A BRIEF HISTORY OF STAR FORMATION AND CHEMICAL ENRICHMENT IN THE BULGE OF THE MILKY WAY

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Abstract.

Observations of the stellar content of the bulge of the Milky Way can provide critical guidelines for the interpretation of observations of distant galaxies, in particular for understanding their stellar content and evolution. In this brief overview I will first highlight some recent work directed towards measuring the history of star formation and the chemical composition of the central few parsecs of the Galaxy. These observations point to an episodic history of star formation in the central region with several bursts having occurred over the past few 100 Myr (e.g. Blum et al. 1996b). High resolution spectroscopic observations by Ramírez et al. (1998) of luminous M stars in this region yield a near solar value for [Fe/H] from direct measurements of iron lines. Then I will present some results from an ongoing program by my colleagues and myself the objective of which is the delineation of the star formation and chemical enrichment histories of the central 100 parsecs of the Galaxy, the “inner bulge”. From new photometric data we have concluded that there is a small increase in mean [Fe/H] from Baade’s Window to the Galactic Center and deduce a near solar value for stars in the central region. For radial distances greater than 1° from the Galactic Center we fail to find a measurable population of stars that are significantly younger than those in Baade’s Window. Within 1° we find a number of luminous M giants that most likely are the result of a star formation episode not more than one or two Gyr ago.
1. Introduction

We care about the bulge of the Milky Way both because of what it tells us about the formation and evolution of our own galaxy and because its structure and stellar content are often used as proxies in the study of other galactic bulges and elliptical galaxies. Thus, in the spirit of this meeting, it serves as a vital link between the near and the far, between the present and the past.

Buried within the Galactic bulge is the center of the Galaxy, a region which, on a small scale, has some properties in common with luminous AGNs and starburst galaxies. Because of its proximity, it can be studied in greater detail than any other such galactic nucleus. On the other hand, between us and it lie clouds of interstellar dust of great enough optical depth that the average visual extinction is about 30 magnitudes. Thus it is only at infrared and longer wavelengths that the central few arc minutes of the Galaxy can be studied. Indeed, out to a radius of about $2^\circ$ (and much farther if observing on or close to the major axis) the visual extinction is still great enough that optical observations are difficult to impossible along most lines of sight.

This review of our current state of knowledge of the star formation and chemical enrichment history of the Galactic bulge will be brief. I will make no attempt to cite the many research papers that have appeared over the past decade or so that deal with these topics. The papers that are referred to, though, do contain extensive references to the literature. Furthermore, the review will be restricted to stars and their optical and infrared photospheric radiation.

Simply put, the history of star formation can be traced by a survey of either hot blue stars or cool red ones. The former, which will primarily be massive main sequence stars, are effective tracers of the most recent epoch of star formation. The latter will not only be effective tracers of the most recent epoch – the late-type supergiants – but will also trace out older epochs of star formation via the presence of luminous AGB stars. This review will deal primarily with surveys of the cool stellar population in the central part of the Milky Way so that star formation can be investigated over a broader period of time. The next section, though, will briefly consider some work on the hot stellar component in the immediate vicinity of the Galactic Center itself.

2. The Central Few Arc Minutes Of The Galaxy

Krabbe et al. (1995) have reported on an extensive survey of the central few arc seconds of the Galaxy. They identified more than 20 luminous blue supergiants and Wolf-Rayet stars in a region not more than a parsec
in radius. The inferred masses of some of these stars approaches $100 \, M_\odot$. From this they conclude that between 3 and 7 Myr ago there was a burst of star formation in the central region. They also identified a small population of cool luminous AGB stars from which one can conclude that there was significant star formation activity a few 100 Myr ago as well.

Blum et al. (1996a) carried out a K-band survey of the central 2 arc minutes of the Galaxy and drew renewed attention to the presence of a significant excess of luminous stars ($K_0 < 6$) when compared to a typical old stellar population such as is found in Baade’s Window, for example. Most of these stars were found by Blum and others to be M stars, presumably a mixture of supergiants and AGB stars. However, as Blum et al. (1996a,b) pointed out, the distinction between an M supergiant and a luminous M-type AGB stars cannot be made on the basis of luminosity alone since there is a two magnitude range in which the luminosities of the two very different class of stars overlap (see Fig. 5 of Blum et al. 1996b). But assigning stars to one class or the other is critical in deciphering the star formation history of this region. With K-band spectra, though, it becomes straightforward to make this distinction for almost all cases (Fig. 1 of Blum et al. 1996b). As first quantified by Baldwin et al. (1973) M-type supergiants can be easily distinguished from ordinary giants of the same temperature (or color) via the strengths of the $H_2O$ and CO absorption bands in K-band spectra.

