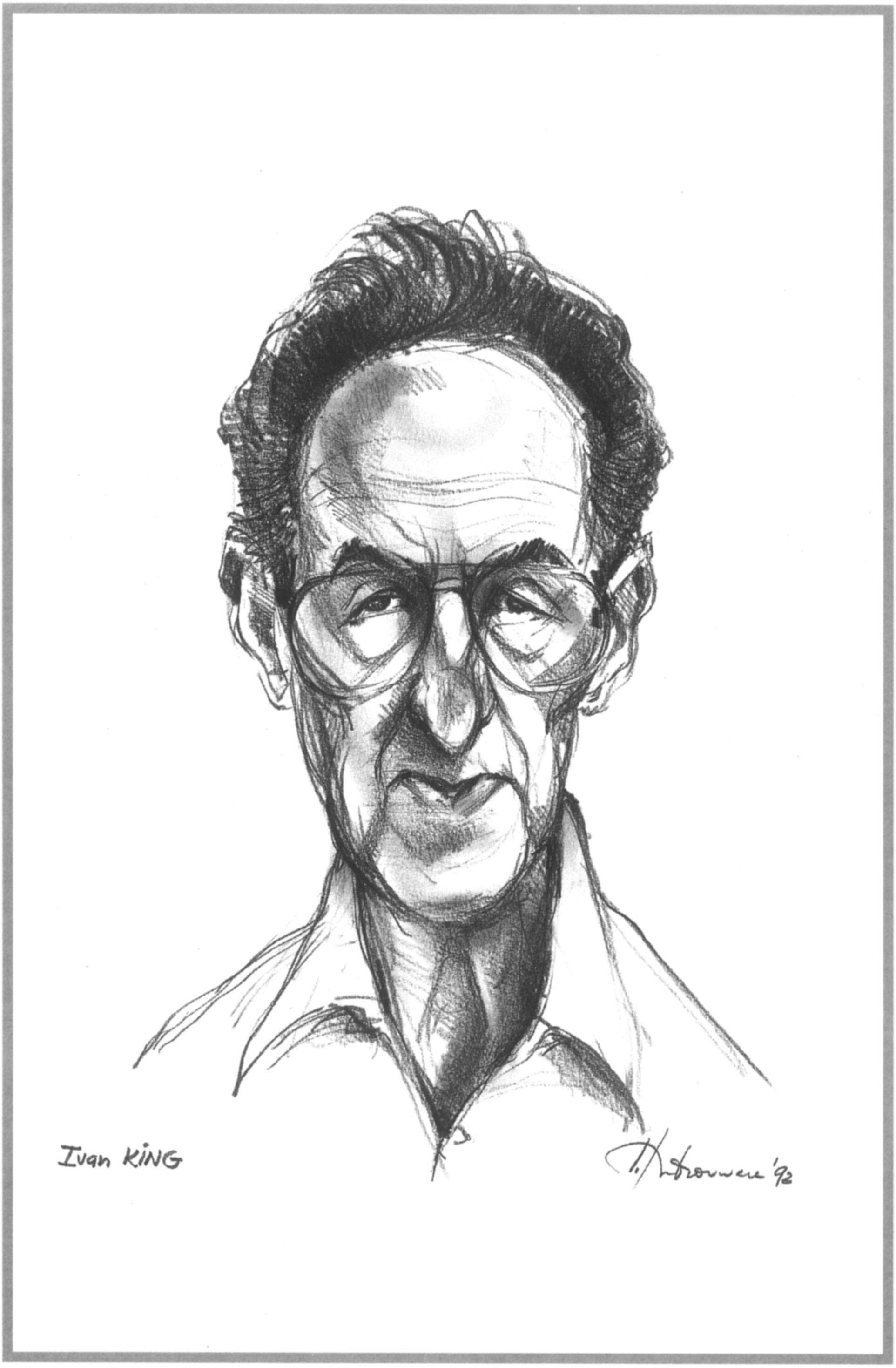
INVITED

REVIEWS


Ivan KING

REVIEW OF THE GALACTIC BULGE

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For sins that I have been unable to identify, I have been asked to give a review talk on the Galactic bulge. This is a subject to which I have not been very close in recent years, so that I have been able to approach it with a fairly open mind, though I must acknowledge a lot of generous help from Mike Rich, Don Terndrup, and Jay Frogel. But any errors, and especially any prejudices, are purely my own. And in my reading I have undoubtedly missed some important papers, but I hope that their authors will forgive me.

This is a field in which the activity has accelerated in recent years, and I think that it is completely appropriate to have another symposium on the subject only 2 1/2 years after the Workshop in La Serena. I am struck that nearly all the papers that I have read in preparing this summary are dated 1989 or later. In fact I rather suspect—and hope—that the subject will look rather different five days from now, after all the material that is presented at this meeting.

1. Historical Background

I have always thought that any subject that involves stellar populations profits from a historical approach, or at least from a historical introduction. People had seen bulges in the middle of galaxies for a long time, but the study of bulges really begins with the detection of red giants at the edge of the M31 bulge by Baade, nearly half a century ago (Baade 1944). This was of course the famous paper in which he invented the concept of stellar populations. Since he saw globular-cluster-like red giants in Andromeda, Baade identified the center of Andromeda with what he called Population II. A few years later he found the RR Lyrae stars in the region that is now known fondly as Baade's Window, and the identification with his Population II became even tighter. But we know now that it was wrong, and that the dominant population, both in the M31 bulge and in Baade's Window, is an old metal-rich population.

I would like to use this as an example of why, after nearly fifty years of further development, we ought to give up completely the use of the terms "Population I" and "Population II." Those terms conjure up all the errors of the past. We should be describing populations as old or young, and metal-rich or metal-poor, not with the simplistic numbers I and II. (There, I promised you some prejudice, didn't I?) The detailed facts, of course, are even worse. We are going to hear talk at this meeting of oxygen-to-iron ratios, nitrogen enhancement, a continuum of ages, and all sorts of things, until the jungle of populations becomes quite impenetrable. Mind you, I am not suggesting that we recite an entire pedigree every time we refer to a population; at our present stage of knowledge, age and metallicity seem to me adequate labels. But my basic point is that population labels should be descriptive, not just a pair of oversimplified pigeonholes labeled I and II.

