Formation and Evolution of Galaxy Bulges
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Kinematics and composition of the Galactic bulge: recent progress

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Abstract. We present recent results from a Keck study of the composition of the Galactic bulge, as well as results from the bulge Bulge Radial Velocity Assay (BRAVA). Culminating a 10 year investigation, Fulbright, McWilliam, & Rich (2006, 2007) solved the problem of deriving the iron abundance in the Galactic bulge, and find enhanced alpha element abundances, consistent with the earlier work of McWilliam & Rich (1994). We also report on a radial velocity survey of *2MASS*-selected M giant stars in the Galactic bulge, observed with the CTIO 4m Hydra multi-object spectrograph. This program is to test dynamical models of the bulge and to search for and map any dynamically cold substructure in the Galactic bulge. We show initial results on fields at $-10° < l < +10°$ and $b = -4°$. We construct a longitude-velocity plot for the bulge stars and the model data, and find that contrary to previous studies, the bulge does not rotate as a solid body; from $-5° < l < +5°$ the rotation curve has a slope of ≈ 100 km s^{-1} and flattens considerably at greater l and reaches a maximum rotation of 45 km s^{-1} (heliocentric) or ~ 70 km s^{-1} (Galactocentric). This rotation is slower than that predicted by the dynamical model of Zhao (1996).

Keywords. Galaxy: bulge, Galaxy: abundances, Galaxy: kinematics and dynamics, Galaxy: formation, galaxies: bulges

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The unique status of the bulge as a stellar population was not firmly established by Baade's discovery of RR Lyrae stars (already known in globular clusters) but rather by the discovery of huge numbers of M giants. These were cataloged using the 4m prime focus grism at Cerro Tololo (Blanco, McCarthy, & Blanco 1984). Discovered by the thousands in the bulge but rare in globular clusters, the M giants would unlock much of the nature of the population and its link to distant galaxies (Frogel & Whitford 1987). Significant advances also include Whitford's (1978) demonstration that the integrated light of the bulge resembles that of ellipticals, the first abundance survey using K giants (Rich 1988) and the demonstration that the abundance distribution fits the simple one zone model of chemical evolution (Rich 1990). The first high resolution study of bulge giants (McWilliam & Rich 1994) showed elevated Mg and alpha elements. This inspired numerous theoretical papers (e.g. Matteucci *et al.* 1999) that constrain from the elevated alphas, a rapid formation timescale of < 1 Gyr for the bulge. Recent efforts (Fig 1)confirm our high alphas (e.g. McWilliam & Rich 2004; Rich & Origlia 2005; Cunha & Smith 2006; Fulbright *et al.* 2007; Lecureur *et al.* 2007; Rich & Origlia 2007). Parenthetically,

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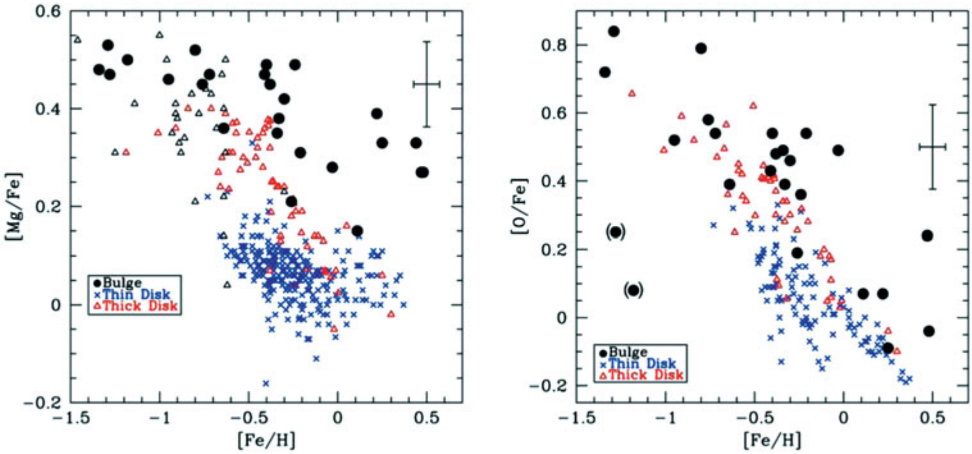

