Galactic Globular Clusters and Other Gifts for Bob Kraft

Judith G. Cohen – Caltech – July 2011

Outline

NGC 2419 – Cohen, Kirby, Simon, & Geha, ApJ 2010, Cohen, Huang & Kirby, ApJ submitted

M15 Rare Earths and C-star – Cohen & Melendez, unpublished

M92 Rare Earths – Cohen, ApJL, submitted

M92 – A Study of Diffusion, Cohen, as yet unpublished

How We Went Astray with Terzan 5 – Cohen & Kirby, unpublished

EMP Halo Field Star Abundances – Cohen for the the 0Z Project

A Present from the Palomar Transient Facility – Branimir Sesar, Carl Grillmair, J. Cohen & the PTF Collaboration

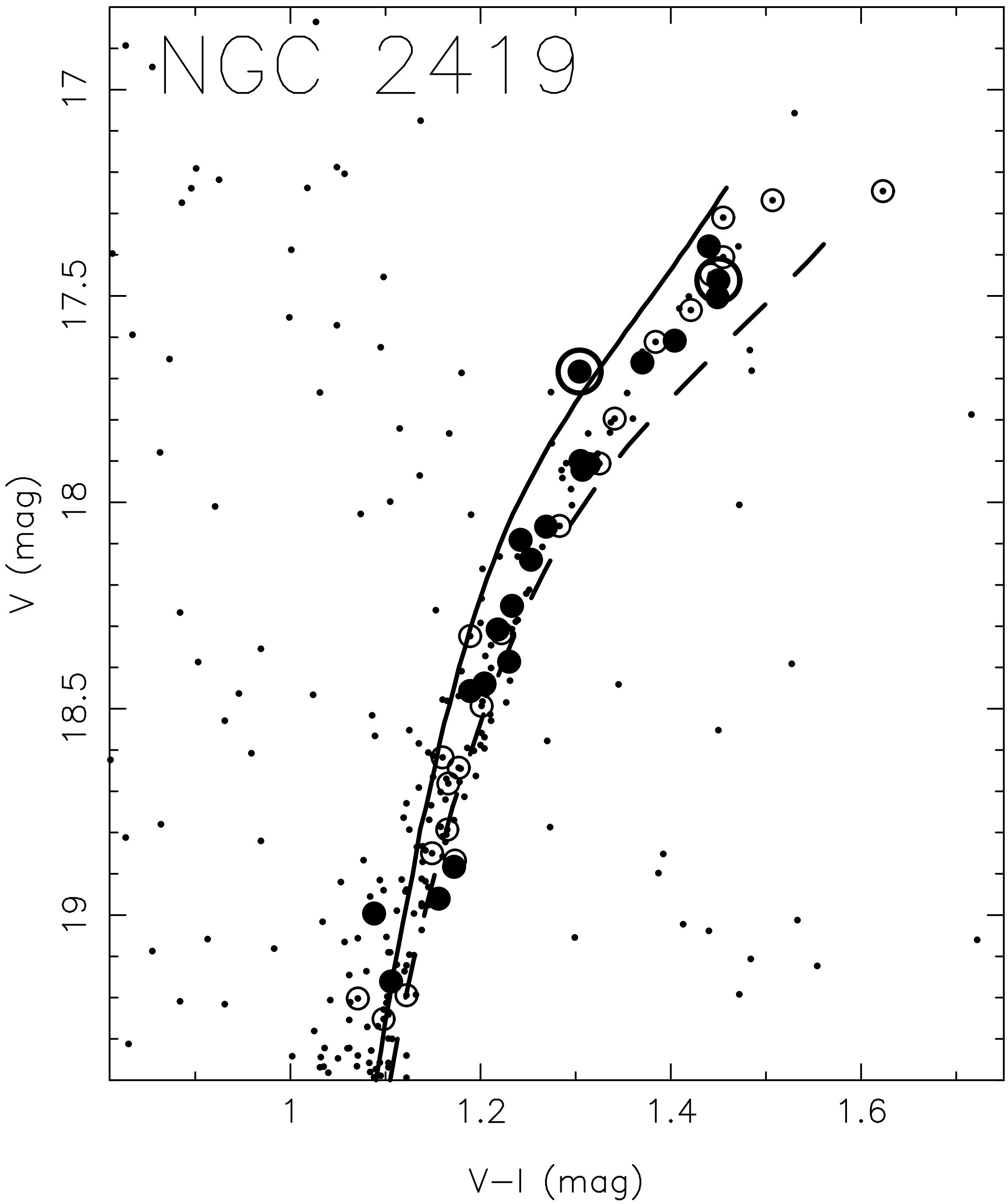

Fig. 1.— The V, V–I CMD for the database of Stetson (2005) in the field of NGC 2419. Those stars in the DEIMOS slitmasks judged to be members of the GC are indicated by open circles (low CaT) or filled circles (high CaT). The two stars whose membership status is still uncertain are circled. Isochrones from Yi et al (2003) with [α/Fe] 0.3 dex, age 12 Gyr, and [Fe/H] -1.90 (dashed line) and -2.2 dex (solid line) (interpolated using the code they supply) are shown. A 0.04 mag offset in $V - I$ was applied to both isochrones to improve the fit to the observations. (Cohen, Kirby, Simon, & Geha 2010)

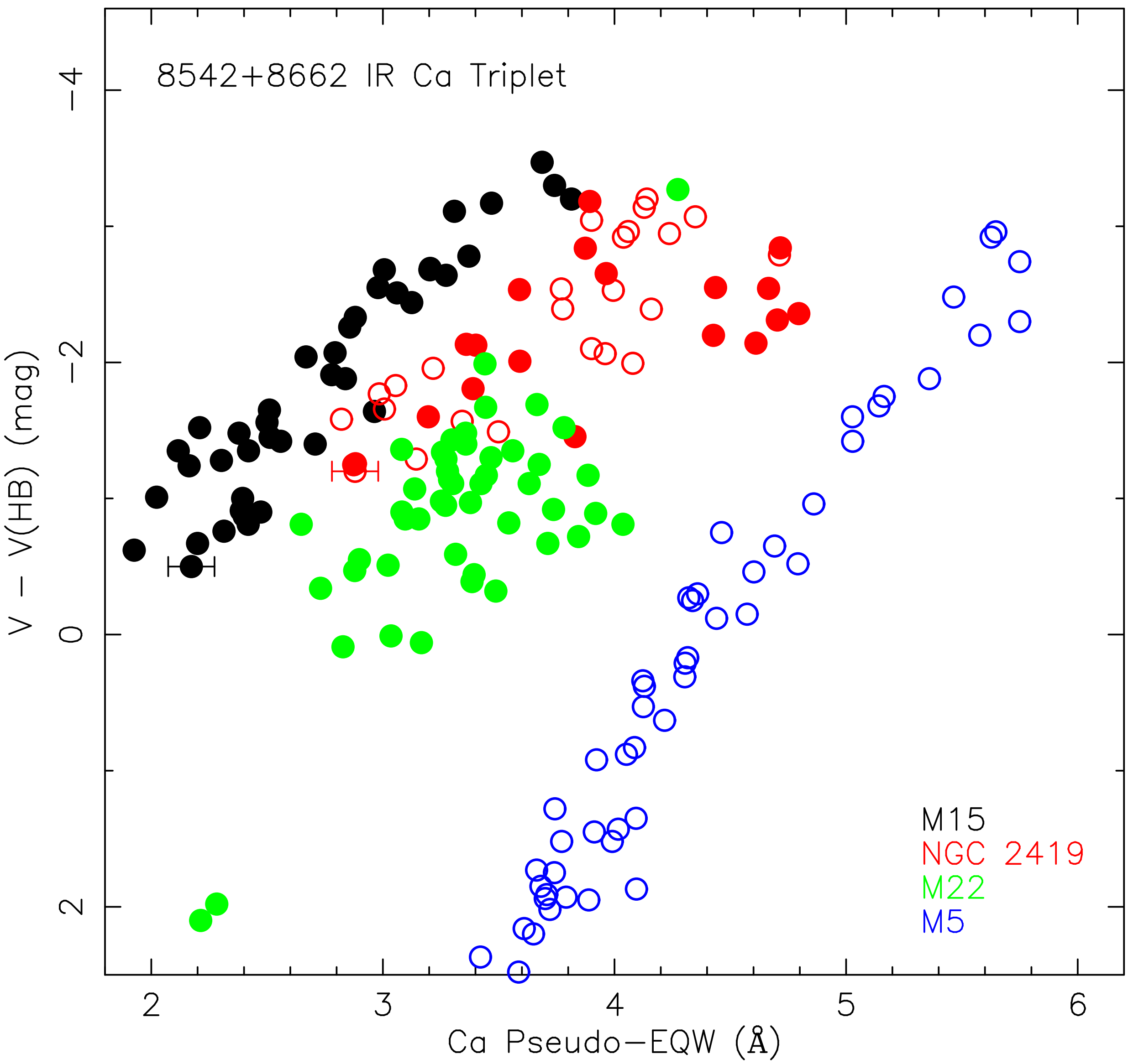

Fig. 2.— The sum of the pseudo-equivalent widths for the two stronger lines of the near-infrared Ca triplet are shown as a function of M_V corrected for extinction and normalized with respect to the location of the horizontal branch for four globular clusters (M15, NGC 2419, M22, and M5, in order of increasing metallicity), each shown as a different color. The NGC 2419 apparent members, shown in red, are filled circles if the star was on both DEIMOS slitmasks, and open circles if included in only one of the two slitmasks. The two stars whose membership in NGC 2419 is still uncertain are not shown. Non-members have been carefully eliminated for NGC 2419 only. The GC M22, which like NGC 2419, also shows a significant spread in this figure, is known to have a small internal range in [Ca/H]. (Cohen, Kirby, Simon, & Geha 2010)

