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Excerpt
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Part I

Abundances in the Galaxy: field stars

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Metal-rich stars and stellar populations: a brief history and new results

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The subject of metal-rich stars has been controversial for over 40 years, and I review some of the major developments in the subject area during that period, emphasizing those papers that set the subject on its present-day course. Metals emerge in the Universe at very high redshift, and galaxies with roughly Solar metallicity are documented even at redshift 3. In the local Universe, disks and bulges are often metal-rich, but metal-rich stars can also be found in distant halo populations, likely ejected into those environments by merger events. The Galactic bulge has a mean abundance of slightly subsolar but contains stars as metal-rich as [Fe/H] $\sim$+0.5; these stars have a complicated enhancement of light elements.

1 Introduction

As a graduate student in the 1980s, I was warned by senior colleagues to stay clear of the issue of high metallicity. That subject, it was said, had been controversial, and careers had foundered on claims of metallicity greater than Solar. My thesis work was on the Galactic bulge, and, in the long run, it would help to return the subject of super-metal-rich stars to respectability. Still, it is surprising that this is the first meeting on the metal-rich Universe. Spheroidal populations, which have elevated metallicity, account for some 50%–70% of the stellar mass in the local Universe (Fukugita *et al*. 1998), and are also known as the hosts of black holes (Tremaine *et al.* 2002). The era of metal production keeps getting pushed back to earlier and earlier epochs; metal lines are found in the most distant quasars, with FeII clearly appearing at $z = 6.4$ (Barth *et al.* 2003), less than 1 Gyr after the Big Bang. In the same quasar, $\sim 10^{10} M_{\odot}$ of molecular gas (CO-line emission) is observed (Walter

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et al. 2004). The association of quasars with galaxy bulges in formation marks them as evidently prodigious sources of metals in the early Universe.

By 2.4 Gyr after the Big Bang, at $z = 2.77$, in an exquisite study of a lensed star-forming (so-called Lyman-break) galaxy, MS 1512-cB58, Pettini *et al.* (2000) find a total metallicity of 0.25 Solar – quite respectable by the standards of the present-day Universe. Galaxies clearly built up their metals early and rapidly. Early spectroscopy of this distant starburst galaxy was of such high signal-to-noise ratio (SNR) that it was necessary to obtain better UV spectra of nearby starbursts in order to have a local comparison sample. The agents of metal buildup are massive stars, and this galaxy is a snapshot of chemical evolution in action. Since the pioneering work of Steidel *et al.* (1996) it has been found that the Lyman-break galaxy population is surprisingly metal-rich, with evidence of metal-enriched outflows. The work of Erb *et al.* (2006) uses the classical strong optical lines, shifted to the infrared, to derive abundances in a population of $z \sim 2$ galaxies. They find supersolar effective yields in their galaxy population and a gas outflow rate of approximately four times the star-formation rate. Although the data are less secure, the abundances derived from the broad lines of quasars have also been claimed to be high (e.g. Hamann *et al.* 2002).

The detection of high metallicity in this high-redshift galaxy should not come as a surprise to those who have followed the study of the Galactic bulge in recent years. Zoccali *et al.* (2003) show that the turnoff age for the bulge is comparable to that of a metal-rich halo globular cluster and estimate an age for the bulge in excess of 10 Gyr, a secure demonstration of the great age hinted at in prior studies (Ortolani *et al.* 1995, Kuijken & Rich 2002). The observation of nearly Solar metallicity at high redshift should come as an expectation, not a surprise.

Yet another means of quantitative measurement of metals in the high-redshift Universe is offered by damped Lyman-alpha systems in quasars. These are gas clouds of sufficient H I column that the associated Lyman-alpha lines have damping wings; associated with these clouds are also metal lines, and it is possible to derive a surprisingly accurate metal abundance for these systems. Dessauges-Zavadsky *et al.* (2006) analyze systems over a redshift range of $1.8 < z < 2.5$, ranging from 1/55 to 1/5 the Solar iron abundance.

Metals at redshift 6 are not confined to quasars or distinct bodies like Lyman-limit or damped Lyman-alpha systems. Metals are distributed widely; Sargent, Simcoe, and collaborators (e.g. Becker *et al.* 2006) have used statistical methods to find C, O, and Si in the intergalactic medium at $z \sim 6$, presumably placed there by wind outflow from star-forming galaxies. There are metals in the Universe as far as the eye can see.

