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A CHEMICAL ABUNDANCE STUDY OF THREE RHB AND TWO RGB STARS IN NGC 6637 (M69)

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RESUMEN

Presentamos un estudio detallado de la abundancia química de estrellas en tres ramas horizontales rojas y dos ramas de las gigantes rojas que pertenecen al cúmulo globular, rico en metales, NGC 6637 (M69). Desarrollamos cálculos LTE y obtenemos [Fe/H] = -0.77 ± 0.02 dex. Se discute la anticorrelación entre las abundancias de oxígeno y sodio en las estrellas del programa y la comparación del cociente [Si/Ti] de NGC 6637 con otros cúmulos.

ABSTRACT

We present a detailed chemical abundance study of three red horizontal branch and two red giant branch stars in the metal-rich globular cluster NGC 6637 (M69). We performed LTE calculations and obtained [Fe/H] = -0.77 ± 0.02 dex. The anticorrelation between oxygen and sodium abundances in the program stars and the comparison of the [Si/Ti] ratio of NGC 6637 with those of other globular clusters are discussed.

Key Words: **GALAXY: BULGE — GLOBULAR CLUSTERS: INDIVIDUAL (M69) — STARS: ABUNDANCES**

1. INTRODUCTION

The Galactic bulge is one of the major component of our Galaxy. However, its formation history is not well-understood. There are two competing bulge formation scenarios. The first one is the merger process. In this hierarchical clustering scenario, bulges are built up during mergers. The dense central region of massive satellites may survive and sink to the center due to tidal friction. In this framework, only the most massive satellite could contribute to the central bulge formation in a Hubble time. The other scenario for bulge formation is an instability in the disk. In fact, the Galactic bulge is dominated by old, metal-rich stars and neither of the two scenarios can explain this nature (Wyse & Gilmore 2005).

The elemental abundances of globular clusters provide crucial information regarding the formation and the evolution of the Galaxy (Freeman & Bland-Hawthorn 2002). Until recently, the number of globular clusters studied employing high-resolution spectroscopy was very small due to the high interstellar extinction values towards the Galactic center region. With the advent of large-aperture telescopes with high-resolution optical or infrared spectrographs during the past decade, detailed chemical compositions of the Galactic bulge globular clusters started to emerge. High-resolution infrared spectroscopy appears to be particularly useful for chemical abundance studies of the bulge globular clusters. However, as Lee, Carney, & Balachandran (2004) discussed, infrared spectroscopy of metal-rich red-giant branch (RGB) stars has potential problems; for example, lack of information on the oscillator strengths and the very limited number of atomic species in the infrared passband.

NGC 6637 (M69) is an old, metal-rich globular cluster approximately 1.6 kpc from the Galactic center. Heasley et al. (2000) studied NGC 6637 using the WFPC2 on the Hubble Space Telescope and they concluded that NGC 6637 has a similar age as 47 Tuc (see also De Angeli et al. 2005). The previous metallicity measurements of NGC 6637 suggest that the metallicity of the cluster ranges from [Fe/H] ≈ -0.6 to ≈ -0.8. Zinn & West (1984) derived [Fe/H] = -0.59 ± 0.19 from the color-magnitude diagram (CMD) morphology and the Q39 integrated light index. Later, Geisler (1986) obtained [Fe/H] = -0.6 with the Washington photometry system. More recently, Rutledge, Hesser, & Stetson (1997 and references therein) measured the metallicity of the cluster using the Ca II triplet lines of the RGB stars in the near infrared passband and they obtained [Fe/H] = -0.72 ± 0.09 on the Zinn & West abundance scale and -0.78 ± 0.03 on the Carretta & Gratton abundance scale.

