Chemical evolution of ytterbium in the Galactic disk

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Aims. Measuring the abundances of neutron-capture elements in Galactic disk stars is an important part of understanding key stellar and galactic processes. In the optical wavelength regime a number of different neutron-capture elements have been measured; however, only the s-process-dominated element cerium has been accurately measured for a large sample of disk stars from the infrared H band. The more r-process-dominated element ytterbium has only been measured in a small subset of stars so far.

Methods. We analyse 30 K giants with high-resolution H band spectra using spectral synthesis. The very same stars have already been analysed using high-resolution optical spectra via the same method, but it was not possible to determine the abundance of Yb from those spectra due to blending issues for stars with [Fe/H] < −1. In the present analysis, we utilise the stellar parameters determined from the optical analysis.

Results. We determined the Yb abundances with an estimated uncertainty for [Yb/Fe] of 0.1 dex. By comparison, we found that the [Yb/Fe] trend closely follows the [Eu/Fe] trend and has clear s-process enrichment in identified s-rich stars. This comparison confirms both that the validity of the Yb abundances is ensured and that the theoretical prediction that the s/−r-process contribution to the origin of Yb of roughly 40/60 is supported.

Conclusions. These results show that, with a careful and detailed analysis of infrared spectra, reliable Yb abundances can be derived for a wider sample of cooler giants in the range −1.1 < [Fe/H] < 0.3. This is promising for further studies of the production of Yb and for the r-process channel, key for galactochemical evolution, in the infrared.

Key words. stars: abundances – stars: late-type – Galaxy: abundances – Galaxy: disk – Galaxy: evolution – infrared: stars

1. Introduction

Stellar elemental abundances play a key role in deciphering Galactic chemical evolution. The photosphere of stars carries a chemical imprint of the molecular cloud from which they formed, making them time stamps of the Galactic environment at that epoch. By measuring the stellar abundances from stars originating from different Galactic epochs, the chemical enrichment in the Galaxy can be traced (see e.g. Bland-Hawthorn & Gerhard 2016, and references therein). The field of Galactic research is increasingly moving to the infrared spectral range, with a different set of spectral lines compared to those available in the optical range. With this comes the possibility of expanding the study of the chemical evolution of the galaxy, in particular to dust-covered regions. Different elements can give us different angles on Galactic formation and evolution, and in this study we consider the heavy element ytterbium.

The production of elements through fusion becomes endothermic above iron, which means that the remaining two-thirds of the elements in the periodic table need another production channel. The idea that heavier elements are created by neutron-capture processes was introduced by Burbidge et al. (1957), who gave these elements the name ‘neutron-capture elements’.

As an atomic nucleus captures a neutron, a heavier isotope of that element is created. If this isotope is unstable, a neutron will convert to a proton through β− decay and create a heavier element. If the isotope is stable, it can capture further neutrons until eventually β−-decaying. This outlines two processes, one where the β− decay is slower than the neutron-capture and one where the β− decay is more rapid than the neutron-capture. These are called the s- and r-processes, and together they produce the heavier elements. Indeed, they produce a majority of the isotopes for elements with Z > 30. An example of elements formed through neutron-capture processes are the lanthanides, some of which are studied in this paper: cerium (Ce; Z = 58), europium (Eu; Z = 63), and ytterbium (Yb; Z = 70).
The neutron-capture rate is not constant but depends on both (i) the local neutron density and (ii) the neutron absorption cross-section of the isotope. This allows some constraints to be put on the environment where they occur. The s-process requires a neutron density of \( \leq 10^{11} \text{ cm}^{-3} \) (Busso et al. 1999) and has been shown to take place in the interior of low-mass asymptotic giant branch (AGB) stars (see Karakas & Lattanzio 2014, and references therein). The r-process requires a neutron density of around \( 10^{24} - 10^{28} \text{ cm}^{-3} \) (see e.g. Kratz et al. 2007), which confines it to extremely neutron-dense environments, such as various supernovae (SNe) and mergers of neutron stars. The first observed neutron-star merger GW170817 (Abbott et al. 2017) indeed contained traces of r-process element production (Tanvir et al. 2017; Drout et al. 2017). In contrast, Kobayashi et al. (2020) found from comparing theoretical models to observations that core-collapse SNe, especially magneto-rotational supernovae (MRSNe), may be the predominant source of r-process production for most neutron-capture elements (see Fig. 39 in Kobayashi et al. 2020).

