The Gaia-ESO Survey: Galactic evolution of sulphur and zinc *


(Affiliations can be found after the references)

Received ...; Accepted ...

ABSTRACT

Context. Due to their volatile nature, when sulphur and zinc are observed in external galaxies, their determined abundances represent the gas-phase abundances in the interstellar medium. This implies that they can be used as tracers of the chemical enrichment of matter in the Universe at high redshift. Comparable observations in stars are more difficult and, until recently, plagued by small number statistics.

Aims. We wish to exploit the Gaia ESO Survey (GES) data to study the behaviour of sulphur and zinc abundances of a large number of Galactic stars, in a homogeneous way.

Methods. By using the UVES spectra of the GES sample, we are able to assemble a sample of 1301 Galactic stars, including stars in open and globular clusters in which both sulphur and zinc were measured.

Results. We confirm the results from the literature that sulphur behaves as an $\alpha$-element. We find a large scatter in [Zn/Fe] ratios among giant stars around solar metallicity. The lower ratios are observed in giant stars at Galactocentric distances less than 7.5 kpc. No such effect is observed among dwarf stars, since they do not extend to that radius.

Conclusions. Given the sample selection, giants and dwarfs are observed at different Galactic locations, and it is plausible, and compatible with simple calculations, that Zn-poor giants trace a younger population more polluted by SN Ia yields. It is necessary to extend observations in order to observe both giants and dwarfs at the same Galactic location. Further theoretical work on the evolution of zinc is also necessary.


1. Introduction

It is known from observations of the Galaxy’s interstellar medium (ISM) that many chemical elements in the gas phase can be depleted into dust grains (such elements are also refereed to as refractory). Zinc and sulphur are two of the few elements that are depleted into dust grains (such elements are also refereed to as refractory). This makes sulphur and zinc interesting elements to investigate, and for this reason we make use of the large sample of stars observed by the Gaia-ESO Survey (GES, Gilmore et al. 2012; Randich et al. 2013), for which both sulphur and zinc have been analysed, to investigate the abundances of these relatively volatile elements in Galactic stars and to exploit their potential as tracers of Galactic chemical evolution.

1.1. Sulphur

Sulphur is produced in the final stage of the evolution of massive stars, type II supernovae (SNe, Woosley & Weaver 1995; Limongi & Chieffi 2003; Chieffi & Limongi 2004, typically on timescales of less than 30 Myr). On the other hand, the elements of the iron-peak are produced by type II SNe but mainly in type Ia SNe (SN Ia), which produce little to no $\alpha$-elements (Nomoto et al. 1984; Iwamoto et al. 1999). To picture the evolution of the stellar populations in a galaxy it is important to derive the chemical abundances of both the $\alpha$-elements and iron-peak elements. In fact, abundance ratios between elements formed on different timescales, such as $[\alpha/\text{Fe}]$, can be used as cosmic clocks and allow us to clarify the star formation history of our targets. The first phases of evolution of a galaxy are characterised by a low content of metals, because only a small number of massive stars have had enough time to evolve and explode and/or transfer mass to a companion which can in turn reach the mass limit and explode. In both cases, they enrich the environment with the metals synthesised during their stellar life. This early environment is mainly characterised by enrichment from type II SNe but there is hardly any contribution from type Ia SNe, possibly with little traces of the products of the promptest type Ia explosions at evolutionary times greater than 30-40 Myr (see Mannucci et al. 2006; Greggio & Renzini 1983). The metal-poor environment is then characterised by an over abundance of $\alpha$-elements with respect to iron-peak elements when compared to the Sun. This is usually referred to as the $\alpha$-elements enhancement, generally observed in metal-poor stars (e.g. Venn et al. 2004; Cayrel et al. 2004; Cayrel et al. 2007).
In listing [Fe/H] and [S/Fe] in these tables we did not attempt to homogenize the respective solar abundance scales, since all the values listed are indicative and would not vary in any significant way.

3 We adopt the multiplet numbering of Moore (1945).

4 In listing [Fe/H] and [S/Fe] in these tables we did not attempt to homogenize the respective solar abundance scales, since all the values listed are indicative and would not vary in any significant way.

2 A(X) = log_10 ([X/H] + 12).

1 [X/Y] = log_10 (N(X)/N(Y)) - log_10 (N(Y)/N(X)).
gin is probably more complex than previously thought. Skúladóttir et al. in preparation). This implies that zinc is not
eq 0.5 - 0.5 < [Fe/H] < 0.3 1 halo star
Francois (1998) 12 - field dwarfs −1.3 < [Fe/H] < −0.5 6 - - 5 are halo stars
Takada-Hidaka & Takeda (1996) 6 11 √ peculiar stars solar
Israëlian & Rebolo (2001) 6 8 - MP - −3.0 < [Fe/H] < −0.6 negligible NLTE
Takada-Hidaka et al. (2002) 6 68 √ field stars −1.0 < [Fe/H] < −0.5 −0.5 < [Fe/H] < −0.5 -
Chen et al. (2002) 6,8,10 26 - disc stars - - -
Chen et al. (2003) 6,8,10 15 - old MR - - 0.1 < [Fe/H] < 0.5 -
Ecuvillon et al. (2004) 8 112/31 - planet/no planet −0.8 < [Fe/H] < −0.5
Francois et al. (2003) 1 1 - FGK stars −0.9 < [Fe/H] < 0.4 large scatter