Figure 1. *(Left):* [Mg/Fe] vs [Fe/H] for the bulge relative to thin and thick disk populations (Fulbright *et al.* 2007). This confirms a long established result (McWilliam & Rich 1994) and is argued in chemical evolution models to support a rapid formation timescale of the bulge (cf. Matteucci *et al.* 1999) The same enhancement is also seen by Rich & Origlia (2005), Lecureur *et al.* (2007) and numerous other studies. *(Right):* Oxygen in the bulge, relative to thin and thick disk populations (see Fulbright *et al.* 2007 for details). Oxygen is less enhanced than Mg; this is unexpected since both elements should be synthesized in hydrostatic burning shells in massive stars. McWilliam *et al.* (2007) propose that oxygen was never produced in the outer layers shed metal rich stars with $M > 30 M_\odot$ in Wolf-Rayet like mass loss.

it is amusing that the [O/Fe] bulge study of Zoccali *et al.* (2007) rediscovers the rapid bulge formation timescale, but was also the subject of an ESO press release claiming the "discovery" of rapid bulge formation.

Recent optical abundance analyses were made possible by a novel solution of the iron abundance problem (Fulbright, McWilliam, & Rich 2006) whereby the extremely well studied red giant Arcturus takes the place of the Sun in providing physical oscillator strengths for iron lines that are weak enough that they retain their abundance sensitivity even at high [Fe/H]. A differential abundance analysis between bulge giants and Arcturus effectively removes lingering concerns about evolutionary status, gravity, and most importantly, non-plane parallel atmospheres. The proper solution of the iron abundance was a prerequisite to all subsequent optical studies of the composition.

The age of the bulge is hard to constrain, due to reddening, spatial depth, contamination from foreground disk stars, and an uncertain distance modulus. One option (Ortolani *et al.* 1995; Zoccali *et al.* 2003) compares the bulge field age with a metal rich globular cluster by force fitting the color-magnitude diagrams at the horizontal branch and main sequence turnoff; in the Zoccali study, the foreground disk was statistically subtracted from the bulge yielding a globular cluster age main sequence turnoff. Kuijken & Rich (2002) demonstrated that when the foreground disk is excised by a proper motion cut, the bulge shows a globular cluster-like turnoff and luminosity function. In any case, young stars *are* present in the inner 100 pc and toward the nucleus (cf. Figer *et al.* 2004). At present, the rapid bulge formation timescale implied by the composition is consistent with constraints from the age. Figure 2 also shows that the recent high resolution survey of abundances (Minniti & Zoccali 2007) is well fit by the One Zone model (confirming Rich 1990); this is consistent with the rapid formation timescale mentioned earlier.

Figures 1 and 2, show some of our core results from Fulbright, McWilliam, & Rich (2007), including the unexpected finding that oxygen is less enhanced than Mg. The

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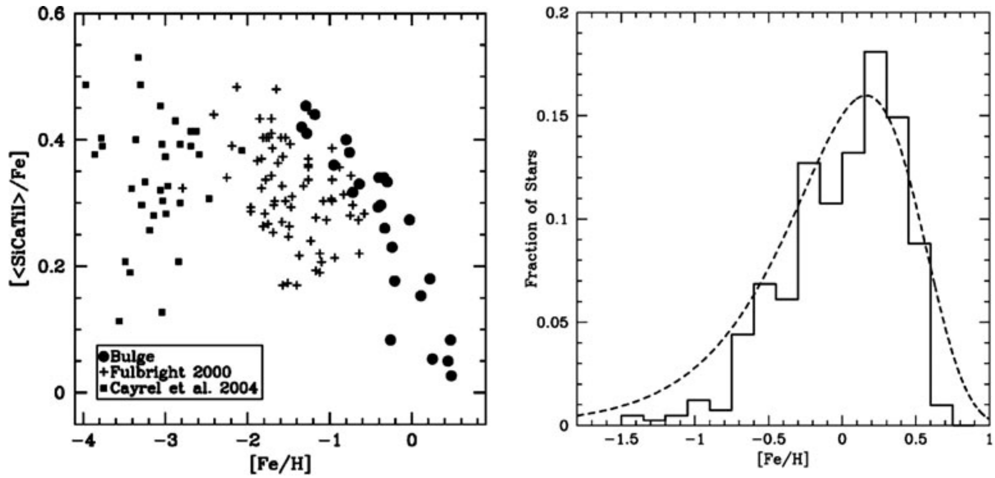