Most neutron-capture elements are produced by a combination of the s- and the r-processes. In the case of Ce, the s-process contributed approximately 85% and the r-process contributed the remaining 15% for stars with solar metallicities (Bisterzo et al. 2014; Prantzos et al. 2020). As such, it is usually referred to as ‘an s-process element’ since the dominating production channel is from this process. As a comparison, Eu is referred to as ‘an r-process element’, with only a 5% contribution from the s-process and the remaining from the r-process (Prantzos et al. 2020).

Yb\(^1\), which is the focus of this study, is the second heaviest of the lanthanides and lies at the very end of the series in the periodic table. As such, it is a heavy neutron-capture element that lies between Ce and Eu, with approximately a 40/60–50/50 predicted contribution from the s- and r-processes, respectively (Bisterzo et al. 2014; Kobayashi et al. 2020; Prantzos et al. 2020). Nonetheless, the precise nature of its cosmic origin and abundance trend in the Galactic disk has not been well constrained, mainly due to the sparsely available observed abundance data.

Spectroscopically, however, Yb is relatively well studied, partially due to the interest in studying Ap stars (Cowley 1984) and ion traps (Olmschenk et al. 2009). The Yb II ion has a hydrogenic electron configuration, with an unpaired 6s valence electron. A consequence of this is that the strongest Yb II lines are the resonance lines, located at 3289.4 and 3694.2 Å\(^2\), while the other spectral lines are significantly weaker. While both resonance lines have issues with blending, the line at 3694.2 Å has been preferred for abundance determination and has been used in a number of studies of low-metallicity stars, such as Honda et al. (2004); Johnson (2002); François et al. (2007); Roederer et al. (2014a,b); Sneden et al. (2009). The analysis is more difficult for stars with higher metallicities due to a larger impact of blending lines and the difficulty of defining the continuum of the spectrum in the bluer part of the optical regime. As a consequence, these lines have not been used for stars with metallicities\(^3\) of \([\text{Fe/H}] \gtrsim -1.5\).

\(^1\) The name ytterbium originates from the small Ytterby mine north-east of Stockholm, Sweden, and the element is one of seven discovered from the minerals found there during the 18th and 19th centuries.

\(^2\) All wavelengths in this study are wavelengths in air.

\(^3\) The metallicity and other abundances are defined using the notation \([\text{A/B}] = \log(N_\text{A}/N_\text{B})_\odot - \log(N_\text{A}/N_\text{B})_\odot\), where \(N_\text{A}\) and \(N_\text{B}\) are the number densities of the elements A and B, respectively. The solar abundances used in this study are from Grevesse et al. (2007), unless another reference is given.

Attempts have been made to fill this gap in metallicity by using the infrared Yb II line in the \(H\) band at 16498 Å. This line is the strongest of the infrared Yb lines and was first measured in the laboratory by Humphreys & Paul (1959). The APOGEE survey (\(R = \lambda/\Delta \lambda \sim 22500\); Majewski et al. 2017) has investigated the utility of this line in their spectra (Smith et al. 2021), but do not consider the determined stellar Yb abundances reliable enough to be included in the final data release (DR17; Abdurro’uf et al. 2021; J. Holtzman et al., in prep.). In a reanalysis of APOGEE spectra in the Kepler field, Hawkins et al. (2016) attempted to use the same line, deriving upper limits for the Yb abundance, but did not publish abundances or further analyses.

Böcek Topcu et al. (2019, 2020) managed to determine Yb abundances for 11 and 10 stars in the open clusters NGC 6940 and NGC 752, respectively, by using the 16 498 Å Yb II line. The temperatures of the stars in these samples are around 5000 K, making a CO blend in the Yb II line close to negligible. Furthermore, Yb abundances of three horizontal-branch stars were determined in Afşar et al. (2018), who used the very same line, again for stars of \(T_{\text{eff}} \sim 5100\) K.

In this article we also attempt to use the Yb II line at 16 498 Å, and we succeed in deriving reliable Yb abundances for 30 K giants in the Milky Way disk, using high-resolution infrared spectra in the \(H\) band observed with the Immersion Grating Infrared Spectrometer (IGRINS). The spectral resolution it provides, \(R \sim 45,000\), is higher than that of APOGEE (\(R \sim 22,500\)), which is important since the Yb II line is both weak and heavily blended with a CO molecular line. We investigate the s- and r-process contributions to the cosmic budget of Yb by comparing the Yb abundances to the abundances of the s-element Ce and the r-element Eu, which have been determined for the very same stars. The Ce abundances are determined from the \(H\) band spectra, while the Eu abundances are taken from Forsberg et al. (2019), where they were determined from optical spectra.