Returning closer to home, metal-rich populations are found in surprising venues. The well-studied open cluster NGC 6791 is found to have [Fe/H] $= +0.4$ even with modern abundance determinations (Gratton *et al.* 2006; Origlia *et al.* 2006). The

Sagittarius dwarf spheroidal galaxy has abundances up to Solar (McWilliam *et al.* 2003; Sbordone *et al.* 2006). Even the stellar halos of luminous galaxies have metallicities approaching Solar (Mouhcine *et al.* 2005b), as does the outer disk of M31 some 30 kpc from the nucleus (Brown *et al.* 2006). Regions and stars of high metallicity provide insight into the star-formation process and nucleosynthesis, and it is now clear that regions of high metallicity must be considered to be of great importance in the formation of galaxies and that they are widespread, not only confined to the nuclear regions.

2 A brief history of supermetallicity

In the 1950s, spectroscopists were aware that the nucleus of M31 has strong CN lines, with strengths similar to the line strengths found for stars in the Solar vicinity (Morgan 1958). Baade (1963) stated that "After the first generation of stars has been formed, we can hardly speak of a generation, because the enrichment takes place so soon, and there is probably very little time difference. So the CN giants that contribute most of the light in the nuclear region of the Nebula must also be called old stars; they are not young." This is a remarkably prescient insight that largely describes the present-day picture of the chemical evolution of spheroids.

The work of Spinrad & Taylor (1969) is considered the seminal work on supermetallicity, but it was predated by an interest in the spectroscopy of galaxies (Spinrad 1961) that resulted in the identification of strong Na lines in the nucleus of M31, a finding that was to be a subject of debate for over two decades. Hindsight finds the most extreme metallicities ([Fe/H] = +0.75 for NGC 6791) to be skirting the bounds of credibility, and this no doubt has contributed to the general atmosphere of skepticism; but one must consider the state of abundance analysis at that time. No doubt NGC 6791 remains today the most metal-rich open cluster; Spinrad and Taylor at least succeeded in getting the correct ranking. Was the supermetallicity in fact a real phenomenon? On the one hand, Gustafsson *et al.* (1974) argued for its reality, using narrow-band *photometry* (with a pulse-counting photometer) of spectral regions selected to have clumps of weak iron lines adjacent to clean continuum; this was an innovative method for its time and turns out to have given the correct answer. On the other hand, Peterson (1976) argued that supermetallicity was spurious and arises from the temperature profile of the stellar atmosphere (boundary cooling). The argument stated that excess CN causes a steepening of the boundary temperature gradient; the anomalous cooling strengthens the lines of neutral metals. This in turn masquerades as supermetallicity. The dispute was largely settled by two papers. The first was that of Branch *et al.* (1978), which was the first modern analysis of the prototype super-metal-rich (SMR) star μ-Leonis, using a reticon detector that yielded spectra with very high SNR (Figure 1.1). The application of a modern detector with a linear response and the capability to produce high-SNR

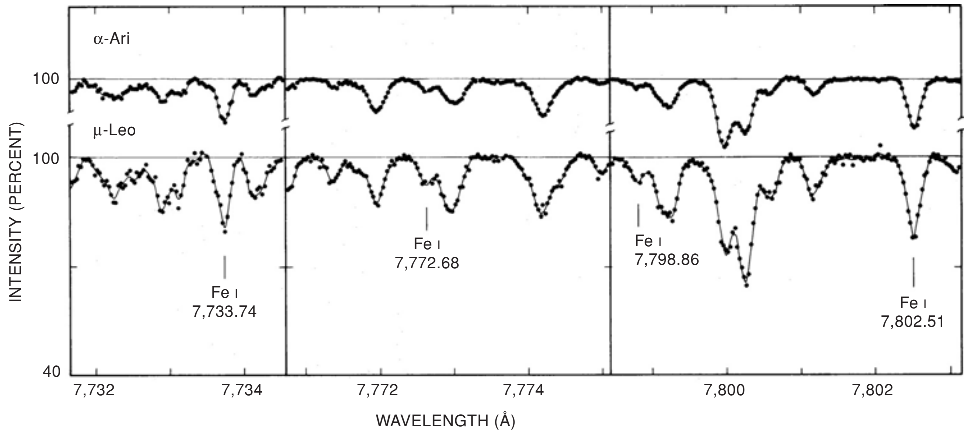

Figure 1.1. One of the first high-resolution digital reticon spectra of μ-Leo, the comparison with Solar-metallicity α-Ari shows the clear enhancement of the weak iron lines relative to the continuum (Branch *et al.* 1978). The enhancement of metals in the super-metal-rich star μ-Leo ([Fe/H] = +0.3) is obvious.