Blum et al. (1996b) analyzed K-band spectra for a representative sample of 19 of the luminous stars identified in their survey area. Only 3 of these stars were found to be supergiants; one of these is the well known IRS 7. The remainder are AGB stars, some of which could be long period variables as well. From the spectra and the multi-color photometry they were able to calculate effective temperatures and bolometric luminosities for the stars. With the assumption that the abundance of the stars they observed is comparable to that of disk stars in the solar neighborhood, they were able to estimate ages for the stars from a comparison with stellar interior models. Rather than continuous star formation, they concluded that there have been multiple epochs of star formation in the central few parsecs of the Galaxy. The most recent epoch, less than 10 Myr ago, corresponds with that found by Krabbe et al. (1995). Blum et al. also identified significant periods of star formation as having occurred about 30 Myr, between 100 and 200 Myr, and more than about 400 Myr in the past. The majority of stars they observed are associated with the oldest epoch of star formation.

What about the abundances of stars in the central few parsecs? Ramírez et al. (1998) have obtained high resolution K band spectra for 10 M giants in this region and did a full spectral synthesis analysis of them. They were able to measure a true $[\text{Fe/H}]$ with their observations of iron lines and thus remove any ambiguity that could arise by inferring $[\text{Fe/H}]$ from measure-
ments of elements that are often used as proxies (e.g. Mg or Ca). For these 10 stars they derive a mean \([\text{Fe/H}]\) of 0.0 with a dispersion no larger than their uncertainties, about ±0.2 dex. Their mean value is a few tenths of a dex greater than the mean \([\text{Fe/H}]\) determined for Baade’s Window K giants (Sadler et al. 1996; McWilliam & Rich 1994). While it may be surprising that the mean \([\text{Fe/H}]\) at the Galactic Center is not super-solar, the small increase in the mean value of \([\text{Fe/H}]\) compared with Baade’s Window is consistent with estimates for the gradient in \([\text{Fe/H}]\) in the inner Galactic bulge (Tiede et al. 1995; Frogel et al. 1999). On the other hand, a non-detectable dispersion in \([\text{Fe/H}]\) stands in contrast to a dispersion that is more than an order of magnitude in size for the K giants in Baade’s Window (Sadler et al. 1996; McWilliam & Rich 1994). It is, however, consistent with the lack of dispersion found for the M giants in Baade’s Window (Frogel & Whitford 1987; Terndrup et al. 1991).

The fact that \([\text{Fe/H}]\) is near solar at the Galactic Center with a star formation rate per unit mass at least at present is considerably in excess of the solar neighborhood value suggests that the rate of chemical enrichment has been quite different at the two locations.

The difference in the measured dispersions between K and M giants remains to be explained. In Baade’s Window there is no detectable population of K giants with luminosities great enough to place them near the top of the giant branch (DePoy et al. 1993). At the same time, it is generally thought that in a stellar population most of whose stars have \([\text{Fe/H}]\) greater than –1.0, nearly all K giants eventually evolve into M giants. Thus the observed dispersions should be similar for the two groups. That they are not could imply that estimates for evolutionary rates and lifetimes near the upper end of the RGB and AGB are wrong. It could also point to problems with the analysis of the M giants, although in the case of the Ramírez et al. work this seems unlikely since the underlying principles of their analysis are basically the same as that employed for the optical studies of the K giants.