We succeed in measuring reliable Yb abundances from the 16 498 Å line for our sample of 30 disk stars. This demonstrates the possibility of larger studies of the r-process channel in the infrared \(i\) band, as well as the possibility of measuring Yb abundances for stars with metallicities of \([\text{Fe/H}] \gtrsim 1\) dex. Knowing how to properly determine Yb abundances from the 16 498 Å line is a useful step towards deciphering the formation history and evolution of dust-covered regions in the Galaxy, such as the bulge.

In Sect. 2 we go through the observations and the data used. In Sect. 3 we go through the analysis, including uncertainty estimations. In Sect. 4 we present and discuss the results before concluding in Sect. 5.

2. Observations

For the present work, we observed 30 K giants, recording high-resolution spectra in the infrared (IGRINS). These stars were selected from a set of about 500 local disk giants, which have accurate stellar parameters determined through a careful optical spectroscopic analysis (PIES; H. Jönsson et al., in prep.) (see our Sect. 3.1).

2.1. IGRINS

The infrared spectra were observed with the IGRINS spectrograph (Yuk et al. 2010; Park et al. 2014) on the 4.3-metre Discovery Channel Telescope (DCT; now called the Lowell Discovery Telescope) at Lowell Observatory (Mace et al. 2018) and on the 2.7-metre Harlan J. Smith Telescope at McDonald...
In this section we go through the stellar parameters determined from optical spectra in Sect. 3.1. Supporting abundances determined from either optical or IGRINS spectra are described

| Star       | 2MASS star name                  | $H_{2MASS}$ (mag) | $K_{2MASS}$ (mag) | Civil date   | Telescope | Exposure (s) |
|------------|----------------------------------|-------------------|-------------------|--------------|-----------|--------------|
| α Boo      | J14153968+1910558                | −2.8              | −2.9              | 2015 April 11 | HJST      | 60           |
| μ Leo      | J09524585+2600248                | 1.3               | 1.2               | 2016 Jan. 31 | HJST      | 26           |
| ϵ Vir      | J13021059+1057329                | 0.9               | 0.8               | 2016 Feb. 2  | HJST      | 26           |
| β Gem      | J07451891+2801340                | −1.0              | −1.1              | 2016 Jan. 30 | HJST      | 23           |
| HD 102328  | J11465561+5537416                | 2.9               | 2.6               | 2016 Feb. 2  | HJST      | 32           |
| HD 102328 (a) | J11465561+5537416             | 2.9               | 2.6               | 2016 Feb. 27 | HJST      | 20           |
| HIP 50583  | J10195836+1950290                | −0.8              | −0.8              | 2016 June 20 | HJST      | 29           |
| HIP 63432  | J1295500+6635502                 | 2.4               | 2.1               | 2016 May 29  | HJST      | 180          |
| HIP 72012  | J14434444+4027333                | 2.6               | 2.4               | 2016 June 16 | HJST      | 120          |
| HIP 90344  | J18255915+653486                 | 2.2               | 2.1               | 2016 June 15 | HJST      | 120          |
| HIP 96014  | J19311935+5018240                | 2.9               | 2.5               | 2016 June 15 | HJST      | 120          |
| HIP 102488 | J20461266+3358128                | 0.2               | 0.1               | 2016 June 19 | HJST      | 26           |
| 2M17215666 | J17215666+4301408                | 7.6               | 7.5               | 2016 July 25 | HJST      | 1080         |
| KIC 3748858 | J19278777+3848096              | 6.4               | 6.3               | 2016 Nov. 17 | DCT       | 240          |
| KIC 3955590 | J19276777+3900456              | 7.8               | 7.7               | 2016 Nov. 23 | DCT       | 480          |
| KIC 4177025 | J19434309+3917436              | 7.6               | 7.5               | 2016 Nov. 22 | DCT       | 360          |
| KIC 5113910 | J19421943+4016074              | 8.2               | 8.0               | 2016 Nov. 22 | DCT       | 720          |
| KIC 5709564 | J19321853+4058217              | 7.6               | 7.5               | 2016 Nov. 23 | DCT       | 480          |
| KIC 5779724 | J19123427+4105257              | 8.0               | 7.8               | 2016 Dec. 09 | DCT       | 600          |
| KIC 5859492 | J19922718+4107236              | 7.9               | 7.8               | 2016 Nov. 23 | DCT       | 480          |
| KIC 5900966 | J19515137+4106378              | 6.0               | 5.8               | 2016 Nov. 22 | DCT       | 120          |
| KIC 6465075 | J19512404+449284                | 8.0               | 7.9               | 2016 Nov. 23 | DCT       | 480          |
| KIC 6547007 | J19525719+4158129              | 8.3               | 8.2               | 2016 Dec. 9  | DCT       | 600          |
| KIC 6837256 | J18464309+4223144              | 8.8               | 8.7               | 2016 Nov. 23 | DCT       | 720          |
| KIC 11045542 | J19530590+4833180            | 8.4               | 8.2               | 2016 Dec. 11 | DCT       | 2000         |
| KIC 11342694 | J19110062+4906529            | 7.6               | 7.4               | 2016 Nov. 17 | DCT       | 480          |
| KIC 11444313 | J19014380+4923062             | 9.1               | 9.0               | 2016 Nov. 23 | DCT       | 720          |
| KIC 11569659 | J19464387+4934210            | 9.4               | 9.3               | 2016 Dec. 9  | DCT       | 2400         |
| KIC 11657684 | J19755511+4946243            | 9.6               | 9.5               | 2016 Dec. 11 | DCT       | 3000         |
| 2M14231899 | J14231899+5540079              | 8.0               | 7.8               | 2016 June 19 | HJST      | 1200         |
| HD 142091 (a) | J15511394+3539264            | 2.6               | 2.5               | 2016 Feb. 29 | HJST      | 44           |

