CHARACTERISTICS AND SPACE DISTRIBUTION OF STARS IN THE BULGE OF THE MILKY WAY

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ABSTRACT. Stars in Baade's Window at b = –4° are described. They are old, metal rich, and have a velocity dispersion greater than 100 km/sec. Their colors are unlike those of any other group of stars. Stars in other windows between b = –3 and –12° differ systematically from those in Baade's Window. The differences are best understood if they are caused by a metallicity gradient in the bulge. The distribution of surface brightness or surface density over the bulge has a much steeper falloff than that seen in other galaxies or in the very center of the Milky Way itself. It is now possible to link together stars in the immediate vicinity of the nucleus with those that are several hundred parsecs out. Understanding this linkage will help in understanding the history and evolution of stars throughout the bulge and that part of the inner disk with which it overlaps.

1. Introduction

A simple view of the stellar content of the Galaxy is that it consists of two components: a spheroid with old and metal poor Population II objects and a disk with younger Population I objects whose metallicities are close to or greater than the solar value. In addition to age and chemical composition, these two populations also have markedly different kinematics. These three parameters - age, chemical composition, and kinematics - are Sandage's (1986) "three dominant parameters in the population concept."

For a long time the Galactic bulge was thought to be merely the inner part of the spheroid and to consist primarily, or even entirely, of Population II stars. While it is arguable whether or not the bulge is part of the spheroid, there can no longer be any doubt that the stars in the bulge are primarily *not* Population II (reviewed in Frogel 1988). Nor do they fit the common conception of Population I since although their mean metallicity is comparable to or greater than solar (Whitford and Rich 1983; Rich 1988), the bulge stars have an age comparable to that of some globular clusters (Rich 1985; Whitford 1986, Terndrup 1988). Neither do they have the kinematics expected of a Population I disk system (cf. Rich 1986). The systems they most closely resemble are the central regions of moderate luminosity E and S0 galaxies (cf. Whitford 1978).

At this conference we have heard a number of speakers address the question of the nature of the stars within the central few parsecs of the galaxy. To further our understanding of the formation and evolution of the whole Galaxy it is necessary to determine how the distribution function for the three key stellar parameters - age, chemical composition, and kinematics - varies with position in the bulge. It is particularly important to measure these quantities for stars at galactic latitudes ≤ |3°|, i.e. inward of the innermost region where optical studies are still possible.

M. Morris (ed.), The Center of the Galaxy, 55–62.

Such an undertaking should also reveal clues as to the connection between the nucleus and the rest of the Galaxy. With the advent of two-dimensional infrared array detectors for imaging and spectroscopy, it has now become possible to make the needed observations.

In this paper I will briefly review what is known about the age, chemical composition, kinematics, and space distribution of the bulge stars. More detailed review articles have recently appeared, *e.g.*, Whitford (1986) and Frogel (1988).

2. Characteristics of Bulge Stars - Baade's Window

The most thoroughly studied part of the bulge (outside of the nuclear region itself) is Baade's Window at b = –3.9° centered approximately on the globular cluster NGC 6522 (Baade 1963). Recent spectroscopic and photometric investigations have revealed how different the stars in Baade's Window are from ones anywhere else in the Galaxy. In this section I will review the facts that have been established regarding these stars. In the next section I will discuss how the physical characteristics that define the Baade's Window stars differ as a function of latitude in the bulge.

2.1 Metallicity

Spectroscopic analysis of samples of K giants in Baade's Window has revealed a range in metallicity, [Fe/H], between –1 and +1 with a mean value of +0.3, twice the solar value (Whitford and Rich 1983; Rich 1988). The fact that a majority of K giants have solar or greater metallicity provides a natural explanation for the unusually large numbers of late M giants found in Baade's Window and elsewhere in the bulge (Nassau and Blanco 1958; Blanco, McCarthy, and Blanco 1984). The reason being twofold: a high [Fe/H] shifts the Hayashi tracks for giants into a very cool domain and, second, the Mould–McElroy (1978) effect results in the enhancement of absorption bands used for spectral classification via an enhanced abundance rather than a reduced temperature. Qualitative confirmation of such a high metallicity comes from observations of absorption bands of TiO and CO in the bulge M giants and from infrared colors and magnitudes of the same stars (Frogel and Whitford 1987; Cook 1987; Terndrup, Frogel, and Whitford 1988). On the theoretical side, models by Arimoto and Yoshii (1987) for star formation and enrichment in elliptical galaxies have successfully reproduced such a metallicity distribution with a single generation of old stars.

