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# GIANO $Y$-band spectroscopy of dwarf stars: Phosphorus, sulphur, and strontium abundances[★]

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## ABSTRACT

*Context.* In recent years a number of poorly studied chemical elements, such as phosphorus, sulphur, and strontium, have received special attention as important tracers of the Galactic chemical evolution.

*Aims.* By exploiting the capabilities of the infrared echelle spectrograph GIANO mounted at the Telescopio Nazionale *Galileo*, we acquired high resolution spectra of four Galactic dwarf stars spanning the metallicity range between about one-third and twice the solar value. We performed a detailed feasibility study about the effectiveness of the P, S, and Sr line diagnostics in the $Y$ band between 1.03 and 1.10 $\mu$m.

*Methods.* Accurate chemical abundances have been derived using one-dimensional model atmospheres computed in local thermodynamic equilibrium (LTE). We computed the line formation assuming LTE for P, while we performed non-LTE analysis to derive $S$ and Sr abundances.

*Results.* We were able to derive phosphorus abundance for three stars and an upper limit for one star, while we obtained the abundance of sulphur and strontium for all of the stars. We find [P/Fe] and [S/Fe] abundance ratios consistent with solar-scaled or slightly depleted values, while the [Sr/Fe] abundance ratios are more scattered (by ±0.2 dex) around the solar-scaled value. This is fully consistent with previous studies using both optical and infrared spectroscopy.

*Conclusions.* We verified that high-resolution, $Y$-band spectroscopy as provided by GIANO is a powerful tool to study the chemical evolution of P, S, and Sr in dwarf stars.

**Key words.** stars: abundances – stars: atmospheres – Galaxy: disk – Galaxy: evolution – line: formation – radiative transfer

## 1. Introduction

The infrared (IR) spectrograph GIANO (Oliva et al. 2012) is mounted at the Nasmyth focus of the 4 m Telescopio Nazionale *Galileo* (TNG) in La Palma. It observes in the range 950−2450 nm at a resolving power of 50 000. We exploit the capabilities of this new facility to perform a feasibility study aimed at verifying the effectiveness of high-resolution spectroscopy in the $Y$ band to derive reliable abundances of phosphorus and two other elements, namely S and Sr, in Galactic dwarf stars.

Phosphorus, with an atomic number of 15, is a light element, which is abundant in the Universe and essential for the life as we know it on Earth. The systematic analysis of phosphorus in Galactic stars is somewhat recent (see Caffau et al. 2011; Roederer et al. 2014). In fact, the presence of P in the stellar atmospheres of F-G stars can be revealed by P I near infrared (IR) lines at about 1050 nm or by ultraviolet (UV) lines at about 213 nm (Roederer et al. 2014), which have to be observed from space. An exhaustive review of the chemical evolution of phosphorus and of its investigations in peculiar stars can be found in the recent paper of Roederer et al. (2014).

Sulphur is an $\alpha$-element that is effectively produced in massive stars at the final stage of their evolution (SNe of type II). Determination of its abundance in F-G-K stars relies on a limited number of S I lines in the visual and near-IR spectral range. The situation with the lines available for measurements in the spectra of metal-poor stars becomes more complicated. Only the strongest IR S I lines of the first (at about 920 nm) and third multiplets[1] are observable in the spectra of stars with metallicities $[\mathrm{M/H}] < -1.5$. The lines of the first multiplet are very strong and also detectable in extremely metal-poor stars (Spite et al. 2011), but they are often contaminated by telluric absorption. The lines of the third multiplet at 1045 nm are not so strong, but clear from telluric absorption and also very useful for abundance determination (Nissen et al. 2007; Caffau et al. 2007a) at metal-poor regimes. As shown by Korotin (2009), the non-local thermodynamic equilibrium (NLTE) effects have different influences on different S I lines.

As for phosphorus, the systematic analysis of the chemical evolution of sulphur is recent (e.g. Ryde & Lambert 2004), but in the latest ten years this research has grown. For an updated

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[★] Based on observations obtained with GIANO.