Figure 2. *(Left):* Compared to two Galactic halo samples, [< SiCaTi > /Fe] (alpha elements produced in the SN explosion) are enhanced in the bulge. Even at the lowest [Fe/H] in the bulge, the explosive alphas define the upper envelope of enhancement relative to the halo (see Fulbright, McWilliam, & Rich 2007 for details). *(right):* Fit of the Simple One Zone model of chemical evolution (Y=0.029) to an abundance distribution of 409 bulge giants near $(l, b) = (0°, -6°)$; Minniti & Zoccali 2007). The result confirms the Rich (1990) finding that the Simple model is a good fit to the bulge abundance distribution.

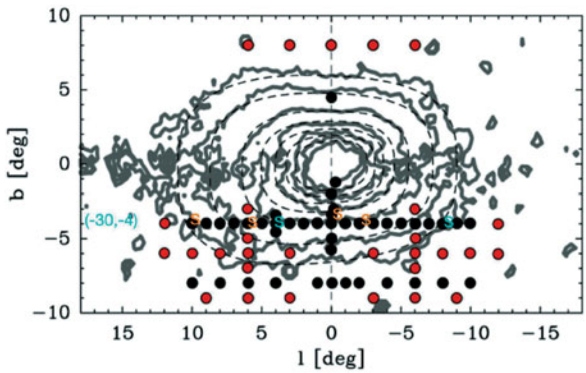

Figure 3. Galactic bulge fields in the *BRAVA* survey, superposed on the bulge 2μm map of Launhardt *et al.* (2002). Points indicated in red are proposed for 2008 with aim of testing for cylindrical rotation and symmetry; ‘S’ indicates $> 2\sigma$ “stream” candidates.

alpha elements Si, Ca, and Ti are thought to be produced in the SN explosion as opposed to O and Mg that are produced in the hydrostatic shells before the SN. The explosive alphas enhanced in the bulge relative to the halo over the full abundance range (Fig. 2). Both Fulbright *et al.* (2007) and Lecureur *et al.* (2007) note that Mg is enhanced even at high metallicity while O shows a much less prominent enhancement, following the disk trend. Considering that both O and Mg are produced in the hydrostatic burning shells of massive stars, the result is of concern. McWilliam & Rich (2004) speculate that mass loss in the early generation of massive stars via a Wolf-Rayet like mechanism might be responsible. Incorporating such mass loss for massive metal rich stars, Maeder (1992) find lower O yields; McWilliam *et al.* (2007) incorporate these into new chemical evolution models that now are consistent with the O vs Mg trends. While further confirmation is important, the O/Mg problem now has an acceptable explanation.

