The Chemical Evolution of the Galactic Bulge

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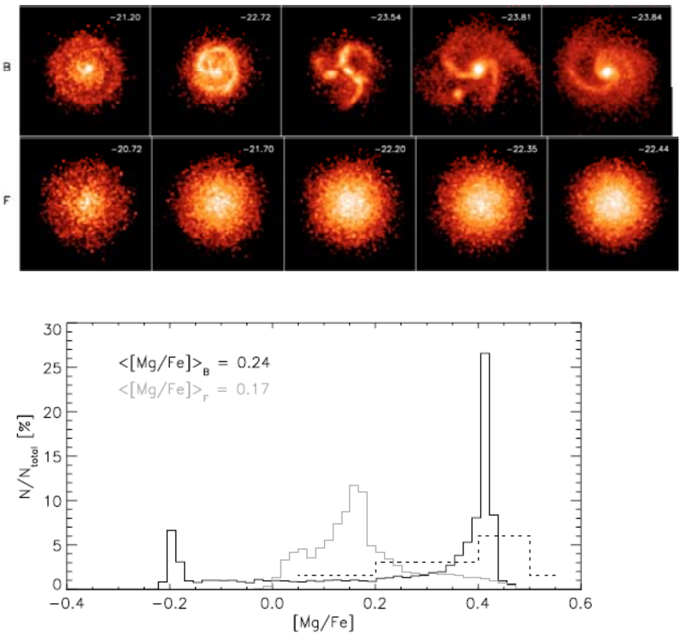
This science white paper addresses the issue of discovering the *chemical evolution of the Galactic bulge*, from which we may learn the initial mass function at the time of the formation of the bulge, the timescale for the initial burst of star formation, any evidence supporting an extended era of star formation, evidence of very early mergers of massive subcomponents, and the fraction of its mass that was contributed by late mergers. A further immediate problem concerns the composition of dwarfs measured from microlensing events versus the abundance scale measured from giants. A companion White Paper (Clarkson & Rich) addresses a set of bulge science questions that require observations at very high angular resolution.

How did the Milky Way bulge form, and how is it related to other major Galactic populations?

The central bulge of the Milky Way is one hundred times closer than that of M31, and is therefore by far the closest example we have of stellar population that might resemble more distant elliptical galaxies, like those in the Virgo cluster and beyond. The Galactic bulge is imperfect in this respect. Its dynamics and morphology place it in the category of pseudobulges, even if it is mostly old (Kormendy & Kennicutt 2004; Howard et al. 2009 in prep.). The bulge metallicity is not as high as that of the the most luminous elliptical galaxies (Puzia et al. 2002). But for the foreseeable future, it is our best laboratory for investigating these more distant stellar populations, and the bulge to our understanding of them (Renzini 2006).

At present, there are three broad notions about how bulges like ours might form (Fig1), and it is possible that all three processes might be important in the same stellar system. A longstanding scenario has bulges forming from early, violent mergers (Eggen, Lynden-Bell, & Sandage 1962) represented below by the LCDM model of Abadi et al. (2003). Updated to reflect the LCDM paradigm, bulges might form via an early, chaotic, process of star formation and violent relaxation, culminating in SN-drive winds. In a modification of this notion, we have merger from clumps (Imelli et al. 2004; Elmegreen et al. 2008), that might leave its calling card in the form of populations with distinct chemistry and perhaps also varying age and kinematic signatures. And finally, there is the idea of secular evolution (in depth discussion in Kormendy & Kennicutt 2004; Combes 2009) in which disk instabilities drive formation of a bar or peanut shaped bulge as occurs in N-body models. Of the three processes, secular evolution has the longest timescale (> 1 Gyr) and might be consistent with younger populations and later generations of star formation, while the merger scenarios might be more appropriate for luminous elliptical galaxies. We will pose our White Paper as a series of science questions.

1. Did the bulge form from a single enrichment event, or did it merge early on (Fig 1) from distinct chemical subcomponents; are the progeny of the first stars in the bulge? Mg and the ratios among the heavy neutron capture elements beyond the Fe peak constrain the importance of Type II SNe in the chemical enrichment (e.g. McWilliam 1997) vs. the longer timescale contributions of Type I SNe, which produce the iron that eventually pushes composition toward Solar. The site of the r-process is still debated, but variations in the r-process would almost certainly be telling in terms of revealing the properties of the massive stars that produced the SNe responsible for the enrichment of the bulge. The very prominent enhancement of Mg relative to iron in bulge giants shows clearly that the bulge's enrichment history is different from that of the disk (Figure 2). Scannapieco et al. (2006) predict that the first stellar generation formed in the cores of the dark matter potentials; could a population of ultra-metal poor stars in the bulge be observable today?



