High resolution near IR spectra of NGC 6624 and NGC 6569*

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ABSTRACT
We present the first abundances analysis based on high-resolution infrared (IR) echelle spectra of NGC 6569 and NGC 6624, two moderately reddened globular clusters located in the outer bulge of the Galaxy. We find [Fe/H]=−0.79±0.02 dex and [Fe/H]=−0.69±0.02 dex for NGC 6569 and NGC 6624, respectively and an average α-elements enhancement of ≈+0.43±0.02 dex and +0.39±0.02 dex, consistent with previous measurements on other metal-rich Bulge clusters. We measure accurate radial velocities of <v_r>=−47±4 km s$^{-1}$ and <v_r>=+51±3 km s$^{-1}$ and velocity dispersions of ≈8 km s$^{-1}$ and ≈6 km s$^{-1}$ for NGC 6569 and NGC 6624, respectively. Finally, we find very low $^{12}$C/$^{13}$C isotopics ratio (<7 in NGC 6624 and ≈5 in NGC 6569), confirming the presence extra-mixing mechanisms during the red giant branch evolution phase.

Key words: Galaxy: bulge, globular clusters: individual (NGC 6569 and NGC 6624) – stars: abundances, late-type – techniques: spectroscopic.

1 INTRODUCTION
The new generation of high-resolution IR spectrographs showed its tremendous potential to study both distant and obscured stellar populations. Particularly in the case of heavily reddened regions such as the Galactic bulge and center, IR spectroscopy offers the best, and sometimes a unique, approach to measuring the composition of the old stellar populations.

In the last few years, we have started a high-resolution spectroscopic survey of the Galactic bulge in the near-IR by using NIRSPEC, a high-throughput IR echelle spectrograph at the Keck Observatory (McLean 1998). H-band (1.5 - 1.8μm) spectra of bright giants in the Bulge globular clusters and field population are ideal for detailed abundance analysis of Fe, C, O and other α-elements, using the approach of synthesizing the entire spectrum. The abundance distributions in the cluster and field populations are crucial in constraining the history of Bulge formation and chemical enrichment (McWilliam 1997).

We have used this method to derive abundances for ten globular clusters in the inner and outer Bulge regions: the resulting abundances for NGC6553 and Liller 1 are given in Origlia, Rich & Castro (2002), for Terzan 4 and Terzan 5 in [Origlia & Rich (2004), for NGC 6342 and NGC 6528 in Origlia, Valenti & Rich (2005), for NGC 6539 and UKS 1 in Origlia et al. (2005), and for NGC 6440 and NGC 6441 in Origlia, Valenti & Rich (2008). We also measured detailed abundances of Bulge M giants in the Baade’s window (Rich & Origlia 2004) and in three inner fields at (l, b) = (0°, −1°) (Rich, Origlia & Valenti 2007), (l, b) = (0°, −1.75°), (l, b) = (1°, −2.65°) (Rich, Origlia & Valenti 2011). We found α-enhancement at a level of a factor between 2 and 3 over the whole range of metallicity spanned by the Bulge clusters in our survey, from [Fe/H]≈−1.6 (cf. Terzan 4) up to [Fe/H]≈−0.2 (cf. Terzan 5).

Here we present the high resolution IR spectra and abundance analysis of bright giants in NGC 6569 and NGC 6624, two globular clusters of the outer Bulge, located at (l, b) = (0.48, −6.68) and (l, b) = (2.79, −7.91), respectively (Harris 1996).

NGC 6569 is a rather compact cluster located in the Sagittarius region. Zinn (1985) from integrated photometry obtained [Fe/H]=−0.86 and E(B-V)=0.55, while from integrated DDO photometry, Bica & Pastoriza (1983) estimated

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[Fe/H] = −0.76 and E(B-V) = 0.59. The optical photometric studies by Ortolani, Bica & Barbuy (2001) and Piotto et al. (2002) suggested a metallicity consistent with that of 47 Tuc. The only IR photometric study is that by Valenti, Ferraro & Origlia (2005) who found [Fe/H] = −0.85 and E(B-V) = 0.49.

No high spectral resolution measurements of this cluster exist so far.