Table 1. Summary of literature regarding Galactic sulphur abundances

<table>
<thead>
<tr>
<th>Reference</th>
<th>Mult. line</th>
<th>N$_{sulf}$</th>
<th>N$_{sul}$</th>
<th>N$_{nlte}$</th>
<th>Target type</th>
<th>Flat range</th>
<th>Slope range</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clegg et al. (1981)</td>
<td>6</td>
<td>20</td>
<td>F&amp;G MS</td>
<td></td>
<td>-</td>
<td>-</td>
<td>−0.9 &lt; [Fe/H] &lt; +0.4</td>
<td>lower than MW, consistent with Sgr dSph</td>
</tr>
<tr>
<td>Francois (1987)</td>
<td>6</td>
<td>13</td>
<td>MP dwarfs</td>
<td></td>
<td>[Fe/H] &lt; −0.5</td>
<td>−0.5 &lt; [Fe/H] &lt; 0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Francois (1998)</td>
<td>12</td>
<td>-</td>
<td>field dwarfs</td>
<td>−1.3 &lt; [Fe/H] &lt; −0.5</td>
<td>-</td>
<td>-</td>
<td>5 are halo stars</td>
<td></td>
</tr>
<tr>
<td>Takada-Hidaka &amp; Takeda (1996)</td>
<td>6 11</td>
<td>√ peculiar stars</td>
<td>solar</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Israëlian &amp; Rebolo (2001)</td>
<td>6 8</td>
<td>- MP</td>
<td>-</td>
<td>−3.0 &lt; [Fe/H] &lt; −0.6</td>
<td>negligible NLTE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Takada-Hidaka et al. (2002)</td>
<td>6 68</td>
<td>√ field stars</td>
<td>-1.0 &lt; [Fe/H] &lt; −0.5</td>
<td>−0.5 &lt; [Fe/H] &lt; −0.5</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chen et al. (2002)</td>
<td>6,8,10</td>
<td>26</td>
<td>disc stars</td>
<td>-</td>
<td>-</td>
<td>3D effects small, two deviant stars</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chen et al. (2003)</td>
<td>6,8,10</td>
<td>15</td>
<td>old MR</td>
<td>-</td>
<td>-</td>
<td>0.1 &lt; [Fe/H] &lt; 0.5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ecuvillon et al. (2004)</td>
<td>8</td>
<td>112/31</td>
<td>planet/no planet</td>
<td>−0.8 &lt; [Fe/H] &lt; −0.5</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Francois et al. (2003)</td>
<td>1 1</td>
<td>- FGK stars</td>
<td>−0.9 &lt; [Fe/H] &lt; 0.4</td>
<td>large scatter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fractional their Sec. 3.2). In principle, measurements of [S/Zn] versus [Zn/H] in stellar photospheres can thus be directly compared with abundances of nearby dwarf and giant stars, which might provide the ISM of formation of these stellar populations (e.g. see Berg et al. 2015, for a recent comparison).

However, [Zn/Fe] is not constant at different [Fe/H] for stars in the thin and thick disks (Prochaska et al. 2000; Reddy et al. 2003, 2006; Bensby et al. 2003, 2005, 2013, 2014; Allende Prieto et al. 2004), the Galactic halo (Primas et al. 2000; Bihain et al. 2004; Cäyrel et al. 2004; Nissen et al. 2004; Nissen et al. 2007; Bonifacio et al. 2009), the bulge (Barbuy et al. 2015) and nearby dwarf galaxies (Sbordone et al. 2007; Venn et al. 2012; Skuladottir et al. in preparation). This implies that zinc is not necessarily a good tracer of iron and that its nucleosynthetic origin is probably more complex than previously thought.

More specifically, the observed [Zn/Fe] is super-solar in the Milky Way halo, reaching [Zn/Fe] ≈ +0.5 at [Fe/H] < −3 (Cayrel et al. 2004; Nissen et al. 2007). In the thin and thick disks, [Zn/Fe] decreases with increasing metallicity, reaching the solar ratio at [Fe/H] ≈ 0 similar to the α-elements (Reddy et al. 2003, 2006; Bensby et al. 2003, 2005, 2013, 2014). Furthermore, Nissen & Schuster (2011) identified two populations in the solar neighbourhood with low- and high-α abundances, which also showed low and high ratios of [Zn/Fe], respectively. In the dwarf galaxies Sagittarius, Carina and Sculptor, measurements of [Zn/Fe] have revealed sub-solar ratios and possible scatter (Sbordone et al. 2007; Venn et al. 2012; Skuladottir et al. in preparation). While there are only very sparse measurements of Zn in ultra-faint dSphs to date, the few data above [Fe/H] > −2.2 that overlap with our sample range agree with our Galactic stars. Likewise, the remainder of the very metal-poor ultra-faint dSph stars with [Fe/H] < −2 fully agree with the metal-poor halo (Frebel et al. 2010, 2014, 2016; Roederer et al. 2016; Ji et al. 2016).

The fact that [Zn/Fe] increases at low metallicities, albeit at much lower metallicities than those of the α-elements and Zn. However, predicted zinc yields of SNe Type II are too low to be compatible with ratios of [Zn/Fe] ≥ 0 (Nomoto et al. 1997a). By invoking models of core collapse SNe with high explosion energy, i.e. hypernova,
which are predicted to produce high levels of zinc, Kobayashi et al. (2006) were able to reproduce the trend observed in the disk. This does not, however, explain the high levels of $[$Zn/Fe$]$ at the lowest metallicities observed in the Milky Way halo. To produce the decreasing trend with metallicity, the ratio of $[$Zn/Fe$]$ in SNe Type Ia yields should be even lower, and they are indeed predicted to be extremely low (Iwamoto et al. 1999). In addition to hypernova and SNe Type II other production sites of zinc have been proposed, such as neutrino-driven winds (Hoffman et al. 1996) and the weak and/or main $s$-processes, but these are not expected to be dominant sources of zinc in the Milky Way (Mishenina et al. 2002; Travaglio et al. 2004).

Furthermore, there is still no clear consensus on the observed zinc abundances at the highest metallicities ($[$Fe/H$] \geq 0$). Some studies have reported an increase in $[$Zn/Fe$]$ with $[$Fe/H$]$ at this metallicity (Bensby et al. 2003, 2005; Allende Prieto et al. 2004), while other suggest a flatter trend (Pompéia 2003; Reddy et al. 2003, 2006; Bensby et al. 2013, 2014). Barbey et al. (2015) observed red giant stars in the Milky Way bulge, and found a spread of $-0.6 < [\text{Zn/Fe}] < +0.15$ for $[\text{Fe/H}] \geq -0.1$, which has not been observed in dwarf stars. On the other hand, Takeda et al. (2016) did not find any significant scatter, nor a discrepancy of measured zinc abundances between field dwarf and giant stars in this same metallicity range.

1.3. The role of the Gaia ESO Survey

The Gaia ESO Survey provides us with a large, homogeneous sample of Galactic stars that can help us to understand the Galactic chemical evolution of sulphur and zinc around solar metallicity. The only features of S I observable in the VLT-UVES (Dekker et al. 2000) ranges observed by GES (415 – 621 nm or 472-683 nm, red arm 520 nm and 580 nm standard settings, respectively) are weak, and belong to Mult. 8, which comprises three features, each consisting of a triplet. Due to the relatively low signal-to-noise ratio ($S/N$) and the relatively low resolving power ($R \approx 47000$) of the observed spectra, only the stronger sulphur triplet at 675.7 nm is useful for abundance determination in this case. As stated by Korotin (2009), NLTE effects are relatively small for this triplet, making our data very useful for this work. Two Zn I lines are observable in the wavelength range, at 481.0 and 636.2 nm.

The structure of the paper is as follows: In section 2, we describe the data. Section 3 presents the chemical abundance analysis for each element and some specific findings, while in Section 4 we discuss these findings and summarise our results.