3. The Inner Galactic Bulge

Now we turn our attention to the inner 3° of the Galactic bulge. This region, which is interior to Baade’s Window, will be referred to as the inner Galactic bulge. With the 2.5 meter duPont Telescope at Las Campanas Observatory I have obtained JHK images of 11 fields within the inner bulge, three of which are within 1° of the Galactic Center. The two questions that are being addressed are: What is the abundance of the stellar population in this region and is there any evidence that a detectable component of the population is relatively young, i.e. significantly younger than globular clusters? To answer
the question about stellar abundances my collaborators and I are taking two independent approaches. The first is based on the finding of Kuchinski et al. (1995) that the giant branch of a metal rich globular cluster in a K, JK color magnitude diagram is linear over 5 magnitudes and has a slope that is proportional to its optically determined [Fe/H]. Results from this part of the study, based on the LCO data, will be summarized here. The second approach, which is expected to give a more detailed and precise answer to the abundance question, and is based on the analysis of K-band spectra obtained at CTIO of about one dozen M stars in each of 11 fields. This is a work in progress.

We have used two indicators to test for the presence of intermediate age stars in the bulge (i.e. an age not more than a few Gyr as opposed to closer to 10 Gyr). The first is a determination of the luminosity of the brightest stars on the giant branch of each of the fields. A sign of a relatively young age would be if there were stars brighter than those found in Baade’s Window. The second indicator involves a comparison of the properties of long period variables in the bulge with their counterparts in Galactic globular clusters.

3.1. ABUNDANCES IN THE INNER GALACTIC BULGE

The best “fixed reference point” in any attempt to determine abundances within the inner bulge is the determination by McWilliam & Rich (1994) of the mean abundance of a sample of K giants in Baade’s Window based on high resolution spectroscopy. They found a mean [Fe/H] of about −0.2. A similar result was found by Sadler et al. (1996) based on spectroscopy of several hundred K giants in Baade’s Window. Furthermore, both of these independent analyses agreed that the spread in [Fe/H] in Baade’s Window was considerably greater than an order of magnitude and could be as large as two orders of magnitude. Observations of Baade’s Window M giants, on the other hand, both in the near IR and of red TiO bands (e.g. Frogel & Whitford 1987; Terndrup et al. 1991) consistently pointed to a greater than solar abundance with no measurable dispersion. The independent estimate of [Fe/H] for the Baade’s Window giants based on the near-IR slope method (Tiede et al. 1995) differed from the previous determinations in that they found an [Fe/H] close to the value based on the optical spectra of K giants.

The near-IR survey of inner bulge fields has yielded color-magnitude diagrams that, except for the fields with the highest extinction, reach as faint as the horizontal branch. Thus, with data for the entire red giant branch above the level of the HB we can apply the technique developed by Kuchinski et al. (1995) which derives an estimate for [Fe/H] based on the slope of the RGB above the HB. Although the calibration of this technique
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is based on observations of globular clusters, the applicability of the method to stars in the bulge was demonstrated by Tiede et al. (1995) in their analysis of stars in Baade’s Window. Although we were able to estimate, statistically, the reddening to each field, the method itself is reddening independent since it depends only on a slope measurement. Based on 7 fields on or close to the minor axis of the bulge at galactic latitudes between $+0.1^\circ$ and $-2.8^\circ$ we derive a dependence of $\langle [\text{Fe/H}] \rangle$ on latitude for $b$ between $-0.8^\circ$ and $-2.8^\circ$ of $0.085 \pm 0.033$ dex/degree. When combined with the data from Tiede et al. we find for $-0.8^\circ \leq b \leq -10.3^\circ$ the slope in $\langle [\text{Fe/H}] \rangle$ is $-0.064 \pm 0.012$ dex/degree, somewhat smaller than the admittedly crude value derived by Minniti et al. (1995). An extrapolation to the Galactic Center predicts $[\text{Fe/H}] = +0.034 \pm 0.053$ dex, in close agreement with the result of Ramírez et al. (1998). Also in agreement with Ramírez et al., we find no evidence for a dispersion in $[\text{Fe/H}]$. Details of this work are in Frogel et al. (1999).

Analysis of the K-band spectra of the brightest M giants in each of the fields surveyed is nearing completion; the results appear to be consistent with those based on the RGB slope method, namely, an $[\text{Fe/H}]$ for Baade’s Window M giants close to the McWilliam & Rich value but with little or no gradient as one goes into the central region. Also, little or no dispersion in $[\text{Fe/H}]$ within each field is visible in the spectroscopic data. Further work on the calibration of these data must be done before definitive conclusions can be drawn.