In the last few years, NGC 6624 has been subject of several studies aimed at investigating its population of "exotic" objects, such as X-ray binaries (see Zdziarski et al. 2007, and reference therein) and millisecond pulsars (see Ransom et al. 2005). Deep optical HST photometry, down to the main sequence turnoff region, have been presented by Heasley et al. (2000); Piotto et al. (2002) finding the cluster to be coeval to 47 Tuc. Its similarity to 47 Tuc is also based on the metallicity, in fact Heasley et al. (2000) found [Fe/H] = −0.63 based on observations of the Ca II IR triplet lines in giant stars of NGC 6624. More recently, Valenti, Ferraro & Origlia (2004a,b) presented a detailed analysis of the cluster Red Giant Branch properties based on high resolution IR photometry, finding E(B-V) = 0.28, (m-M) = 14.63 and a metallicity like 47 Tuc. However, also in the case of NGC 6624, no high resolution spectroscopic measurements have been published so far.

A description of the observations and abundance analysis follows in § 2, while in § 3 and § 4 we present and discuss our results.

2 OBSERVATIONS AND ABUNDANCE ANALYSIS

Near-IR, high resolution echelle spectra of bright giants in the core of the Bulge globular clusters NGC 6569 and NGC 6624 have been acquired with the IR spectrograph NIRSPEC (McLean 1998) mounted at the Nasmyth focus of the Keck II telescope. NGC 6569 was observed on May 2006, while NGC 6624 on April 2004, May 2005 and May 2006. The high resolution echelle mode, with a slit width of 0.43′′ (3 pixels) and a length of 12 − 24′′ and the standard NIRSPEC-5 setting, which covers most of the 1.5 − 1.8µm H-band, have been selected. Typical exposure times (on source) are ≈8 min. A total of 6 and 5 giants have been observed in NGC 6569 and NGC 6624, respectively. Figures 1, 2 show the IR image and the colour-magnitude diagram (CMD) (Valenti, Ferraro & Origlia 2005, 2004a) of the core region of NGC 6569 and NGC 6624, respectively. The position in the

Table 1. Coordinates and photometric parameters for the giants observed in NGC 6569 and NGC 6624.

| Star   | R.A.      | Decl. | (J-K) / (m-M) | M^bol |
|--------|-----------|-------|---------------|-------|
| NGC 6569-s1 | 18:13:39.015 | -31:49:18.88 | 0.91 | -3.06 |
| NGC 6569-s2 | 18:13:39.392 | -31:49:21.00 | 1.01 | -3.85 |
| NGC 6569-s3 | 18:13:38.276 | -31:49:41.29 | 0.88 | -2.83 |
| NGC 6569-s4 | 18:13:38.165 | -31:49:35.40 | 0.91 | -2.79 |
| NGC 6569-s5 | 18:13:38.029 | -31:49:39.28 | 0.91 | -2.91 |
| NGC 6624-s1 | 18:23:40.129 | -30:21:53.72 | 1.04 | -3.76 |
| NGC 6624-s2 | 18:23:40.100 | -30:21:47.57 | 1.04 | -3.41 |
| NGC 6624-s3 | 18:23:41.646 | -30:21:41.19 | 1.01 | -3.05 |
| NGC 6624-s4 | 18:23:40.635 | -30:21:44.83 | 1.01 | -3.12 |
| NGC 6624-s5 | 18:23:42.136 | -30:21:26.29 | 1.08 | -3.85 |

(a) NGC 6569: J, K colours, E(B-V) = 0.49, and (m-M) = 15.40 from Valenti, Ferraro & Origlia (2005).
(b) NGC 6624: J, K colours, E(B-V) = 0.28, and (m-M) = 14.63 from Valenti, Ferraro & Origlia (2004a).
near-IR CMD of the giant stars spectroscopically observed is also shown. Table 1 lists the absolute coordinates, intrinsic J, K colours and bolometric magnitudes of the giant stars in our sample.

The two raw dimensional spectra were processed using the REDSPEC IDL-based package written at the UCLA IR Laboratory. Each order has been sky subtracted by using the pairs of spectra taken with the object nodded along the slit, and subsequently flat-field corrected. Wavelength calibration has been performed using arc lamp and a second-order polynomial solution, while telluric features have been removed dividing by the featureless spectrum of an O star.

The near-IR spectra of cool stars are characterized by many CN, OH and CO molecular lines. At the NIRSPEC resolution R = 25,000 several single roto-vibrational OH lines and CO bandheads can be measured to derive accurate oxygen and carbon abundances. Most of the CN molecular lines are, instead, faint and blended with the stronger CO, OH and atomic lines, preventing any reliable abundance estimates of nitrogen. Other metal abundances can be derived from the atomic lines of Fe I, Mg I, Si I, Ti I, Ca I and Al I.