data represented a breakthrough in the subject. While the abundance of μ-Leonis is debated at the 0.1-dex level, that study finds what is essentially the modern value of [Fe/H] for μ-Leonis. The second was that of Deming & Butler (1979), who considered the abundances of binary-star companions of SMR stars; these authors also find a genuinely elevated iron abundance in SMR stars. Deming (1980) argued that Peterson's work had been affected by a subtle misplacement of the continuum in her photographic spectra (a continuum misplacement of 1% leading to a 0.1-dex effect on metallicity).

A sidebar to this debate was Spinrad's (1961) claim that enhanced Na D lines in the M31 nucleus argued for dwarf enhancement in that population. The resulting controversy continued through studies by Whitford (1977), on the FeH Wing–Ford bands, and Faber & French (1980), on the Na 8190 lines in the nucleus of M31, while ultimately settling on giant-dominated light on the basis of infrared studies (e.g. Frogel & Whitford 1987). Studies of the Galactic-bulge luminosity function (Zoccali *et al.* 2000) do not find an abnormally bottom-heavy mass function; the issue is resolved in favor of giant-dominated light.

The effect of the debate over supermetallicity has been, nonetheless, to cast aspersions on the subject. That is in part why we had to wait until 2006 for a meeting on the metal-rich Universe.

2.1 Supermetallicity and stellar evolution

The rich globular cluster systems of the Milky Way and the Magellanic Clouds have provided a set of stellar-population templates spanning from very low to Solar metallicity. However, only the open cluster NGC 6791 is metal rich at +0.4 dex. The Galactic bulge is a complex population with a range in abundance with even some age spread possible; see e.g. Zoccali *et al.* (2003). At high metallicity, we observe the RGB to become dominated by M giants; metal-line and TiO opacity in those stars can cause the V magnitude of the RGB tip to be as faint as the horizonal branch. The I band is also affected; the first giant-branch tip appears to curve downward or descend. The AGB becomes populated with Miras and OH/IR stars; these are numerous in the bulge, and the early work of Blanco found large numbers of M giants toward the Galactic Center. The progression to cool, luminous giant branches with Mira and OH/IR stars is the dominant effect observed at high metallicity.

The helium-burning stars are generally confined to the red clump, with a blue horizontal-branch extension seen only in old, metal-poor populations – at least in the classical view of stellar populations. However, blue EHB populations are observed in NGC 6388 and 6441. These are not super-metal-rich clusters, but are metal-rich enough that such blue HBs should not exist (Rich *et al.* 1997). Blue HB stars are also found in NGC 6791 (Peterson & Green 1998). In red elliptical galaxies with no sign of star formation, a hot component (now known as the UVX) has been detected since the early days of satellite astronomy (Code 1969) and remains unexplained (O'Connell 1999). Burstein *et al.* (1988) in an influential paper found that ellipticals and bulges exhibit a correlation between the UVX and the metallicity-sensitive Mg_2 index; this has not been confirmed in a larger sample of GALEX-selected quiescent early-type galaxies from the SDSS (Rich *et al.* 2005) and there remains only a weak correlation in a larger sample of nearby elliptical galaxies (Rich *et al.*, work in preparation). While UV light is present in many early-type galaxies, its cause remains mysterious. A full review is beyond the scope of this paper, but additional factors (subpopulations with enhanced helium abundance) might be at play.

3 Supermetallicity in stellar populations

The major paradigm in the chemical evolution of stellar populations is that the chemical enrichment due to massive-star SNe relative to Type Ia SNe reflects the rate of star formation; the emergence of Solar abundance ratios is a reflection of the point at which the Type Ia SNe begin to produce substantial iron (Wheeler *et al.* 1989; McWilliam 1997).