[1] Here and elsewhere in the paper we adopt the multiplet numbering of Moore (1945).

vision on the status of S chemical investigations, see Matrozis et al. (2013).

Strontium is an astrophysically interesting element, since its abundance is often used as a measurement of the efficiency of the slow neutron capture process in the intermediate mass stars. Together with Y and Zr, strontium belongs to the peak of light s-process elements. In the visual part of the spectrum there are only a few lines of Sr II. Among them there are two resonant lines at 407.7 nm and 421.5 nm, and a subordinate line at 416.1 nm.

All the lines in the visual part are blended to some extent. For instance, the wing of the resonant line at 407.7 nm is distorted by the La II line at 407.73 nm, Cr II line at 407.75 nm, and Dy II line at 407.79 nm. Another resonant line at 421.5 nm has an even more distorted profile due to blending with a strong Fe I line at 421.543 nm and molecular CN band. The subordinate line at 416.1 nm is situated in the red wings of the two strong Fe I 416.149 nm and Ti II 416.153 nm lines, and, moreover, it is blended with molecular bands of CN and SiH.

Another problem with using resonant Sr II lines for the abundance determination is their weak sensibility to the abundance change in stars of the solar metallicity (they are strong). In contrast, IR Sr II lines are free of these problems, they are practically unblended. Nevertheless, as it was shown by Andrievsky et al. (2011) they are strongly affected by the NLTE effects. Depending upon the atmosphere parameters and metallicity, the NLTE corrections can achieve up to −0.5 dex and more.

In summary, reliable abundances of Sr in the atmospheres of cool stars of different metallicities can be derived from their near-IR lines with the help of the NLTE analysis only (Spite et al. 2011; Andrievsky et al. 2011).

We present the chemical analysis of phosphorus, sulphur, and strontium in four unevolved stars observed with GIANO. Two of these stars also have CRIRES spectra and we find a good agreement with the $P$ abundance derived by Caffau et al. (2011). For sulphur, we compared the $S$ abundance we derived from the GIANO spectra to observations taken with SOPHIE and to previous analysis based on multiplets eight and six. We find a good agreement with the SOPHIE spectra, but not always with previous analysis. For the analysis on Sr, we compared the results based on the GIANO observations with UV lines in SOPHIE spectra and find a good agreement.

## 2. Observed spectra

The GIANO spectra of the four Galactic dwarfs were acquired during two technical nights on October 22 (HD 1355 and HD 22484) and 23 (HD 146 and HD 22484), 2013. GIANO is interfaced to the telescope with a couple of fibers mounted on the same connector at a fixed projected distance on sky of 3 arcsec. We observed the science targets by nodding on fiber, i.e. target and sky were taken in pairs and alternatively acquired on fiber A and B, respectively, for an optimal subtraction of the detector noise and background. HD 1461 was observed by setting two pairs of AB exposures for a total on-source integration time of 20 min, while for the other three stars (brighter) only one pair of AB spectra for a total exposure time of 10 min have been acquired. We also observed the hot (O6.5V) dwarf star HIP 029216 as a telluric standard.

From each pair of exposures, an (A-B) 2D-spectrum has been computed. As a result of the image slicer, each 2D frame contains four tracks per order (two per fiber). To extract and wavelength-calibrate the echelle orders from the 2D GIANO spectra, we used the ECHELLE package in IRAF and some new, ad hoc scripts grouped in a package named GIANO_TOOLS, which can be retrieved at the TNG WEB page[2]. We used 2D spectra of a tungsten calibration lamp taken in the daytime to map the geometry of the four spectra in each order and for flat-field purposes. A U-Ne lamp spectrum was used for wavelength calibration. We extracted the positive (A) and negative (B) spectra of the target stars and summed them together to get a 1D wavelength-calibrated spectrum with the best possible signal-to-noise ratio (S/N).