H. Dejonghe and H. J. Habing (eds.), Galactic Bulges, 3–20.

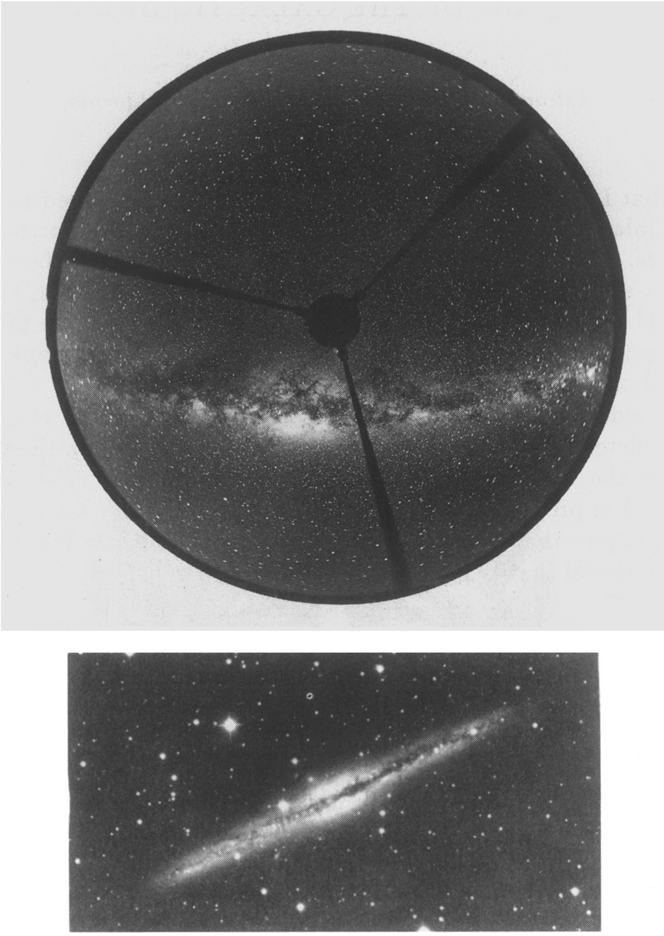

Fig. 1. The Galactic bulge seen in the near infrared with a "fisheye" camera, compared with the edge-on galaxy NGC 891.

But back to bulges, more specifically. The populations of bulges got straightened out much better in the 1950's. First Baum and Schwarzschild (1955) showed that the bulge of Andromeda had far too high a surface brightness for its paltry sprinkling of red giants. The light had to be coming from some other component. Then the situation became a lot clearer during that wonderful summer that Bill Morgan spent going through Nick Mayall's spectra at Lick Observatory. The spectra of bulges turned out to be like those of solar-type stars (Morgan and Mayall 1957). (And, by the way, during this same orgy of classification Morgan [1956] discovered the strong-lined globular clusters.) And after that it went even farther: by the mid-1960's Spinrad (1966; also Spinrad and Taylor 1967) was talking about super-metal-rich bulges. And that gets us onto the modern track.

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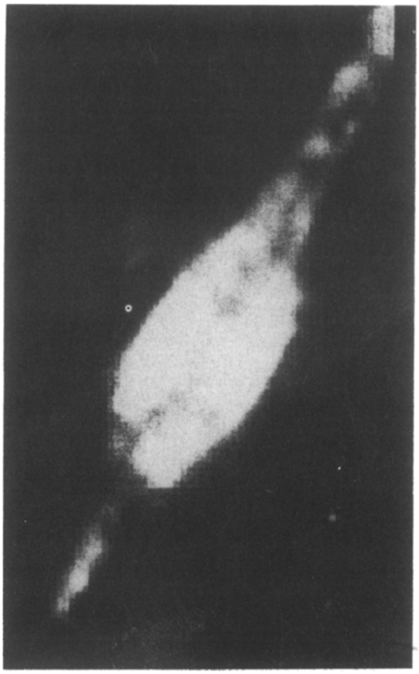

Fig. 2. The Galactic bulge as seen in the 1–4 μ region with the DIRBE camera of the COBE satellite.

It is easy to observe the bulges of other galaxies, but our own bulge is much more obscure. (That was an intentional pun.) As you all know, there are 30 magnitudes of visual absorption between us and the Galactic center, and one has to go to fairly long wavelengths to see through it. But fortunately our bulge *does* bulge out; and a little bit off the plane, shorter wavelengths penetrate. The bulge was first detected by Stebbins and Whitford (1947), at a wavelength of 1 micron. (I am happy to note that 45 years later Albert Whitford is still working actively on the bulge, and is present at this meeting.) A few years later the Henyey–Greenstein camera was able to photograph the edges of the bulge on infrared film. What I will show you instead (Fig. 1) is a more modern picture, made by the University of Bochum camera; the comparison galaxy is NGC 891. Here we can see the bulge peering out on both sides of the obscuring matter, but notice how much less obscured it is on the southern side, where our "windows" are.

Finally, in the modern era we have spacecraft. The COBE DIRBE map (Fig. 2) is probably the best delineation of the red giant stars of the bulge that we have.

At longer wavelengths, IRAS is very informative. The IRAS survey map, in which all the bands are color-coded and mixed, does not show the bulge; but the situation changes completely if we single out the IRAS point sources, as shown in the 12-micron map (Fig. 3). These are dominated by stars with circumstellar

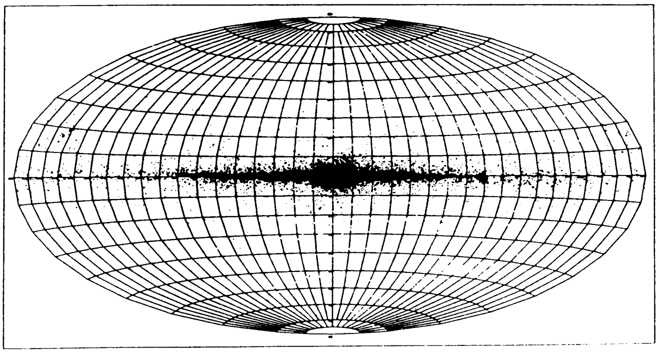

Fig. 3. The IRAS point-source map, which in the bulge is dominated by emission from the dust shells surrounding OH/IR stars.

dust shells—principally the OH/IR stars—and we see the bulge quite clearly. But I will not emphasize this map now, because the stars that it shows belong to a later discussion of the populations in the bulge.