Note: this figure also appears in the Clarkson & Rich white paper and is reproduced here to support this science, as this paper is intended to be a stand-alone document

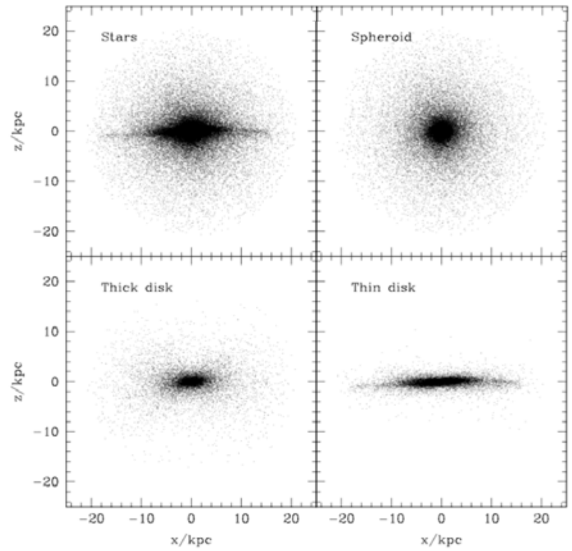
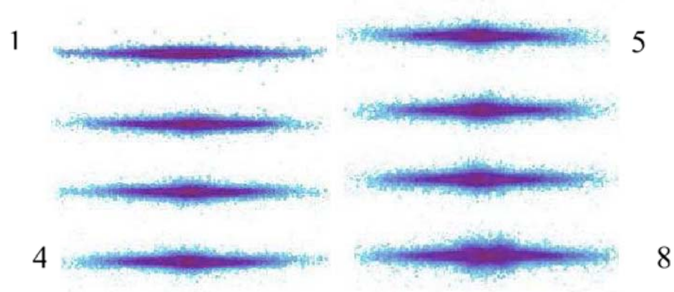


Fig. 1- A range of bulge formation scenarios, with observable consequences. *Upper Left color image:* upper panel (corresponding to the bimodal [Mg/Fe] distribution below) considers bulge formation via a merger of clumps (Imelli et al. 2004); lighter (single mode) histogram corresponds to standard scenario shown in lower color panel. This multimodal picture may be tested by very large sample, high resolution spectroscopic surveys. *(Upper Right):* LCDM model of Abadi et al. (2003) produces an old, spheroidal bulge population, but predicts little or no abundance gradient or rotation. *(Below):* According to Combes et al. (2009) the accretion of gas may promote the regeneration of a bar (peanut bulge) perhaps resulting in population subgroups exhibiting discrete ages and kinematics.



N-body model including gas accretion by Combes (2009). Numbers indicate the sequence of time steps, with time starting at upper left and proceeding down to step 4, with model continuing at step 5. Gas infall has regenerated the bar, which then thickens vertically into an x-shaped bulge.

2. What is the correct iron abundance scale for the bulge? A handful of microlensing event are extremely amplified by up to a factor of several hundred, briefly endowing a 6-10m telescope with the light gathering power of a telescope 20m or larger. A handful of the microlensed dwarfs have been analyzed in the literature and their metallicity distribution is not consistent with the distribution of the giants; the dwarfs are apparently iron-enhanced (Fig 3, left). When *log g* and T_{eff} are derived from the spectra, the stars fall on intermediate-age isochrones in the H-R diagram (Johnson et al. 2008). Cohen (2009; private com) report 5 out of 6 such microlensed bulge dwarfs are metal rich - [Fe/H]>+0.3.