2. The Gaia-ESO data

The Gaia ESO Survey is one of ESO’s large public spectroscopic surveys. It is an ambitious project which aims at collecting and analysing high quality spectra for about $10^9$ stars by the time the survey will be completed, which will complement the spectroscopic capabilities of the Gaia satellite Gaia Collaboration et al. (2016) at faint magnitudes. The GES provides high quality information about the kinematics and chemistry of the Milky Way bulge, the thin and thick disk, the halo and of a selected sample of about 60 open clusters covering a range of ages and masses. Additionally, data is collected for a number of clusters and benchmark stars for calibration purpose (Pancino & the Gaia-ESO Survey collaboration 2016). The project is run at the Paranal Observatory on the Chilean Andes, using the FLAMES (Pasquini et al. 2002) multi-object facility mounted at the UT2 telescope of the VLT.

The data analysed in the present paper belong to the fourth internal release (henceforth iDR4). iDR4 includes observations from the beginning of the survey (31 December 2011) until end July 2014. In this paper, only the UVES part of the collected data is considered. UVES observations are conducted mainly with the 580 nm setup which covers the wavelength range 472-683 nm. The fiber target allocation is summarised in Smiljanic et al. (2014); Stönküt et al. (2016). F- and G-type dwarf stars are the primary targets in solar neighbourhood fields and should cover distances up to 2 kpc from the Sun, while a smaller selection of giants extends to larger distances. In globular clusters, all the targets belong to the RGB or the red clump. In open clusters, red clump stars are the main UVES targets in old and intermediate age open clusters, with F-G dwarfs being also observed mainly in young clusters, and close intermediate-age ones. The data reduction of the UVES spectra (Sacco et al. 2014) makes use of the ESO FLAMES-UVES CPL pipeline5. A detailed description of the structure of the GES UVES sample, and of the strategy adopted to analyse it, is presented in Smiljanic et al. (2014).

3. Chemical abundance analysis

The UVES spectra have been analysed using the multiple pipelines strategy described in Smiljanic et al. (2014). The individual results of the pipelines are combined with an updated methodology to define a final set of recommended values of the atmospheric parameters and abundances (see Casey et al. in preparation). We adopted here the homogenised stellar parameters from GES iDR4.

With fixed stellar parameters (effective temperature, surface gravity, micro-turbulence and $[$Fe/H$]$) at the values derived in the homogenised iDR4, we ran MyGIsFOS (Sbordone et al. 2014) to derive $A(\text{S})$ from a line profile fitting of S I Mult. 8, located at 675 nm. We chose to redetermine S abundances rather than employ the GES homogenised values due to an extra S I component mistakenly introduced in the second version of the GES line-list, which would skew the homogenised results towards lower S abundances.

A grid of synthetic spectra computed with turbospectrum (Alvarez & Plez 1998; Plez 2012), based on the grid of OS-MARCS models provided by the GES collaboration (Smiljanic et al. 2014) were fit the observed S I triplet. The employed atomic

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5 http://www.eso.org/sci/software/pipelines/
Table 3. $S$ and $Zn$ lines analysed in this work.

<table>
<thead>
<tr>
<th>Element</th>
<th>$\lambda$ [nm]</th>
<th>$E_{\text{low}}$ [eV]</th>
<th>$\log gf$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>675.6750</td>
<td>7.87</td>
<td>$-1.67$</td>
</tr>
<tr>
<td>$S$</td>
<td>675.6960</td>
<td>7.87</td>
<td>$-0.83$</td>
</tr>
<tr>
<td>$S$</td>
<td>675.7150</td>
<td>7.87</td>
<td>$-0.24$</td>
</tr>
<tr>
<td>$Zn$</td>
<td>481.0528</td>
<td>4.078</td>
<td>$-0.16$</td>
</tr>
<tr>
<td>$Zn$</td>
<td>636.2338</td>
<td>5.796</td>
<td>$+0.14$</td>
</tr>
</tbody>
</table>

Fig. 2. The stars analysed in this work are shown in the $T_{\text{eff}}$ vs. $\log g$ plane.

data are presented in Table 3. The $\log gf$ of the $S$ components used by Takeda et al. (2016) are slightly larger than the values chosen by the GES collaboration and correspond to about a global $\log gf$ 0.01 dex larger. The values suggested in NIST provide a global $\log gf$ 0.11 dex lower that would provide larger sulphur abundances. A comparison of the GES homogenised $S$ abundances with the one we derived (giving a systematic difference of $-0.03$ dex) is presented in Fig. 1. The $S$ abundances we derived are made available as an online table through GDS.

We visually inspected all the UVES spectra of F, G and K stars, and retained spectra for which a safe measurement of the $S$ line could be made. We ended up with a sample of 1301 stars. Our sample spans 2741 K in effective temperature ($4153 \leq T_{\text{eff}} \leq 6624$ K), $3.45$ dex in surface gravity ($1.23 \leq \log g \leq 4.68$), and $1.68$ dex in metallicity ($-1.07 < [\text{Fe/H}] < +0.61$). In Fig. 2, the effective temperature and surface gravity of our sample of stars are shown. To assure us that this way of selecting the stars did not introduce a bias, we compared $[\text{Zn/Fe}]$ in the complete sample and the selected ones and we could not find any systematic difference (see Sec. 3.3).

One star (21300738+1210330, a member of the cluster M 15) with [Fe/H] = $-2.65$, shows a feature at the wavelength of the sulphur triplet (see Fig. 3) but due to a $S/N$ of 100, which is low when compared to the weak line, we cannot exclude this as a spurious result.

We have relied on the homogenised abundances provided by iDR4 for zinc (and also compared to the abundances from our MyGlS FOS node) and the other elements shown here. The abundances are derived from two $Zn$ lines at 481.0 and 636.2 nm. For the majority of the stars in the sample, zinc abundances are derived from both lines, but for 92 stars the abundances rely on a single $Zn$ line. The zinc lines used are listed in Table 3. The 636.2 nm line is affected by the Ca I 636.1 nm auto-ionisation line and also blending CN lines (see Barbuy et al. 2015, for a discussion).

The solar abundances we have used for reference in our analysis are presented in Table 4. In the table we also provide the corresponding iDR4 recommended values from GES analysis of an UVES solar spectrum.