The COBE map (Fig. 2) shows the potential of the near infrared for penetrating the absorption between us and the Galactic center. Fortunately this is not a venture that has to be done completely from space. We have a good ground-based window at 2 microns that has already produced useful information. But now this so-called K band has been revolutionized by the appearance of array detectors. Figure 4 (Gatley *et al.* 1989) is a K-band montage of rather less than a square degree around the Galactic center, which I imagine is the bright spot in the lower middle. You can see by the patchiness that absorption troubles have by no means disappeared, but my uninformed hope is that we will eventually be able to get around them by using something like a JHK two-color diagram in a way similar to what we do with the UBV two-color diagram in the visible. This is an exciting new prospect, and it is just beginning to be exploited, although there do appear to be difficulties in the interpretation (Davidge 1991). The general subject of K-band imaging will be the topic of the following paper, by Glass.

While I am on the topic of instrumental developments, there is another one that is very important for this field. Until recently, nearly all spectra were taken one at a time. But now nearly every major observatory has, or is developing, a multi-object spectrograph. It will be of tremendous value to studies of the Galactic bulge to be able to get radial velocities, spectral classes, and chemical abundances in great numbers—and, in fact, we will hear of such studies during this symposium.

And there are other new contributions from space, too. Bill Baum will be telling us about Hubble Space Telescope observations of Baade's Window, and I am pleased to say that late tomorrow evening HST will be pointed at Baade's Window again, imaging with the Faint Object Camera, which has four times the resolving power of the material that Bill will be talking about (but unfortunately over a much smaller

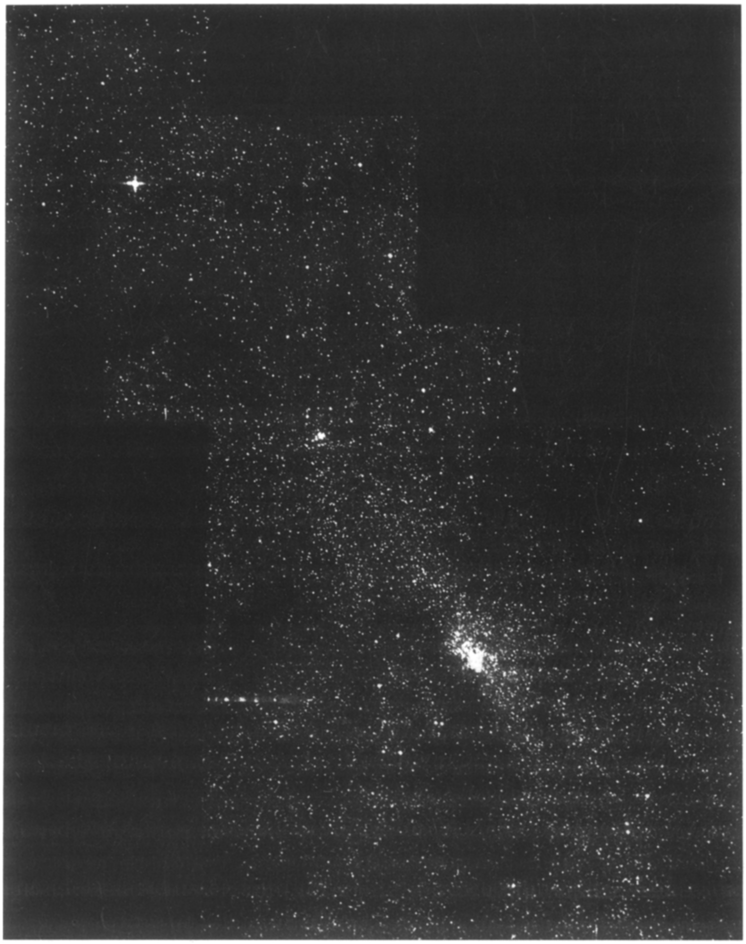

Fig. 4. Mosaic of K-band images, showing a region around the Galactic center.

field)[1].

2. The Problems of the Bulge

But this is enough general introduction; now I want to talk about the characteristics of the bulge itself: what we know and what we don't know, and what we are likely to be discussing in the next few days. I will have occasion, of course, to refer to a lot of specific papers, but I am not attempting to give comprehensive literature references, partly because other speakers will give detailed lists in their fields, and partly because I hope and expect that much of the work to which I refer will be superseded by presentations given at this meeting.

[1] The images were taken on 18 August 1992 and appear to be quite satisfactory.

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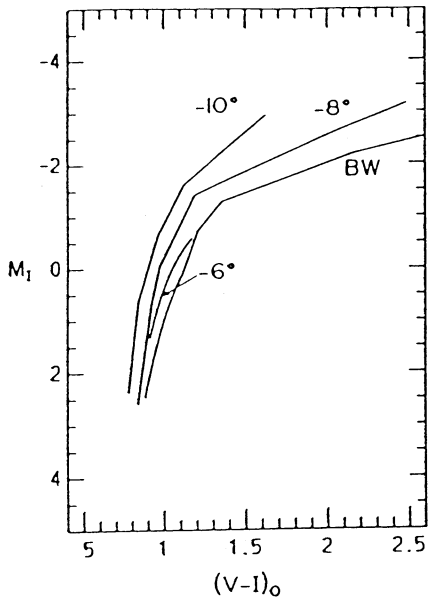

Fig. 5. Schematic giant branches derived by Terndrup (1988) in Baade's Window and in other fields farther from the Galactic center.