Metal-rich populations have turned up in unexpected locations, not only in the Galactic bulge or elliptical galaxies. In Baade's original population model, Population II was thought to be older and more globular-cluster-like, and therefore more metal-poor. These ideas persisted well into the 1950s, aided by the

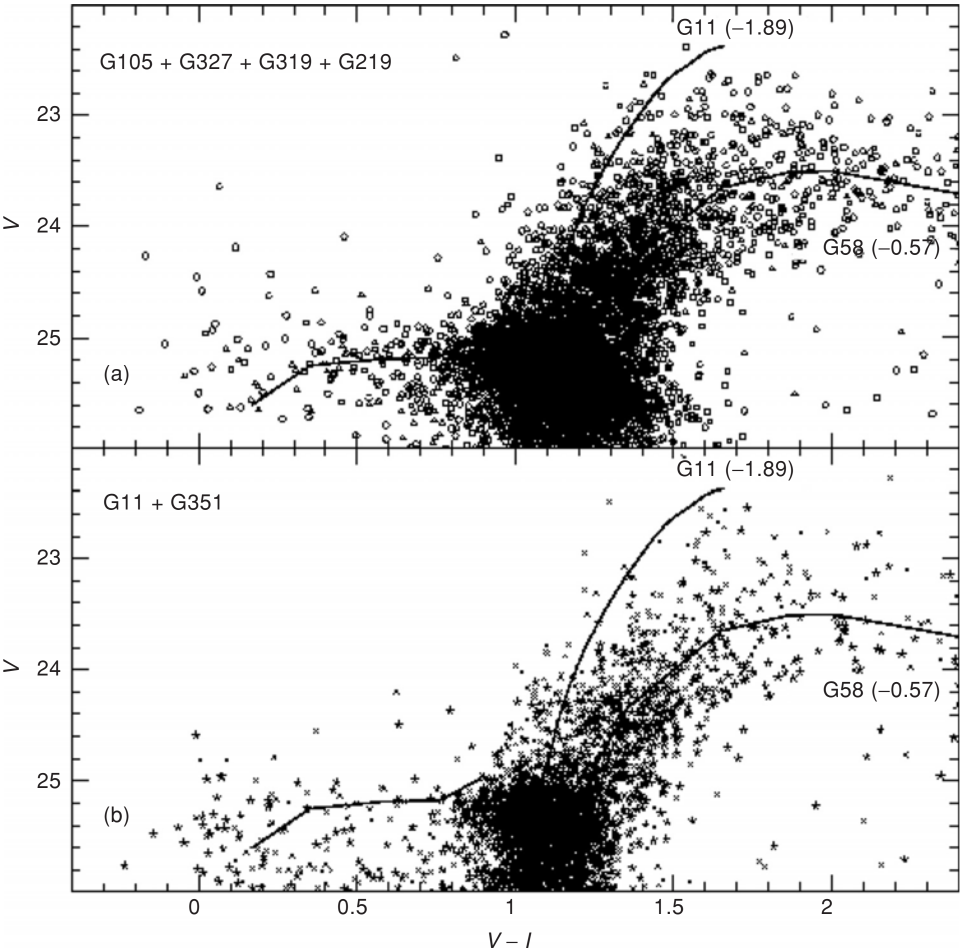

Figure 1.2. Color–magnitude diagrams of the field population in the halo of M31, derived from the field populations of the globular clusters indicated, obtained using WFPC2 on the HST (Bellazini *et al*. 2003). The blue HB ridgeline is that for M68 while the RGB ridges are for G11 ([Fe/H = −2) and G58 ([Fe/H] = −0.6). Notice the large numbers of fainter, redder stars that must clearly be more metal-rich. These populations may reflect either an extension of the spheroid or the debris of merger events.

difficulties of actually making quantitative measurements in the Galactic bulge. At present, metal-rich stars are found in the old (10–11 Gyr) disk (Castro *et al.* 1997; Pompeia *et al.* 2002, 2003) and in NGC 6791, as mentioned earlier. In fact, the metallicities of these populations reach extremes as high as those found in the Galactic bulge. One important difference, however, is that these disk populations generally have scaled Solar abundances for the light elements, in contrast with the bulge, for which the levels of light elements (especially Mg) remain enhanced to