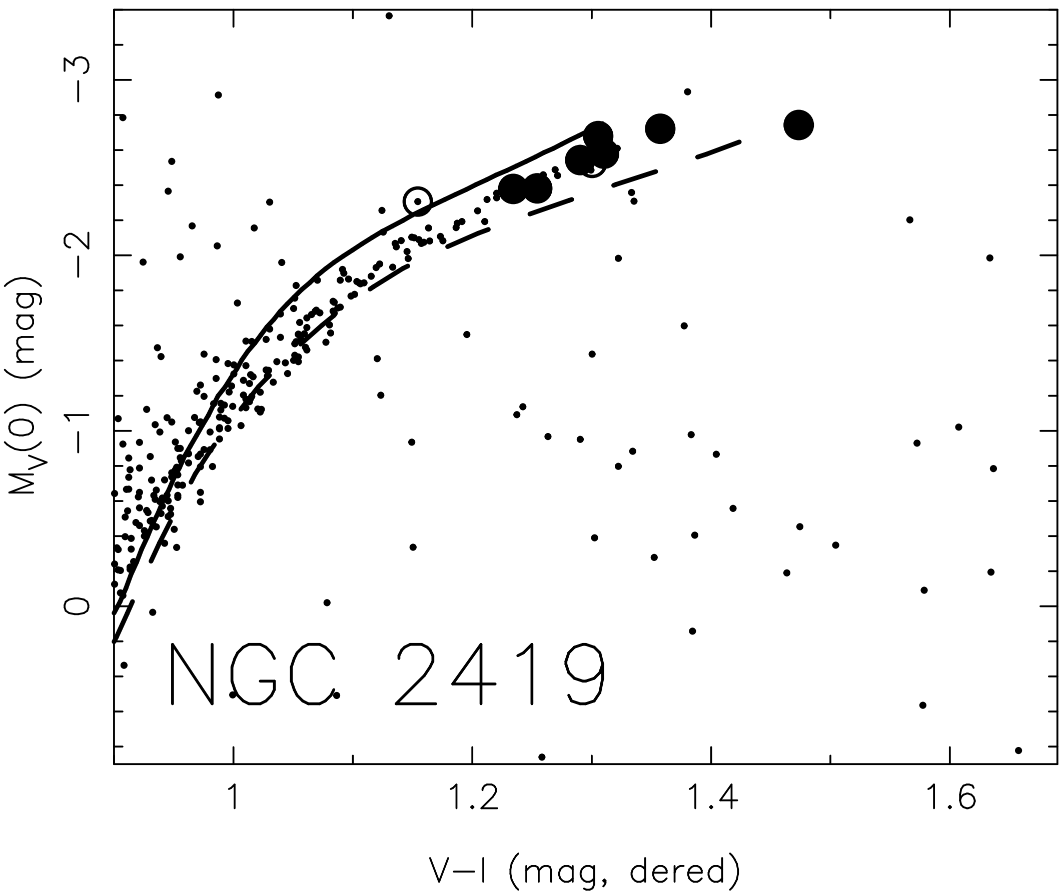

Fig. 3.— A $M_V(0)\ -\ (V-I)_0$ CMD for the RGB in NGC 2419 is shown from the Stetson (2005) on-line database. The 7 giants in our HIRES sample are indicated by large filled circles. Two other stars with lower SNR HIRES spectra, whose membership is questionable, are indicated by open circles. The two 12 Gyr Y2 isochrones (Yi et al 2003) shown have [Fe/H] −2.2 and −1.9 dex, with [α/Fe] +0.3 dex. (Cohen, Huang, & Kirby, ApJ, submitted)

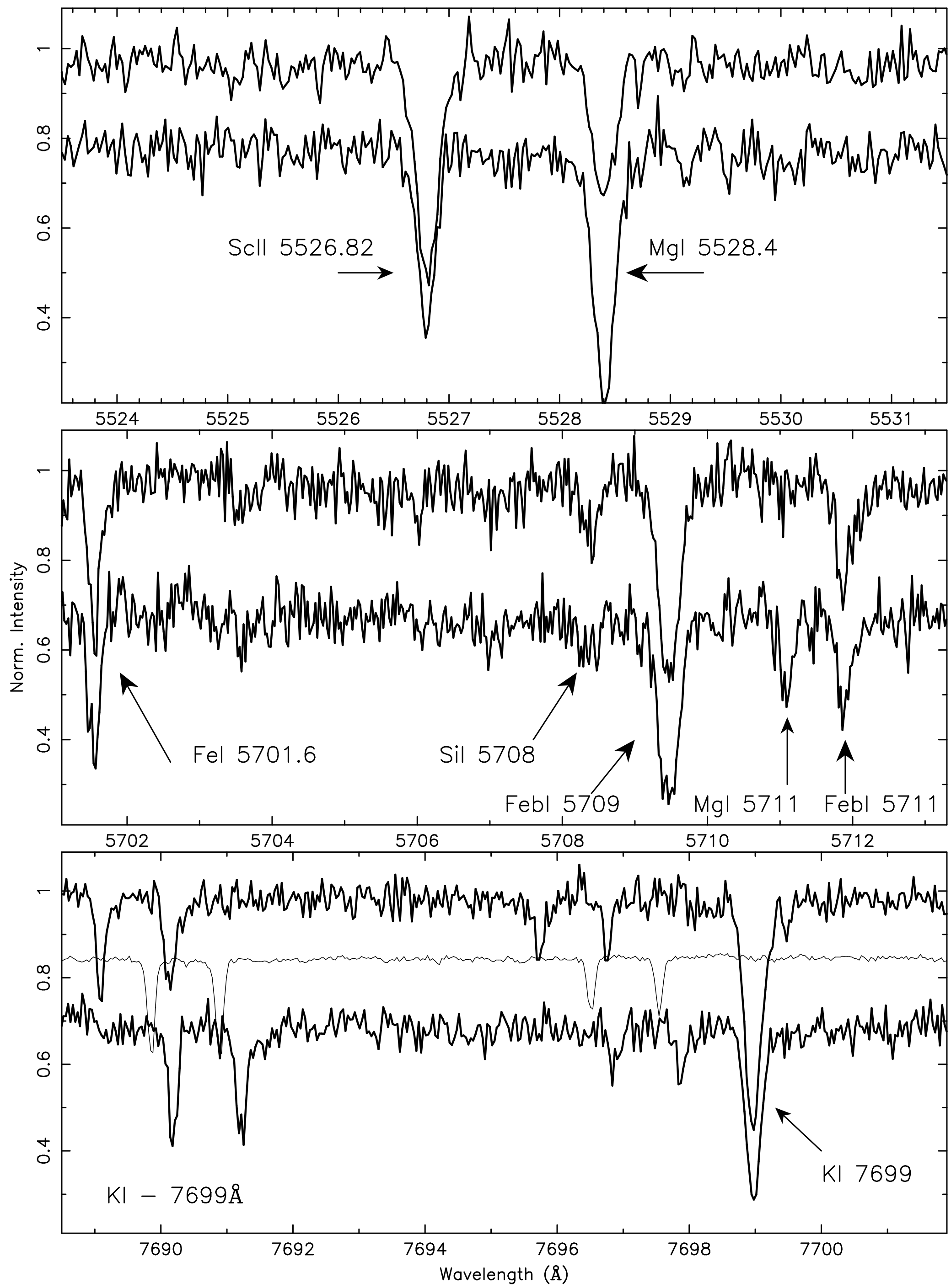

Fig. 4.— The regions of the spectrum near two Mg I lines and a line of K I, shifted in wavelength into the rest frame, are shown for NGC 2419 S1131 as compared to S1209, whose spectrum is shifted slightly lower for clarity. These two giants differ in V by 0.2 mag and in deduced $T_{\rm eff}$ by less than 100 K. The lines identified include a number of blends of FeI lines or FeI and NiI lines labeled as "Febl". S1131 is more metal-rich and Mg-poor than S1209 and the other NGC 2419 giants. The thin line in the bottom panel is that of a rapidly rotating B star. The slight shifts in wavelength of the telluric lines between the spectra is a reflection of the differing heliocentric corrections for each spectrum. (Cohen, Huang, & Kirby, ApJ, submitted)

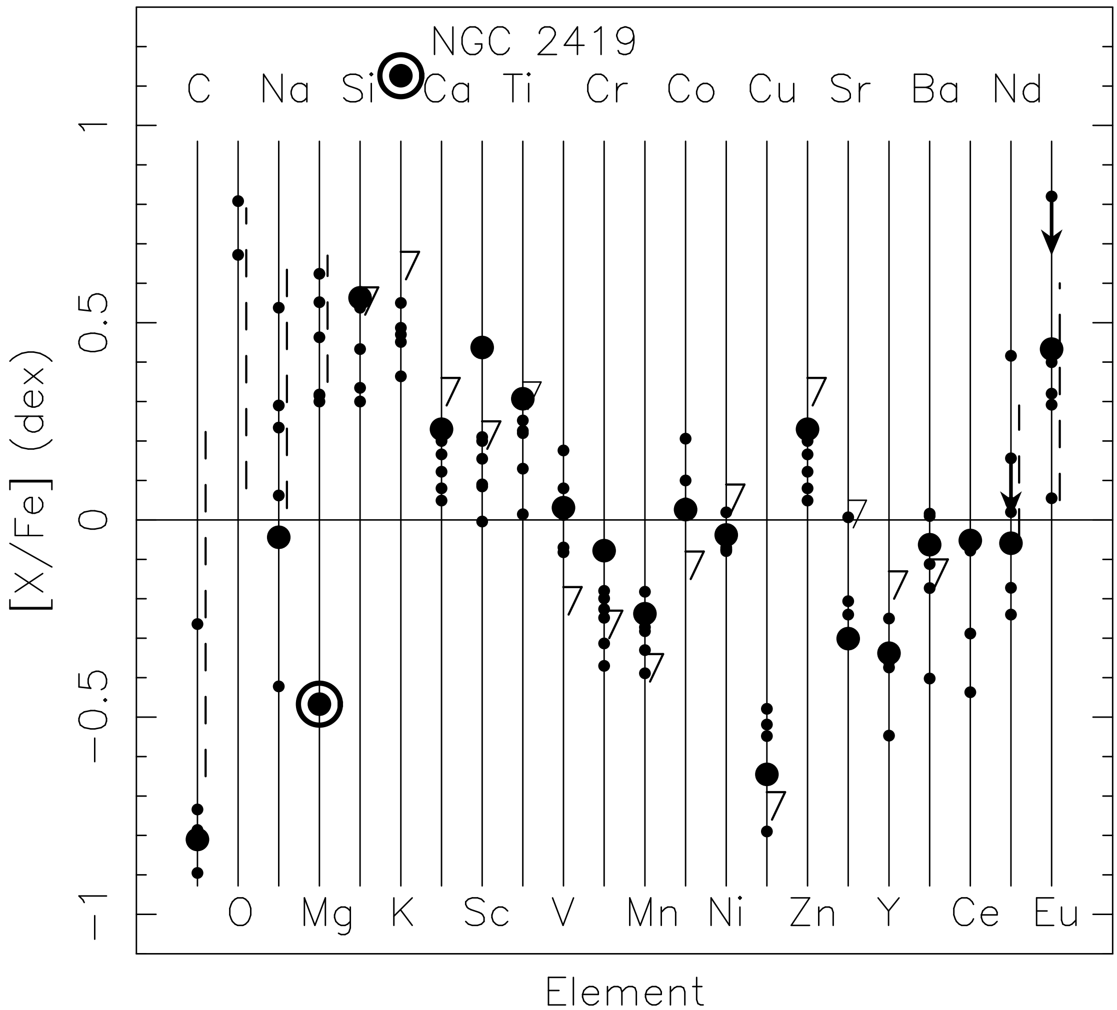

Fig. 5.— Abundance ratios for the detected elements in the NGC 2419 sample of 7 red giants, with the large filled circles indicating S1131. The highly unusual abundance ratios of [Mg/Fe] and [K/Fe] for NGC 2419 S1131 are circled. The reference species is FeI for neutral species and FeII for ionized ones. The averages of TiI and TiII and of SrI and SrII are plotted when both are available. Average abundance ratios from our analyses of HIRESr spectra of red giants in the inner halo cluster M30 (NGC 7099) are indicated by "7". For elements with a large range in M30, the range is indicated by a dashed line. (Cohen, Huang, & Kirby, ApJ, submitted)