Notes. DCT: the Discovery Channel Telescope, a 4.3 m telescope at Lowell Observatory, Arizona. HJST: the Harlan J Smith Telescope, a 2.7 m telescope at McDonald Observatory, Texas. (a) Data from the IGRINS Spectral Library (Park et al. 2018).
in Sect. 3.2. We cover the method and atomic data used in Sects. 3.3 and 3.4. Details of the Yb abundance and handling of the CO blend are described in Sect. 3.5, and the uncertainties are covered in Sect. 3.6.

3.1. Stellar parameters
Our sample of stars has accurate stellar parameters determined through a careful spectroscopic analysis of the optical FIES data. This analysis will be described in Jönsson et al. (in prep.) and builds upon and improves the analysis described in Jönsson et al. (2017). The main difference between the determination of stellar parameters in Jönsson et al. (2017) and Jönsson et al. (in prep.) is that the latter use the entire wavelength region available in the FIES spectra, which was restricted to 5800–6800 Å in the former. This of course leads to more available Fe I and, in particular, Fe II lines, improving the accuracy of the determined stellar parameters in general. It also removes the systematic difference of 0.1 dex in $\log(g)$ when comparing to asteroseismic values found in the 2017 analysis. The uncertainties of the stellar parameters from the optical analysis are estimated to typically be 50 K in $T_{\text{eff}}$, 0.1 dex in $\log(g)$, 0.05 dex in [Fe/H], and 0.1 km s$^{-1}$ in $\varepsilon_{\text{macroturb}}$.

Macro turbulence, $\varepsilon_{\text{macroturb}}$, depends on large-scale motion in the stellar atmosphere and the instrumental profile of the spectrograph. As such, it cannot be adopted from the optical data and is instead determined from a set of Fe I lines in the infrared, with accurate van der Waals broadening parameters supplied by P. Barklem (2018, priv. comm.).

3.2. Other elemental abundances
In this paper we also make use of some of the stellar abundances derived from the optical spectra, in particular C, N, and O, for modelling the ubiquitous molecular lines in the IGRINS spectra. The C, N, and O abundances are derived from the forbidden O I doublet at 6300 and 6364 Å and selected CN and C$_{2}$ molecular lines. The general uncertainties of these abundances are estimated to be of the order of 0.05 dex. To ensure the highest accuracy in modelling the blending CO line, the C abundances for some of the stars were supplemented with measurements from C I lines in the IGRINS spectra.

