible to extend the study of bulge populations to M31 and M32. The most luminous bulge giants 750pc from the M31 nucleus are late M giants, just as has been found by Blanco in the Milky Way. Perhaps that is not surprising, given the long-known presence of TiO bands in galaxy spectra. Rich & Mould (1991) resolve the M31 bulge in the IR, 500 pc from the nucleus, and measure a giant branch extended to $M_{bol} = -5$ (Figure 5). Davies *et al.* (1991) suggest that the giants brighter than −4.75 are contamination from an inner disk population thought to resemble the LMC Bar West. Even using Kent's (1989) maximum disk model, they cannot account for the large number of bright giants in these fields. Further, their model succeeds only because they shift the original Frogel & Whitford (1987) luminosity function 0.31 magnitude brighter, due to a change in the adopted distance modulus. Their revised bulge luminosity function now extends to $M_{bol} = -4.75$, ***a full 1.1 magnitudes above the He core flash luminosity.*** Surprisingly, the elliptical companion M32 has a nearly identical population of luminous giants; Freedman (these proceedings) reports on a population of IR luminous giants even brighter than those in the M31 bulge. Freedman and I have begun to take spectra of these unusual stars in M32; we are interested to see if any are luminous carbon stars.

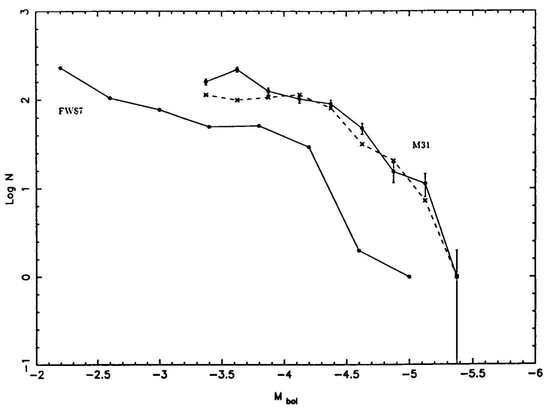

Fig. 5. Luminosity functions for the M31 bulge (Rich & Mould 1991) corrected for completeness and compared with Frogel & Whitford's (1987) luminosity function of Blanco's Baade Window M giants. The dashed line function is the result of applying bolometric corrections dependent on color; the solid line (a larger sample) employs $BC_K = 3.1$ for all stars. A color-magnitude diagram is published in Rich & Mould 1991; a similar J, K CMD for a field in M32 may be found in Freedman's paper in these proceedings.

Of course, disk contamination and blue straggler progeny (Greggio & Renzini, 1990) may be sufficient to explain the extended giant branches. Further, the extended giant branches consist largely of variable stars observed at one epoch, and the luminous tip may be enhanced with giants at maximum light. It is interesting that the observed termination of the M31 AGB at −5.4 is consistent with the bolometric luminosities of the Milky Way bulge's 770 day Miras. If these stars are the relics of intermediate age and young populations, how did it come to be that the bulges of the Galaxy, M31, and M32 come to have the same extended star formation histories? In order to address these questions in depth, Mould, Graham and myself are surveying the M31 bulge in the IR.

It is important to recall that the disk population in photometrically deconvolved disk/spheroid models extends to the very nucleus. If this is indeed an intermediate age stellar population, like the LMC bar, then we must wonder how this population formed deep within the bulge's potential well, and whether some bulges might be closely related to these inner disks, as Kormendy (1991) has suggested.

5. Challenges for Future Bulge Research

The foregoing is an attempt to describe our present state of knowledge in the study of the galactic bulge. The following questions and comments illustrate where we may deepen our understanding.

1. Could the bulge have a complex star formation history, like the Magellanic Clouds or the Carina Dwarf? Specifically, could the metal rich bulge have formed in a burst taking place after the formation of the globular clusters?
2. Luminous IR galaxies are observed with $\approx 10^{10} M_{\odot}$ of molecular gas in their centers. Could such gas experience a starburst and later form a bulge?
3. Is the galactic bulge actually a bar? If so, how does it connect to the nucleus and to the halo?
4. Are there genuine kinematic differences as a function of abundance? Do these represent different populations (bar vs. halo), or the evolutionary history of the galactic bulge?
5. Are secular accelaration mechanisms important in producing the bulge's present structure, especially spatial thickness?
6. Given that the bulge has spatial thickness and a range in abundance, can one hope to derive the age range from turnoff photometry?
7. What is the connection between the bulge and the central molecular gas and activity?