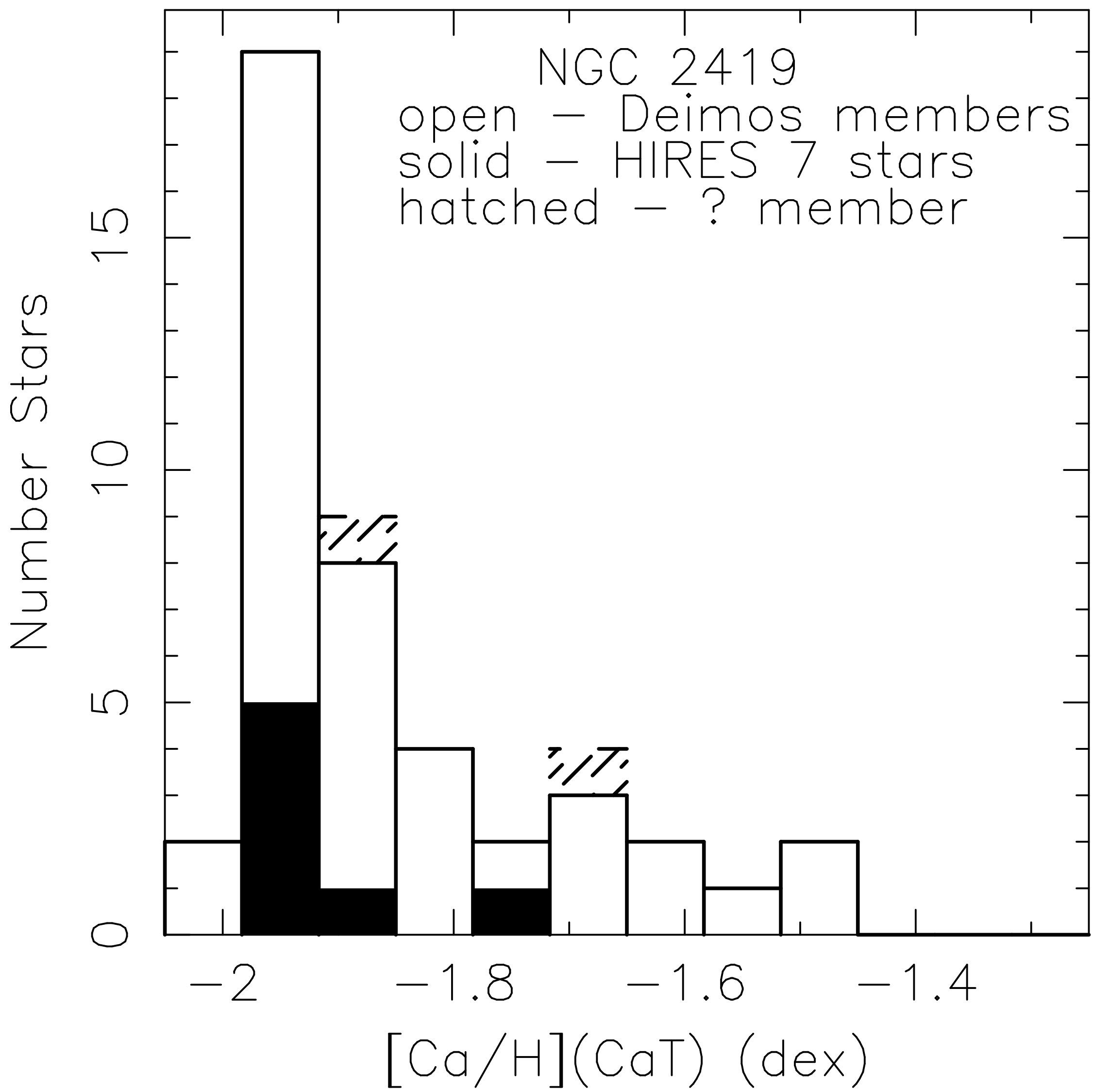

Fig. 6.— A histogram of [Ca/H] as inferred from the Deimos moderate resolution spectra of Cohen et al (2010) is shown for the sample of 43 definite members of NGC 2419 isolated in that paper. The present sample of 7 RGB stars in this GC with HIRES spectra is shown by the solid fill. The two additional stars in the Deimos survey which are probable members, both of which have low SNR HIRES spectra, are indicated by the hatched areas, which are placed above the histogram defined by the definite members. (Cohen, Huang, & Kirby, ApJ, submitted)

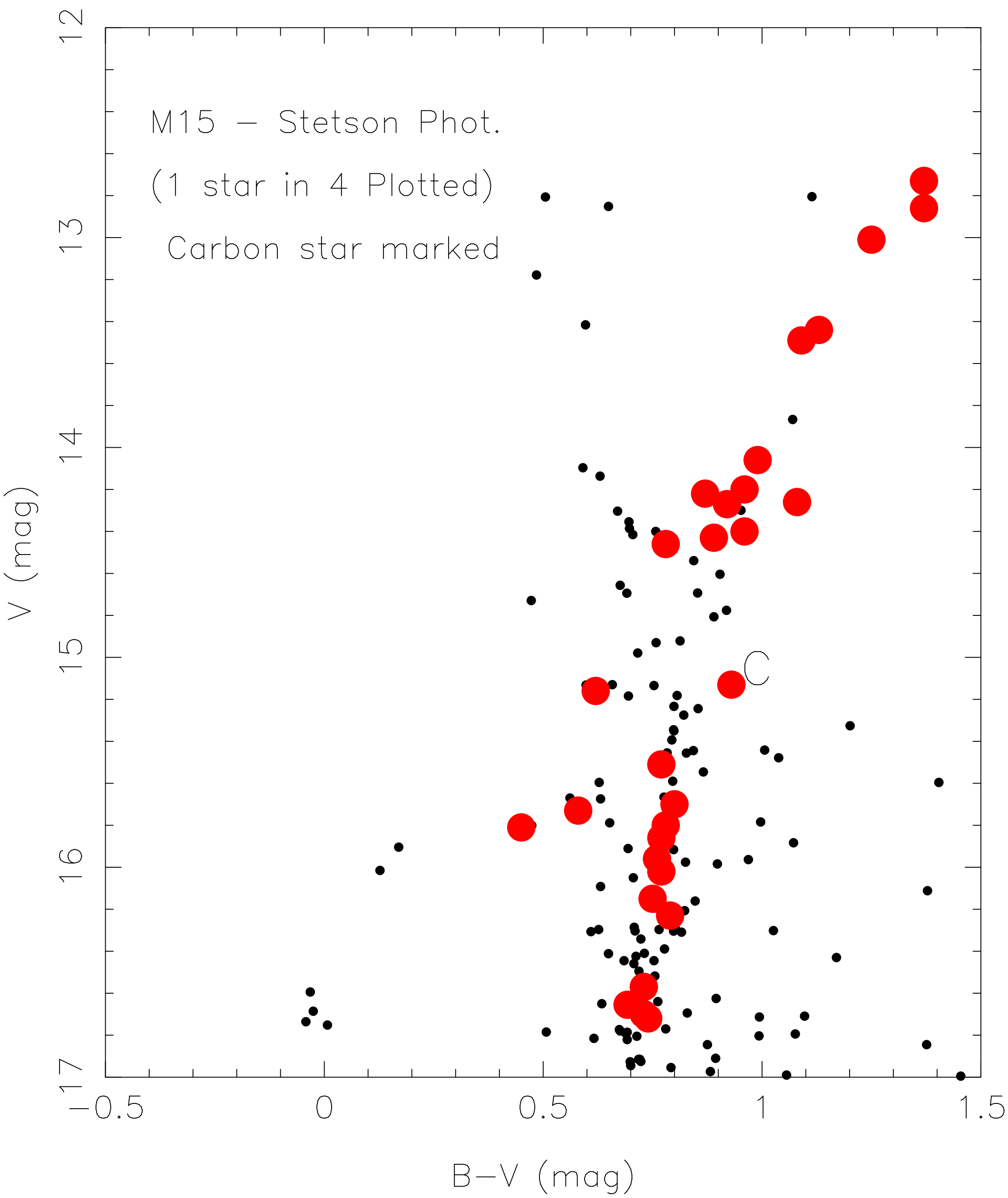

Fig. 7.— A $M_V(0)\ -\ (V-I)_0$ CMD for tM15 is shown from the Stetson (2005) on-line database. The HIRES sample is indicated by large red filled circles. A s-process rich carbon star discovered through our spectroscopy is marked.