Table 4. Solar abundances used in this work compared with GES homogenised values

<table>
<thead>
<tr>
<th>Element</th>
<th>GES iDR4</th>
<th>Adopted</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A(\text{Fe})$</td>
<td>7.43</td>
<td>7.52</td>
<td>Caffau et al. (2011)</td>
</tr>
<tr>
<td>$A(\text{S})$</td>
<td>7.03</td>
<td>7.16</td>
<td>Caffau et al. (2011)</td>
</tr>
<tr>
<td>$A(\text{Zn})$</td>
<td>4.47</td>
<td>4.62</td>
<td>Lodders et al. (2009)</td>
</tr>
<tr>
<td>$A(\text{Ca})$</td>
<td>6.21</td>
<td>6.33</td>
<td>Lodders et al. (2009)</td>
</tr>
<tr>
<td>$A(\text{Na})$</td>
<td>6.21</td>
<td>6.30</td>
<td>Lodders et al. (2009)</td>
</tr>
</tbody>
</table>

Fig. 3. The observed spectrum (solid black) of the star 21300738+1210330 in the range of the Mult. 8 of sulphur. A synthetic (dashed red) spectrum with the sulphur abundance derived of $A(S) = 6.26$ by the analysis is also included. Vertical dashed black lines highlight the positions of the $S$ lines of the Mult. 8.

3.1. Sulphur

The spectra we investigate are usually of good quality. For the spectra for which we derive sulphur abundance, we have a mean signal-to-noise ratio, in the sample of spectra, of $112$ K and 0.22 dex, respectively. Propagation of these errors imply an uncertainty in the sulphur abundance determination. We considered five representative stars and derived the impact of changes in $T_{\text{eff}}$ and $\log g$ on the determination of $A(S)$. The results are presented in Table 5. The uncertainties associated with temperature and gravity in the iDR4 sample are 112 K and 0.22 dex, respectively. Propagation of these errors imply an uncertainty in $A(S)$ of about $\pm 0.10$ dex in both cases.

Figure 5 depicts the $[\text{Ca/Fe}]$ versus $[\text{Fe/H}]$ (provided by the iDR4 of the GES), which is a typical and well studied $\alpha$-
ours may cover overlapping regions in terms of galactocentric distances and heights over the galactic plane (see Fig. 14 and 15). A detailed comparison is, however, not possible. In fact, the trends detected in the APOGEE samples make use of a [$\alpha$/Fe] parameter obtained by combining measures of O, Mg, Si, Ca, Ti and S. Calcium and sulphur abundances presented by Holtzman et al. (2015) show trends qualitatively similar to ours. Additionally, the APOGEE samples sizes are significantly larger than ours.

In the sample of stars we analysed there are some that have been observed as being members of globular clusters (54 stars) and of open clusters (312 stars). We verified the membership comparing radial velocities and metallicities. For the young clusters we considered the members identified by Spina et al. (2017, see their Fig. 14) show trends qualitatively similar to ours.

At odds with the results presented by Nidever et al. (2014); Hayden et al. (2015) from APOGEE data, our data show no indication of two different sequences in the [$\alpha$/Fe] vs. [Fe/H] planes for sulphur or calcium (see Fig. 5). The APOGEE samples and ours may cover overlapping regions in terms of galactocentric distances and heights over the galactic plane (see Fig. 14 and 15). A detailed comparison is, however, not possible. In fact, the trends detected in the APOGEE samples make use of a [$\alpha$/Fe] parameter obtained by combining measures of O, Mg, Si, Ca, Ti and S. Calcium and sulphur abundances presented by Holtzman et al. (2015, see their Fig. 14) show trends qualitatively similar to ours. Additionally, the APOGEE samples sizes are significantly larger than ours.
Fig. 7. [S/Fe] vs. [Fe/H] for the complete sample of stars: black, stars cooler than 5000 K; red 5000 \(\leq\) \(T_{\text{eff}}\) < 5500 K; green 5500 \(\leq\) \(T_{\text{eff}}\) < 6000 K; blue hotter than 6000 K.

Fig. 8. [S/Fe] versus effective temperature for the 19 stars in NGC 6705.

For some open clusters (e.g. Trumpler 20, Trumpler 23, NGC 6705, Berkeley 81) the high [S/Fe] could be explained by the low \(T_{\text{eff}}\) of the member stars. This is in line with what was found in M 67 for which, when selecting only the stars with \(T_{\text{eff}}\) > 5000 K, we have a smaller star-to-star scatter, [S/Fe] = +0.0 \(\pm\) 0.02. Also the 19 giant members of NGC 6705 show a clear trend of increasing [S/Fe] by decreasing the stellar effective temperature. The effect is evident in Fig. 8. However, this cannot explain the high [S/Fe]=+0.21 of NGC 2516 from two relatively warm stars (\(T_{\text{eff}}\) > 5500 K).

In Fig. 9 we compare the [S/Fe] versus [Fe/H] relation from the literature for open and globular clusters to our measurements after NLTE corrections are applied to our sulphur values. This figure is an update of figure 4 of Caffau et al. (2014), see references therein. For added samples: crossed black squares are from this work, blue stars are stars belonging to Sculptor dSph from Skúladóttir et al. (2015), open blue circles are field stars from Jönsson et al. (2011), and red filled squares are field stars from Ecuvillon et al. (2004).

3.2. A possible S - Na correlation in 47 Tucanae

Sulphur abundances in NGC 104 (47 Tuc) were investigated by Sbordone et al. (2009). They determined sulphur abundances in 4 turn-off and 5 subgiant stars, using VLT-UVES spectra and measuring lines of S i Mult. 1 around 922 nm. They claimed a statistically significant positive correlation of [S/Fe] with [Na/Fe], which, if confirmed, would be of high interest in the context of the investigation of multiple populations in globular clusters, especially because there is no obvious mechanism of sulphur production as part of any currently considered globular cluster self-enrichment mechanisms (Sbordone et al. 2009).

In Fig. 10 we plot [S/Fe] vs. [Na/Fe] for stars in NGC 104. Black points are GES measurements in giants, red points are Sbordone et al. (2009) TO and SGB stars, shifted to our adopted solar abundance scale. Linear fits are included, the magenta line indicating the fit to the whole sample. A conservative error estimate is also shown.