Abundance analysis is performed combining full spectrum-synthesis techniques with equivalent width measurements of representative lines. Using an updated version (Origlia, Rich & Castro 2002) of the code described in Origlia, Moorwood & Oliva (1993) we compute suitable synthetic spectra of giant stars. The main features of the code and the overall spectral synthesis procedure have been widely discussed and tested in our previous papers and they will not be repeated here. Here we only stress that the code use the LTE approximation and is based on the molecular blanketed model atmospheres of Johnson, Bernat & Krupp (1980) at temperatures < 4000 K and the ATLAS9 models for temperatures above 4000 K. The reference solar abundances are from Grevesse & Sauval (1998).

A grid of model spectra is produced by varying the stellar parameters around the photometric values and the abundances and abundance patterns over a large range. Stellar temperatures are estimated from the (J-K)0 colours (see Table 1) and from molecular lines. Gravity is derived from the theoretical evolutionary tracks according to the location of the stars on the red giant branch. An average value ξ=2.0 km s⁻¹ has been adopted for the microturbulence velocity (see also Origlia et al. 1997). Tighter constrains on stellar parameters are obtained by the simultaneous spectral fitting of several CO and OH molecular bands, which are very sensitive to variations of temperature, gravity and microturbulence. As a figure of merit we adopt the difference between the model and the observed spectrum (hereafter δ). In order to quantify systematic discrepancies δ is more powerful than the classical χ² test, which is instead equally sensitive to random and systematic scatter. Equivalent widths of selected lines (see Table 2) are computed by Gaussian fitting the line profiles with a ±20% overall uncertainty. The model that best reproduces the overall observed spectrum is the same model that best reproduces the equivalent widths of the selected lines and is chosen as the best-fit model. Solutions with ΔTeff = ±200 K, Δlog g ±0.5 dex and Δξ = ±0.5 km s⁻¹ and corresponding ±0.2 dex abundance variations from the best-fitting one as well as solutions with ±0.1 dex and ±0.2 dex abundance variations, are typically significant at 1 ≤ σ ≤ 3 level only, using the figure of merit mentioned above (see Origlia & Rich 2004). If the stellar parameters are varied simultaneously, appreciable variations in the spectrum can be measured for smaller (by a factor of 2-3) variations of the single quantities, depending on the range of temperature and metallicity of the observed stars. The adopted variation for the stellar parameters are somewhat conservative and have been empirically estimated comparing observed spectra with synthetic ones covering a fine grid of stellar parameters. At the observed spectral resolution (R=25,000) and signal-to-noise (30-50), single variation of 100-200 K in T eff or 0.5 dex in log g or 0.5 km s⁻¹ in ξ produce variations in the spectrum which can be reliably measured/disentangled from the observational errors. Typically, for the observed red giant branch stars in metal-rich globular clusters these variations can introduce a maximum systematic uncertainty in the derived abundances between 0.1 and 0.2 dex. It must be noted, however, that since the stellar features under consideration show a similar trend with variation in the stellar parameters, although with different sensitivity, relative abundances are less dependent on the stellar parameter assumptions (i.e. on the systematic errors) and their values are well constrained down to ≈±0.1 dex.

3 RESULTS

3.1 NGC 6569

Photometric stellar temperature estimates and bolometric magnitudes have been computed using the near-IR photometry by Valenti, Ferraro & Origlia (2005), their cluster reddening (E(B-V)=0.49) and distance ((m - M)₀=15.40) values, and the colour-temperature transformations and bolometric correction of Montegriffo et al. (1999), specifically calibrated for globular cluster giants. We constrain bolometric magnitudes in the range-3.0< logLM< -2.8 (see Table 3). The final adopted temperatures, listed in Table 4, are then derived by fitting the CO and, in particular, the OH bands, which are especially temperature sensitive in cool giants.

Figure 3 left panel, shows our synthetic best-fitting models superimposed on the observed spectrum of one out of six observed giants in NGC 6569. For this cluster we find an average heliocentric radial velocity of < v_r > = -47±4 km s⁻¹ and a velocity dispersion of ≈ 8 km s⁻¹. Our radial velocity estimate does not agree with the available literature value reported by Harris (1996) (i.e. -28.1 km s⁻¹) based on optical integrated spectroscopic measurement performed by Hesser, Shawl & Meyer (1986). A possible reason for such discrepancy could be the presence of bright foreground field stars along the cluster core line of sight, which could eventually dominate the result of the integrated spectrum. Indeed, the [V, V-I] CMD of the innermost cluster region (r < 1', see Fig. 4 of Ortolani, Bica & Barbuy (2001)) shows the presence of 3 field stars brighter than the RGB tip. From our overall spectra analysis, we find average [Fe/H]= -0.79 ± 0.02 dex, [O/Fe]= +0.48 ± 0.04 dex, [α/Fe]= +0.43 ± 0.02 dex, [Al/Fe]= +0.38 ± 0.10 dex, and a carbon depletion of [C/Fe]= -0.27 ± 0.04 dex. Low 12C/13C ≲ 7 have been also measured.
Figure 2. H-band image of the core region (left panel) and the K, J-K CMD (right panel) of NGC 6624 (Valenti, Ferraro & Origlia 2004a). The stars spectroscopically observed are numbered (cf. Table 1).