In the discussion in Sect. 4, the star’s abundances of the neutron-capture elements Ce and Eu are used. The Ce abundances were determined using the Ce II lines at 16 595.18 Å and 17 058.88 Å. The two lines have minor blends, Mg I and Fe I respectively, which do not appear to affect the measurements significantly. The derived abundances agree well with the optical measurements from Jönsson et al. (in prep.). The Eu abundances are taken from Forsberg et al. (2019), who used the same FIES spectra as Jönsson et al. (in prep.) but with the stellar parameters from Jönsson et al. (2017).

Within the Jönsson et al. (in prep.) analysis, several stars with unexpectedly high abundances of s-elements were found. On the other hand, these stars have ‘normal’ abundances of the other elements, following the general $[X/\text{Fe}]$ versus [Fe/H] trend. This indicates both the precision of these optical measurements and the high confidence we can have in the determined s-element enhancement. Three of these stars are among the presently analysed sample of stars and stand out in terms of their s-process element Ce abundances (see Sect. 4). This is useful when discussing our Yb measurements.

All stellar parameters and abundances for the IGRINS sample of stars are provided in Sect. 4. The s-enriched stars are indicated, as is a classification of the stars into different stellar populations, the thin disk, the thick disk, or the halo. This division into stellar populations was made using a combination of high- and low-α abundances ([Mg/Fe]) combined with kinematics in a scheme similar to the method used in Lomaeva et al. (2019) and Forsberg et al. (2019).

3.3. Spectral synthesis
We determined the abundances using the spectral synthesis code Spectroscopy Made Easy (SME; Valenti & Piskunov 1996; Piskunov & Valenti 2017). This code interpolates a model atmosphere from a grid of spherically symmetric 1D MARCS models (Gustafsson et al. 2008), computing local thermodynamic equilibrium (LTE). The abundance is determined by finding a best fit to the observed spectrum using $\chi^2$ minimisation of the synthetic spectrum from the model atmosphere grid.

In order to synthesise a spectrum, SME requires, in addition to a line list with atomic data and a model atmosphere, a segment within which the line mask and several continuum masks are defined. We defined the line and continuum masks manually and examined all synthetic spectra by eye to ensure a good fit to the observed spectra. In the cases where the final spectra still had some modulation in their continuum levels, this was taken care of by defining specific local continua around the spectral line in those stars.

3.4. Atomic data
The basis of the line list used in this study is an extraction of atomic lines from the VALD3 database (Ryabchikova et al. 2015). As a number of the lines in the studied wavelength range lack reliable measurements of their $\log(gf)$ values, these values were shifted to match the solar spectra, most notably the Fe I and Zn I lines in the vicinity of the Yb II line. Additionally, we adjusted the log $gf$ value of a nearby Ni I line to fit the spectrum of µ Leo using a [Ni/Fe]$_{\mu\text{Leo}}$ = 0.07 since it presented a blending problem for super-solar metallicity stars while not being visible in the Sun.

For molecular lines, a number of additional sources were used: $^{12}$C$^{14}$N and $^{13}$C$^{14}$N from Sneden et al. (2014); $^{12}$C$^{16}$O and $^{13}$C$^{18}$O from Li et al. (2015); and $^{16}$OH from Brooke et al. (2016). H$_2$O lines are present in the H band, but for the stars in this paper the impact on the spectra around the Yb II line is below 0.1% of the continuum level. As this is far below the noise level, the H$_2$O lines are not included. No other molecules are expected to show significant lines in K-giant H band spectra.

For the 16 498 Å line of Yb II used in this study, the atomic data were sourced from Biémont et al. (1998), which presents log $gf$ values calculated using the Hartree-Fock approximation (Cowan 1981). The data for the line are given in Table 2 together with the most prominent blends.

The Ce II lines used to determine Ce abundances for the stars have wavelengths and excitation energies from Corliss (1973). There are no laboratory measurements of the log($gf$) values. They were instead determined astrophysically, by adjusting log($gf$) line by line such that the mean abundances agree with the measurements of the same stars in Jönsson et al. (in prep.).

3.5. Ytterbium determination
The Yb II 16 498 Å line is rather weak, although detectable in high-resolution spectra with high S/N. The main difficulty in analysing the line comes from the molecular lines that blend it. Primarily, this blend is made up of a CO line, but with a
Fig. 1. Comparison between the observed and the synthesised spectrum for KIC 5779724 around the Yb II line at $\lambda_{\text{air}} = 16498.42$ Å, with the residuals plotted below. Additional curves show the impact of increasing and decreasing the Yb abundance by 0.2 and 0.4 dex, respectively.