**Table 1.** Infrared lines analysed in this work.

| Element [nm] | $\lambda$ [nm] vacuum/air | $E_{\rm low}$ [eV] | log $gf$ |
|---|---|---|---|
| P I | 1053.241/1052.952 | 6.95 | +0.240 |
| P I | 1058.447/1058.157 | 6.99 | +0.450 |
| S I | 1045.8316/1045.5449 | 6.86 | +0.250 |
| S I | 1045.9622/1045.6757 | 6.86 | −0.447 |
| S I | 1046.2272/1045.9406 | 6.86 | +0.030 |
| Sr II | 1003.9405/1003.6654 | 1.805 | −1.312 |
| Sr II | 1033.0139/1032.7309 | 1.839 | −0.353 |
| Sr II | 1091.7864/1091.4887 | 1.805 | −0.638 |

For the scientific purpose of this paper aimed at deriving the abundances of phosphorus, sulphur, and strontium, we focused our analysis on the GIANO spectral orders between #76 and #70, covering the $Y$ band between 1.00 and 1.10 $\mu$m. This band is rather clean from telluric contamination and contains a number of suitable transitions for the chemical species we are interested in.

In order to make a comparison of $S$ and Sr abundances derived from IR and optical spectra, we retrieved from the SOPHIE archive[3] spectra observed at Observatoire de Haute Provence for HD 13555 and HD 22484. For HD 13555, we retrieved 30 spectra observed in the high resolution (HR) mode of SOPHIE ($R \approx 76\,500$), observed between November 2006 and September 2008. The spectra were coadded providing $S/N \approx 700$ at 550 nm. For HD 2483, we only retrieved two HR SOPHIE spectra observed on October 23 and 26 2013 with exposure times of 200 s and 150 s, respectively. The S/N of the summed spectrum is about 300 at 550 nm. SOPHIE (Bouchy & Sophie Team 2006; Perruchot et al. 2008, 2011) is an echelle spectrograph fiber-fed from the Cassegrain focus of the 1.93 m telescope at Observatoire de Haute-Provence (OHP). It can work at high efficiency (HE) or HR, corresponding to a resolving power of about 40 000 and 80 000, respectively. SOPHIE spectra have a wavelength range from 387.2 nm to 694.3 nm. SOPHIE spectra are reduced by the Geneva pipeline, which also provides radial velocity.

## 3. Chemical abundance analysis

We analysed two P I lines of Mult. 1 at 1052 nm and 1058 nm, the three S I lines of Mult. 3, located at 1045 nm, and three lines of Sr II located at 1003, 1032, and 1091 nm. The atomic data we used are shown in Table 1.

For our four stars, we adopted the stellar parameters ($T_{\rm eff}$/log $g$[Fe/H]) listed in Table 2 from Chen et al. (2002), Takada-Hidai et al. (2002), González Hernández et al. (2010). For each star, we computed a 1D-LTE model atmosphere with

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[2] http://www.tng.iac.es/instruments/giano/gia\discretionary-no_tools_v1.2.0.tar.gz

[3] http://atlas.obs-hp.fr/sophie/

**Table 2.** Stellar parameters and phosphorus abundances of our programme stars and comparisons, when available, with the analysis on the CRIRES spectra from (Caffau et al. 2011).

| Target | $T_{\rm eff}$ | $\log g$ | [Fe/H] | [S/H] | Ref. | *EW* [pm] | | $A(P)$ | | *EW* [pm] | | $A(P)$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Crires | Giano | Crires | Giano | Crires | Giano | Crires | Giano |
| | K | | | | | 1053.2 | | 1053.2 | | 1058.4 | | 1058.4 | |
| HD 1461 | 5765 | 4.38 | +0.19 | −0.05 | G10 | 2.00 | 2.10 | 5.59 | 5.62 | 2.70 | 2.70 | 5.59 | 5.59 |
| HD 10453 | 6368 | 3.96 | −0.46 | −0.29 | C02 | | | | | | <3.00 | | <5.28 |
| HD 13555 | 6470 | 3.90 | −0.27 | −0.25 | T02 | 1.80 | 2.34 | 5.14 | 5.28 | 2.90 | 3.13 | 5.22 | 5.27 |
| HD 22484 | 5960 | 4.02 | −0.25 | −0.28 | T02 | | 1.90 | | 5.33 | | 3.00 | | 5.41 |