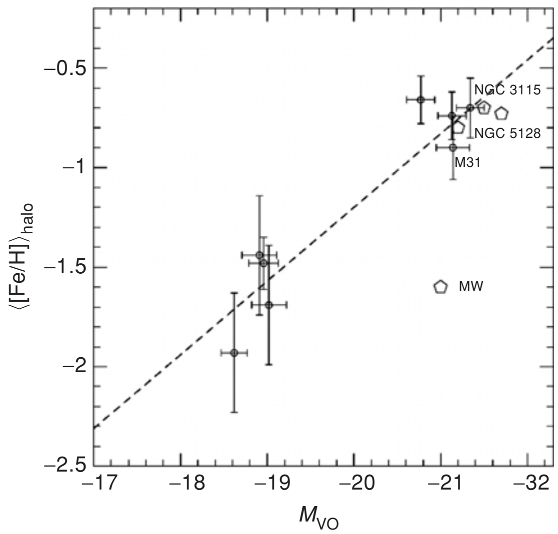

Figure 1.3. Correlation between the photometric metallicity (from the red giant-branch color) of halo populations roughly 10 kpc distant from the plane, and luminosity, for spiral and S0 galaxies (Mouhcine *et al.* 2005a). At this time, it is not clear whether we are observing a trend, or a bimodal distribution, where the presence of metal-rich stars arises from the extension of massive bulges. In some of the most luminous galaxies, it appears that the halo is indeed an outer extension of the spheroid. However, the distant-field population in M31 is polluted by material from merger remnants; this process likely also populates the halo with metal-rich stars.

metallicities even above the Solar value. The galaxy NGC 6791 has, in fact, subsolar abundances.

There is now evidence for resolved metal-rich populations in the halo and disk of M31. Bellazzini *et al.* (2003) find descending metal-rich giant branches in the M31 halo (Figure 1.2), and numerous studies since the pioneering work of Mould & Kristian (1986) find a metal-rich halo extended to 30 kpc (e.g. Durrell *et al.* 2004). Brown *et al.* (2003, 2006) have undertaken deep HST/ACS imaging of M31 halo fields and find evidence for suprasolar metallicities both in the disk (32 kpc distant from the nucleus) and in the spheroid (12 kpc from the nucleus). In the case of the M31 fields, the case for the super-metal-rich populations is based on the modeling of the main-sequence turnoff. Keck spectroscopy of the stars in these populations (Koch *et al.*, work in preparation) now in progress will further test whether super-metal-rich stars are present in these low-density environments.

The galaxy M31 is not alone in possessing an extended population of metal-rich stars. Mouhcine *et al.* (2005a) find a trend of halo metallicity with parent-galaxy luminosity (Figure 1.3), with the field populations spanning 1.5 dex in metallicity. However, M31 does remain as having among the most metal-rich halos in our sample of nine galaxies. Is the complex interaction history of M31 an anomaly, or does it suggest a mechanism for populating the stellar content of the halos of massive galaxies? Since it is difficult to form metal-rich stars in the very-low-density environments of halos, one might instead suspect that these stars form in dense star clusters or in bulges and inner disks. It is more likely that the presence of these metal-rich populations at great distances is the result of their ejection via one or more significant mergers; it will be interesting to model this mechanism in detail.

4 The Galactic bulge

The metal-rich populations in NGC 6791 and the old disk have Solar or subsolar scaled alpha abundances, suggesting that those populations have enriched over timescales longer than 1 Gyr, so that Type Ia SNe stars had time to contribute substantial iron. Bulges form more rapidly. The Galactic bulge's formation timescale is likely $\sim$1 Gyr or less (Ortolani *et al.* 1995; Zoccali *et al.* 2003). When disk stars in the foreground of the bulge are excluded by proper motion (Kuijken & Rich 2002) the remaining bulge population bears a strong resemblance to the main-sequence turnoff of an old globular cluster; the constraint on the numbers of stars brighter than the turnoff (even blue stragglers) is remarkable. In short, there appears to be very little room for an extended star-formation history in the bulge, arguing both from the standpoint of the main-sequence turnoff and from the chemical-enrichment perspective (see below).