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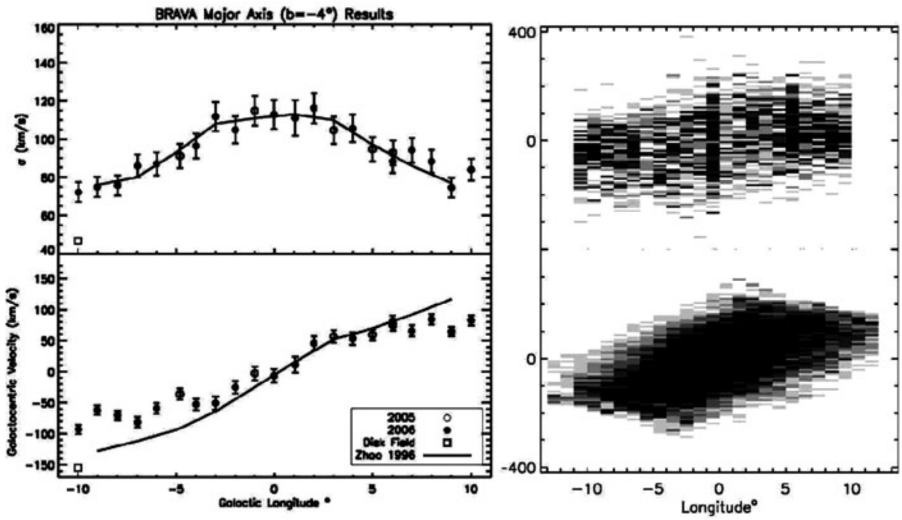

Figure 4. *(Left):* First and second moment results from *BRAVA* including Galactocentric correction, compared to the Zhao (1996) model predictions. Notice that no single solid body model fits this rotation curve. v, σ for the disk $(l, b) = -30^\circ, -4^\circ$ is indicated with an open square; disk contamination of *BRAVA* is ruled out. *(Right):* $l - v$ greyscale plot (heliocentric) for the bulge observations (upper) and the Zhao model (lower). The slower rotation of the data is evident. As the dataset improves the Zhao (1996) model will be adjusted to fit the data.

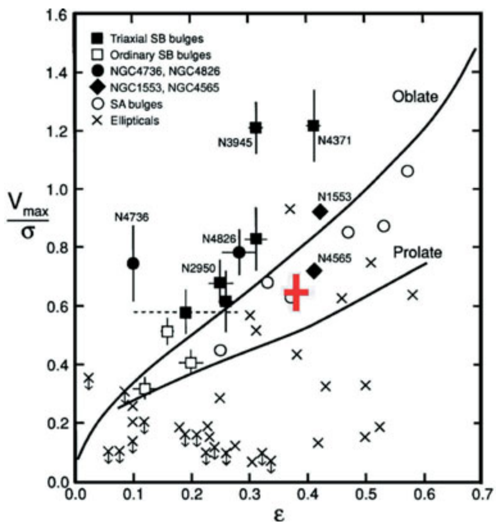

Figure 5. (V_{max}/σ) plot from Kormendy & Kennicutt (2004) with the Galactic bulge indicated (red cross). The MW bulge lies under the oblate supported line and less rotationally supported than the pseudobulges (filled symbols) but is similar to classical bulges (open symbols).

There have been many studies of bulge dynamics using a variety of probes. Early work includes that of Minniti (1992) for K giants and bulge globular clusters, while recently, PNe have been employed (Beaulieau *et al.* 2000). A host of late-type stars have been surveyed via radio techniques (e.g. SiC masers; Izumiura *et al.* 1995). With the completion of the 2MASS survey, I realized that M giants would make an ideal kinematic probe. We sample from the red giant branch in K, $J - K$ without metallicity bias (see Rich *et al.* 2007). M giants have both Ti O bands and the Ca infrared triplet, so there is