Table 2. Spectral line data for the line used to determine Yb abundances and nearby molecular lines, as well as the Ce II lines used to measure Ce.

|      | $\lambda_{\text{air}}$ (Å) | log($g_f$) | $E_{\text{low}}$ (eV) | Reference |
|------|-----------------------------|------------|------------------------|-----------|
| CN   | 16496.815                   | -1.584     | 1.307                  | S14       |
| OH   | 16497.737                   | -5.448     | 1.266                  | B16       |
| OH   | 16497.979                   | -5.448     | 1.266                  | B16       |
| CO   | 16498.273                   | -5.606     | 1.847                  | L15       |
| YbII | 16498.420                   | -0.640     | 3.017                  | B98       |
| Ni I | 16499.131                   | -1.363     | 6.257                  | K08       |
| Ce II| 16595.180                   | -2.114     | 0.122                  | C73       |
| Ce II| 17058.880                   | -1.425     | 0.318                  | C73       |

Notes. The log ($g_f$) values for the Ni I and Ce II lines are the ones measured in this study. The Ce II line at 16595 Å was also measured astrophysically by Cunha et al. (2017), the $\Delta \log(g_f) = 0.076$.

References. S14: Sneden et al. (2014), B16: Brooke et al. (2016), L15: Li et al. (2015), B98: Biémont et al. (1998), K08: Kurucz (2008), C73: Corliss (1973).

significant contribution from an OH doublet for cooler, low-metallicity stars.

The strength of the CO blend presents the largest obstacle to measuring the Yb abundance in our stars. To make sure that the CO lines are properly modelled, the fit of nearby CO lines was inspected. From this inspection, it became evident that the fit between the observed and the synthesised spectra is dependent not only on the species of the lines, but also on the vibrational and rotational state of the CO molecule. The CO line at 16498 Å is caused by a 7-4 vibrational, R 59 rotational transition. Several other lines from this vibrational state can be seen in Fig. 1. Lines from lower rotational transitions, such as the 7-4 R 6 line at 16503.4 Å, appear to be too weak, while the more highly excited 7-4 R 58 line at 16490.5 Å appears to fit the observed spectra well. The reason for this discrepancy is likely related to the atmospheric depth where the lines form: lines with lower excitation energies form farther out, where the modelling of the atmosphere is less certain and 3D and non-LTE effects may play a large role.

Figure 2 shows CO lines from vibrational-rotational transitions similar to the CO line blending the Yb II line. As these lines should form in a similar way and the line-to-line strength differences are very accurately understood, the fit between them and the spectra should act as a proxy for evaluating the modelling of the Yb-blending CO line. Because of issues with blending, the quality of the fit is not always clear, although the lack of major discrepancies reassures us that the CO line of interest should not spoil the measurement of Yb.

The OH lines are less disruptive for the majority of the stars as the lines are generally weaker and farther to the blue side of the Yb II line. The low excitation energies of the lines make their strengths inversely dependent on temperature and move their formation farther out into the atmosphere, increasing the risk of modelling errors due to, for example, 3D effects. The strong oxygen enhancement for metal-poor stars further increases their strength relative to other lines, which in combination with a low
**Fig. 2.** Comparison between the observed and the synthesised spectra for the star KIC 5779724 around the CO 7-4 lines with rotational transitions between R 54 and R 65. The line blending the Yb II line is from the CO 7-4 R 59 transition. Details of the observation are listed in Table 1, and the parameters and stellar abundances are listed in Table 3.

$T_{\text{eff}}$ can make the OH lines equal to the CO line in strength and significantly disrupt the Yb II line. The placement of the line mask and the visual inspection of the fit are therefore critical for measuring Yb in metal-poor stars with $T_{\text{eff}} < 4300$ K. A nearby CN line at 16 496.8 Å may be a blending factor at lower resolutions but does not influence the Yb II line in the spectra studied in this paper.

### 3.6. Uncertainty analysis

#### 3.6.1. Systematic uncertainties

The main sources of systematic uncertainty in abundance measurements are errors in stellar parameters and atomic data as well as assumptions made in the model atmosphere. As described in Sect. 3.1, the stellar parameters derived by Jönsson et al. (in prep.) are believed to be both precise and accurate, based on comparisons to benchmark values for $T_{\text{eff}}$ and $\log(g)$ from angular diameter and asteroseismological measurements. Assessing whether there is a bias in the elemental abundances due to stellar parameters is sometimes done by plotting them against one another. This validation cannot be performed for this study, as there is an observational bias in our sample. Low-metallicity stars are often farther away; when such stars are observed with the optical 2.5 m NOT/FIES telescope/high resolution spectrograph combination, the metal-poor targets tend to have lower surface gravities and temperatures.