I should mention, by the way, that I am going to confine my attention to the smooth stellar bulge, which after all is what we can compare with other galaxies. That means that I am not going to discuss the disorderly conduct that is going on in the Galactic center, where we have ionized gas, supernova remnants, and maybe even a mini-AGN. That is galaxy-nucleus stuff; I don't want to mix it up with the bulge.

The problems of the bulge fall into four general areas: what is there, how it is distributed, how it moves, and how it got that way. I don't mean that these are separate areas; they are very much interrelated. But at least we can distinguish separate areas of fact—except for the last one, "how it got that way," which still has a lot more fancy in it than fact. (Sorry; more prejudice. But I *am* glad to see that Colin Norman has labeled his "formation" talk with the word "speculation.")

3. Populations

First, the populations in the bulge. (Notice that I use the plural.) Again, we can subdivide this into three questions: what kind of stars are we able to observe, what chemical abundances do they have, and what are their ages?

3.1. Population Tracers

One approach is just to see what we see—to make a color–magnitude diagram. Obviously for this we want a relatively unobscured region, and the favorite has

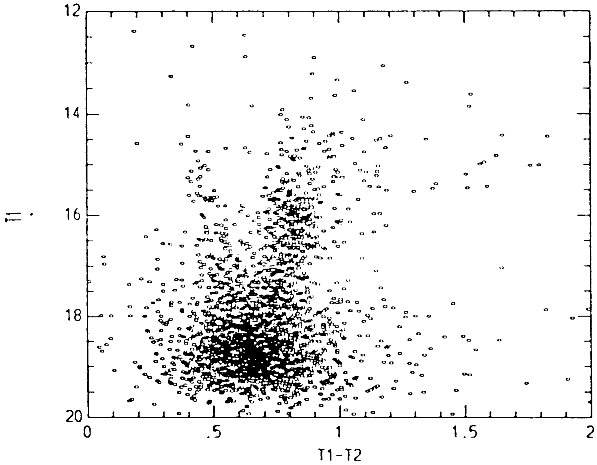

Fig. 6. A color-magnitude diagram in Baade's Window, in the Washington photometric system (Geisler and Friel 1992).

been Baade's Window. Here are some examples. Figure 5 shows Terndrup's (1988) schematic rendition of the giant branches in Baade's Window and in some other fields. It really is schematic, though. In Figure 6 are some actual data, from Geisler and Friel (1992), in the Washington photometric system. You can see that there is a lot of scatter, and a lot of interference from field stars, particularly from the main-sequence disk stars of the foreground. And at a not-very-faint magnitude, crowding gets you. That is why we are so interested in using HST in Baade's Window.

And I should mention that interesting CMD work can be done in other fields (see, especially, Tyson [1991 and in this volume], and two poster papers by Harding and Morrison in this volume), and in other bands (Davidge 1991).

Then there are particular types of stars. The M giants are especially useful, because they are luminous, spectroscopically easy to recognize, and particularly easy to observe at the longer wavelengths. They are also a population indicator, because metal-poor populations don't make late-type gM's. Victor Blanco and his associates have done a lot with M giants. (For a summary, with detailed references, see McCarthy and Blanco 1990.)

A related problem is the search for carbon stars. The fact that there are so few C's in the bulge, compared with, say, the Magellanic Clouds, is another indication that we are dealing with a metal-rich population. (The work on C stars is also summarized by McCarthy and Blanco 1990.)

Another type of M stars is the Miras, the long-period pulsators. They are not regular M giants, though. They sit at the tip of the asymptotic giant branch; so this is a pinpointed evolutionary stage. Also, each Mira has a period; and this is another population indicator, although I am not sure that it is a totally calibrated pointer. For further details about Miras, see Whitelock in this volume.

As a Mira evolves farther up the AGB, it develops a shell of dust and gas, and

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becomes an OH/IR star. As this name applies, these stars have radio emission, and they also show up as point sources in the IRAS survey. In both cases we get a view that is free of interstellar absorption. For further details about OH/IR stars, see both Habing and Dejonghe in this volume.

In the next stage of evolution, the star throws off a gas shell and evolves rapidly to the left in the HR diagram. It gets so hot that it sets the shell into luminescence as a planetary nebula. (I might remark parenthetically that a year ago I didn't know a thing about planetaries, but then I looked at my first ultraviolet HST image of the center of M31, and it was full of post-asymptotic-giant-branch stars, which are the nuclei of planetaries. I had to learn about them in a hurry. In a similar way I took on the preparation of this talk as an exercise to get me ready to do something intelligent with my HST observations of Baade's Window. In the bookstore on my campus they sell a sign that says, "Four years ago I couldn't even spell inginere, but now I are one." My position is a little bit like that.) A fair amount has been done about planetaries in the Galactic bulge; for further details, see Stasinska in this volume.

But we can go no further with this evolutionary track. The next stage is to become a white dwarf, and they are too faint to see in the bulge.

The stellar types that I have mentioned so far are all characteristic of a particular stage of evolution, and in some cases of a particular kind of population. So it is appropriate that I end the list with the RR Lyrae stars. Betty Blanco has done a great deal of work on RR Lyraes in the bulge (Blanco 1984, 1992), but unfortunately she is not here. But we are happy to have with us George Preston, who is a patriarch of the field, and he will tell us about RR Lyraes.

3.2. Abundances

These are the objects whose observational status we will be discussing. Now for the basic questions about them. First there is the nature of the populations in the bulge. This raises two kinds of questions: abundance and age. Let us look first at the abundances. It is immediately obvious that there is a large range, when we see RR Lyraes that are a signature of a metal-poor population and late M giants that occur only in a metal-rich population. But to study the *distribution* of abundances, we can use neither of these types, because each of them is so biased toward one end of the distribution. (Notice that the Miras and the OH/IR stars may also be biased in this way.) The one type of luminous star that occurs in populations of all abundances is the K giants.

The abundance distribution of a sample of K giants in Baade's Window was studied spectroscopically by Rich (1988), and more recently Geisler and Friel (1992) have studied a much larger sample, using Washington-system photometry. In Figure 7 is shown their distribution of [Fe/H]; I call attention to three striking characteristics: it has a big spread, the mean is greater than zero, and the extreme high is around +1.