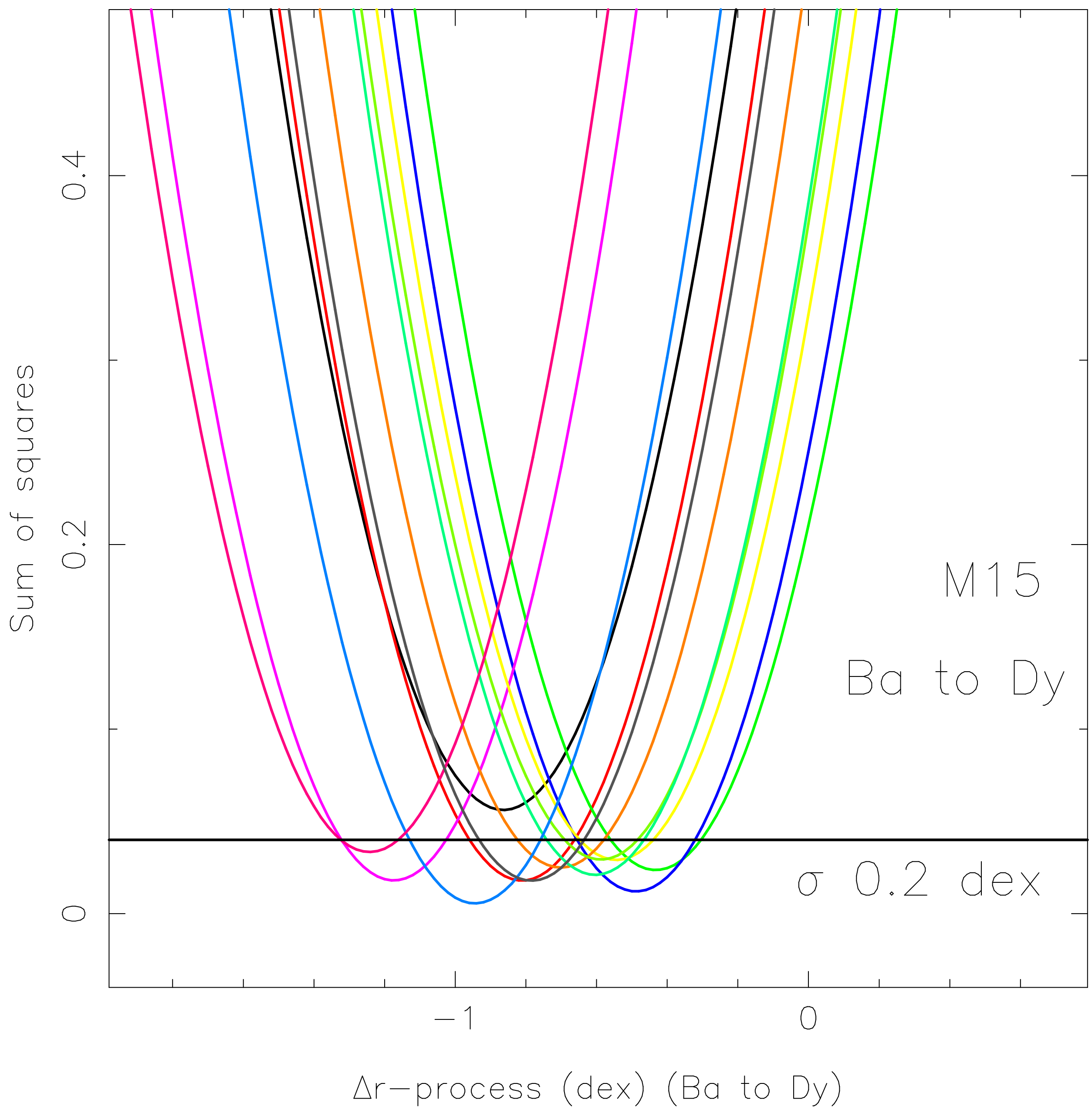

Fig. 8.— A demonstation that the heavy neutron capture elements vary from star to star within M15 and their formation is dominated by the *r*-process. The *r*-process element production yields are adopted with a variable ratio of *r*-nuclei to Fe. The rms sum of the residuals for all detected elements between Ba and Dy is shown for 13 stars (with 4 to 7 such elements detected per star). The minimum shows a low value consistent with the uncertainty of the abundance of a single such element, indicating the *r*-process distribution applies. The range along the X-axis indicates the range in the ratio of *r*-nuclei to Fe. Unpublished data by J.Cohen, circa 2008, following work of Sneden et al (2000) and Otsuki et al (2006).

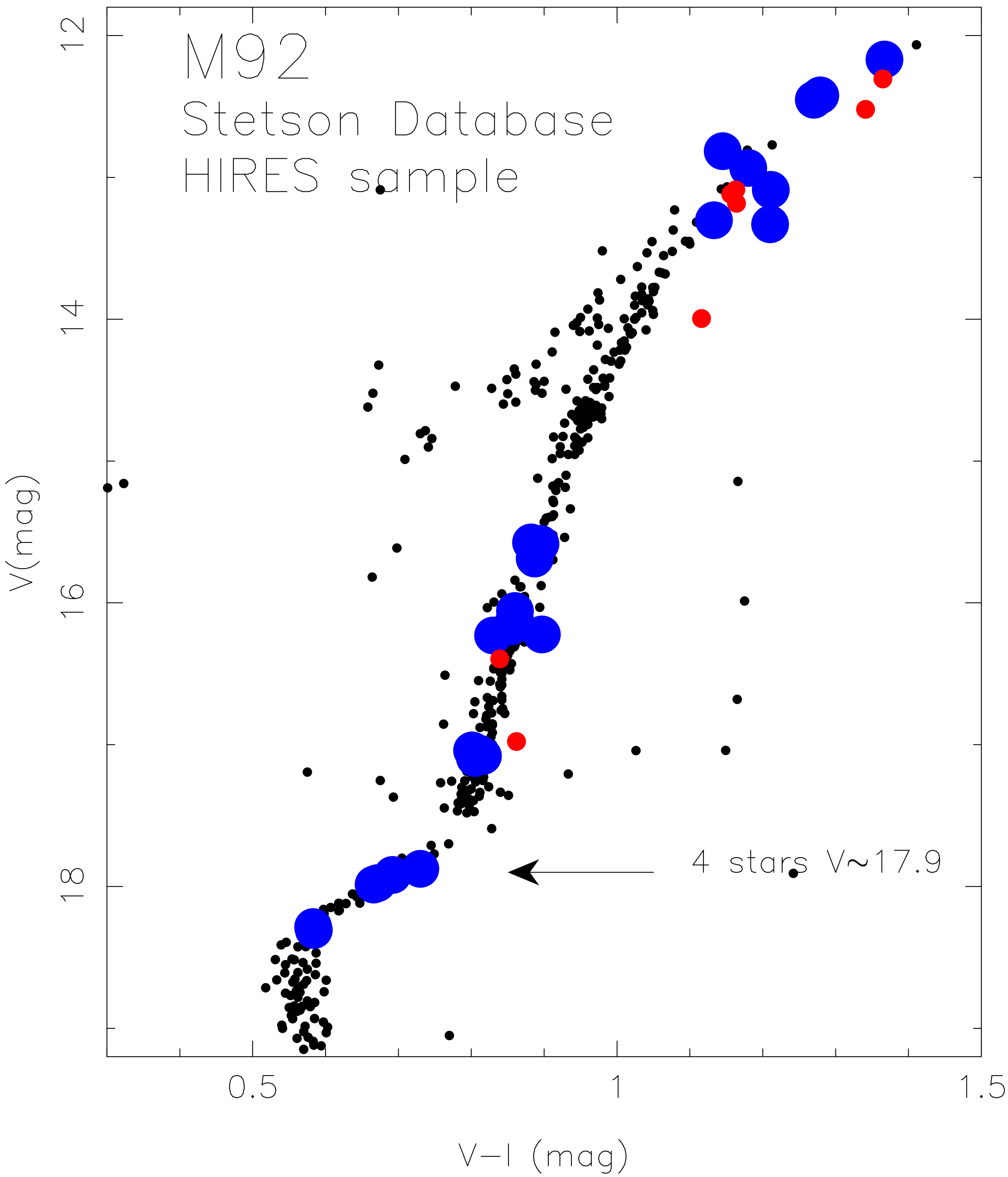

Fig. 9.— $V - I$ CMD using data from Stetson (2005). The blue circles denote observations with HIRES/Keck taken after the detector was upgraded in Aug. 2004, while the red circles denote spectra taken earlier with considerably less spectral coverage. The brightest 7 giants with high quality spectra were used for the rare earth study, while the entire sample of 36 stars is being used for the diffusion study.

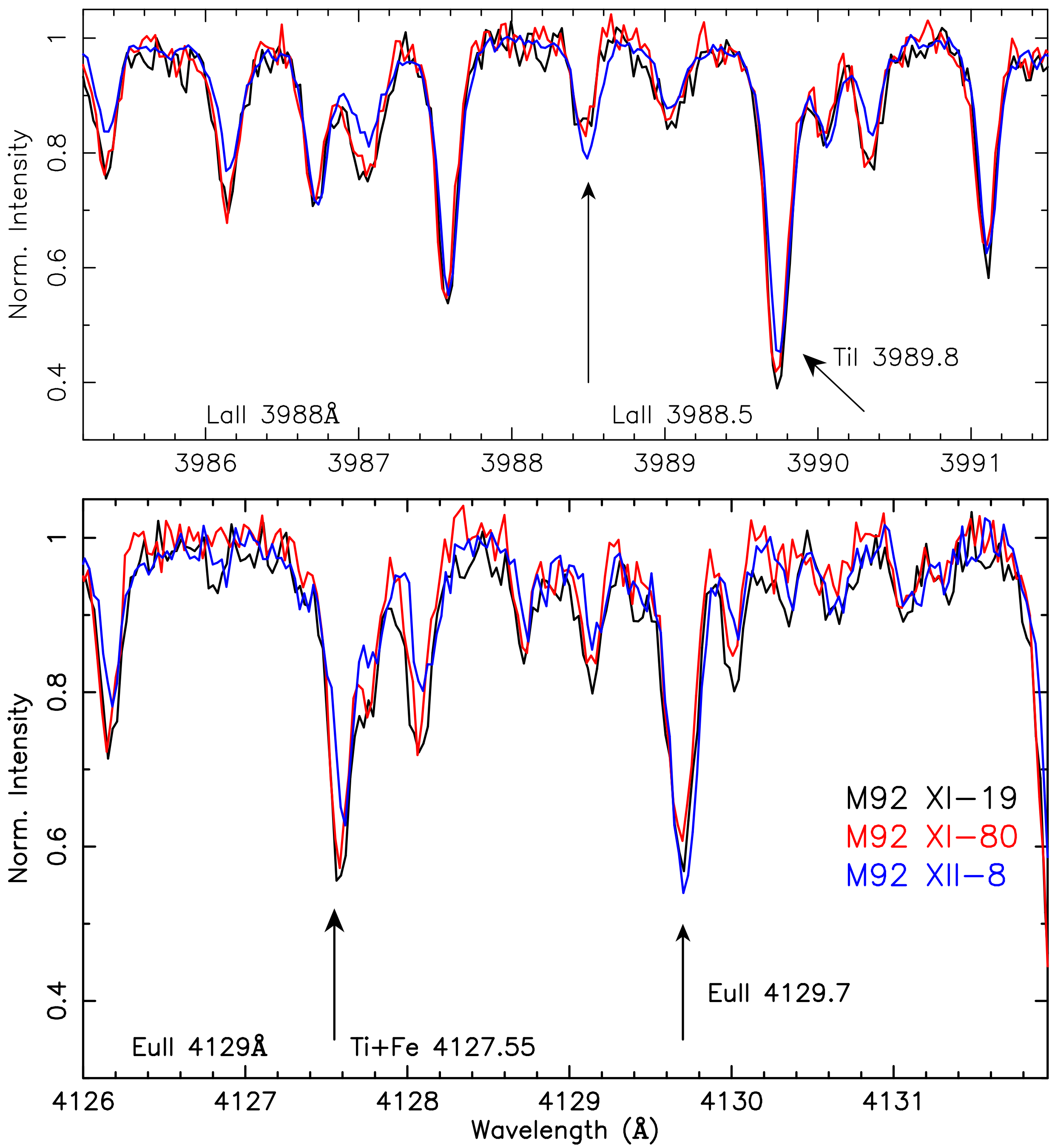

Fig. 10.— Secti8ns of spectra for M92 XI-19, M92 XI-80, and M92 XII-6 are shown for the 3988 Å LaII line and the 4129 Å EuII line. These stars have V between 12.78 and 13.09 mag. These three stars were included in the sample of Roederer & Sneden (2011); spectra of two of them in the vicinity of the same La II line and a Eu II line at 3907 Å are shown in their Fig. 7.