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Question & Answer Section

Freedman: I wanted to comment (and I will discuss this in more detail in my talk tomorrow) that there is a population of luminous stars in M32 that are more luminous than $M_{bol} = -4.2$ and unlike for the bulge of M31, cannot be explained by M31 disk contamination.

Rich: Mould and I proposed disk contamination as one possible explanation for the most luminous M31 bulge stars. Frogel's model depends on use of the Frogel & Whitford (1987) luminosity function *shifted 0.3 mag brighter* due to his new adopted distance modulus. FW87's old luminosity function dropped at -4.2 and now that drop occurs at -4.5. If we can make such a large (0.3) magnitude change in the luminosity of the AGB termination point and not affect conclusions about the age, then we might just as well not bother to continue these observations.

Te Lintel Hekkert: The OH/IR stars in the bulge are not extreme in terms of luminosity and periods (and thus mass). They lie well within the ranges for the Mira variables from Whitelock *et al.*

Rich: Using a new distance modulus of 14.5 kpc, we have good agreement between the luminosities of the longest period Miras (800 days), the AGB tip, and the OH/IR stars. I think we must now ask whether even the 400 day Miras would be extreme progeny for a 15 Gyr old population.

Pagel: A comment on helium: if a substantial amount of He comes from intermediate-mass stars,

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there could be an analog of the O/Fe effect in the sense of there being less helium in old populations even if metal-rich.

Suntzeff: I believe that there is no obvious problems with the lack of metal rich RR Lyraes in the bulge. Assuming the galactic globular clusters are good templates for the formation of RR Lyraes we (Suntzeff *et al.* 1991) showed that the rate of the probablility of formation of metal-rich to metal-poor RR Lyraes is 1:50. Thus, the lack of metal rich RR Lyraes may not be very surprising unless there is a large old metal rich population.

Rich: More than 80% of the K giants in Baade's Window exceed -0.5 dex in abundance. The bulge is far more metal rich than the solar neighborhood, yet in the solar vicinity, approximately 1 out of 3 RR Lyraes are metal rich. I think we will attain the deepest understanding by stressing the bulge/solar vicinity comparison.

Frogel: 1. It doesn't matter if a luminosity function with C stars is used as a representative intermediate-age population since the fraction of C stars depends on [Fe/H]. Change [Fe/H] and C stars turn into M stars without changing the luminosity function substantially. 2. There may well abe a small fraction of the bulge that is relatively young but the fact that the L.F. of the LPVs in the bulge is identical to that for globular clusters means that based on LPVs, most of the bulge population must have an age similar to that of the metal rich globulars. 3. While we have shown that (J-K) appears to be a good termperature indicator for non-variable M giants, I would hesitate to use this color for LPVs for which blanketing problems are very severe.

Rich: (1) The maximum luminosity attainable by an AGB star depends on how mass loss terminates the AGB. I do not think we understand the final stages of C and M star AGB evolution sufficiently to assert that AGB termination point is not a function of metallicity, as well as age. (2) I think you will be hard pressed to show me examples of 600 day Miras in Globular Clusters.

Faber: How does the luminosity function change as a function of latitude?

Frogel: My IR photometry of Blanco's optically selected M giants finds no variation in the luminosity function with latitude, even beyond 1 kpc. In M31, I find a larger number of stars with $M_{bol} < -4.75$ at greater distances from the nucleus; I attribute these stars to contamination by a disk population similar to the LMC Bar West.

Renzini: Has Whitelock actually determined luminosities for the individual bulge Miras?

Whitelock: The longest period Miras in our bulge sample are around 700 days but there are only a few this long and they can plausibly be explained as binary mergers as you (Renzini) had suggested. The ongest period single stars are around 600 days and will have luminosities about $M_{bol} = -5$ fromt he PL relations. We have no easy way of determining absolute luminosities of individual stars because of the large line of sight depth of the bulge.

Mateo: 1. Exactly what are the pulsation masses Wood & Bessell (1983) derive for the 500-day Miras? 2. Assuming the answer is about 2 $M_\odot$and your claim that there is certainly no 1-2 Gyr population in the bulge, then whey are these pulsation masses so large?

Whitelock (responding to Mateo): The effective temperatures of the Miras are really very difficult to measure, but with plausible values the pulsation masses of the longest period objects in the bulge are in the range 1.0-1.5 $M_\odot$. It is of course the initial masses that are important and these may be significantly larger than the pulsation masses if the star has experienced much mass loss.