In summary, several independent lines of evidence point to an $[\text{Fe/H}]$ for stars within a few parsecs of the Galactic Center of close to solar. The gradient in $[\text{Fe/H}]$ between Baade’s Window and the Center is small – not more than a few tenths of a dex. Exterior to Baade’s Window there is a further small decline in mean $[\text{Fe/H}]$ (e.g. Terndrup et al. 1991, Frogel et al. 1990; Minniti et al. 1995). It remains to be seen whether this gradient arises from a change in the mean $[\text{Fe/H}]$ of a single population or a change in the relative mix of two populations, one relatively metal rich and identifiable with the bulge, the other relatively metal poor and more closely associated with the halo. Support for the latter interpretation is found in the survey of TiO band strengths in M giants in outer bulge fields by Terndrup et al. (1990) for which they found a bimodal distribution. McWilliam & Rich (1994) proposed an explanation based on selective elemental enhancements as to why earlier abundance estimates of bulge M giants seemed to consistently yield $[\text{Fe/H}]$ values in excess of solar. What still remains to be understood is why even recent measurements of the M giant abundances do not reveal any evidence for an intrinsic dispersion in $[\text{Fe/H}]$ in any given field. Finally, an issue that needs further investigation is the degree to which the indirect methods used for getting at $[\text{Fe/H}]$ are influenced by selective
element enhancements.

3.2. STELLAR AGES IN THE INNER GALACTIC BULGE

If a stellar population has an age significantly younger than 10 Gyr, say not more than a few Gyr, then stars on the AGB can reach luminosities several magnitudes brighter than they would in an older population. After correction for extinction we noted that our fields closest to the Galactic Center had significant numbers of bright, red stars. With the stars in Baade’s Window as a guide we chose a reddening corrected K magnitude of 8.0 as the limit to the brightest magnitude obtainable in an old population and counted the number stars in each surveyed field brighter than this relative to the number in a predefined, fainter magnitude interval. We found that at radial distances greater than 1.3° the ratio was constant with a value equal to that for Baade’s Window. On the hand, for the fields closer to the center than 1.0° this ratio was significantly larger, implying the presence of a relatively young population of stars, not more than a couple of Gyr old. This is consistent with Blum et al.’s work on the inner few arc minutes of the bulge. Details are in Frogel et al. (1999)

The second test we applied to see if there is evidence for a young population in the Galactic bulge was to compare the luminosities and periods of bulge long period variables (LPVs) with those found in globular clusters (Frogel & Whitelock 1998). For LPVs of the same age, those with greater [Fe/H] will have longer periods. LPVs with longer periods also have higher mean luminosities. In the past, claims have been made for the presence of a significant intermediate age population of stars in the bulge based on the finding of some LPVs with periods in excess of 500–600 days. It is necessary, however, to have a well defined sample of stars if one is going to draw conclusions based on the rare occurrence of one type of star. The M giants in Baade’s Window are just such a well defined sample (e.g. Frogel & Whitford 1987). Frogel & Whitelock (1998) presented a detailed comparison of LPVs in the bulge and in metal rich globular clusters. They demonstrated that with the exception of a few of the LPVs in Baade’s Window with the longest periods, the distribution in bolometric magnitudes of the LPVs from the two populations overlap completely. Furthermore, because of the dependence of period and luminosity on [Fe/H] and the fact that there has been no reliable survey for LPVs in globulars with [Fe/H] > −0.25, while a significant fraction of the giants in Baade’s Window have [Fe/H] > 0.0 (McWilliam & Rich 1994), the brightest Baade’s Window LPVs can be understood as a result of this higher [Fe/H] compared with globular clusters.

Finally, observations with the Infrared Astronomical Satellite (IRAS)
at 12µm were used to estimate the integrated flux at this wavelength from the Galactic bulge as a function of galactic latitude along the minor axis. Galactic disk emission was removed from the IRAS measurements with the aid of a simple model. These fluxes were then compared with predictions for the 12µm bulge surface brightness based on observations of complete samples of optically identified M giants in minor axis bulge fields (Frogel & Whitford 1987; Frogel et al. 1990). No evidence was found for any significant component of 12µm emission in the bulge other than that expected from the optically identified M star sample plus normal, lower luminosity stars. Since these stars are themselves fully accountable by an old population, the conclusion from this study was, again, that most of the Galactic bulge has no detectable population of stars younger than those in Baade’s Window, i.e. younger than an age comparable to that of globular clusters.

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