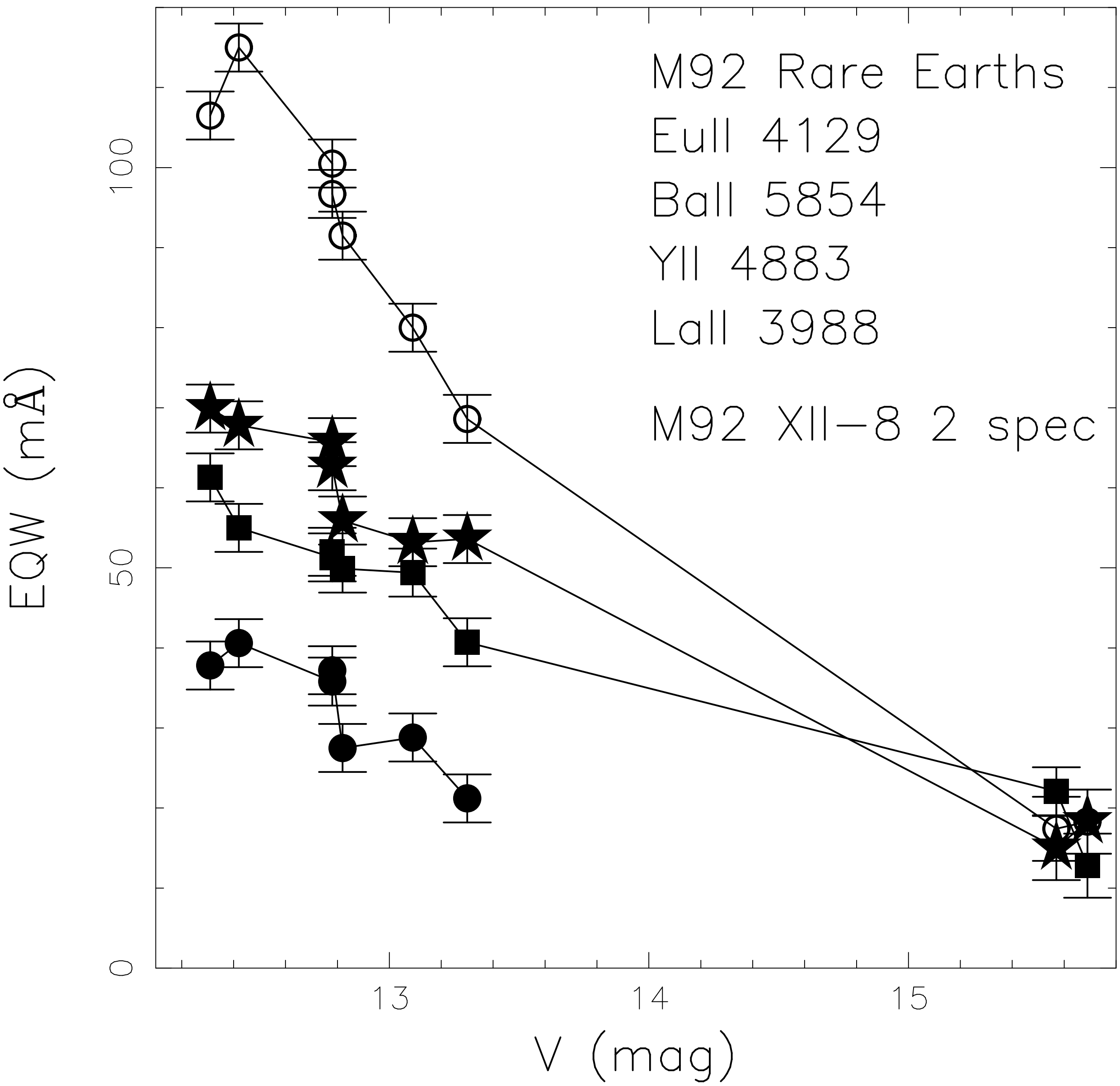

Fig. 11.— Equivalent widths of the strongest rare earth lines are shown for 8 luminous red giants in M92. There are two spectra taken 5 years apart of M92 XII-8, hence two points at $V = 12.78$ mag.

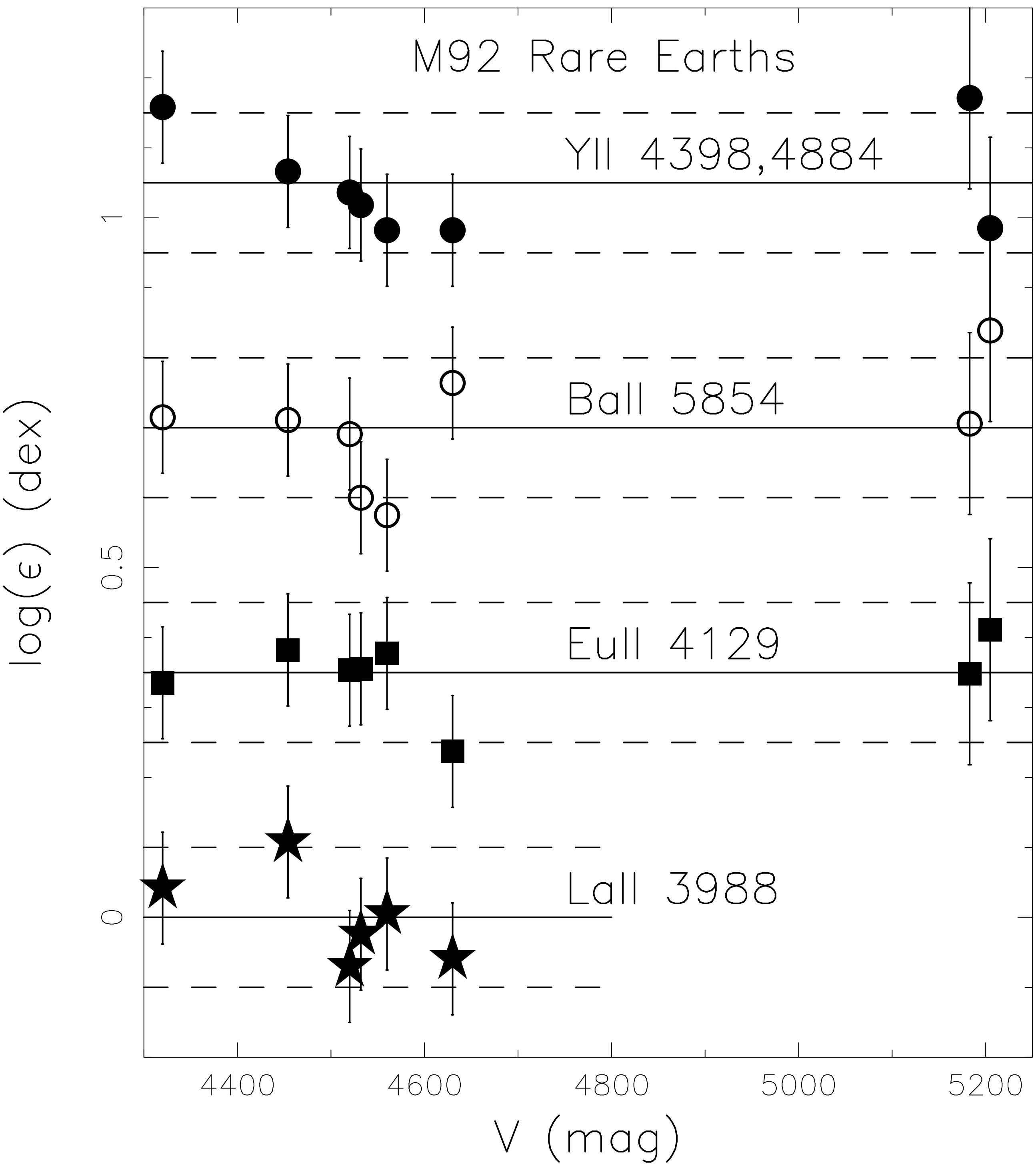

Fig. 12.— Abundances deduced from the strongest rare earth lines are shown for 8 luminous red giants in M92. The solid horizontal line represents the mean abundance of the element, while the dashed lines are offset above and below the mean by 0.1 dex. The vertical axis values are offset by a different constant for each line.

Table 1. M92 Sample for Rare Earth Study

ID	V (mag)	T_{eff} (K)	log(g) (dex)
X-49	12.31	4320 (25)	0.68
III-65	12.42	4454 (30)	0.83
XII-8	12.78	4520 (25)	1.02
XI-80	12.82	4532 (35)	1.12
XI-19	13.09	4560 (35)	1.07
III-82	13.30	4630 (30)	1.31
X-20 (S2302)	15.57	5183 (35)	2.48
VI-90 (S721)	15.69	5215 (24)	2.53

Table 2. Statistics for Absolute Abundances of Rare Earths in M92

Species	Lines (Å)	Num. Stars	Mean (dex)	σ (dex)	Min log(ϵ) (dex)	Max log(ϵ) (dex)	$<$[X/Fe]$>$[a] (dex)
YII	4398, 4884	8	−0.28	0.08	−0.34	−0.15	−0.19
BaII	4554	8	−0.43	0.08	−0.55	−0.29	−0.23
LaII	3988	6	−1.36	0.07	−1.43	−1.25	−0.17
EuII	4129	8	−1.51	0.05	−1.52	−1.45	+0.31

[a]Assumes [Fe/H](M92) = −2.33 dex.

Table 3. M92 Abundances vs NGC 7099 Abundances

Species Species	M92 <[X/Fe]> (dex)	σ (dex)	Nstars	NGC 7099 <[X/Fe]> (dex)	σ (dex)	Nstars
[FeI/H]	−2.35	0.09	5	−2.42	0.07	5
[FeII/H]	−2.31	0.11	5	−2.38	0.04	5
[SiI/FeI]	0.60	0.03	5	0.52	0.07	5
[CaI/FeI]	0.25	0.07	5	0.29	0.05	5
[ScII/FeII]	0.21	0.02	5	0.18	0.03	5
[Ti/Fe][a]	0.26	0.08	5	0.28	0.05	5
[CrI/FeI]	−0.29	0.07	5	−0.30	0.03	5
[MnI/FeI]	−0.44	0.05	5	−0.40	0.06	5
[CoI/FeI]	0.13	0.05	4	−0.16	0.12	5
[NiI/FeI]	0.01	0.08	5	0.02	0.07	5
[ZnI/FeI]	0.05	0.02	4	0.16	0.07	5
[YII/FeII][b]	−0.22	0.07	5	−0.23	0.15	5
[BaII/FeII][b]	−0.22	0.12	5	−0.18	0.04	5
[LaII/FeII][b]	−0.15	0.14	5	−0.02	0.17	5
[NdII/FeII]	−0.07	0.11	4	0.14	0.10	5
[EuII/FeII][b]	0.31	0.15	5	0.41	0.18	5

[a]Mean of [TiI/FeI] and [TiII/FeII].

[b]Abundances from every line detected, less accurate than those given above from the best lines of selected rare earths.