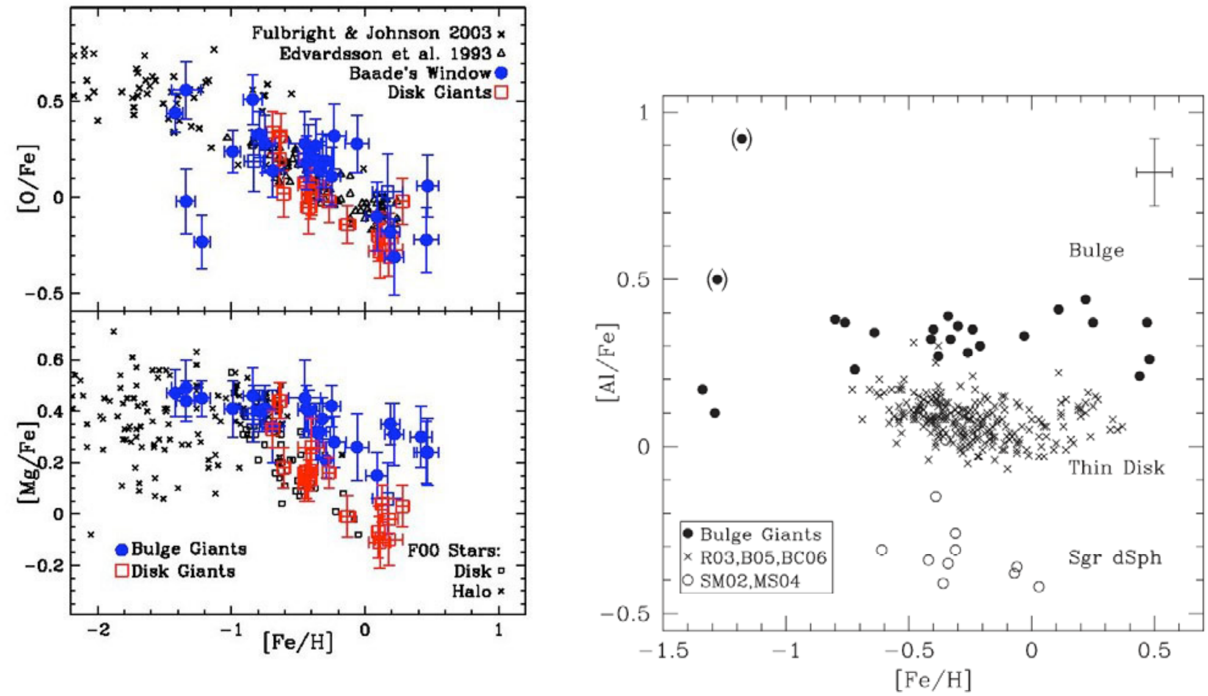


Fig 2-(Left): Behavior of Mg and O for Galactic bulge (Baade's Window) giants, as a function of [Fe/H], compared to disk giants. Notice that Mg is less enhanced than O, although [O/Fe] is elevated relative to the disk; the failure of Mg to track O might be due to the peculiar enrichment of SNe resulting from a hypothetical generation of massive, metal rich stars that lost their envelopes in a Wolf-Rayet wind (McWilliam et al. 2008). Models predict other observable consequences that might be tested with a wide field spectroscopic survey or observations in the infrared. (Right): [Al/Fe] is remarkably different for the Sgr dSph, thin disk, and bulge. Al might be a useful population marker in very large scale studies; stars with low [Al/Fe] would be candidates for membership in disrupted dSphs (plots from Fulbright et al. 2007).