In this paper, we explore the detailed elemental abundances for two RGB stars and three red-

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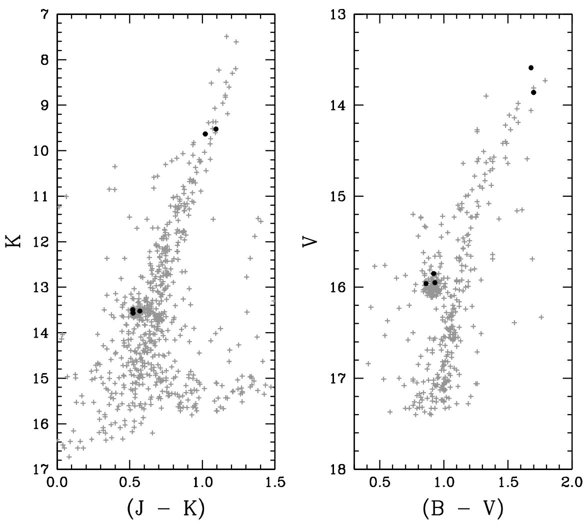

Fig. 1. Color-magnitude diagram of NGC 6637 showing the positions of our program stars.

TABLE 1

PROGRAM STARS IN NGC 6637

ID	V	$(B-V)$	K
I-30	13.59	1.68	9.63
I-6	13.86	1.70	9.53
I-37	15.85	0.92	13.52
III-37	15.95	0.93	13.50
IV-1	15.96	0.86	13.57

horizontal branch (RHB) stars in NGC 6637. Since RHB stars are considerably hotter than RGB stars, there are a number of major advantages to using RHB stars (for example, see Cohen et al. 1999).

This study is tied directly to that of Lee & Carney (2002) and Lee, Carney, & Habgood (2005) with the same analysis methods.

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out during three different observing seasons. We selected our program stars from the BV photometry of Sarajedini & Norris (1994) and the 2MASS JK photometry. The positions of our target stars in the color-magnitude diagram are shown in Figure 1. In Table 1, we provide identifications (Hartwick & Sandage 1968), V magnitudes, $(B-V)$ colors (Sarajedini & Norris 1994) and K magnitudes of our target stars.

Observations of the RGB stars were obtained using the CTIO 4-meter telescope and its Cassegrain echelle spectrograph in July 1998 and June 1999. The Tek 2048 × 2048 CCD, 31.6 lines/mm echelle grating, long red camera, and G181 cross-disperser were employed. The slit width was 150 μm, or about 1.0 arcsec, that projected to 2.0 pixels and yielded an effective resolving power $R = 28{,}000$. Each spectrum had complete spectral coverage from 5600 to 7800 Å. All program star observations were accompanied by flat lamp, Th-Ar lamp, and bias frames. The raw data frames were trimmed, bias-corrected, and flat-fielded using the IRAF ARED and CCDRED packages. The scattered light was subtracted using the APSCATTER task in the ECHELLE package. The echelle apertures were then extracted to form 1-d spectra, which were continuum-fitted and normalized, and a wavelength solution was applied following the standard IRAF echelle reduction routines.

Observations of the RHB stars were obtained with the Magellan Telescope using the Magellan Inamori Kyocera Echelle spectrograph (MIKE; Bernstein et al. 2003) in June 2005. A 0.7″ slit was used, providing a resolving power of 29,000 in the red with wavelength coverage from 4950 Å to 7250 Å. We used MIKE Redux[2] to correct for the tilted slit.

Equivalent widths were measured mainly by direct integration of each line profile using the SPLOT task in the IRAF ECHELLE package. We estimate our measurement error in equivalent width to be ±2 – 3 mÅ from the size of noise features in the spectra and our ability to determine the proper continuum level.

3. ANALYSIS

For our selection of lines, laboratory oscillator strengths were adopted whenever possible, with supplemental solar oscillator strength values. In addition to oscillator strengths, taking into account the damping broadening due to the van der Waals force, we adopted the Unsöld approximation with no enhancement (Lee & Carney 2002; Lee, Carney, & Habgood 2005).

For our analysis, we rely on spectroscopic temperatures and photometric surface gravities, following the method described in Lee & Carney (2002). The initial estimates of the program star temperatures were obtained using BVK photometry and the empirical color-temperature relations given by Alonso, Arribas, & Martinez-Roger (1999). To derive photometric surface gravity relative to that of the Sun, we use $\log g_{\odot} = 4.44$ in cgs units, $M_{\mathrm{bol},\odot} = 4.74$ mag, and $T_{\mathrm{eff},\odot} = 5777$ K for the Sun.