Another feature of Fig. 7 that is noteworthy is that the horizontal scale at the left is linear, unlike the customary logarithmic [Fe/H]. The quantities shown are therefore just what is wanted by those who model scenarios of element enrichment,

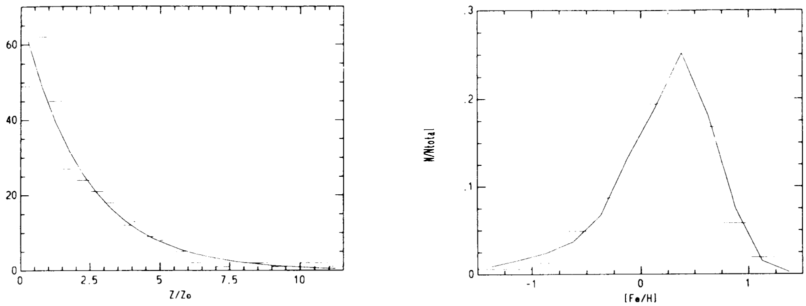

Fig. 7. The distribution of abundances in Baade's Window (Geisler and Friel 1992), on linear and logarithmic scales. The horizontal lines represent their histograms; the continuous lines are from theoretical models.

because they need to deal in actual amounts rather than ratios.

Geisler and Friel made careful efforts to avoid biasing their selection of K giants, but even here there is one bias that still seems to remain. Although they appear to have produced an unbiased abundance distribution of K giants, this is still one step removed from the basic answer. The remaining question to ask is, what is the ratio, at each abundance, of the number of K giants to the number of middle-main-sequence stars? It is the latter that we should take as the indicator of true numbers. This is an important additional question, yet I am not aware of its ever being treated.

We should remember also that there are more quantities to be concerned about than just [Fe/H]. At the Santa Cruz globular-cluster workshop a month ago, Frogel (1993) showed some infrared color-color diagrams in which the bulge stars didn't match up with any other population. In fact, there were other mismatches too; for example, in these diagrams the field population of the halo doesn't match any type of globular cluster. I don't really know what to make of facts like these, but I think that they may be trying to tell us something quite important. Try the following: because different elements affect various parts of the spectrum in different ways, these differences in two-color diagrams are telling us that the details of the enrichment process depend on the environment. If that is true, it is a very important statement.

And if the foregoing is really so, it constitutes an argument against the formation of the bulge by mergers. We cannot produce a unique population by merely mixing ordinary ones.

Uniqueness also makes one think of the RR Lyrae stars in Baade's Window. (See the discussion by Blanco 1984.) For a given shape and amplitude of light curve, they have shorter periods than any other RR Lyraes known. It would be fascinating to know what RR Lyraes are like even closer to the Galactic center. Yet strangely, in a field only a degree and a half farther from the center (Blanco 1992) the RR Lyraes have the periods of an ordinary Oosterhoff Type I globular cluster.

An interesting discussion of the ability of various populations to produce RR

Lyrae stars is given by Renzini and Greggio (1990), in a paper to which I shall soon have occasion to refer again.

The RR Lyraes in Baade's Window offer an excellent example, by the way, of population selection in the distribution of abundances. Walker and Terndrup (1991) find, from ΔS values, that their [Fe/H] distribution peaks sharply around -1, quite unlike that of the K giants. But this is surely a result of the fact that RR Lyrae stars are made much more readily in the low-metallicity part of the population. This bias is also illustrated by the fact that RR Lyraes are not found in the more metal-rich globular clusters. They exist in the field, though; putting these two facts together, it is easy to conclude that their number per main-sequence star must be very low in metal-rich populations.

The low abundances found by Ratag *et al.* (1992) for planetary nebulae in the bulge may have a similar explanation. The central stars of planetaries are post-asymptotic-giant-branch stars, and these may be lacking in old populations of high metal abundance.

The details of chemical abundances in the Galactic bulge certainly pose a problem. For the discussion of a possible scenario, see the bold approach by Matteucci and Broccato (1990). But in any case, this is a problem that is going to be with us for a long time.

3.3. Ages in the Galactic Bulge

Now for the problem of ages. To start with, it is obvious that in the bulge we are dealing with an old population. But there are two important age questions about this population: *how* old is it? and is any of it appreciably younger than the rest?

I would like to look at the second question first. The strongest evidence for younger stars in the bulge is the excessively bright upper limit of the asymptotic giant branch, which in our familiar solar-metal-abundance population would be a sure sign of more-massive, younger stars. But Frogel (1990) argues strongly that this luminosity might instead be an effect of the supermetallicity that we know exists in the bulge. This is a very uncertain area of questions, however. The best theoretical exploration that I know of (Renzini and Greggio 1990) emphasizes the extent to which late evolution for metal-rich stars depends on the rate of helium production during metal enrichment. (For an example, see Figure 8.) This is a quantity that we know very little about—except that it is surely not zero and is likely to be at least 1 or 2. The only direct evidence I know to cite is that the Sun's helium content has a ΔY of 0.04–0.05 above the primeval value, along with a ΔZ of 0.02. But evolutionary tracks change with Z, so who knows how $\Delta Y/\Delta Z$ changes with Z itself? For further details I refer you directly to their paper, and of course to whatever Renzini has to say later in this volume.

As for the ages of the oldest stars in the bulge, I just don't know. We have very little direct evidence. For this reason I am looking forward very much to Bill Baum's account of the work of HST's WFPC team in Baade's Window—as I am looking forward to my own observations there. *If* we can do accurate enough photometry, correct reliably for interstellar absorption, and trust the theoretical isochrones that we fit to, then the main-sequence turnoff can give us an age (or a distribution of

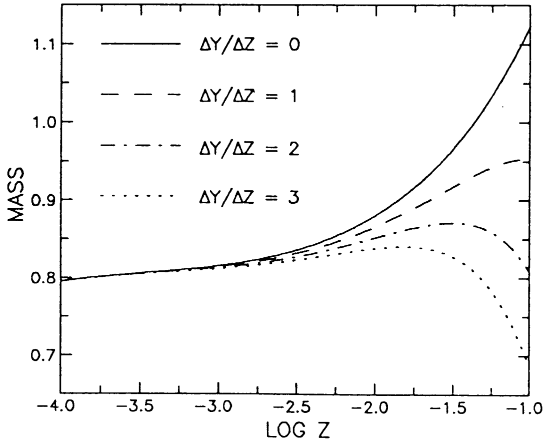

Fig. 8. The mass of stars evolving off the main sequence at age 15 Gyr, as a function of metal abundance and helium production rate (Renzini and Greggio 1990). Note how rapidly the different curves diverge at metal abundances above solar ($\log Z = -1.7$).

ages).