When looking at the Sbordone et al. (2009) and GES sample separately, neither produces a significant slope when fitted linearly (GES, 0.30 \(\pm\) 0.34, Sbordone et al. 2009 0.47 \(\pm\) 0.37). The Sbordone et al. (2009) sample showed a very high likelihood of correlation between [S/Fe] and [Na/Fe] through a Kendall \(\tau\) test. However, when the two samples are taken together the slope of the linear fit is highly significant (0.76 \(\pm\) 0.18). Also, it is remarkable how the two samples cover different ranges in [Na/Fe]. The GES sample appears to cover a range consistent with recent [Na/Fe] measurements in NGC 104 giants (Cordero et al. 2014, Thygesen et al. 2014, Johnson et al. 2015), while analyses of TO and SGB stars find a distribution significantly more extended towards low Na abundances (Dobrovolskas et al. 2014, Article number, page 7 of 15
Table 6. Distances, [Fe/H], [S/Fe] and [Zn/Fe] for stars belonging to clusters.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Type</th>
<th>$R_0$</th>
<th>$R_{GC}$</th>
<th>[Fe/H]</th>
<th>[S/Fe]</th>
<th>[Zn/Fe]</th>
<th>N Stars</th>
<th>Comment</th>
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</thead>
<tbody>
<tr>
<td>NGC 104/47 Tuc</td>
<td>GC</td>
<td>7.13</td>
<td>+0.01</td>
<td>+0.51</td>
<td>+0.46</td>
<td>+0.18</td>
<td>19</td>
<td>G</td>
</tr>
<tr>
<td>NGC 1851</td>
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Notes. GCs distances from Harris (1996) (2010 edition). For OCs: distance for NGC 2243, Bragaglia & Tosi (2006); Be 25, Carraro et al. (2007); M 67, Montgomery et al. (1993); all the others from Spina et al. (2017) and reference therein. Galactocentric radii have been computed assuming a distance of the Sun to the Galactic center of 7.94 kpc (Eisenhauer et al. 2003). [Fe/H] is derived averaging among the selected stars in each cluster. The solar abundances here applied are those of the third column in Table 4. Average [Fe/H] values for the open clusters are by about 0.1 dex below those reported by Jacobson et al. (2016) and Spina et al. (2017), due to the use of different solar reference values, and to the inclusion only of the subset of stars with measured sulphur.

Marino et al. (2016). It is particularly intriguing that when stars belonging to the bright and faint SGB of 47 Tuc (bSGB, fSGB) are discriminated in Marino et al. (2016), the bSGB stars appear Na-poor, and match the range in Na observed by Dobrovolskis et al. (2014) and Sbordone et al. (2009). The fSGB stars, on the other hand, match the Na abundances covered in the GES sample and other RGB-based studies. On the one hand, the bSGB is more populated and brighter so it is reasonable that the Sbordone et al. (2009) and Dobrovolskis et al. (2014) samples, designed to study the weak Li $\lambda 670.8$nm doublet, were drawn from this population. On the other hand, it is unclear why RGB samples appear to lack the Na-poor tail detected in the prominent bSGB. Investigating the [Na/Fe] distributions of different NGC 104 populations is outside the scope of the present paper, but the similarity between the [Na/Fe] distribution in the two NGC 104 SGBs, and the two samples here investigated for sulphur and zinc, suggest the possibility that the Sbordone et al. (2009) and the GES samples might be drawn from different subpopulations of the cluster, possibly each without internal [S/Fe] spread, but rather characterised by different [S/Fe] values. In this case, once the Sbordone et al. (2009) sample is brought to the solar abundance scale employed in our analysis, they would correspond to [S/Fe] $\equiv 0.16 \pm 0.14$ and [S/Fe] $\equiv 0.53 \pm 0.13$ (Sbordone et al. 2009, GES).

Caution in the comparison is in order since different multiplets are used, as well as stars of different atmospheric parameters, so systematic differences between the two samples might be induced if line formation systematics (3D, NLTE...) are not correctly accounted for. However, the currently available data indicate that NGC 104 displays either a spread in [S/Fe], strongly correlating with [Na/Fe], or two subpopulations characterised by significantly different values of [S/Fe].

3.3. Zinc over iron

In Fig. 11 we show the [Zn/Fe] versus [Fe/H] for the sample of stars analysed for sulphur. A large scatter in [Zn/Fe] is evident overall around solar metallicity. When we divide the sample into dwarf stars (log g $> 3.45$) and giant stars we realise that the large spread is mainly due to giants. The 897 stars classified as dwarfs give $\langle [Zn/Fe]_d \rangle = 0.07 \pm 0.11$ while the 404 giants give $\langle [Zn/Fe]_g \rangle = -0.12 \pm 0.22$. Hence, the scatter of [Zn/Fe] for giant stars is larger than both the observational error, which is on average $\approx 0.12$ (Fig. 11), and the dispersion observed within dwarf stars. On average, giants show lower [Zn/Fe] than dwarfs. Such differences are even more evident when we select the 525 stars around solar metallicity, $-0.1 < [Fe/H] < 0.1$, for which we derive $\langle [Zn/Fe]_g \rangle = -0.06 \pm 0.19$. In this case the 295 dwarfs contribute with $\langle [Zn/Fe]_d \rangle = 0.04 \pm 0.10$ and the 230 giants with $\langle [Zn/Fe]_g \rangle = -0.20 \pm 0.20$. The same calculations for the 162 stars (mainly giants) that are members of clusters provide $\langle [Zn/Fe]_g \rangle = -0.19 \pm 0.22$ for the overall sample, and $\langle [Zn/Fe]_d \rangle = -0.20 \pm 0.20$ for stars around solar metallicity. Stars in clusters contribute to lower the average [Zn/Fe] of the giant sample at [Fe/H] $\approx 0.0$ but apparently they are not the main drivers of the large scatter, as can be seen in Fig. 11.

To investigate if the differences between dwarfs and giants are real or if the observed trend is driven by analysis and/or observational biases we made several tests.

First, we checked if this behaviour is a consequence of restricting the GES sample to stars with detected sulphur. This is shown in Fig. 12, where we plot [Zn/Fe] vs [Fe/H] for the complete sample of 1724 stars. In the solar-metallicity regime we can see that both the low [Zn/Fe] values and the large scatter are clearly reproduced in the case of giant stars.

Second, we tested possible biases due to NLTE effects. Using the computations of Takeda et al. (2005) we could derive for our sample a NLTE correction of $-0.06 \pm 0.02$ for zinc, which is well within the observational uncertainty. Furthermore the correction
dynamical models and their reference 1D LHD on the abundances we computed zinc abundances for 22 hydro-
expected to be negligible and to depress the $\text{[Zn/Fe]}$ always positive. Thus, also in this case the NLTE e-
mate of the NLTE e

for two gravities (4.0 and 4.5). In all cases but one (for the
model and three e

ff

CIFIST grid (Ludwig et al. 2009), for two metallicities (0.0 and
and two at 4500 K (gravity 2.0 and 2.5). The 3D corrections
vestigated three models at 5000 K (gravity of 2.5, 3.0 and 3.5)
481 nm and 636 nm line respectively. For the giant stars we in-
the 3D corrections are positive, on average 0.02 for the 481 nm and
636 nm line respectively. Hence, also the granulation effects are
also comparable to the uncertainties.