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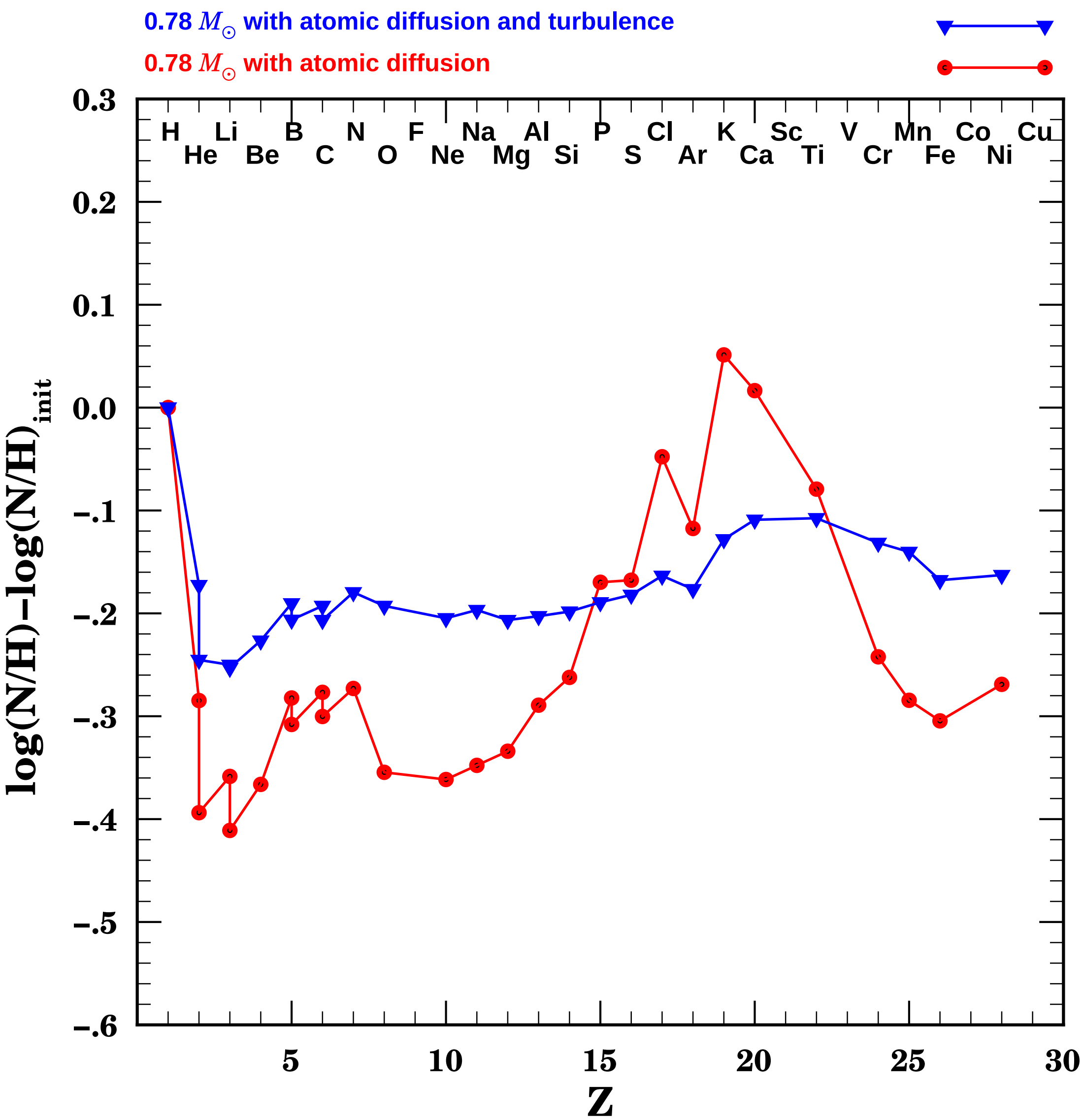

Fig. 13.— Predictions by O. Richard for depletion between the initial abundance ratio of elements and their abundance near the main sequence turnoff as a function of atomic number [Fe/H] = −1.5 dex. Two different theoretical curves are shown. Both include diffusion, radiative levitation, and the nominal mixing expected in convective zones. The blue curve includes additional turbulence below the outer convection zone, which is needed to reproduce the ^{7}Li plateau seen in warm halo stars. The efficiency of this extra turbulent mixing is parameterized in a physically justified but ad hoc manner with two tunable parameters; the values of the parameters are not accurately known at present.

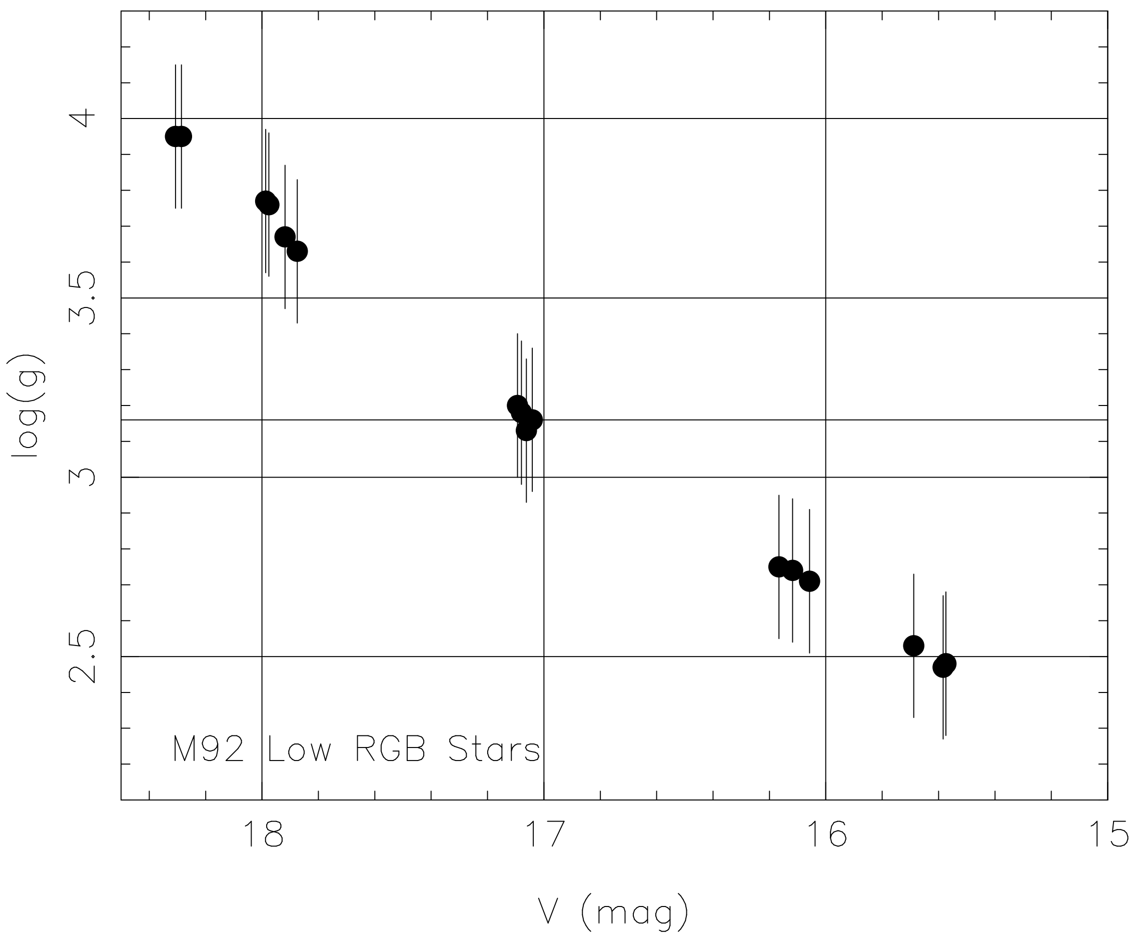

Fig. 14.— Faint sample in M92 with HIRES spectra for studying diffusion.

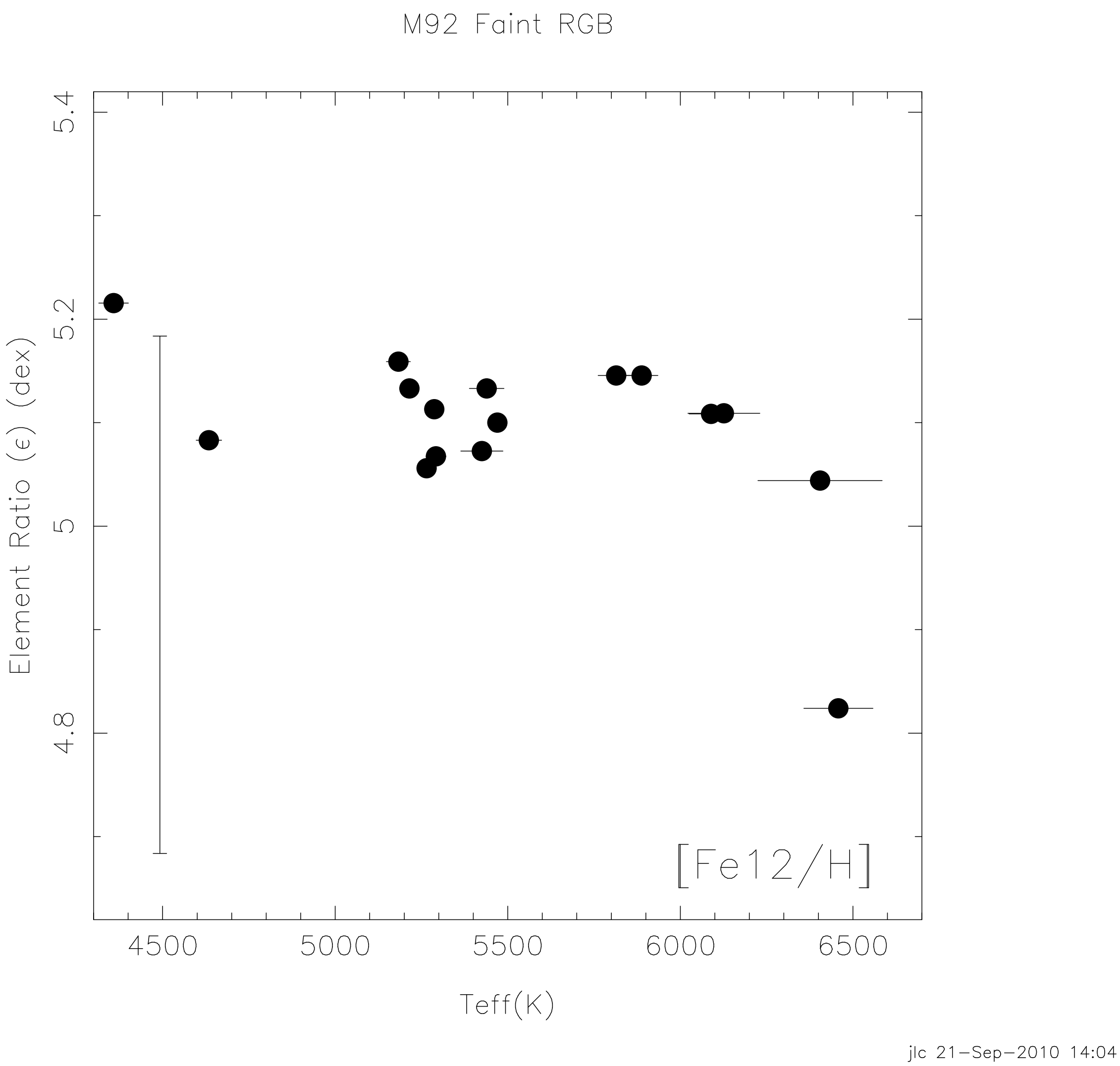

Fig. 15.— Mean of [FeI/H] and [FeII/H] for the faint sample in M92 shown as a function of T_{eff}. Note the very expanded vertical scale for [Fe/H]. The King & Boesgaard sample lies at $V = 17.9$ with $T_{eff} = 5950$ to 6100 K. They claim that [Fe/H] among their stars is 4.91 dex, 0.3 dex lower than that of M92 red giants, and they interpret this as a sign of diffusion. **WE FIND THERE IS NO SIGN OF A DROP IN FE/H IN M92 AT THE SUBGIANTS NEAR THE MAIN SEQUENCE.** The abundance errors for the two main sequence turnoff stars are very large. Another 2 nights of data were acquired in June 2011 to try to cut down the errors there if at all possible.