The suggestion has been made on other grounds, however, that the bulge is the oldest population in the Galaxy. Young-Wook Lee (1992) believes his theories of horizontal branch structure and evolution well enough that he claims to be able to age-date the RR Lyrae stars in Baade's Window. His ages are relative rather than absolute, but he asserts that the bulge is a gigayear older than the oldest halo population. I am not really competent to judge Lee's arguments, but Renzini's discussion of the uncertainties in helium production makes me skeptical of them.

Before I leave the problem of population mixtures in the bulge, let me make one firm point. Dynamically, there *must* be a mixture. Because of the very behavior of potential wells, the halo stars must have their highest absolute density at the Galactic center (even though they surely constitute only a small fraction of the population there), so they must be a contributor to the bulge. This is less obvious for the population of the thin disk, where rotation-supported circular orbits do allow the possibility of a hole in the center. Such a hole does seem unlikely, however, in view of the results presented later in this volume by Whitford, who points out the existence of a set of OH/IR stars in a flattened, rapidly rotating disk close to the Galactic center.

4. Relation of the Bulge to Other Components

Perhaps the most intriguing question about the bulge population is, what other component(s) of the Milky Way is it related to? Is it the center of the disk (or perhaps of the thick disk), or of the halo, or is it a completely independent component of the Milky Way? For that matter, we know that there are strong population gradients within the bulge itself; is the bulge a single component or a mixture of several?

In this connection, I want to speak out on another abuse of terminology that I think creates a great deal of unnecessary confusion, and sometimes even error, in the attempt to understand the overall structure of the Milky Way. This is the use of the pernicious term "spheroid" to mix, in a single unhappy pot, the metal-rich bulge and the metal-poor halo. This is very common terminology (and can undoubtedly be found in numerous papers in this volume, to whose authors I apologize for criticizing them so), but it is truly an abomination. It is used in of one of the most popular stellar-distribution models for the Galaxy, and in the most widely read book on galactic astronomy. What it does is to tempt the unwitting reader to equate the bulge with the center of the halo and then to slip even more unwittingly into thinking of the bulge as metal-poor. It is possible that they *might* be part of the same population, with a continuous transition from one to the other—although I rather doubt it. But the burden of proof is on the facts, and is not to be avoided by naïvely using the same name for both. Please, let us relegate the term "spheroid" to describing geometrical shapes of astronomical bodies; it is indeed useful for that. But in the context of components of the Galaxy it simply creates a mess and should be abolished. Just because the halo and the bulge both have a spheroidal shape, that does not make them population siblings.

Please excuse that diatribe, but I think that the subject of it is important. Back now to what other components the bulge is related to. At one time I used to feel very comfortable with the idea that a bulge is simply what a stellar disk likes to do dynamically at its center. There might have been some dynamical virtue in the idea, but it fails completely to address the population difference. There is clearly a thin-disk population represented at the Galactic center, and the scandalous goings on in the innermost 20 parsecs of the plane do not accord at all with the serene distributions in an old bulge.

Perhaps a similar dynamical idea could be used to connect the bulge with the thick disk. Again there are population differences, but we know that population gradients exist in the bulge. The principal difficulty is that on the dynamical side this hypothesis is merely hand-waving. I know of no dynamical analysis or modeling that either supports or refutes it. But there are other more direct difficulties. We know very little about the structure of the thick disk, except vertically in the solar neighborhood. Of course the suggestion has been made that the thick disk is part of the same system as the disk globular clusters, in which case we do know something about its density distribution. But this connection raises the population difficulty that the system of disk globulars shows no tendency for metallicities to increase inward.

Allowing for population gradients does indeed open the question of whether the bulge could be the inward continuation of the halo, with the population gradient simply getting very strong in this innermost region that we call the bulge. I see two strong arguments against this. One is that the halo does not have a strong metallicity gradient at all, and perhaps has none at all when the disk globulars are properly separated from the halo globulars. The other is that the halo has much less flattening than the bulge, so that tying the two systems into one would require a rather unlikely change of ellipticity with radius. (The same statement can alternatively be couched in terms of amount of rotation.)

All in all, I have to admit that I have no idea whether the bulge has an intimate relationship with any other component of the Milky Way. For an interesting discussion of many of the facts and arguments, see Carney *et al.* (1990).

5. Density Distribution

Now into another major area, the density distribution in the bulge. Let us look first at the radial distribution. The very center was first mapped by Becklin and Neugebauer (1968). At 2.2 μ they found a central spike that was not resolved by their smallest aperture of 5 arcsec, and outside it a dropoff that went spatially as the -1.8 power of distance. They mapped out to 10 arcmin. A source of information at greater radii is the 2.4-μ survey of Kent *et al.* (1991). Their vertical profile suggests that the Becklin–Neugebauer trend continues out to about 1°, beyond which the distribution becomes exponential, with a scale height of about 375 pc. Another study was done by Harmon and Gilmore (1988), who looked at the distribution of IRAS point sources at 12 μ. They were unable to sample the innermost 4° because of IRAS confusion, but outside that radius their distribution agrees quite well with an exponential of 375 pc scale height.

Here again we have to take note of some uncertainties. The K-band studies refer to red giant stars in general, whereas the IRAS data sketch the distribution of OH/IR stars. Population gradients could lead to systematic differences. And the 12-μ data are absorption-free, whereas the K band is subject to an absorption of 2 1/2 to 3 magnitudes, which is spatially variable. Surely the mapping of the absorption in the surroundings of the Galactic center is one of our urgent needs.