[2] http://web.mit.edu/~burles/www/MIKE/

TABLE 2

MODEL ATMOSPHERE PARAMETERS

ID	T_{eff} (K)	$\log g$	v_{turb} (km/s)	[Fe/H]
I-30	3890	0.8	1.85	−0.78
I-6	3900	0.7	1.85	−0.76
I-37	5175	2.5	2.10	−0.79
III-37	5025	2.5	1.80	−0.73
IV-1	5100	2.5	1.46	−0.78

TABLE 3

ELEMENTAL ABUNDANCES

Abundance	Mean	σ	n
[Fe/H]	−0.77	0.02	5
[O/Fe]	0.20	0.31	5
[Na/Fe]	0.35	0.29	5
[Mg/Fe]	0.28	0.17	5
[Al/Fe]	0.49	0.18	4
[Si/Fe]	0.45	0.12	5
[Ca/Fe]	0.20	0.17	5
[Sc/Fe]	0.07	0.14	5
[Ti/Fe]	0.24	0.13	5
[Mn/Fe]	−0.41	0.08	5
[V/Fe]	0.03	0.15	5
[Ni/Fe]	0.06	0.11	5
[Cu/Fe]	−0.50	0.20	5
[Ba/Fe]	0.22	0.31	5
[Y/Fe]	0.13	0.26	3
[La/Fe]	0.21	0.34	3
[Eu/Fe]	0.45	0.11	4

With initial photometric temperature and surface gravity estimates, 72-depth plane-parallel LTE model atmospheres were computed using the program ATLAS9 with enhanced abundances of all the "α" elements (O, Ne, Mg, Si, S, Ar, Ca, and Ti) by 0.4 dex (Kurucz 1993). The abundance analysis was performed using the current version of the LTE line analysis program MOOG (Sneden 1973). Adopting the photometric temperature and surface gravity as our initial values, we began by restricting the analysis to those Fe I lines with $\log(W_\lambda/\lambda) \leq -5.2$ (i.e., for the linear part of the curve of growth), and comparing the abundances as a function of excitation potential. New model atmospheres were computed with a slightly different effective temperature until the slope of the log n(Fe I) versus excitation potential relation was zero to within the uncertainties. The stronger Fe I lines were then added and the microturbulent velocity $v_{\rm turb}$ altered until the log n(Fe I) versus $\log(W_\lambda/\lambda)$ relation had no discernible slope. Table 2 shows the temperatures thus derived and also the surface gravity of the program stars.

4. RESULTS AND DISCUSSION

4.1. *Elemental abundances*

In Table 3, we present the mean elemental abundances of our program stars using photometric surface gravities and spectroscopic temperatures. The [el/Fe] ratios for neutral elements are estimated from [el/H] and [Fe I/H] ratios, with the exception of oxygen. The [el/Fe] for singly ionized elements (Ti II, Ba II, La II, and Eu II) and oxygen are estimated from [el/H] and [Fe II/H] ratios. (Lee & Carney 2002; Lee, Carney, & Habgood 2005). In the Table, n is the number of stars used for the calculations of mean elemental abundances. Systematic errors, such as in adopted gf values as a function of excitation potential, which could lead to systematically erroneous temperature estimates, are not included. The mean [Fe/H] of −0.77 dex for our five stars is measured with a small internal uncertainty of ±0.02 dex. Our [Fe/H] value for NGC 6637 is in good agreement with previous estimates by others.

4.2. *A Na-O anti-correlation in RHB stars in NGC 6637: Mixing or Primordial Variations?*

Many globular clusters appear to show anti-correlations between the abundances of oxygen and sodium, and of magnesium and aluminum. The subject was reviewed by Kraft (1994), and has been revisited by numerous authors. The approach often taken has been that these anti-correlations arise from deep mixing, whereby material whose chemical composition has been altered by proton captures within the CNO cycle is brought to the stellar surface. This concept has become less plausible with the discovery that such anti-correlations are seen in relatively unevolved stars in the metal-poor clusters NGC 6397 and NGC 6752 (Gratton et al. 2001) and in the metal-rich cluster 47 Tuc (Carretta et al. 2004).