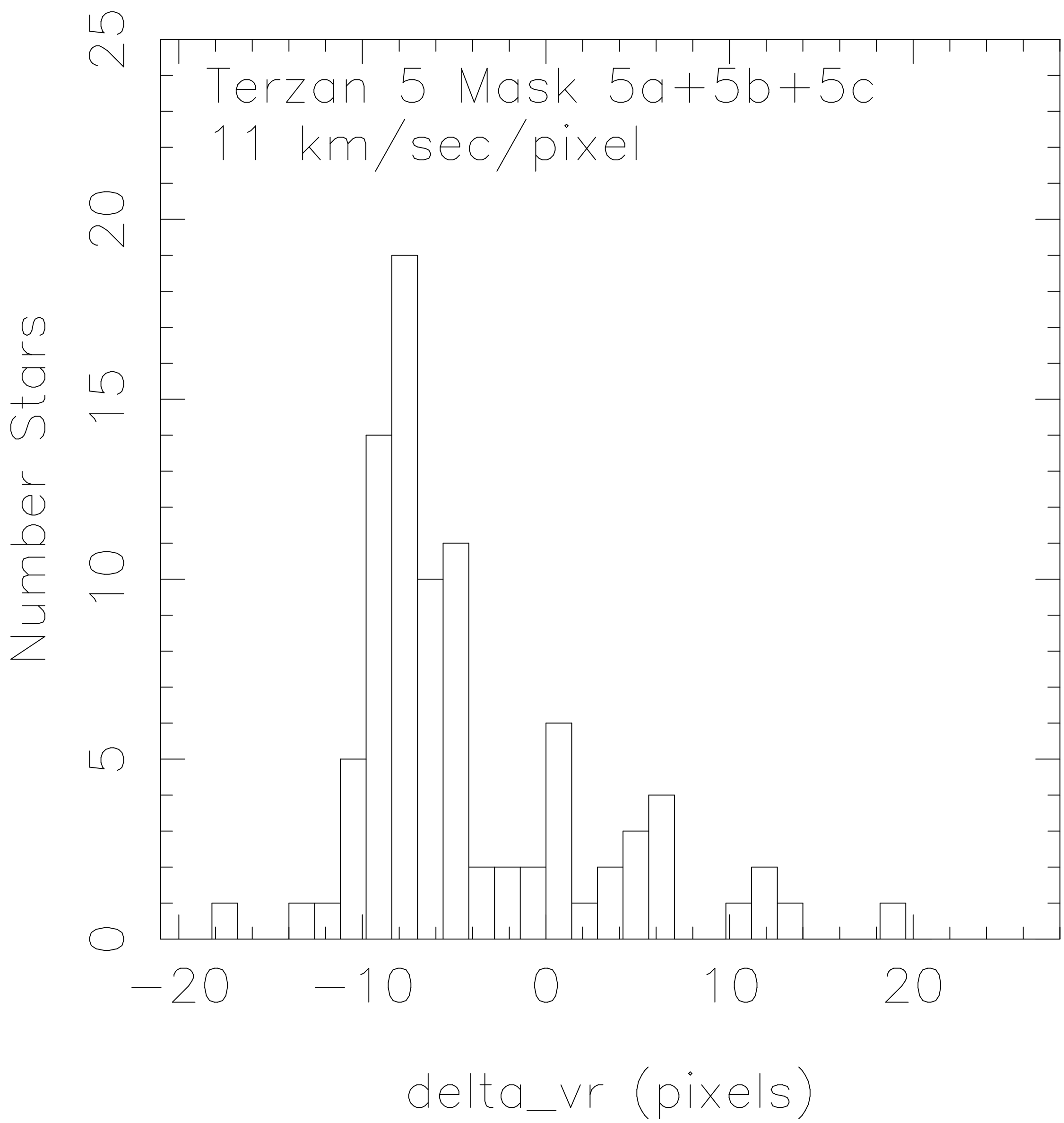

Fig. 16.— Stars in the field of Terzan 5 from 3 Deimos slitmasks which might be members of the cluster based on their spectra. Obvious misfits were rejected. All these stars are within 90 arcsec of the center of the cluster.

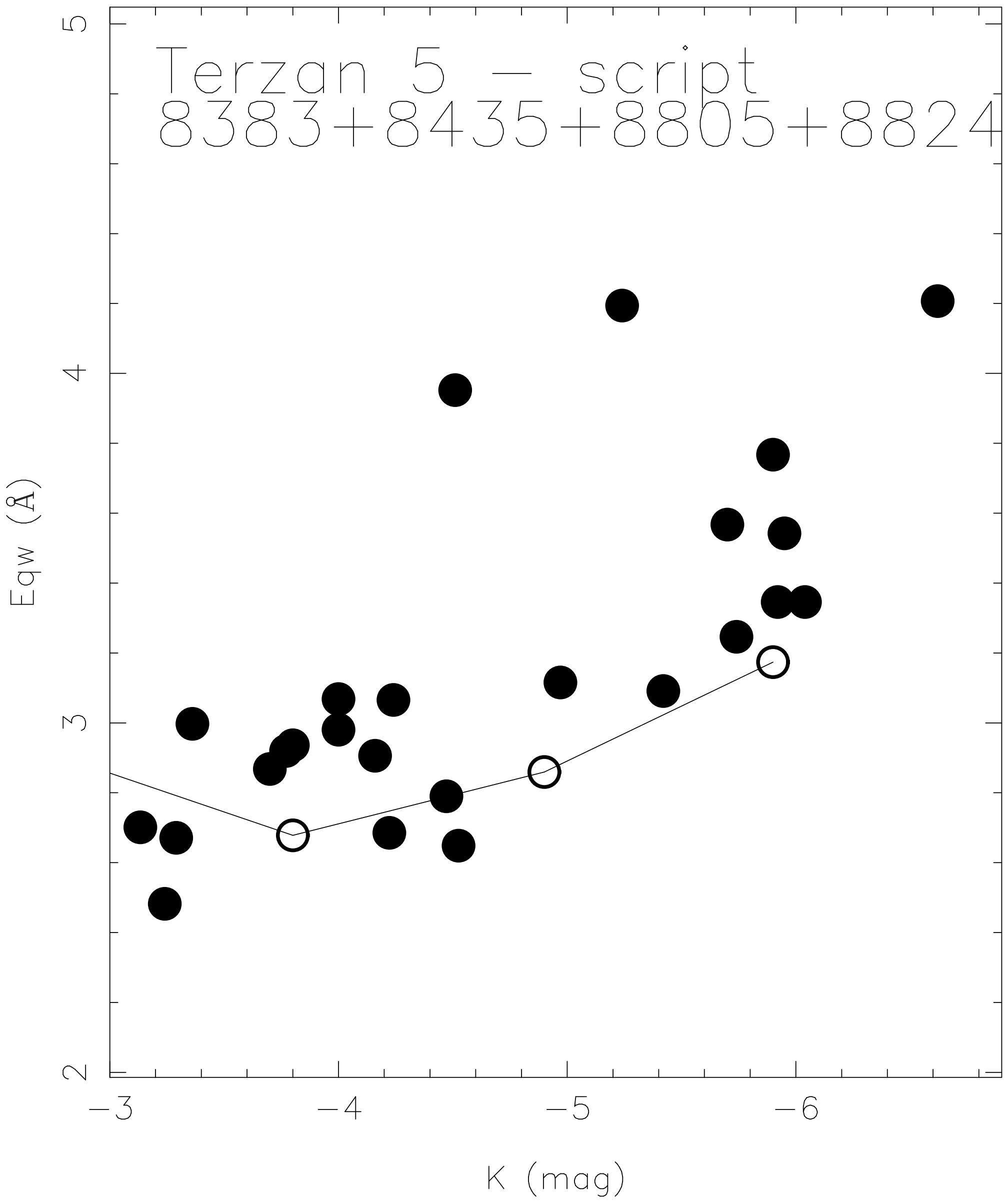

Fig. 17.— Since the Ca triplet CANNOT be used for such metal-rich giants, we go to the much weaker Mg and Fe lines in the 8500 Å spectral region. The sum of the strength of the 4 lines listed above is shown as a function of K mag. The open circles connected by lines indicate the expected behavor of the summed line strength with the appropriate T_{eff} modeled for an appropriate isochrone for constant abundances. All these stars are within 90 arcsec of the center of the cluster. **We could not decide about the status of the three strong-lined stars. Are they field stars or are they the second population detected by Ferrara et al in Terzan 5 ? We ended up rejecting the second option because of the low ratio of strong-lined to weak-lined stars, but in fact the underlying cause of there being only 3 strong-lined stars is the extremely high central concentration of the strong-lined population. Have we missed other such very concentrated populations in high-dispersion or especially in moderate-resolution highly multiplexed studies of other globular clusters ?**