Fourth, we considered the zinc abundances derived by My-
GIsFOS when fitting the strongest of the two Zn i lines at 481.0 nm. In principle, if there was a problem in the abundances
derived from the 636.2 nm line, either due to the blending CN
lines or to the Ca i 636.1 nm auto-ionisation line, we may ex-
pect a systematic difference. The result is shown in Fig. 13.
We notice that, although the star-to-star scatter is smaller than
in $\text{[Zn/Fe]}$, the difference of about 0.08 dex at metal-rich
regime), the different behaviour of dwarf and giants is still there,
in particular around solar-metallicity, giant stars show much
smaller [Zn/Fe] values than dwarfs. Furthermore, opposite to the
case of sulphur (Fig. 8), a clear trend of increasing/decreasing zinc abundance as a function of the effective temperature is not
evident. We also selected giant stars, similar in stellar parameters
but with a difference of at least 0.4 dex in [Zn/Fe], we com-
pared the observed spectra and checked the results we obtained
from MyGIsFOS. The spectra of low- and high-Zn abundance
goes in the opposite direction, i.e. it is negative, meaning that it
further decreases the [Zn/Fe] value. For iron, we provide an esti-
mate of the NLTE effects using the results of Mashonkina et al.
(2008, see also Lind et al. 2012). According to their calculations
the NLTE correction, mainly affects the Fe i lines, is smaller than
0.1 dex for both giants and dwarfs at solar metallicity, and it is
always positive. Thus, also in this case the NLTE effect is ex-
pected to be negligible and to depress the [Zn/Fe] values further on.

Third, to investigate the effects that granulations can have
on the abundances we computed zinc abundances for 22 hydro-
dynamical models and their reference 1D LHD models from the
CIFIST grid (Ludwig et al. 2009), for two metallicities (0.0 and
−1.0) and we computed the 3D correction as in Caffau & Ludwig
(2007). To study the effects in dwarf stars, we selected the solar
model and three effective temperatures (5500, 5900 and 6250 K)
for two gravities (4.0 and 4.5). In all cases but one (for the
481 nm line and the hottest model at log $g$=4.0 and [Fe/H]=0.0),
the 3D corrections are positive, on average 0.08 and 0.06 for the
481 nm and 636 nm line respectively. For the giant stars we in-
vestigated three models at 5000 K (gravity of 2.5, 3.0 and 3.5)
and two at 4500 K (gravity 2.0 and 2.5). The 3D corrections
are slightly smaller for giants, 0.04 and 0.02 for the 481 nm and
636 nm line respectively. Hence, also the granulation effects are
also comparable to the uncertainties.

Finally, to investigate the impact of the uncertainties in the
stellar parameters on [Zn/Fe], we took into consideration a gi-
ant star with a low-Zn abundance. With MyGIsFOS we derived
the Fe and Zn abundances by changing effective temperature,
gravity and micro-turbulence according to their uncertainties. A
change in $±110$ K in $T_{\text{eff}}$ implies a change in [Zn/Fe] by $±0.07$;
by changing log $g$ by $±0.22$ the change in [Zn/Fe] is of $±0.03$; a
change in the micro-turbulence of $±0.10$ km s$^{-1}$ implies a change
in [Zn/Fe] of about $±0.02$. All the changes in [Zn/Fe] are too
small to alter the above-described picture.

In conclusion, after all these tests we believe it is unlikely
that the difference in [Zn/Fe] between dwarfs and giants is due to
some systematic error in the analysis. We therefore address
the question if the two samples come from the same parent pop-
ulation.
3.4. Different populations, and radial gradient in [Zn/Fe]?

The selection function specific to the GES UVES targets (Smiljanic et al. 2014) results in a magnitude-limited sample primarily aimed at local FGK dwarfs, while the (less numerous) giants generally reside at much larger distances from the Sun. The giant stars are also targeted on purpose with UVES in the bulge fields and in the CoRoT fields. In fact, in the giant sample 20% are in the bulge direction (actually inner disk giants) and 10% in the CoRoT fields. This combined with the open clusters fully explain why the sample is strongly concentrated on the galactic plane. For the clusters we took the distances from the literature (see Table 6). For the field stars, distance moduli are computed using a Bayesian method on the Padova isochrones (Bressan et al. 2012, CMD 2.7) and using the magnitude independent of extinction $K_{J} = K - \frac{A_{J}}{\sqrt{A_{V}}} (J - K)$ with extinction coefficients computed applying the Fitzpatrick & Massa (2007) extinction curve on the Castelli & Kurucz (2003) SEDs. The prior on the mass distribution used the IMF of Chabrier (2001) while the prior on age was chosen flat. Stars too far from the isochrones were rejected using the $\chi_{99}^{2}$ criterion. Moreover, giants were targeted predominantly in open clusters, or in globular clusters that were observed as calibrators (Pancino & the Gaia-ESO Survey collaboration 2016). The dwarf sample happens to be entirely located within $\leq 1.5 \text{kpc}$ from the Sun, with a peak of the distribution at $D \approx 0.5 \text{kpc}$. Giant stars cover a much larger range in distance, $0.0 < D/\text{kpc} < 16$, with all stars, but one further than 6 kpc from the Sun residing in clusters. The distant giants sample is at low metallicity ([Fe/H]$\leq -0.5$), and almost entirely hosted in globular clusters. Local giants are predominantly metal-rich, and largely hosted in open clusters.

In Fig. 14 we show the [Zn/Fe] ratio as a function of the height above (or below) the Galactic plane. The histogram in Fig. 14 is driven by the superposition different selection effects. On the one hand, giant stars appear to be much more concentrated on the plane, thus likely belonging preferentially to a younger population than the dwarfs. On the other hand, Zn-poor giants appear to prevalently belong to the inner disk, and all display thick disc objects, while the field giants and the open clusters are an almost pure thin disc population.

On average, giants have been observed with UVES in the Gaia-ESO Survey at Galactic latitudes lower than dwarfs: $\langle b_{\circ} \rangle \approx 9^\circ$, while dwarfs $\langle b_{\circ} \rangle \approx 30^\circ$. This bias is not compensated by the geometrical bias: for a given apparent magnitude, giants are more distant, so that they are observed at larger heights from the Galactic plane than dwarfs of the same apparent magnitude and Galactic latitude. Of course the distinction between thin and thick disc based only on the height from the Galactic plane is very crude. The second Gaia data release will provide parallaxes and proper motions for all these stars. When coupled with our radial velocities we shall be able to compute Galactic orbits for all these stars and classify them as belonging to the thin or the thick disc.