2.2 Age

The best age estimate for stars in the bulge comes from the optical color-magnitude study by Terndrup (1988). From the position of the main sequence turnoff he derives a mean stellar age of 11-14 Gyr. Furthermore, he finds the turnoff to be too red to permit a detectable population of stars with an age ≤ 5 Gyr (see also Rich 1985). The sizes of the uncertainties in fitting isochrones to the observations are such that a short "single burst" model for star formation in the bulge is possible (cf. Arimoto and Yoshii 1987). Terndrup's age estimate is consistent with the most recent age of 47 Tucanae, 13.5 ± 2 Gyr by Hesser, *et al.* (1987). The implication, then, is that the disk system of globular clusters (Zinn 1985; Armandroff 1988) and the galactic bulge are coeval. The infrared c-m diagram of bulge giants (Frogel and Whitford 1987), in particular the luminosity function of the AGB stars including the long period variables, is consistent with an old age as well. It is the high metallicity that provides fuel for the ascent of the bulge stars up the AGB. Another consistency argument for the old age of the bulge stars comes from the upper limit of ~$0.3M_{\odot}$ to the masses of planetary nebulae in the bulge (Kinman, Feast, and Lasker 1988). This implies a lower limit of 5 Gyr for the ages of their progenitors. What we have in the bulge then, is the oldest population of metal rich stars known in the galaxy.

2.3 Colors

The optical and infrared colors of Baade's Window stars set them apart from all other stellar groups in the Galaxy. Some of these colors are indicative of a greater than solar metallicity for the stars, *e.g.* the *J-H, H-K* relation and the main sequence turnoff in an optical c-m diagram. Other colors, both optical and infrared of the K and M giants, are so blue as to be inconsistent with the age and metallicity estimates discussed above. Three possible explanations for these blue colors invoke blanketing effects arising from the high metallicity (Frogel and Whitford 1987), the mode of energy transport in the stellar interior, and the effects of non-solar ratios for the heavy elements (Terndrup 1988). In any case, the unique colors of the bulge stars could serve as a valuable diagnostic in separating out such a population from more solar like stars that may also exist in the central region of the galaxy; for example members of the inner disk.

2.4 Kinematics

The radial velocity dispersion of a group of stars is generally a good indicator of age - young stars have small dispersions while old ones, including globular clusters, have large dispersions. Since for the galactic disk and spheroid there is a well defined inverse correlation of age with metallicity, large velocity dispersions are also associated with metal poor stars whereas small dispersions are characteristic of metal rich stars. The first measurement of the velocity dispersion of the late M giants in Baade's Window was made by Mould (1983) who found a value of 113 ± 11 km/sec, comparable to or higher than values found for RR Lyrae variables and planetary nebulae in the bulge. It is also considerably higher than the 59 ± 14 km/sec for the line of sight radial velocity dispersion found by Armandroff for disk globular clusters. Rich's analysis of the radial velocities of his sample of K giants in Baade's Window yielded a mean value in agreement with Mould's for the M stars and failed to reveal any significant dependence on their metallicity. Most recently Freeman, *et al.* (1988) measured the radial velocity of the integrated light from the bulge and found a value in excellent agreement with those of Mould and Rich.

Hence, the kinematics of the bulge stars appears to reflect their age rather than metallicity and points to a pressure supported system rather than a rotationally supported one. Freeman (1986, 1987), though, has argued that under certain circumstances an exponential disk could give a high velocity dispersion in the plane of the disk. A proper motion study would be required to distinguish between pressure and rotational support (cf. Frogel 1988). In any case, the velocity dispersion and its dependence on radius (see below) must be reconciled with formation theories for the bulge and the galactic nucleus.

3. Dependence of Characteristics on Radius

3.1 Metallicity Gradient and Other Observables

Optical and infrared photometry and spectroscopy of the inner one and a half kiloparsecs of the Galactic bulge show a strong metallicity gradient. The best quantitative estimate for its value comes from Terndrup's (1988) analysis of c-m diagrams for 4 fields between b = –3.9° and –10°. He finds the mean metallicity of the bulge population declines by ~0.5 dex over this distance. Other evidence for a metallicity gradient comes from: the steep decrease in the relative number of the latest M giants compared to all M giants (Blanco 1988); a decrease in the mean strength of the CO and TiO absorption bands observed in the M giants; and the steady progression of the locus occupied by the giants in a *J-H, H-K* diagram (Frogel, Terndrup and Whitford 1988; Terndrup, Frogel, and Whitford 1988). An analysis of Whitelock, *et al.*'s (1986) and Glass' (1986) observations of bulge IRAS sources indicates that sources further from the center have, in the mean, thinner and hotter dust shells than sources close to the center (Frogel 1988). This, too, is consistent with a metallicity gradient. Finally there is evidence that the metallicity gradient may continue out to distances of 3 to 5 kpc (Rodgers *et al.* 1986) or, perhaps, levels off to a mean metallicity characteristic of the metal rich globular clusters (Bahcall *et al.* 1983).