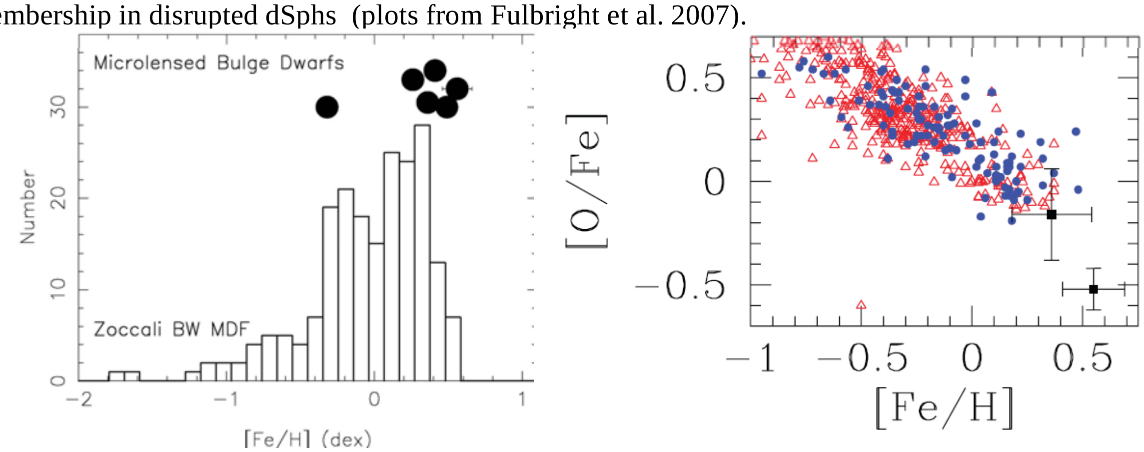


Fig 3-(Left): The abundance distribution derived from microlensed bulge dwarfs is compared with that of Zoccali et al. (2008) for bulge giants in the -6^{o} bulge field (Figure from Cohen, Bensby, & Johnson, private com.). 5 out of 6 microlensed dwarfs have [Fe/H]>+0.3, raising concerns that the bulge abundance scale derived from giants might not be correct (see Cohen et al. 2008). (Right): [O/Fe] for two microlensed bulge dwarfs (Johnson et al. 2008) follows the disk trend, in contrast to what is seen for the bulge giants (Figure 2).

Two lensed bulge dwarfs have [O/Fe] Solar (in contrast to bulge giants that are generally enhanced). Which abundance scale is correct? Is some process selectively removing the most luminous metal rich giants? If so, do we correctly know the abundances of spheroidal populations whose stars we cannot resolve? Dwarfs are unaffected by a host of nucleosynthetic processes that taint abundance determinations for the light elements in giants; hence spectroscopy of dwarfs is vital.

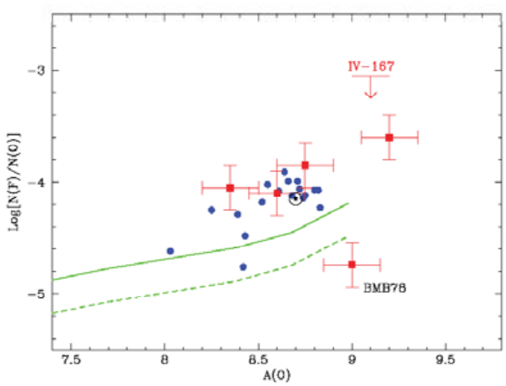
3. Why is the bulge composition not internally consistent with predictions for massive star nucleosynthesis? Although [Mg/Fe] and the explosive alphas (Si,Ca, Ti) are enhanced in bulge giants, O is markedly less so (Fulbright et al. 2007; Lecureur et al. 2007). Since O and Mg are modeled to form in the hydrostatic burning shells of massive stars, one would expect both of these alpha elements to be enhanced (Woosely & Weaver 1995). McWilliam et al. (2008) propose that selective mass loss in an early generation of massive Wolf-Rayet stars stripped the hydrostatic burning layers that would normally produce oxygen, instead shedding them into the ISM before oxygen could be produced. However, such a process would have other consequences, like an enhanced production of carbon. Can this anomaly be explained? If we find that carbon is not enhanced, we will need to pursue other explanations, and that in turn will require large scale surveys of bulge giants at high resolution. Why is the [O/Fe] measured from infrared studies (e.g. Rich & Origlia 2005, Rich et al. 2007; Cunha & Smith 2006) generally higher than that found from optical studies (Fulbright et al. 2007; Lecureur et al. 2007). The only published study of the r-process (McWilliam & Rich 1994) and preliminary analyses of heavy elements (Fulbright et al. 2009 in prep) do not find the expected enhancement of the r-process; this adds another troubling inconsistency to the picture of rapid, early, chemical enrichment for the bulge.