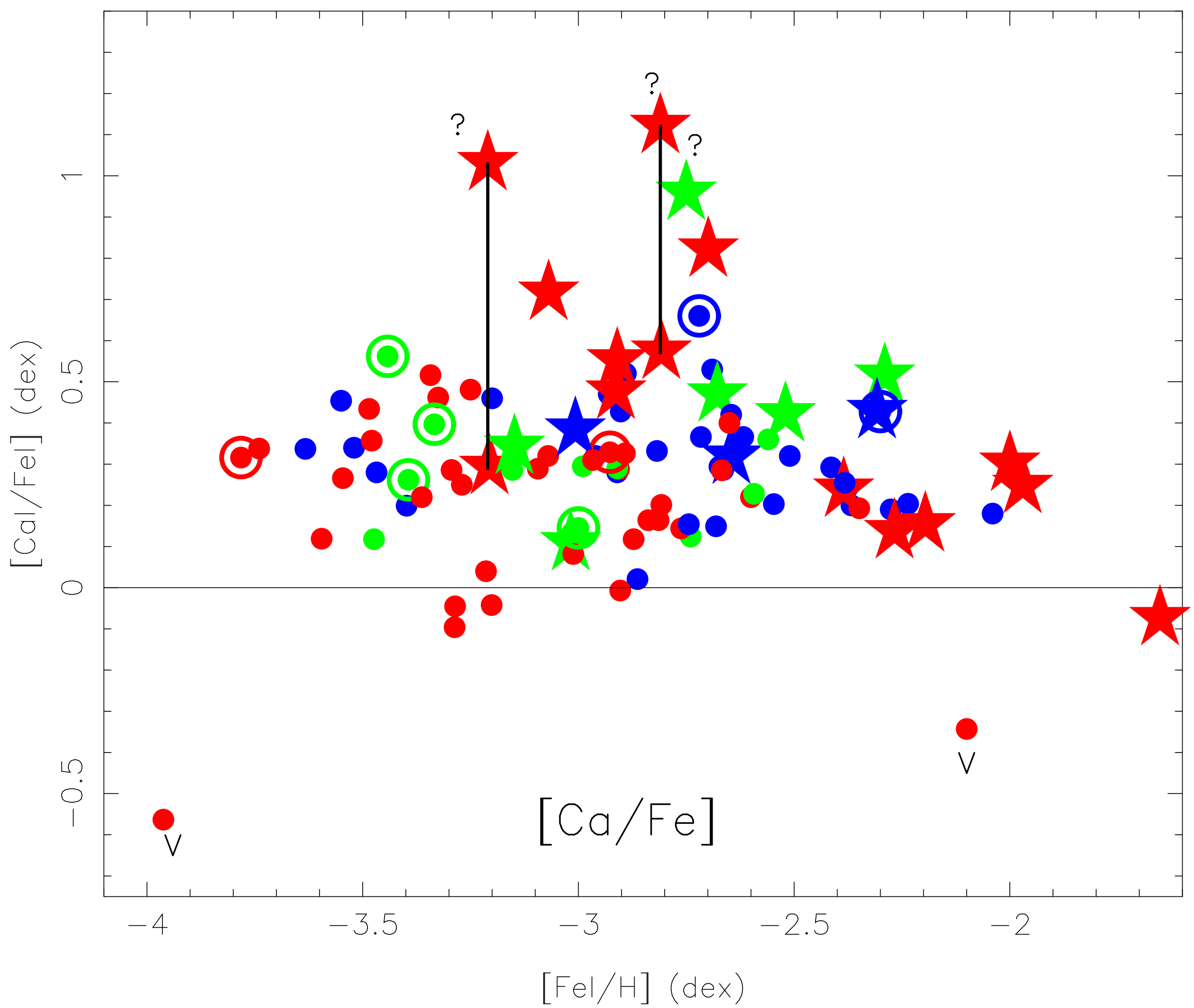

Fig. 18.— 0Z project, 103 EMP candidates, HIRES spectra, analysis by J. Cohen. [Ca/Fe] vs [Fe/H]. checking of outliers now in progress. 2 C-star outliers with spectra from before the HIRES detector upgrade, hence limited spectral range, were eliminated by taking new spectra reaching the 6160 Å region to get a clean Ca I line.

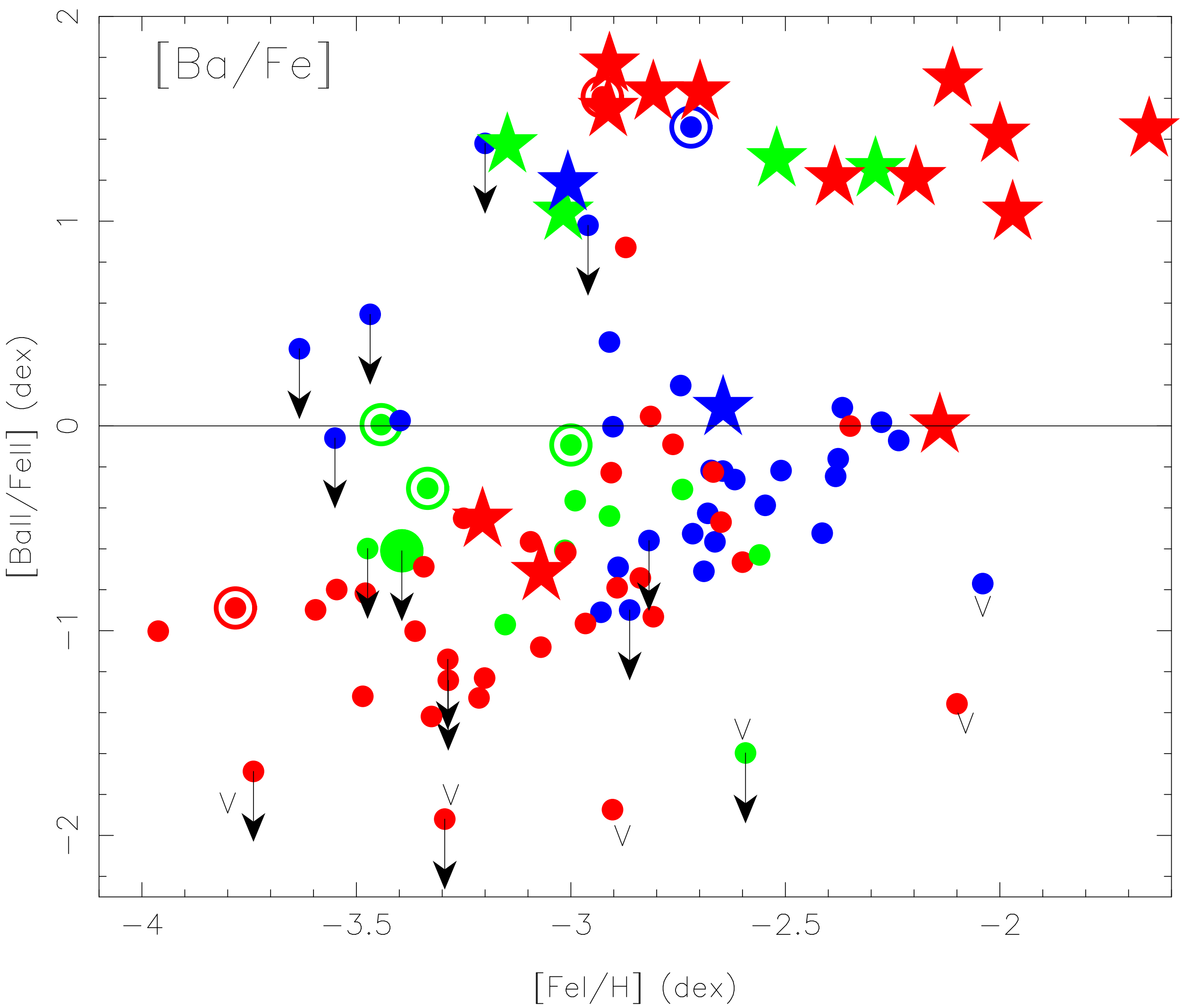

Fig. 19.— [Ba/Fe] vs [Fe/H]. Note enormous range in [Ba/Fe]. Blue is main sequence turnoff region stars, so upper limits are not very interesting. Upper limits for giants (red) are very interesting. C-stars mostly *s*-process rich until [Fe/H] < −3 dex.

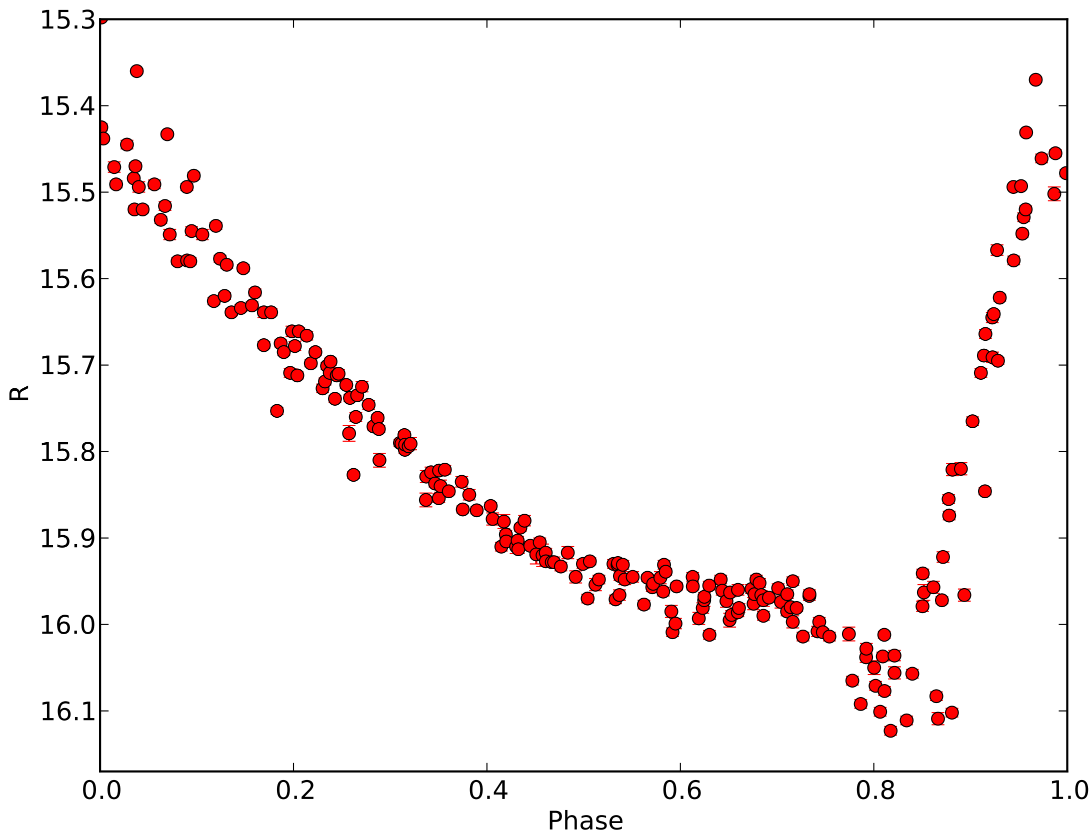

Fig. 20.— The light curve for the first RR Lyrae variable star extracted from the PTF database. At present there are about 7000 sq deg of high Galactic latitude sky with 30 or more epochs of imaging in the PTF database. By the end of the PTF project we expect to find and characterize more than 15,000 halo RR Lyr variables reaching out to about 80 kpc. Postdoc Branimir Sesar is leading this effort with Carl Grillmair, Judy Cohen, and the PTF collaboration.

Happy Birthday Bob !!!!