In contrast to the bulge, Lewis and Freeman (1988) find no metallicity gradient amongst stars of the old galactic disk ($\tau \geq 1$ Gyr) for R between 1 and 15 kpc. Furthermore, while nearly half of the sample of Baade's Window K giants have metallicities greater than solar with a range of nearly two dex (Whitford and Rich 1983; Rich 1988), the innermost bin of the Lewis and Freeman sample has an $<[Fe/H]> \approx -0.35$ with a range of only ± 0.3. These results could indicate a demarcation in the range and spatial distribution of metal abundances between the bulge and the old disk.

A set of objects that may also be a part of the old disk - the metal rich globular clusters - do show some evidence for a radial metallicity gradient. These clusters may be as much as a factor of 10 older than the stars in the sample of Lewis and Freeman (1988) and have a considerably greater scale height, about 1100 pc (Armandroff 1988). This scale height for the disk globular clusters, their kinematic properties, and their range in metallicity are, as Armandroff points out, all close to values for these quantities determined for stars in the Galactic thick disk. It is still an open question, though, what the relative ages are of the thick disk stars and the disk globular clusters.

The question then is what happens as you go inward from Baade's Window. Is the population in the inner few hundred parsecs dominated by the bulge, the disk (thick or thin), a combination, or something else? What is the relation of the luminous stars found by Lebofsky and Rieke (1987) within the central one degree to the rest of the bulge? At this conference R. M. Catchpole has reported on an extensive survey of the inner 2° of the galaxy based on the images made by Glass, Catchpole, and Whitelock (1987). He finds that the stellar luminosity function varies with latitude in the sense that there are more bright stars closer to the center. Do the types of stars found in the bulge windows studied by my colleagues and myself make up part of this inner luminosity function?

3.2 Velocity Dispersions

The velocity dispersion found by Rieke and Rieke (1988) from observations of individual bright giants within 6.5 pc of the Galactic center is ~75 km/sec, independent of distance. McGinn *et al.*

(1988 and this conference) find a similar mean value from measurements of the velocity dispersion of the background 2.2 μm light but also find clear evidence for a radial gradient over the central 10 pc. These values for the galactic center region are substantially less than the 100 - 120 km/sec dispersion for stars in Baade's Window 500 pc above the center. With the advent of infrared spectrometers having array detectors it would be a worthwhile undertaking to determine the run of velocity dispersion from the center outwards.

McGinn *et al.* (1988) note that the velocity dispersion within the inner 10 parsecs is everywhere greater than their measured rotational velocity. This would imply bulge-like kinematics with the stars supported by heating rather than rotation. Again the variation of this quantity with distance out to Baade's Window would be good to know. Kinman *et al.* (1988) have looked at the kinematics of planetary nebulae in the Galactic bulge. They find a velocity dispersion (after removing a rotational component) for 147 planetaries with $|\Delta l| < 10°$ of 103 km/sec, essentially identical to Rich's (1986) value for K giants. Their results also show that velocity dispersion dominates rotation indicating that the planetaries are part of the bulge population rather than the disk.

There are a number of programs in progress whose results will give considerably more information on the structure and kinematics of the bulge. V. M. Blanco and D. M. Terndrup are extending the M star surveys of Blanco (1988) in order to get the rotation and shape of the bulge. A. E. Whitford is working on proper motion surveys to investigate the separation between bulge and disk stars.

3.3 Distribution of Matter and Comparison With Other Galaxies

In his review article Bahcall (1986) suggests that the next step to be taken in generalizing the galactic model that he and his collaborators have built is to include a bulge. By bulge he means the spheroidal distribution of stars within the central kiloparsec of the galaxy. As a first estimate of the density distribution in the bulge he takes that determined by Oort (1977) from the data of Becklin and Neugebauer (1968) for the inner 20 pc. This is $\rho \propto r^{-1.8}$ or a surface brightness $\propto r^{-0.8}$. The mass within a kiloparsec is 10^{10} $M_\odot$. Other authors have derived the same value for the exponent from new data, *e.g.* Rieke and Lebofsky (1987) and several of the papers presented at this meeting. Nearly all of these determinations, however, are based on observations of only the central few arc minutes of the galaxy.