In Figure 2 we show a plot of [Na/Fe] vs. [O/Fe] for NGC 6637, in comparison with the results for main sequence stars (MS) and sub-giant stars (SGB) in 47 Tuc from Carretta et al. (2004). As can be seen in the figure, an anti-correlation between [Na/Fe]

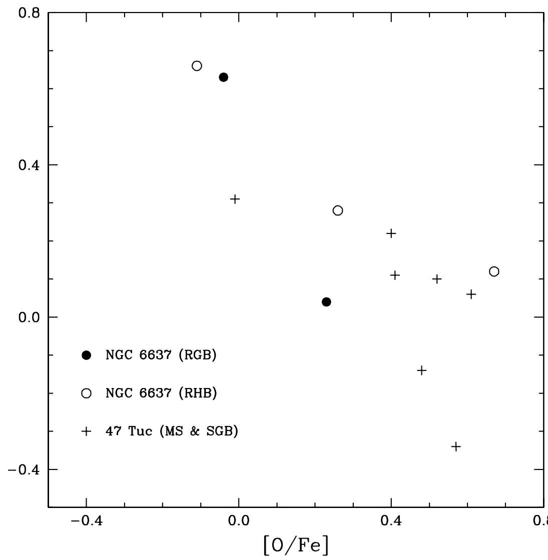

Fig. 2. A comparison of [Na/Fe] vs. [O/Fe] for MS and SGB stars in 47 Tuc vs. RGB and RHB stars in NGC 6637.

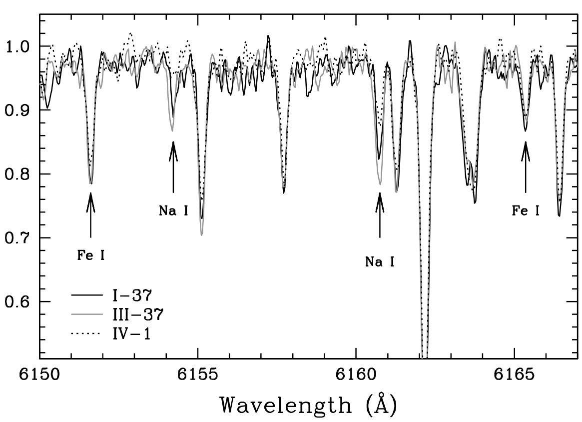

Fig. 3. A comparison of observed spectra of three RHB stars in NGC 6637.

and [O/Fe] appears to exist not only in RGB stars but also in RHB stars in NGC 6637. In Figure 3, we show a comparison of observed spectra of three RHB stars in NGC 6637. As shown in Table 2, these stars have almost identical stellar physical parameters. Figure 3 shows that absorption line strengths of two iron lines at λ6151.62Å and λ6165.36Å are identical, while those of sodium lines at λ6154.23Å and λ6160.75Å vary significantly among RHB stars, indicating that the sodium abundance variations are real. It is thought that the deep mixing scenario cannot explain this [Na/Fe] vs. [O/Fe] anti-correlation in RHB stars in NGC 6637.

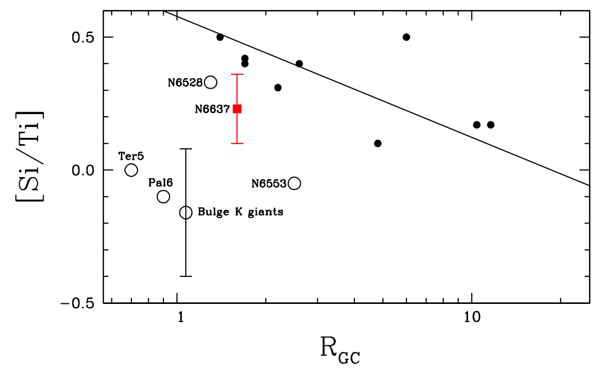

Fig. 4. [Si/Ti] as a function of R_{GC}. Dots represent 9 OHGCs analyzed by Lee (2007, in preparation). The solid line represents the bisector linear fit to the data. A non-parametric Spearman rank-order test indicates a probability of ≈ 0.09 % that the anti-correlation between [Si/Ti] and R_{GC} of the clusters is random.