**References.** The column "Ref" refers to the reference for the stellar parameters and [S/H], and corresponds to G10: González Hernández et al. (2010); T02: Takada-Hidai et al. (2002); C02: Chen et al. (2002).

the code ATLAS 12 in its Linux version (Kurucz 2005; Sbordone et al. 2004; Sbordone 2005).

Our sample of stars includes four unevolved stars. The star HD 10453 is an astrometric binary, the companion is 1.3 mag fainter and has moved from a distance of about 4″ in 1820 to 50 mas in 2011. This should not affect the spectra. The broadening in the spectrum seems much larger than that expected from the resolving power of 50 000 of the spectrograph. By investigating the P I and S I lines, we presume the star has a rotational velocity of at least 15 $\rm km\,s^{-1}$. According to Ammler-von Eiff & Reiners (2012), the stellar rotation is definitely lower ($V\sin(i) = 7.4 \pm 0.4\ \rm km\,s^{-1}$).

We analysed the SOPHIE spectra of the stars HD 22484 and HD 13555, which we used to confirm the $S$ and Sr abundances we derived from GIANO spectra. For both stars, we found a very good agreement with previous analysis. The derived stellar parameters ($T_{\rm eff}$ /$\log g$/[Fe/H], microturbulence) are 5933/3.97/−0.17, 1.32 $\rm km\,s^{-1}$ for HD 22484 and 6470/3.83/−0.18, 1.47 $\rm km\,s^{-1}$ for HD 13555. The difference in [Fe/H] of about 0.1 dex with respect to the previous analysis for the latter star can be explained by the lower microturbulence of 1.47 $\rm km\,s^{-1}$ we derived, to be compared to 2.4 $\rm km\,s^{-1}$ by Takada-Hidai et al. (2002). HD 13555 shows a rotational velocity of about 10 $\rm km\,s^{-1}$ in its SOPHIE spectrum, which is also confirmed by the GIANO spectrum.

### 3.1. Phosphorus

We measured the equivalent width (EW) of the P I lines, by using the `iraf`[4] task `splot` with a Gaussian profile for the line profile fitting. The two P I lines we could detect (at 1052 and 1058 nm) are blended with a Ni I and Si I line, respectively. According to the strength of the lines and the stellar $V\sin i$, we fitted the P I line alone, or took into account the close-by line at the same time, using the deblending option of `splot`. The two P I lines are present in both order 72 and 73. We analysed both spectra and took as EW the average value. We used the code WIDTH (Kurucz 1993, 2005; Castelli 2005) to derive the $P$ abundance from the EW values. The results are listed in Table 2.

For HD 1461, we have previous observations with CRIRES and we find a good agreement between the abundances derived from the CRIRES and GIANO observations (see Fig. 1).

For star HD 13555, we did not use the order 72 to derive the EW of the line at 1053 nm because of the low S/N. The agreement with the results from the CRIRES spectra is not perfect (about 0.1 dex in $P$ abundance) but is still good.