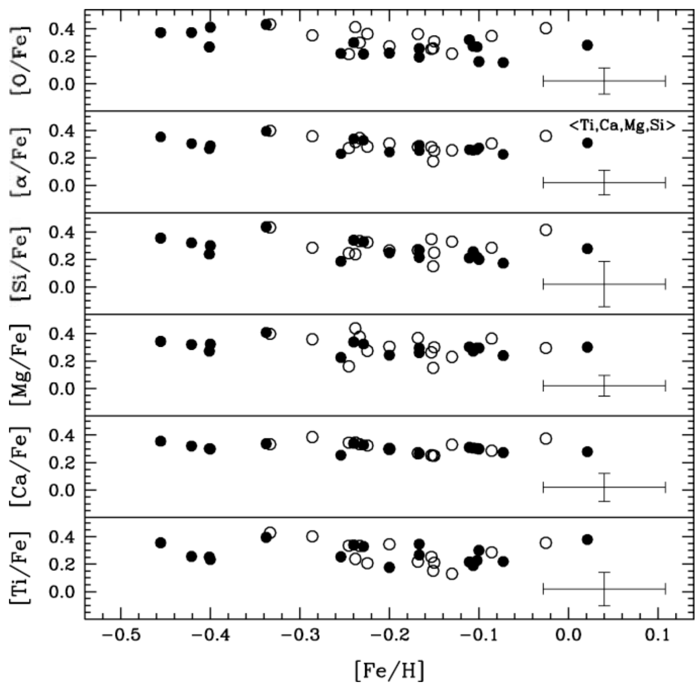
4. Was the chemical evolution of the bulge brief (<1 Gyr) or extended? To first order, the enhancements of Mg and the explosive alphas are consistent with a brief, explosive nucleosynthesis for the bulge. Yet we observe populations of evolved stars that are associated with massive progenitors, such as long period Miras and OH/IR stars (e.g. Groenewegen & Blommaert 1995). It is possible that the ongoing star formation in the inner 100 pc affected the chemical evolution in that volume, compared to the more distant bulge where the population is more uniformly old (Zoccali et al. 2003; Clarkson et al. 2008). The measurements of F and Rb, that are believed to be produced in intermediate mass AGB stars, are either available for only a handful of stars (Cunha et al. 2008) or lacking altogether.

5.How can the Galactic bar/bulge have an abundance gradient if it formed via a purely dynamical process? The dynamical characteristics of the Milky Way bulge are consistent with its being a rapidly rotating bar, and in the Binney plot (Figure 5 below) it falls among the pseudobulges. Howard et al. (2009; Figure 5) find evidence of cylindrical rotation (the same rotation speed at $b=-8^o$ as is found at $b=-4^o$) and the dynamics is most consistent with pseudobulges in N-body bar models. Zoccali et al. (2008) find a clear abundance gradient outside of -4^o. However, the physical mechanisms that are believed responsible for the vertical thickening of N-body bars are purely dynamical (e.g. Combes 2009) and there is no obvious path, other than (perhaps) an extended history of star formation or addition of younger material, that might produce an abundance gradient under such a formation scenario. Yet the evidence is strong that the bulge outside of 200 pc from the nucleus is dominated by an old population;

perhaps only 1% can be younger than 10 Gyr (Clarkson et al. 2009 in prep). The presence of this abundance gradient would appear to challenge the well established theoretical paradigm that explains the origin of bars via the dynamical instabilities of a massive disk. Note that this paradigm has implications for understanding galaxy evolution in general.

Fig 4-(Left): The first measurements of F (2.34um) for a handful of bulge giants (Cunha et al. 2008). F may constrain the importance of intermediate mass AGB stars in bulge nucleosynthesis. (Right): (Rich et al. 2007) Keck/nirspec abundances of alpha elements for bulge stars at -4^{o} (open circles) and -1^{o} (filled circles). All alpha elements are enhanced, with no evidence of an abundance gradient. Infrared spectroscopy gives the most secure measurements of CNO elements and is clearly in need of larger surveys.





6. Did the bulge experience any late accretion? How homogeneous is the bulge's chemistry? Is there evidence of multiple dynamical components/populations in the bulge? The LCDM paradigm favors mergers as being important in the formation history of galaxies. One might reasonably expect the bulge to have accreted mass via the infall of other systems, e.g. dwarf galaxies. The present generation of massive dwarf galaxies have subsolar [α/Fe] (e.g. Venn et al. 2004), while the newly identified low mass dwarfs are very metal poor (Simon & Geha 2007) as are a subset of the stars in the massive dSphs like Draco (Cohen & Huang 2009). Therefore, if some fraction of stars in the bulge today originated in such systems, there should be clear evidence from the chemistry and kinematics (Fig 2 [Al/Fe] varies by 1 dex, bulge to dSph).