There are other components that behave quite differently, however. The late M giants, studied by Victor Blanco (1988), drop off extremely steeply. This is not really a density gradient, however; it is a population gradient. Its most plausible interpretation is that only very metal-rich stars *can* be late M giants, and as the metallicity falls off away from the center these stars no longer occur. In fact, contemplating this phenomenon leads me to wonder whether we have any information at all on the density distribution in the bulge that is free from bias by population selection. Which brings me to an even more fundamental question: what do we really mean by the bulge, anyway? Rather than trying to answer that, I leave it for everyone to contemplate.

The abundance gradient is clearly important, but we are not in good agreement about it. In Figure 9 I have reproduced two versions of it. Frogel (1990), using infrared indices, finds a steady dropoff. Tyson (1991, p. 183), who used Washington photometry, interprets his results as showing a level abundance out to 10° latitude, followed by a sharp drop. We just don't have our facts straight yet.

Another question is the flattening of the bulge. There have been various answers about this, but I think that the best of them is the COBE map Fig. 2, which shows the bulge as rather flattened and quite boxy. This map refers to the 1–4 μ range, so it is red-giant light that we are looking at. Perhaps here again we need to worry a little about what a representative population is.

Finally, there is the question of the symmetries of the bulge. The evidence is

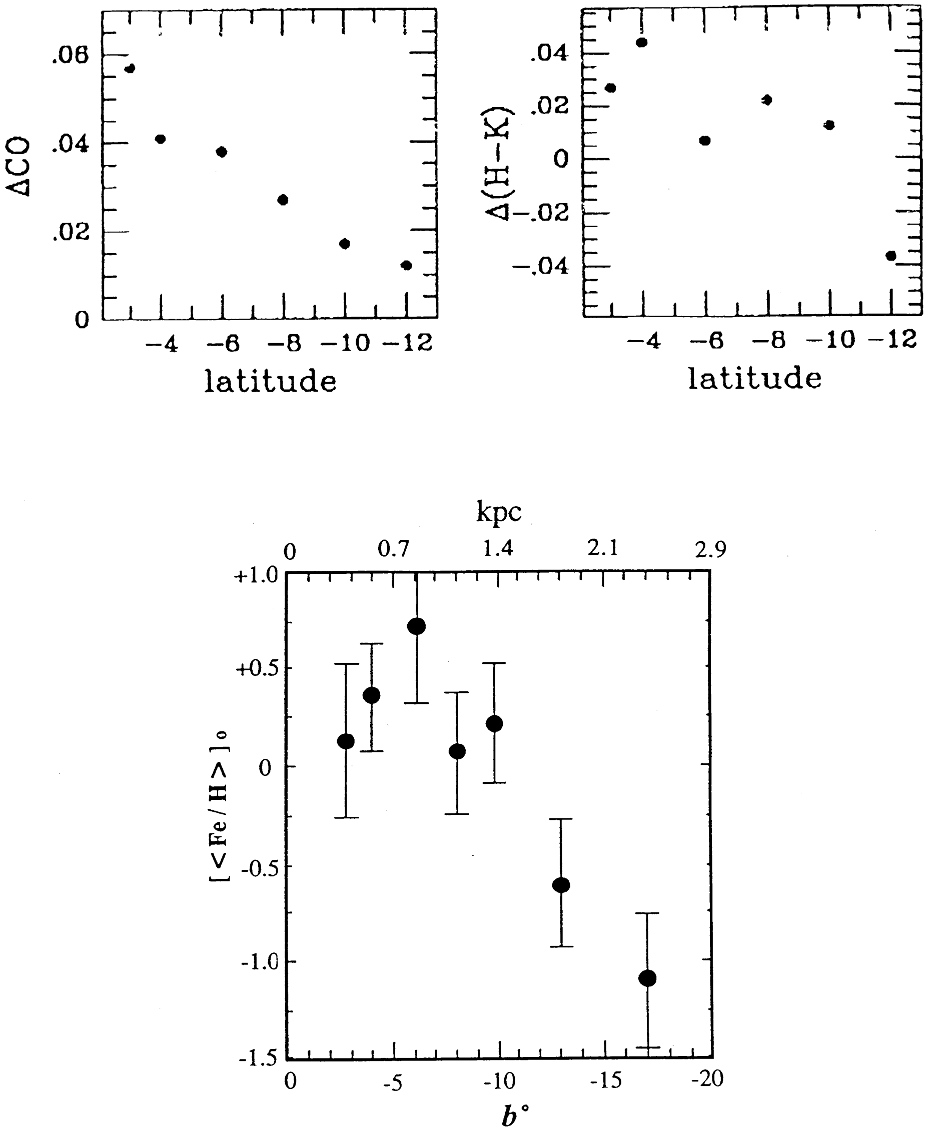

Fig. 9. Dependence of metal abundance on Galactic latitude, according to Frogel (top, 1990) and Tyson (bottom, 1991).

becoming increasingly strong that the bulge is triaxial, with a shape that is often referred to alternatively as a bar. First, Blitz and Spergel (1991) showed that the 2.4-μ map of the bulge indicated in many separate ways that the bulge has a barred shape, inclined both to the line of sight and to the Galactic plane—on a scale of the order of a kiloparsec. (Note, by the way, that this, if interpreted as a true bar, would make us a barred spiral with a peculiarly short bar.) Then Binney *et al.* (1991) showed that the gas motions were very much in accord with such a picture. But perhaps the most compelling evidence is the claim by Whitelock and Catchpole (1992), using the period-luminosity-color relation developed by Feast *et al.* (1990), that the bulge Miras at positive Galactic longitude are closer than those at negative longitude. But strangely, the stellar kinematics do not show any sign of the influence of a bar. I hope that de Zeeuw's paper in the present volume will shed more light on these perplexing questions.

It should be noted in this connection that there is no *a priori* reason to expect the Galactic bulge to be axisymmetric. We know, after all, that giant elliptical galaxies are triaxial, and the isophote twist in the M31 bulge shows that it is triaxial too.