Figure 3. Selected portions of the observed echelle spectra (dotted lines) of one giants in NGC 6569 (left panel) and in NGC 6624 (right panel) with our best-fitting synthetic spectrum (solid line) superimposed. A few important molecular and atomic lines of slight interest are marked.
Table 2. Measured equivalent widths (in units of mÅ) of a few representative lines for the giants observed in NGC 6569 and NGC 6624

| Star   | #1 | #2 | #3 | #4 | #5 | #6 | #1 | #2 | #3 | #4 | #5 |
|--------|----|----|----|----|----|----|----|----|----|----|----|
| Ca λ1.61508 | 161 | 187 | 168 | 150 | 155 | 150 | 228 | 231 | 210 | 208 | 230 |
| Fe λ1.61532 | 165 | 170 | 171 | 154 | 151 | 168 | 184 | 183 | 192 | 198 | 190 |
| Fe λ1.55317 | 138 | 142 | 139 | 133 | 140 | 134 | 140 | 155 | 152 | 167 | 172 | 160 |
| Mg λ1.57658 | 397 | 395 | 387 | 395 | 404 | 396 | 405 | 393 | 415 | 410 | 406 |
| Si λ1.58884 | 472 | 510 | 473 | 477 | 468 | 457 | 497 | 508 | 495 | 476 | 515 |
| OH λ1.55688 | 244 | 326 | 236 | 240 | 253 | 252 | 304 | 339 | 263 | 245 | 340 |
| OH λ1.55721 | 250 | 330 | 243 | 248 | 256 | 256 | 307 | 348 | 270 | 256 | 356 |
| Ti λ1.55437 | 281 | 340 | 275 | 280 | 285 | 286 | 358 | 341 | 335 | 329 | 360 |
| Al λ1.67633 | 291 | 303 | 276 | 275 | 296 | 297 | 330 | 325 | 310 | 312 | 332 |

3.2 NGC 6624

The near-IR photometry of Valenti, Ferraro & Origlia (2004a) and their derived $E(B-V) = 0.28$ reddening and $(m-M)_0 = 14.63$ distance modulus have been used to derive the photometric estimates of the stellar temperatures and bolometric magnitudes for the giants observed in NGC 6624. As shown in Table 1, these stars have bolometric magnitude in the range $-3.0 \leq M_{bol} \leq -3.8$.

The giants in our sample are likely to be cluster members with an average heliocentric radial velocity of $<v_r> = +51 \pm 3$ km s$^{-1}$ and a velocity dispersion $\sigma \approx 6$ km s$^{-1}$, in agreement with the value ($<v_r> = +54.3$ km s$^{-1}$) listed by Harris (1996).

For this cluster our abundances analysis (see Table 3) gives an average $[\text{Fe/H}]= -0.69 \pm 0.02$ dex, $[\text{O/Fe}]= +0.41 \pm 0.06$ dex, $[\alpha/\text{Fe}]= +0.39 \pm 0.02$ dex, $[\text{Al/Fe}]= +0.39 \pm 0.02$ dex, and a carbon depletion of $[\text{C/Fe}]= -0.29 \pm 0.08$ dex. Low $^{12}\text{C}/^{13}\text{C} \approx 5$ have been also measured.

4 DISCUSSION AND CONCLUSIONS

The $[\alpha/\text{Fe}]$ enhancement (where $\alpha = Ti, Si, Mg, Ca$) measured in both NGC 6569 and NGC 6624 is consistent with those measured in the other 10 GCs and in the four inner Bulge fields surveyed by our group. Moreover, an overall agreement is also found with the results obtained so far in outer regions along the minor axis from $-3^\circ$ to $-12^\circ$ galactic latitude by Lecureur et al. (2007), Alves-Brito et al. (2010), Johnson et al. (2011), Gonzalez et al. (2011). All this measurements indicate that the bulk of the Bulge population as a whole, likely formed from a gas mainly enriched by type II SNe on a short timescale, before substantial explosion of type Ia SNe and at early epochs, as suggested by old age ($\geq 10\text{ Gy}$) Kuijken & Rich 2002, Zoccali et al. 2003, Sahu et al. 2006.