Even proper motion-cleaned samples of bulge giants have blue stars that are brighter than the turnoff, yet pass the kinematic cut (Clarkson et al. 2008). Some of these stars are likely to be blue stragglers that belong to the old population, while some may in fact be genuinely young stars in the bulge with ages < 5 Gyr. One wants to study how this population and its properties vary throughout the bulge. Adding radial velocities to proper motions, along with effective temperature, gravity, and abundance, can help settle the question of the origin of these stars, and whether they are the progeny of the long period Mira, OH/IR, and SiC and similar AGB populations.

7. How does the composition of the bulge/bar relate to the nuclear region and to the inner disk? Present surveys of the bulge and thick disk populations have determined the compositions for tens or hundreds of stars (e.g. Fulbright et al. 2007; Lecureur et al. 2007). To extend these studies toward regions of higher extinction, one must push into the infrared, where to date only tens of stars have been subjected to abundance analysis (Ryde et al. 2009). The IR offers the best possibility to determine CNO and abundances of the light elements, and the iron peak is accessible (but the elements heavier than the iron peak are difficult). With effort, it may be possible to work redward of 8000A in regions of moderate extinction, but infrared techniques are required for spectroscopy in the inner 100 pc. The nuclear region is complicated, with a history of ongoing star formation and massive stars (Figer et al. 2004). It is likely that proper motion measurements will be made for stars in the inner pc scale, but it would be desirable to have spectroscopy (with abundances and radial velocities) that connects the nuclear region with the Galactic bulge.

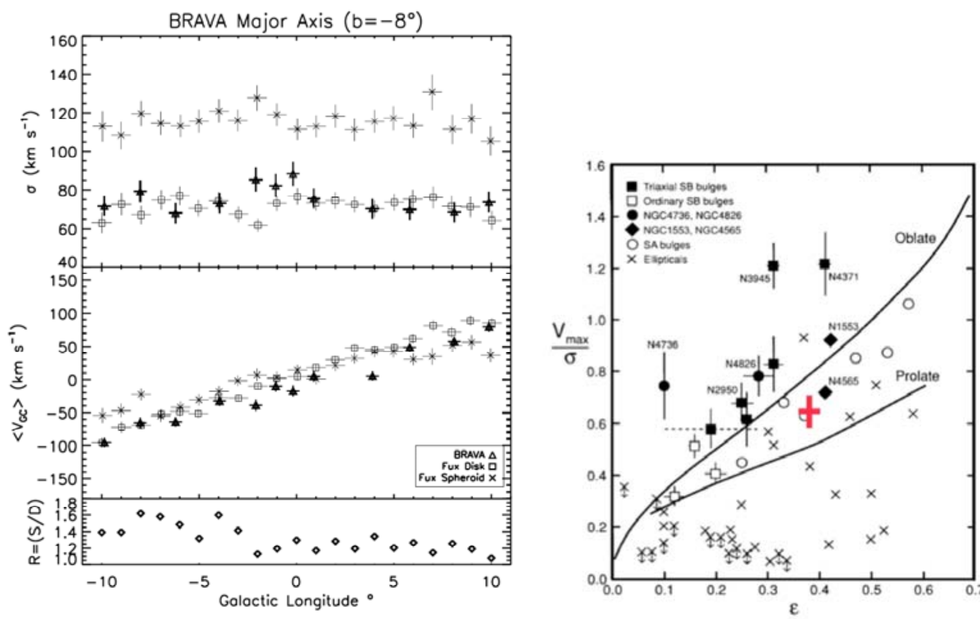


Fig 5-(Left) Bold points are mean radial velocity and dispersions for Galactic bulge fields from the BRAVA survey (Rich et al. 2007). Light open squares are the Fux (2009; private com) N-body "disk/bar" and the crosses are the Fux spheroid. Notice the excellent agreement with the N-body bar. (Right) Binney plot of rotation support vs. shape from Kennicutt & Kormendy (2004) including the Galactic bulge (red cross). The bulge falls among the pseudobulges including the peanut-bulge edge-on spiral, NGC 4565.

How can we address these questions with new facilities in the next decade?

We must settle the question of whether or not the bulge abundance scale derived from giants is correct. The bulge main sequence is faint (V>19) and crowded; success requires large ground-based telescopes with high resolution spectrographs (preferably multi-object) located at sites with excellent seeing. Slit-fed, high throughput, multiobject spectrographs on giant segmented telescopes, with R>15,000, are needed to settle Question 2 in a definitive manner. An example of such a proposed facility is MOBIE on the TMT. In the next decade, we might observe 100 microlensed dwarfs- maybe more. But we need *in situ* spectroscopy of hundreds of dwarfs in multiple bulge fields if we are to determine the abundance scale for the bulge/bar.