(And note also that triaxiality could defeat any attempt to find the distance to the Galactic center by comparing radial velocities with proper motions.)

One final point about the shape of the bulge: Kent (1992) has done a quite nice dynamical model of the bulge, but it is axisymmetric. I hope that it can now be modified in some way to take into account the apparent asymmetry.

6. Kinematics of the Bulge

I now turn to the kinematics of the bulge, with a little dynamics thrown in. The basic dynamical fact to seize upon is the virial theorem, which, in simple language says, "You've got to have motion in order to resist gravitation." The motion is of course a mixture of rotation and random velocity dispersion. In the z direction the only support is velocity dispersion, so the vertical extent of the bulge tells us to expect a sizable dispersion. This is also borne out by the flattening of the bulge, where rotation and velocity dispersion combine to draw the bulge out farther in its equatorial plane. In fact, one can easily show, from the tensor virial theorem, that for a bulge the shape of ours one should expect comparable levels of rotation and velocity dispersion—and that is just about what we see. And to pursue this line of reasoning a bit further, if you want a bar, you've got to have more velocity dispersion in the direction of the long axis.

There have been many radial-velocity studies of various types of object in the bulge. K giants have been studied by Minniti *et al.* (1992), M giants by Walker *et al.* (1990), Miras by Catchpole (1990) and by Menzies (1990), OH/IR stars by Lindkvist *et al.* (1989) and by Le Poole and Habing (1990), planetary nebulae by Kinman *et al.* (1989), and main-sequence stars (perhaps at too high a latitude really to be called bulge) by Harding (1990). And no doubt this enumeration has missed some studies.

I will not go into these studies individually, as their results are rather similar. We tend to see linear rotation curves, typically with a slope of about 12 km/sec per degree of longitude. Typical velocity dispersions are 100–120 km/sec. But there is a tendency for the higher-metal-abundance types to rotate a little faster, and be a little more flattened to the plane. In this connection, it is time to repeat here my caution about the inhomogeneity of the K giants. In any kinematical study they should be divided into abundance groups. Something similar applies to the Miras and their various successor types.

In addition one other interesting study should be mentioned, although it is not clear that it refers to the bulge rather than to the center of the disk. McGinn *et al.* (1989) and Sellgren *et al.* (1989) discuss radial velocities of stars within 100 arcsec of the Galactic center. They find a rapid rotation, with the mean velocity changing by more than 100 km/sec in a few parsecs. This would argue for a disky population. On the other hand, their velocity dispersion of 100 km/sec would argue for a bulgy population. What are we to make of this?

There is one new development that I find quite exciting. That is the entry of proper motions into the field. Spaenhauer, Jones, and Whitford (1992) have worked with repeats of Baade's original plates and have measured proper motions in Baade's Window. Their accuracy is good enough for the velocity dispersions to be highly significant. Not that these motions are simple to interpret, however. In the latitude direction we see only the effect of velocity dispersion, whereas the proper motions in longitude also include the effect of rotation. The near and far sides of the bulge go in opposite directions; we of course can't tell them apart, so rotation has the effect of making the dispersion in proper motions larger in the longitude component. This effect does show up, and as one might expect, it is greater for the metal-rich stars than for the metal-poor stars.

7. The Origin of the Bulge

This is a subject that I won't even try to touch on. I will just refer you to Colin Norman's paper in this volume.

8. How Typical is Our Bulge?

Whether our bulge is typical of those of other galaxies is almost impossible to answer (although Frogel 1990 assembles a very useful summary of the facts). The problem is that we can see the bulges of many other galaxies so clearly, whereas we have to look at our own bulge through all the intervening muck. In many ways what we can see of it does seem typical, but there is one way in which it differs very much from the bulge of M31. The latter looks like a purely old population, whereas we get all sorts of young-population signals from a thin layer around the very center of the Milky Way. No doubt there will be more to say on this general question at the next symposium that is held on the fascinating problems of the Galactic bulge.

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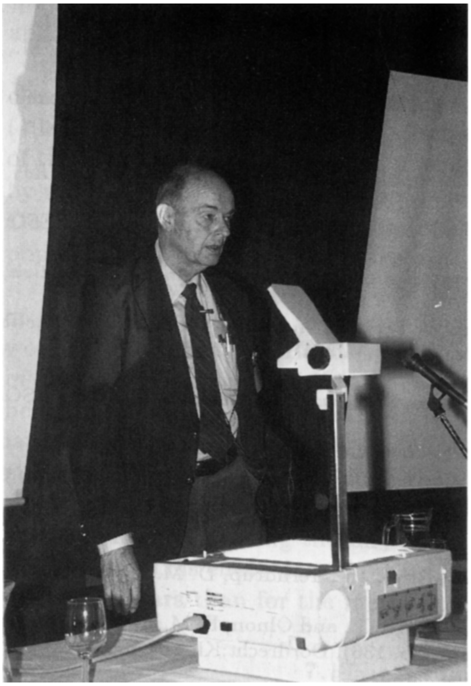

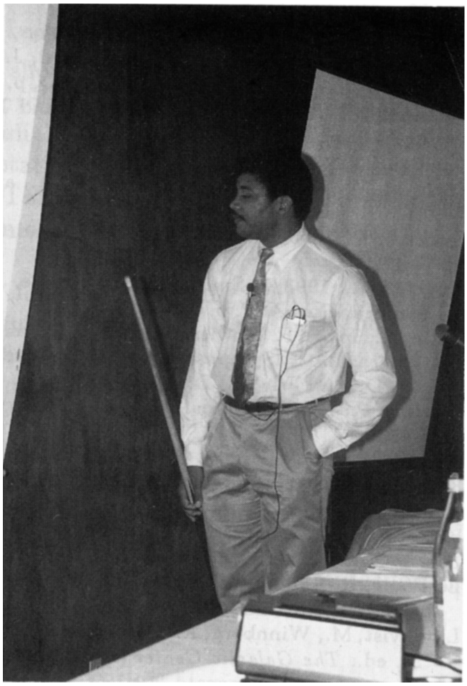

W. Baum and N. Tyson, each during his talk

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