In the case of the bulge, the Blancos produced an R, I color–magnitude diagram that for the first time revealed a clear red giant branch. Armed with the new pulse-counting detectors developed by Shectman at Las Campanas, Whitford and I took the first digital spectra of bulge giants in the 1980s (Whitford & Rich 1983). At the telescope, the bulge giants looked remarkable, especially their strong Na D and Mg lines, which exceeded dramatically anything from the standard stars. My original abundance scale was high (another pang in the supermetallicity controversy). Two factors likely contributed to this. First, I derived an abundance scale based on iron, but using the Mg b 5170 (Mg2) index (and not accounting for selective Mg enhancement). A second factor is more subtle: the standard stars observed in Rich (1988) and Rich (1990) were very bright and were observed behind heavy neutral-density filters. Even so, they frequently came close to or exceeded the coincidence count limits, diminishing the measured depth of the Mg index in the standard stars. Nonetheless, the Rich (1990) abundance scale was only 0.3 dex higher than the McWilliam & Rich (1994) scale based on high-resolution echelle spectra. The present-day iron-abundance scale of Fulbright *et al.* (2006a), derived from $R =$ 67,000, SNR $>$ 50 Keck echelle spectra, is very close to the original McWilliam &

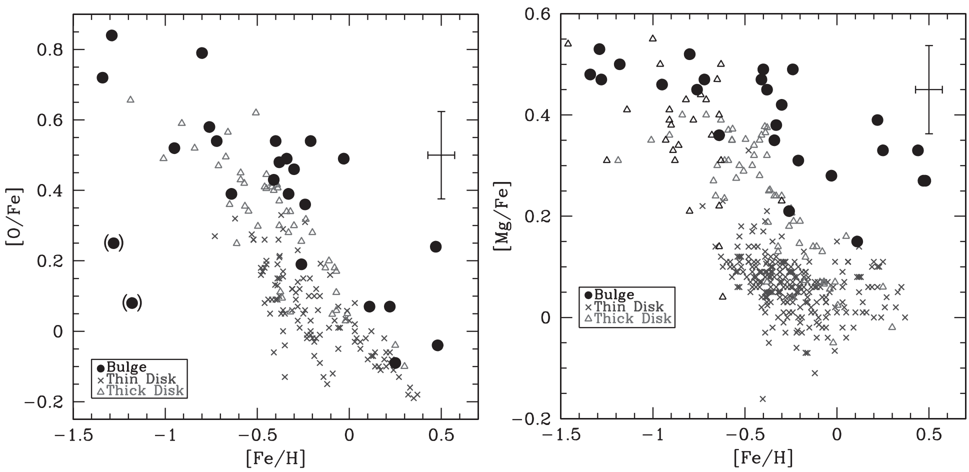

Figure 1.4. Left panel: [O/Fe] versus [Fe/H] for Galactic-bulge giants (filled symbols) and the thin/thick-disk population (Fulbright *et al.* 2006b). Notice that the bulge [O/Fe] is only mildly elevated relative to the disk. Right panel: the trend of [Mg/Fe] versus [Fe/H] for the bulge stars (filled symbols), also from Fulbright *et al.* (2006b). Notice the very strong enhancement of Mg that is carried through to the highest metallicities. This is not characteristic of the SMR disk population. The enhancement in Mg is also seen in the integrated light of elliptical galaxies (Worthey *et al.* 1992).

Rich (1994) scale. The mean [Fe/H] is slightly subsolar, extending to [Fe/H] = +0.5 (which is also, coincidentally, the upper limit of the old disk stars). With the problem of the bulge iron-abundance scale settled (Fulbright *et al.* 2006a) we may turn to the determination of the alpha abundances (Fulbright *et al.* 2006b). However, we should emphasize that the bulge is not extremely metal-rich; rather, ⟨[Fe/H]⟩ is somewhat subsolar. It is in the alpha elements than one can observe striking differences in composition relative to the disk. Figure 1.4 shows a fundamental result that has been established since McWilliam & Rich (1994): that Mg remains elevated in the bulge to [Fe/H] = +0.5. It has been known for more than a decade that Mg is also elevated in massive elliptical galaxies (Worthey *et al.* 1992). However, oxygen, which is also believed to be formed in hydrostatic burning, follows a trend very similar to that of the disk, with only marginal elevation relative to the Solar vicinity. Because O and Mg are believed to be produced in the hydrostatic burning envelopes of massive stars, the disconnect between these two elements is not understood. Fortunately, both our results and that of Zoccali *et al.* (2006), derived on a different sample of bulge giants, find this trend for oxygen. It is possible that the early generations of massive stars underwent substantial mass loss via a Wolf–Rayet phase; much of the outer envelope was lost to the interstellar medium before the nucleosynthesis of substantial oxygen (McWilliam & Rich 2004).