All of our science questions will benefit from a wide field, multifiber spectrograph on a 6-10m class telescope, provided R>30,000. Present facilities (FLAMES on the VLT) reach R~17,000 for the 100 fiber mode, and it is possible additionally to feed 8 fibers into UVES (attaining R~40,000). It is imperative that any new multiobject spectrograph reach no less than R=15,000, if slit fed, or R>30,000, if fiber fed. In general, spectroscopy of the bulge has been frustrating because bulge stars so faint (16<V<18) that spectroscopy even with a 10m telescope is time consuming; being metal rich and cool, the continuum is hard to locate amid a thicket of neutral iron-peak lines and molecular absorption. *Effective multiplexing at high resolution R>30,000 is crucial for meaningful progress.* A 6-10m class telescope will still require exposure times exceeding 8 hrs if we are to attain S/N>100; consequently one would like to observe >1000 stars at a time. An example of the required facility is WFMOS, proposed for the Gemini project. As spectral resolution increases, the lines deepen, and blends become less of a problem; the best resolution is the highest possible.

So much of the *mass* of our Galaxy is observed behind substantial extinction that pushing to the infrared is vital. Science question 7 will require large scale surveys in the infrared, at high resolution. The *APOGEE* survey is to obtain IR H-band spectra at R~20,000 for ~10^5 giants in the bulge and inner disk—addressing many of the science questions we raise here.

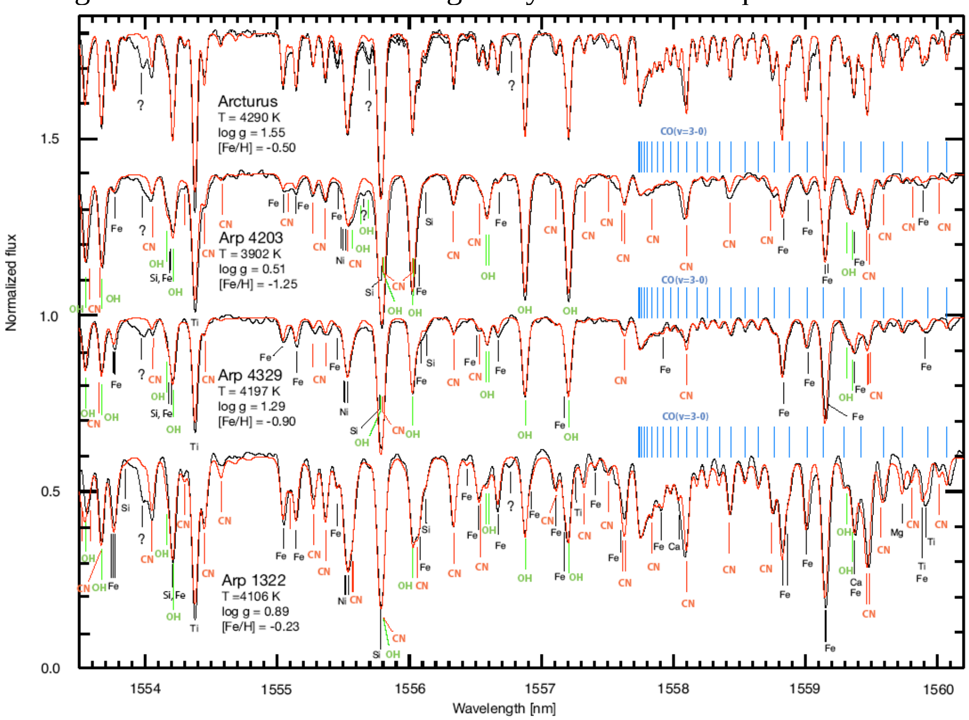


Fig 6- R=50,000 H band region for Arcturus and 3 Galactic bulge giants from Fulbright et al. 2007. Spectrum obtained with CRIRES (VLT) shows a wealth of CNO molecules, Fe, and alpha element lines available for study (Ryde et al. 2009). Unfortunately, there are few lines of elements heavier than iron in the IR; these are useful for learning element production in SNe and AGB stars. Optical high resolution is vital to get their abundances.

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