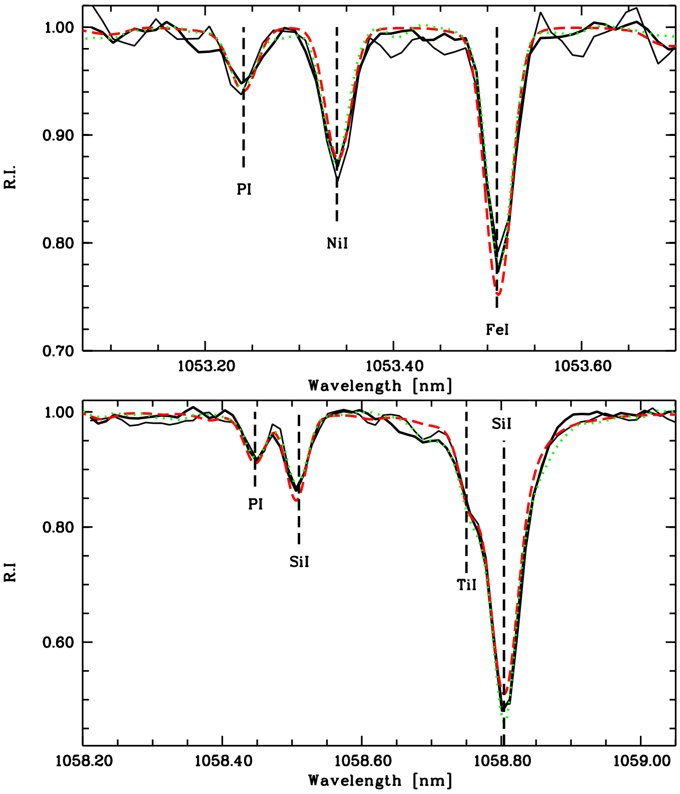

**Fig. 1.** Two P I lines (solid black line thinner and thicker for order 72 and 73, respectively) in the case of HD 1461, in comparison with a synthetic spectrum with $A(P) = 5.60$ (dashed red). The CRIRES spectrum is also over-plotted (dotted green) degraded at the resolution of GIANO.

The only P I line detectable in the spectrum of HD 10453 is that at 1058 nm, but it is blended with a Si I line and no $P$ abundance can be derived because of the relatively high rotation of the star. However, we can provide an upper-limit on $A(P)$.

The spectrum of HD 22484 is the best quality spectrum. The two lines of P I give abundances in good agreement, $A(P) = 5.36 \pm 0.04$, but we decided to exclude the line at 1052 nm from the order 72 owing to the low S/N.

As the uncertainty in $A(P)$ we quadratically added the observational uncertainty (the scatter of the abundance derived from the two lines added to the uncertainty in the EW measurement) to the systematic uncertainty related to uncertainty in the stellar parameters. We are aware of no NLTE study on phosphorus, nor of the existence of any model atom. Caffau et al. (2007b) investigated the granulation effects in the case of the Sun and derived very tiny effects on these weak lines.

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[4] Image Reduction and Analysis Facility, written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. `http://iraf.noao.edu/`

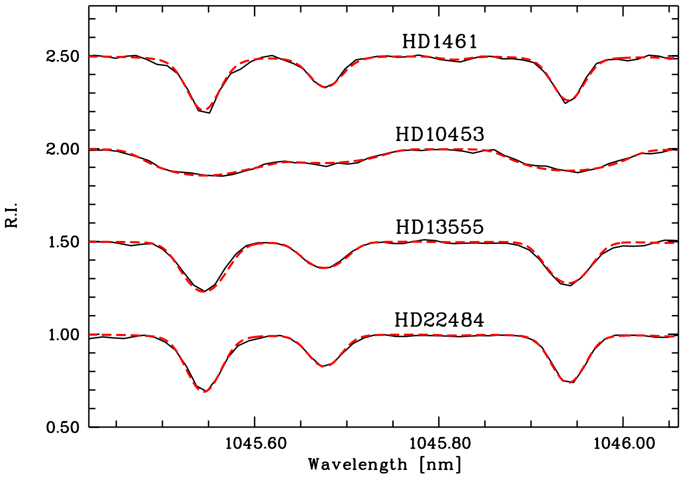

**Fig. 2.** Three S I lines of Mult. 3 (solid black) in comparison with the best fit (dashed red). For display purposes, the spectra are vertically displaced.

### 3.2. Sulphur

We derive the sulphur abundance by fitting the S I lines of Mult. 3 located at 1045 nm with NLTE profiles based on the ATLAS 12 models. The S I lines of Mult. 3 are clearly detected in all four stars (see Fig. 2) and we derived the $S$ abundances reported in Table 2. The three S I lines have been fitted simultaneously so that we cannot derive a line-to-line scatter. An uncertainty of 0.13 dex takes the random (0.05 dex) and systematic (0.12 dex) uncertainties into account.