Following the findings of Fuhrmann (1998, 1999, 2004), that have been verified by subsequent investigations (see, e.g. Wojno et al. 2016; Haywood et al. 2016; Mikolaitis et al. 2014; Recio-Blanco et al. 2014, and references therein), one expects (kinematically selected) thin disc stars to have lower $\alpha$-to-iron ratios than thick disc stars of the same metallicities. If our dwarf stars sample is dominated by the thin disc stars, as suggested by Fig. 14, we would expect higher $\alpha$-to-iron ratios than in the giant star sample. However, as can be appreciated in Fig. 5, there is no clear distinction between dwarfs and giants in the $\alpha$-to-iron ratios.

In Fig. 15 we plot chemical abundances of giants, dwarfs, and stars in clusters as a function of their distance (from Table 6) from the Galactic centre. In panels (a), (c) and (d) of Fig. 15, we can see the dwarfs’ sample (black open circles) located at around 8 kpc from the Galactic centre (where the Sun is situated), consistent in [Fe/H] and [Zn/H] with disc stars. Giant stars belonging to clusters (globular or open) are depicted in panels (a), (c) and (d) of Fig. 15 as red squares with blue crosses. In panel (b) we binned the abundances in various distance bins. For Galactocentric distances larger than 7.5 kpc, on average $\langle \text{Zn/Fe} \rangle \approx 0$, with a good agreement between field giants, giant stars in clusters and dwarf stars. As we move to smaller distances from the Galactic centre the giants and the cluster stars display a smaller $\langle \text{Zn/Fe} \rangle \approx -0.2$, while the dwarf stars remain at $\langle \text{Zn/Fe} \rangle \approx 0$.

However, panels (a) and (b) in Fig. 15 do not allow to disentangle the superimposed effects of metallicity and galactocentric distance. For this purpose, we plot [Zn/Fe] versus the galactocentric radius, but splitting the whole sample in four metallicity ranges. Once this is done, a few general behaviors of the sample appear with more clarity:

- At low metallicity ([Fe/H]< $-0.5$) both dwarfs and giants show slightly super-solar [Zn/Fe], constant at all galactocentric radii.
- As metallicity increases ($-0.5 \leq [\text{Fe/H}] < -0.25$), sub-solar [Zn/Fe] giants appear in the inner disk. The average value for dwarfs decreases to $[\text{Zn/Fe}] \approx 0$. At the same time, at the solar radius there is little evidence of a discrepancy between dwarfs and giants.
- The most Zn-poor giants all appear at small galactocentric radii ($R_{GC} < 7 \text{kpc}$ and for high metallicities ([Fe/H] $> 0$)).

It thus appears that the dwarf-giants discrepancy in Fig. 11 to 15 is driven by the superposition different selection effects. On the one hand, giant stars appear to be much more concentrated on the plane, thus likely belonging preferentially to a younger population than the dwarfs. On the other hand, Zn-poor giants appear to prevalently belong to the inner disk, and all display
Fig. 15. Panels a, c, d: The [Zn/Fe] (a), the [Fe/H] (c), and the [S/Fe] abundances (d) for the sample of stars analysed for sulphur as a function of their Galactocentric distance. Symbols are the same of Fig. 11. Panel b: The average [Zn/Fe] in different distance bins for dwarfs (black circles), giants (red squares) and for stars in clusters (blue crosses).

solar, or supersolar metallicities. Although it cannot be excluded that a systematic difference in the analysis exists between dwarfs and giants above [Fe/H] ≈ 0, due to the limited overlap in R_GC at high metallicity, the trend appears already quite evident in the $-0.25 \leq [\text{Fe/H}] < 0$ bin, where there is a healthy sample of giants at higher galactocentric radii whose [Zn/Fe] is in agreement with the one of the dwarfs. It is also worth noticing that there is a small subpopulation of dwarfs with low [Zn/Fe] but their small number (seven dwarfs with [Zn/Fe]$< -0.3$) prevents us from drawing any strong conclusion. These are prevalently cool dwarfs, hence faint ones, and closer to the galactic plane that the bulk of the dwarfs in our sample. We are thus inclined to consider the low [Zn/Fe] ratios we observe as a real signature of the chemical enrichment of the inner MW disk.

The complex behavior of [Zn/Fe] with R_GC, metallicity, and age is shown in two recent investigations of high precision abundances in nearby solar twins. Nissen (2015) analyzes a sample of 21 solar twins and finds a clear trend in [Zn/Fe], which increases with increasing stellar age (by about 0.1 dex over about 8 Gyr). A similar trend is found also for [Mg/Fe] and [Al/Fe]. Similar results are found by Spina et al. (2016) in a study of 9 objects. The much more heterogeneous, and lower quality GES sample cannot detect such subtle variations, and lacks precise age estimates: in Fig. 16, the distribution of solar-metallicity, solar-galactocentric-radius dwarfs disperse in [Zn/Fe] by a value comparable to the extent of the correlation found by Nissen (2015) (and Mg and Al have comparable dispersion). These works, however, support the finding of a dependency of [Zn/Fe] from the star formation epoch and environment that is in such stark display in our inner-disk giants.

3.5. A possible effect of SN Ia dilution?

The concentration of low [Zn/Fe] stars on the galactic plane and at small galactocentric radii suggests they might represent a younger population than the dwarf sample, whose Zn would then be more diluted by SN Ia ejecta (which are believed to be almost Zn-free). However, said dilution would affect α elements as well to some extent. We thus proceeded to test this scenario through a simple calculation. Inspecting Fig. 5 and 11, one notices that at A(Fe) = 7.22 (i.e. [Fe/H]$\approx -0.3$) giant and dwarf stars show on average the same ratios of alpha elements, in particular A(Ca)-A(Fe) and A(S)-A(Fe), along with (at or outside the solar circle) the same A(Zn)-A(Fe). By remembering that: 

$$A(\text{Fe}) = \log \frac{N_{\text{Fe}}}{N_{\text{H}}} + 12 = \log \frac{N_{\text{Fe}} \times m_{\text{Fe}}}{N_{\text{H}} \times m_{\text{H}}} + 12 - \log \frac{m_{\text{Fe}}}{m_{\text{H}}} \approx \log \frac{N_{\text{Fe}} \times m_{\text{Fe}}}{M_{\text{g}}} + 12 - \log \frac{m_{\text{Fe}}}{m_{\text{H}}}$$

$$= \log \frac{M_{\text{Fe}}}{M_{\text{g}}} + 12 - \log \frac{m_{\text{Fe}}}{m_{\text{H}}}$$

Article number, page 11 of 15
A gas, which leads to

We can then exploit the derived $M$ of gas, $M$, formed. For example, for $M$ function of the mass of gas, $M$ we can compute the mass of each chemical element, $M$, split to contain only stars in the indicated metallicity range.

where $m_{Fe}$ ($m_H$) is the atomic mass of iron (hydrogen), and that

$$A(X) - A(Fe) = \log \frac{M_X}{M_{Fe}} - \log \frac{m_X}{m_{Fe}}$$

we can compute the mass of each chemical element, $M_X$, as a function of the mass of gas, $M_g$, out of which these stars have formed. For example, for $M_g \approx 10^{10}M_\odot$, we get $M_{Fe} = 9.2 \times 10^6M_\odot$.