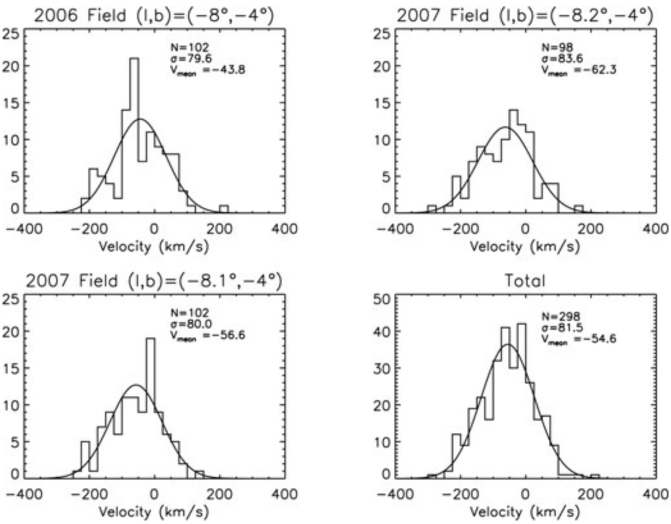

Figure 6. A single season of observations (upper left) finds a candidate 2.5 σ cold kinematic feature at $(l, b) = -8^{\circ}, -4^{\circ}$. New observations in 2007 did not confirm this feature; the summed velocity distribution appears Gaussian (lower right). *BRAVA* is finding a number of these candidates, each needing followup.

certainty of obtaining excellent radial velocities. Mould (1983) measured the first bulge velocity dispersion using M giants, while Sharples, Walker & Cropper (1990) employed multiobject fiber spectroscopy to the problem, yielding samples of ~ 250 stars. M giants are advantageous in that they represent a long lived evolutionary stage and are therefore common. Further, they account for much of the light at 2-4μm, the wavelengths for which maps of the bulge are constructed. We find that the M giants are excellent probes, giving repeat measurements of ~ 4 km s^{-1}.

The Zhao (1996) self-consistent rapidly rotating bar model was fit to extent velocity data. To best constrain the model, data spanning the greatest range across the bulge are needed in (l, b), along with a sample size large enough to produce a credible line of sight distribution. I concluded that the *BRAVA* survey would be the ideal path for constraining the bulge model. Examples of the line of sight velocity distribution are found in Rich *et al.* (2007) and Figure 6 of this work.

Figure 3 shows our existing survey and our proposed study for 2008. Fields probing the edges of the bulge will search for the cylindrical rotation that might be expected of a boxy pseudobulge (Kormendy & Kennicutt 2004) and probe asymmetries predicted by the Zhao (1996) model. We illustrate the resulting major axis rotation curve and l-v plot vs Zhao (1996) in Figure 4 compared with the Zhao rapidly rotating bar. Note that our plots also include dynamics of a disk field at $(l, b) = -30^{\circ}, -4^{\circ}$. We now have the benefit of hindsight: the K giant fields of Minniti *et al.* (1992) appear to fall on the *BRAVA*rotation curve, but their dispersion measurements lie below the M giants (see Minniti & Zoccali 2007), perhaps indicative of disk contamination. The bulge rotation curve departs from a solid body at roughly $\pm 4^{\circ}$; this is the first time such a departure is noted.

In my presentation, I asked how we would plot the BRAVA result on the Binney (1978) diagram. We estimate $\epsilon = 1 - e$ from Launhardt *et al.* (2002). V_{max} and σ are from Figure 4. We propose $V_{max} = 75\ km\ s^{-1}$ and $\sigma = 115\ km\ s^{-1}$ (giving 0.65 ± 0.5) with the main uncertainty arising from our lack of an extragalactic perspective on the

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Milky Way. One concern is whether there is a thick disk or bulge component outside of the central bulge isophotes that is colder and and more rapidly rotating. We place our bulge near that of NGC 4565, sometimes proposed as a twin of the Milky Way. The Galactic bulge *clearly* falls below the oblate rotator line and near classical bulges (as classified by Kormendy & Kennicutt 2004) and is significantly, more slowly rotating than proposed pseudobulges. As they note, it is not correct to classify bars as "rotation supported" and this diagram is of limited utility when in fact, we have the Zhao model and a huge kinematic sample.

We have seen hints of substructure in our data; 6 fields clump at the 2.5σ level. Figure 6 shows that with an increased sample size, one candidate is not confirmed. Substructure, arising from disrupting satellites, sub populations, or stars in unique orbit families, will be sought and confirmed by spatial coherence, kinematics, and abundance. In the future, it would also be desirable to constrain the makeup of the bar in terms of age and metallicity. Soto, Rich, & Kuijken (2007) use proper motions and radial velocity to find some indication that the bar at $(l, b) = (0.9°, -4°)$ is comprised of metal rich stars.

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