Also the $[\text{C/Fe}]$ depletion and the low $^{12}\text{C}/^{13}\text{C}$ are consistent with previous measurements of Bulge giants and confirming the presence of extra-mixing process during the evolution along the RGB in metal-rich environments.

The relatively small number of giants observed in NGC 6569 and NGC 6624 do not allow us to properly check for possible Al-O and Al-Mg anti-correlations.

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Table 3. Stellar parameters and abundances for the giants observed in NGC 6569 and NGC 6624

| Star | NGC 6569 | NGC 6624 |
|------|----------|----------|
|      | #1 | #2 | #3 | #4 | #5 | #1 | #2 | #3 | #4 | #5 |
| T_{eff}[K] | 4000 | 3600 | 4000 | 4000 | 4000 | 4000 | 3600 | 3600 | 3800 | 3800 | 3600 |
| log g | 1.0 | 0.5 | 1.0 | 1.0 | 1.0 | 1.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| v_{r}[^{\circ}km s^{-1}] | -33 | -49 | -42 | -48 | -56 | -54 | 51 | 48 | 45 | 53 | 60 |
| [Fe/H] | -0.75 | -0.81 | -0.75 | -0.85 | -0.84 | -0.76 | -0.72 | -0.73 | -0.65 | -0.64 | -0.69 |
| ±0.10 | ±0.07 | ±0.09 | ±0.09 | ±0.09 | ±0.10 | ±0.08 | ±0.09 | ±0.10 | ±0.10 | ±0.10 | ±0.09 |
| [O/Fe] | +0.50 | +0.37 | +0.37 | +0.58 | +0.52 | +0.53 | +0.38 | +0.60 | +0.37 | +0.22 | +0.49 |
| ±0.10 | ±0.09 | ±0.10 | ±0.10 | ±0.09 | ±0.10 | ±0.10 | ±0.12 | ±0.11 | ±0.10 | ±0.11 |
| [Ca/Fe] | +0.35 | +0.28 | +0.35 | +0.35 | +0.29 | +0.25 | +0.42 | +0.43 | +0.35 | +0.35 | +0.43 |
| ±0.16 | ±0.13 | ±0.15 | ±0.16 | ±0.15 | ±0.16 | ±0.14 | ±0.14 | ±0.15 | ±0.15 | ±0.14 |
| [Si/Fe] | +0.47 | +0.53 | +0.48 | +0.56 | +0.56 | +0.36 | +0.42 | +0.43 | +0.35 | +0.24 | +0.48 |
| ±0.16 | ±0.19 | ±0.16 | ±0.16 | ±0.16 | ±0.16 | ±0.19 | ±0.25 | ±0.20 | ±0.19 | ±0.20 |
| [Mg/Fe] | +0.49 | +0.54 | +0.40 | +0.55 | +0.56 | +0.46 | +0.50 | +0.43 | +0.42 | +0.37 | +0.39 |
| ±0.17 | ±0.16 | ±0.17 | ±0.16 | ±0.16 | ±0.17 | ±0.15 | ±0.16 | ±0.17 | ±0.19 | ±0.15 |
| [Ti/Fe] | +0.35 | +0.41 | +0.35 | +0.45 | +0.44 | +0.41 | +0.42 | +0.33 | +0.35 | +0.34 | +0.39 |
| ±0.19 | ±0.16 | ±0.19 | ±0.19 | ±0.18 | ±0.19 | ±0.15 | ±0.16 | ±0.18 | ±0.20 | ±0.16 |
| [Al/Fe] | +0.35 | +0.31 | +0.25 | +0.35 | +0.54 | +0.46 | +0.42 | +0.38 | +0.40 | +0.38 | +0.39 |
| ±0.20 | ±0.17 | ±0.18 | ±0.20 | ±0.18 | ±0.20 | ±0.14 | ±0.14 | ±0.15 | ±0.15 | ±0.14 |
| [C/Fe] | -0.45 | -0.19 | -0.25 | -0.35 | -0.16 | -0.24 | -0.18 | -0.17 | -0.45 | -0.56 | -0.11 |
| ±0.12 | ±0.10 | ±0.12 | ±0.12 | ±0.11 | ±0.12 | ±0.11 | ±0.12 | ±0.12 | ±0.12 | ±0.11 |

(a) Heliocentric radial velocity.
The random error due to EW measurement is quoted for each element abundance.

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