We compared a synthetic spectrum with the $S$ abundance derived from the third multiplet to the S I lines of multiplet six in the SOPHIE spectra of each star and derived a very good correspondence for all four stars. We also find a general good agreement in the $A(S)$ with previous determination based on Mult. 6 and 8 for our stars except for the star HD 13555. For this star, the $S$ abundance we derive from the third multiplet in the GIANO spectra is about 0.3 dex lower than the previous analysis by Takada-Hidai et al. (2002) based on Mult. 8. We use the same stellar parameters, except for microturbulence, where they derive 2.4 km s$^{-1}$ and we adopt 1.5 km s$^{-1}$, which cannot explain the difference because a larger microturbulence would cause an even larger disagreement.

Caffau et al. (2007a) investigated the granulation effects on the $A(S)$ determination from Mult. 3, in the solar case. The 3D corrections happen to be of the order of 0.1 dex in the solar spectrum. In the case of hotter stars, the 3D corrections are larger; e.g. for Procyon they became more than twice the solar case, while at lower temperature they are smaller, e.g. for a 5000 K dwarf star model they became negligible (see Caffau et al. 2007a for details).

### 3.3. Strontium

We derived the Sr abundances by line profile fitting using NLTE synthetic profiles, and the Sr abundances we derived are presented in Table 2. In Fig. 3 we show the Sr II lines for HD 13555. The Sr abundances derived from the best fit on the Sr II lines in the GIANO spectra have been used to synthesise profiles to compare to the Sr II lines in the SOPHIE spectra, at 407.7, 416.1, 421.5, and 430.5 nm. The agreement is generally very good. Two of our stars show a [Sr/Fe] of about +0.2 and one a low value of −0.1. This large scatter in [Sr/Fe] around solar metallicity is not unknown and consistent with what is found by Mashonkina & Gehren (2001).

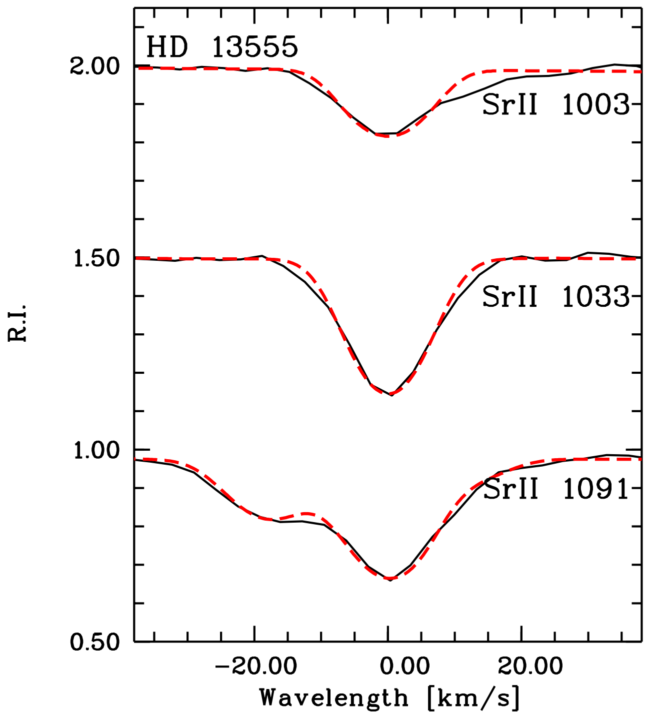

**Fig. 3.** Three Sr II lines for HD 13555 (solid black) in comparison with the best fit (dashed red). For display purposes, the spectra are vertically displaced.

The uncertainty in the $A$(Sr) determination is of 0.12 dex. It is related to the uncertainty in the line profile fitting (0.1 dex, mainly due to continuum determination) and systematic uncertainty related to uncertainty in the stellar parameters (0.05 dex).