By assuming that the following chemical enrichment of the gas, which leads to $A(Fe)^{obs} = 7.52$ (i.e. $[Fe/H]^{obs} \approx 0.0$) and $A(Zn) - A(Fe)^{obs} = -3.1$, is only driven by SN Ia, we can compute the required mass of SN Ia, $M_{SNIa}$, along with the final mass of gas, $M_g^{fin}$, by using the following equations:

$$A(Fe)^{obs} = \log \frac{M_{Fe} + Y_{Fe_{SNIa}} \times M_{SNIa}}{M_g^{fin}} - \log \frac{m_{Fe}}{m_{H}} + 12$$

$$(A(Zn) - A(Fe))^{obs} = \log \frac{M_{Zn} + Y_{Zn_{SNIa}} \times M_{SNIa}}{M_{Fe} + Y_{Fe_{SNIa}} \times M_{SNIa}} - \log \frac{m_{Zn}}{m_{Fe}}$$

We can then exploit the derived $M_{SNIa}$ and $M_g^{fin}$ values to get the expected (“out”) alpha-to-iron ratios of several chemical elements. By using the different SN Ia yield models from Iwamoto et al. (1999), and averaging among the corresponding results, we get $(A(Mg) - A(Fe))^{out} = 0.12 \pm 0.002$, $(A(Ca) - A(Fe))^{out} = -1.14 \pm 0.04$ and $(A(S) - A(Fe))^{out} = -0.28 \pm 0.03$, which are in good agreement with the observed values at $A(Fe) = 7.52$, i.e. $(A(Mg) - A(Fe))^{obs} = -1.16$, $(A(S) - A(Fe))^{obs} = -0.28$, with the exception of Mg, for which $(A(Mg) - A(Fe))^{obs} = 0.24$ is 0.12 dex higher than the theoretical expected value. Thus, although this picture needs to be carefully tested against other chemical elements and by exploiting detailed cosmochemical chemical evolution models, we conclude that it is plausible.

Clearly, if the enrichment of SN Ia is really at the origin of the low zinc to iron ratio observed in giant stars located in the inner thin disk, the same trend should be observed in dwarf stars, once observed in the same region. Thus, it can in principle be tested observationally, although 30m-class telescopes will likely be needed.

3.6. Sulphur over zinc

In Fig. 17 the $[S/Zn]$ versus $[Zn/H]$ abundances for the sample of stars analysed for sulphur are shown, by distinguishing among dwarfs, giants and stars in clusters. As already noticed for the $[Zn/Fe]$ vs $[Fe/H]$ trend, we clearly see that dwarfs and giants behave very differently. Dwarf stars show a constant $[S/Zn]$ trend with $[Zn/H]$ increasing more rapidly than $[Zn/Fe]$ as metallicity decreases. On the other hand, giant stars show a declining $[S/Zn]$ trend with $[Zn/H]$, with super-solar $[S/Zn]$ values at $[Zn/H] < 0.0$ and large scatter. This is due to the giant sample reaching deeper in the inner disk, where the metal rich population shows solar $[S/Fe]$ but subsolar $[Zn/Fe]$.

4. Conclusions

We analysed the sulphur and zinc abundances in a large sample of Galactic stars. We here below summarise what we found on the analysed sample.

On sulphur:

- Sulphur behaves as an $\alpha$-element, with a typical behaviour of $[S/Fe]$ compatible with 0.0 within uncertainties for stars

These findings are independent on the assumed mass of gas, $M_g$.
around solar metallicity with, at around [Fe/H] of −1.0, a constant value of [S/Fe]. Unfortunately, due to the weak sulphur feature, the stars in our sample with [Fe/H] ≤ −1.0 are only seven, so that we cannot make conclusions on the behaviour of sulphur in the metal-poor regime.

With the line-list we used, we detect a clear trend of [S/Fe] as a function of T_eff. Further investigations on the contribution of CN molecules in the wavelength range will follow.

We could not find a cluster with “low” [S/Fe], like Trumpler 5 that, according to Caffau et al. (2014), has a [S/Fe] compatible with Local Group galaxies (Caffau et al. 2005b). All the clusters with [Fe/H] ≤ −0.4 are enhanced in S, as are field stars.

The open clusters around solar metallicity on average show high [S/Fe] values, but we attribute it to the presence of cool stars whose sulphur abundances are systematically “high”.

We confirm and strengthen the detection (Sbordone et al. 2009) of a significant [S/Fe] spread in NGC 104, which appears to correlate to a high degree of significance with [Na/Fe]. While at face value the data appear to show an actual trend of [S/Fe] with [Fe/H], we cannot rule out that we may actually be sampling two different NGC 104 populations, one S-rich and one S-poor, but each without internal sulphur spread.

On zinc:

- In the GES sample, there is a sizeable scatter in the [Zn/Fe] ratios. This scatter is limited to the giant stars around solar metallicity. The giants also appear to be much more concentrated on the thin disk plane.

- At low metallicity ([Fe/H] < −0.5) [Zn/Fe] appears constant at all galactocentric radii, and slightly supersolar.

- As higher metallicities, [Zn/Fe] decreases to the solar value for stars roughly outside R_GC > 7kpc.

- Conversely, stars at R_GC < 7kpc show an increasing depletion of Zn with increasing metallicity, down to about [Zn/Fe]=−0.3 for stars with [Fe/H]> 0, despite with a significant dispersion. This behavior is in agreement with the low [Zn/Fe] values found in the Milky Way Bulge giants by Barbary et al. (2015).

The low [Zn/Fe] observed in the (inner) thin disk giants can tentatively be explained as due to dilution from almost Zn-free SN Ia ejecta, since a compatible level of dilution is observed in Ca and S. However, the observed [Mg/Fe] is 0.12 dex too high with respect to what our simple calculation indicates.

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Article number, page 13 of 15

Duffau et al.: Gaia-ESO Survey S and Zn