Optical and infrared data at galactic latitudes between –4 and –12° *show a power law dependence of surface brightness (or surface density) on radius with an exponent 3 to 4 times greater than that based on observations in the Galactic center by itself.* This result is based on a number of independent determinations including counts of M giants (Blanco 1988), counts of K giants and the integrated surface brightness at *V* and *I* measured from CCD frames (Terndrup 1988), IRAS source counts, LPV counts, and the *K* surface brightness determined from both the ground and balloon data (Frogel 1988, Frogel, *et al.* 1988; but see paper presented by G. Rieke at this conference). *All* indicators of the mass distribution between 0.4 and 1.5 kpc from the center show the bulge population to be far more concentrated than would be deduced from either data in the center itself or from the Bahcall and Soneira (B&S) standard model for the galaxy. In fact, extrapolation of the B&S spheroidal component into Baade's Window predicts only about 25% of the number of giants actually observed (Terndrup 1988). This illustrates the need for a bulge component in the B&S models. However, it is clear that to base the density distribution of such a component on observations of *only* the central region may not be correct. Terndrup (1988) discusses some possible models for the spheroid, one of which does not require the bulge to be a separate component, but just to be the metal rich inner spheroid. Such a model would be quite different from Zinn's (1985) division of galactic globular clusters into two distinct populations differentiated by their metallicities, spatial distributions, and kinematics.

Between 0.4 and 1.5 kpc from the Galactic center all measures of surface brightness and surface density falloff like r^{-n}, with values of n between 2.5 and 3.5. How does this compare with what is seen in other galaxies? For a preliminary examination of this question, I have considered 22 Sb, Sbc, and Sc spirals with surface photometry by Kent (1986, 1987). For Galactic bulge fields between b = –3° and –12° the integrated *K* surface brightness falls by 3.6 magnitudes (Frogel, *et al.* 1988). This is consistent with the decline extrapolated from the optical data of Terndrup (1988) and is the same as would be obtained from the M star counts of Blanco (1988). Ignoring differences in size between the Milky Way and the galaxies in Kent's samples, if we ask how much does the surface brightness falloff along the minor axes of his 22 galaxies in the same equivalent radial distance (scaled by the distances to the galaxies as given by Kent) we find a mean falloff of 1.65 mags with a dispersion of ±0.6. Only 3 galaxies of the 22 have falloffs as great as 2.5 mags. There does not appear to be any difference between nearby and distant galaxies in Kent's two samples. Nor is there any correlation of falloff with observed disk ellipticity as might be expected if the disk were flattening out the bulge contribution. It is possible that internal reddening causes a flattening of the surface brightness. Observations of a sample of galaxies in the infrared will be able to evaluate the effects of reddening on the distribution of optical surface brightness. One well studied galaxy with a very steep light falloff along the minor axis is NGC 4565. Van der Kruit and Searle (1981; they refer to earlier studies of this galaxy that are in good agreement with theirs) find the visual surface brightness to be proportional to radial distance along the minor axis of NGC 4565 to the -3.3 power, comparable to that seen for the M giants and the K light in the bulge of our Galaxy. In any case, the contrast between our Galaxy and most other spirals is striking and demands some explanation.

4. Desiderata

Many of the processes observed in and around the Galactic center are unique to that region and are probably the result of relatively recent events that have taken place there. Participants at this conference seem to consider an age of 10^8 years as appropriate for the current cycle of events in the Galactic center. Most of the work I have reviewed, on the other hand, concerns objects with ages 10 to 100 times greater than this. However, there is no escaping history. The formation, collapse, and enrichment of the Galactic bulge (spheroid?) set the stage for what is seen today in the nucleus. In a previous review (Frogel 1988) I emphasized the need to understand how the bulge relates to the larger spheroid and the disk. Here the emphasis shifts to clarifying the relation between the bulge exterior to 0.4 to 0.5 kpc, the innermost part that can still profitably be studied with optical as well as infrared techniques, and the central part of the galaxy. The advent of infrared array detectors gives us the ability to carry out efficient, systematic studies of this inner region for the first time.

- Metallicity cannot just keep increasing with decreasing radius. Where does it flatten off and to what value? Is the flattening off a result of self-limiting enrichment or of mixing of stellar orbits that smoothed out an established gradient?

- Do metallicity and kinematics still distinguish between a disk and a bulge population in the inner few hundred parsecs?

- If an episode of star formation took place within the last 10^8 years over a region that might be as extensive as the central couple of degrees of the Galaxy, what triggered it? What effect would many such episodes have on the characteristics of the stars observed in the bulge windows?

I have had many insightful conversations with my collaborators on bulge research Drs. V. M. Blanco, D. M. Terndrup, and A. E. Whitford. Terndrup reminded me of the van der Kruit and Searle work on NGC 4565.

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