We investigated granulation effects for these Sr II lines by analysing three hydrodynamical models (solar model, 5900/4.0/0.0, 6250/4.0/0.0) from the CIFIST grid (Ludwig et al. 2009) computed with the code CO$^5$BOLD (Freytag et al. 2012). The 3D effects are small for all three Sr II lines in the solar model, lower than 0.08 dex. These effects becomes larger (about 0.1 dex for the line at 1003 nm and about 0.25 dex for the other two lines) for a model with parameters 5900/4.0/0.0, and a similar size for a hotter model with parameters 6250/4.0/0.0 (0.08 dex for the line at 1003 nm, 0.17 dex for the line at 1032 dex, 0.15 dex for the line at 1091 nm). In Fig. 4, the contribution function of the weakest (1003 nm) and strongest (1032 nm) Sr II lines, in the case of the 5900/4.0/0.0 model, is shown. For the line at 1003 nm, the contribution function has a smooth shape with a maximum at about −1.5 in log $\tau$. In the case of the stronger 1032 nm line, the contribution function shows a double peak. This also happens in the case of the Li I doublet at 670.7 nm as shown in Fig. 1 by Steffen et al. (2010), where the authors state that in the case of lithium that NLTE effects are large and this is evident by comparing the contribution function for the 3D-LTE and the 3D-NLTE synthesis. We know that 1D-NLTE effects for the Sr II IR lines are somewhat large, but we do not have 3D-NLTE computations at present.

## 4. Discussion and conclusions

In this work, we analysed the GIANO spectra in the $Y$ band of four unevolved Galactic stars, spanning a metallicity range

**Table 3.** Stellar parameters, sulphur, and strontium abundances of our programme stars.

| Target | $T_{\rm eff}$ K | log $g$ | [Fe/H] | $A(P)$ | [P/Fe] | $A(S)_{\rm NLTE}$ | [S/Fe] | $A$(Sr) | [Sr/Fe] |
|---|---|---|---|---|---|---|---|---|---|
| HD 1461 | 5765 | 4.38 | +0.19 | 5.60 | +0.05 | 7.26 | −0.09 | 3.07 | +0.04 |
| HD 10453 | 6368 | 3.96 | −0.46 | <5.28 | <+0.28 | 6.81 | +0.06 | 2.67 | +0.21 |
| HD 13555 | 6470 | 3.90 | −0.27 | 5.28 | −0.09 | 6.67 | −0.22 | 2.82 | +0.17 |
| HD 22484 | 5960 | 4.02 | −0.10 | 5.37 | +0.01 | 7.01 | −0.05 | 2.72 | −0.10 |

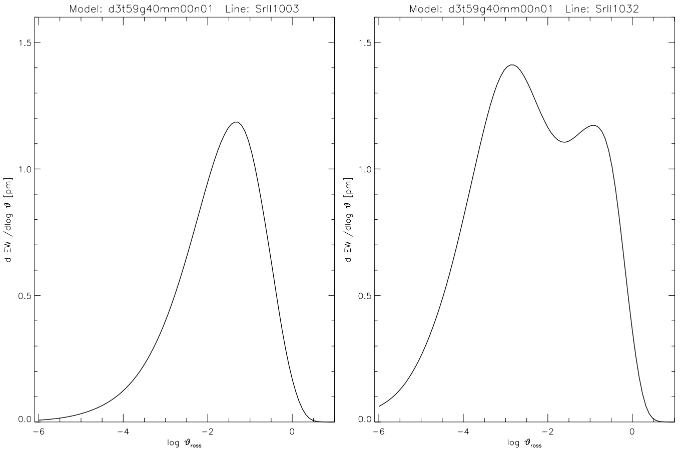

**Fig. 4.** Contribution function for the EW for two Sr II lines in the case of the CO$^5$BOLD model with parameters 5900/4.0/0.0.