4.3. *[Si/Ti] ratios of globular clusters*

A recent study by Lee & Carney (2002) found that the [Si/Ti] ratio in old halo globular clusters (OHGC) increases towards the Galactic center. To interpret this finding they propose that (i) the inner parts of the Galaxy have been metal-enriched by Type II supernovae (SNe II) explosions of stars that are more massive than the stars in the outer parts, and (ii) the metal enrichment in the inner parts of the Galaxy is further enhanced by the higher density of material in those regions, which causes a higher retention rate of the material expelled by the supernovae.

In Figure 4 we show [Si/Ti] of NGC 6637 and 9 OHGC (solid circles) as a function of Galactocentric distance. It should be emphasized that these 9 OHGC were observed with the same instrument setups (the CTIO 4m telescope with its echelle spectrograph) and were analyzed employing the same method (Lee 2007 in prep.). In Figure 4 we show the fit to the data and a non-parametric Spearman rank-order test indicates a probability of ≈ 0.09% that the variation of [Si/Ti] ratios with Galacto-centric distances of OHGCs is random. Also illustrated in the figure are the three metal-rich globular clusters NGC 6528 (Carretta et al. 2001), NGC 6553 (Cohen et al. 1999), NGC 6637, and Palomar 6 (Lee et al. 2004).

NGC 6637 and NGC 6528 seem to follow [Si/Ti] abundance ratios found by Lee & Carney (2002). NGC 6553 and Palomar 6, on the other hand, seem to have [Si/Ti] abundances similar to galactic bulge K giants (McWilliam & Rich 1994), where the Ti abundances are enhanced. There seem to be, therefore, two different groups of metal-rich globular clusters in the inner Galaxy, one that follows the [Si/Ti] trend of old halo stars, and another group that has [Si/Ti] ratios similar to the giants stars in the Bulge, indicating that these two different groups were formed in different physical environments.

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REFERENCES

Alonso, A., Arribas, S., & Martinez-Roger, C. 1999, A&AS, 140, 261
Bernstein, R., Shectman, S. A., Gunnels, S. M., Mochnacki, S., & Athey, A. E. 2003, Proc. SPIE, 4841, 1694
Carretta, E., Cohen, J. G., Gratton, R. G., & Behr, B. B. 2001, AJ, 122, 1469
Carretta, E., Gratton, R. G., Bragaglia, A., Bonifacio, P., & Pasquini, L. 2004, A&A, 416, 925
Cohen, J. G., Gratton, R. G., Behr, B. B., & Carretta, E. 1999, ApJ, 523, 739
De Angeli, F., Piotto, G., Cassisi, S., Busso, G., Recio-Blanco, A., Salaris, M., Aparicio, A., & Rosenberg, A. 2005, AJ, 130, 116
Freeman, K., & Bland-Hawthorn, J. 2002, ARA&A, 40, 487
Geisler, D. 1986, PASP, 98, 847
Gratton R. G., et al. 2001, A&A, 369, 87
Hartwick, F. D. A., & Sandage, A. 1968, ApJ, 153, 715
Heasley, J. N., Janes, K. A., Zinn, R., Demarque, P., Da Costa, G. S., & Christian, C. A. 2000, AJ, 120, 879
Kraft, R. P. 1994, PASP, 106, 553
Kurucz, R. 1993, CD-ROM 13 (Cambridge: SAO)
Lee, J.-W., & Carney, B. W. 2002, AJ, 124, 1511
Lee, J.-W., Carney, B. W., & Balachandran, S. C. 2004, AJ, 128, 2388
Lee, J.-W., Carney, B. W., & Habgood, M. J. 2005, AJ, 129, 251
Lee, J.-W. 2007, in preparation
McWilliam, A., & Rich, R. M. 1994, ApJS, 91, 749
Rutledge, G. A., Hesser, J. E., & Stetson, P. B. 1997, PASP, 109, 907
Sarajedini, A., & Norris, J. E. 1994, ApJS, 93, 161
Sneden, C. 1973, PhD Thesis, The University of Texas at Austin
Wyse, R. F. G., & Gilmore, G. 2005, astro-ph/0510025
Zinn, R., & West, M. J. 1984, ApJS, 55, 45