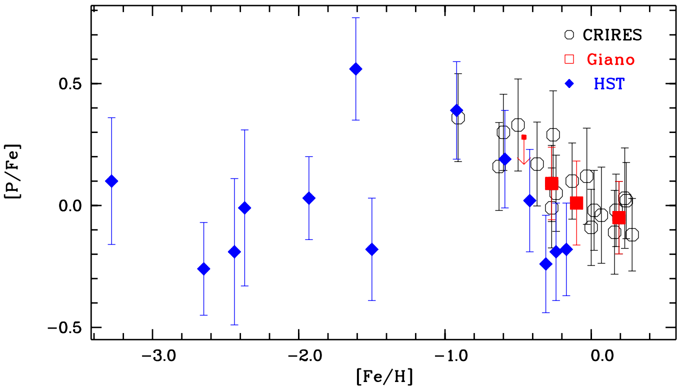

**Fig. 5.** [P/Fe] vs. [Fe/H] is shown for the four stars analysed (solid red squares) in comparison with the results from Caffau et al. (2011; black open squares) and from Roederer et al. (2014; solid blue diamonds).

between about one-third and twice the solar value, with the purpose of measuring accurate abundances of $P$, $S$, and Sr. For three out of four stars, we could derive $P$ abundance, and for the fourth an upper limit. For the two stars for which CRIRES spectra are available we find a concordance in the derived abundances. Phosphorus abundances from the GIANO spectra also fit perfectly into the [P/Fe] versus [Fe/H], derived by Caffau et al. (2011) and plotted in Fig. 5, where [P/Fe] smoothly decreases with increasing stellar metallicity with solar-scaled values within one $\sigma$ at [Fe/H] ≥ 0.0.

The trend is similar to what is expected for an $\alpha$-element and, as discussed in Cescutti et al. (2012), such a Galactic evolution of phosphorus can be explained with P mainly produced in core-collapse supernovae with a minor contribution from supernovae type Ia. However, the yields have to be increased by a factor of about three to fit the observed abundances. In Fig. 5, the abundances derived by Roederer et al. (2014) from UV lines are also shown (blue solid diamonds) for comparison. At its highest metallicities, these measurements show a similar behaviour in [P/Fe] vs. [Fe/H] as ours, although the increase in [P/Fe] with decreasing [Fe/H] has a steeper slope. At $[{\rm Fe/H}] < -1.5$, [P/Fe] show a constant value around the solar-scaled value. Jacobson et al. (2014) explain this behaviour as a buildup of P with increasing Fe (see their Fig. 2). From the sample of Roederer et al. (2014) and according to Jacobson et al. (2014), it is not so clear which is the enhancing factor for the yields needed to reproduce the observed trend.

The GIANO $Y$-band S I lines of the third multiplet are particularly useful for deriving $S$ abundance in metal-poor stars because they are strong, but not contaminated by strong telluric absorption as are the stronger lines of the first multiplet. We derived $S$ abundance from third multiplet for our stars with metallicities in the $-0.46 < [{\rm Fe/H}] < +0.19$ range, and we find a good agreement when comparing synthetic profiles with the derived $A(S)$ with weaker S I lines, e.g. those of the sixth multiplet at optical wavelengths. We find [S/Fe] abundance ratios consistent with solar-scaled or slightly depleted values.

Three mostly clean Sr II lines are also present in the GIANO $Y$-band spectra of dwarf stars. We derived Sr abundance from these IR lines and compared synthetic spectra computed with our Sr abundances to optical Sr II lines in SOPHIE spectra, finding a good agreement. We find [Sr/Fe] abundance ratios scattered by ±0.2 dex around the solar-scaled value.

This feasibility study has thus demonstrated that the GIANO spectra in the $Y$ band are perfectly suited to derive $P$ abundance in Galactic stars. We proved that the $A(P)$ derived from GIANO are consistent with those obtained with CRIRES, by using the same line diagnostics but higher spectral resolution. We also verified that $S$ and Sr abundances as derived from the $Y$-band GIANO spectra are trustable and consistent with those obtained from different diagnostic lines at optical wavelengths.

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