Non-LTE corrections have not been computed for Yb, and as such their impact cannot be quantified. As all stars have similar temperatures and surface gravities ($T_{\text{eff,mean}} = 4520 \pm 250$ K, $\log(g)_{\text{mean}} = 2.2 \pm 0.5$), we would expect possible non-LTE effects to have a small impact on the shape of the [Yb/Fe] versus [Fe/H] trend.

There are seven stable isotopes of Yb, two of which have hyperfine structure splitting. Both the isotope shifts and the hyperfine structure splitting have been assessed for the resonance lines of Yb (e.g. Mårtensson-Pendrill et al. 1994), but no information is available for the 16 498 Å line. No sign of additional broadening from such factors has been seen in the spectra.
3.6.2. Random uncertainties

To estimate the uncertainties in the abundance measurements stemming from random uncertainties in the stellar parameters, a Monte Carlo technique was used. For each star, the spectra were reanalysed 500 times using parameters drawn from normal distributions, with the adopted values of $T_{\text{eff}}$, log($g$), [Fe/H], $\xi_{\text{micro}}$, and [C/Fe] taken as the mean of the distribution and the measurement uncertainty used as the standard deviation. The adapted uncertainties are 50 K in $T_{\text{eff}}$, 0.1 dex in log($g$), 0.05 dex in [Fe/H], 0.1 km s$^{-1}$ in $\xi_{\text{micro}}$, and 0.05 dex in [C/Fe]. Varying these parameters gives a good measure of the uncertainty in the analysis of the Yb II line itself as well as the uncertainty introduced by the blending lines. The mean average deviation of the Yb measurements performed with the varied stellar parameters was then adopted as the uncertainty in [Yb/Fe]. In Sect. 4 the upper and lower quantiles are used to create error bars for the measurement of each star.

The mean random uncertainty for our entire sample is 0.11 dex, which is slightly larger than the spread in Yb abundance measured for the open clusters NGC 6940 and NGC 752 of 0.05–0.08 dex (Böcek Topcu et al. 2019, 2020). The larger uncertainty in our study is possibly caused by a lower mean temperature in the stars studied here, increasing the influence of the molecular blends. Figure 3 provides support for this view, showing the calculated uncertainties for Yb plotted against $T_{\text{eff}}$. A clear trend can be seen with large uncertainties for cooler stars and smaller values for the hotter stars, matching the results for the open clusters.

The star HD 102328 has been observed twice, allowing us to estimate the effect of random errors unrelated to stellar parameters, such as S/N and continuum determination. The difference in [Yb/Fe] between the two spectra is 0.06 dex, which matches the spread of 0.05–0.08 from Böcek Topcu et al. (2019, 2020) well. It should be noted that the difference in S/N between the spectra is sizeable (125 and 250) and likely contributes a significant part to the difference between the measurements.

4. Results and discussion

The Yb abundances derived in this work are presented in Table 3 and are shown in Fig. 4 as [Yb/Fe] versus [Fe/H]. In the figure the error bars are based on the first and third quartiles in the uncertainty calculations described in Sect. 3.6.2.

The spread in abundance that we see in our study is more likely to be the result of uncertainties in the analysis rather than a large cosmic spread in Yb abundances. The error bars represent the uncertainty from stellar parameters only, with factors such as continuum determination and errors in molecular line modelling not included.

To put these results in context, Fig. 5 shows our results together with previously published Yb measurements. The lack of a larger sample of measurements for [Fe/H] > −1 illustrates the historic difficulty in determining Yb abundances for higher-metallicity stars using the resonance lines in the UV. Validating that similar abundances are obtained with the infrared line used here and the resonance lines is not trivial, since the line we use is weak and thus ill-suited for studying metal-poor stars.

It may be possible to observe both lines for a portion of the sample in Fig. 5, the very metal-poor stars with [Fe/H] < −2 and [Yb/Fe] > 1. The low metallicity would reduce the blending in the near-UV while the high [Yb/Fe] enhancement would strengthen the $H$ band line enough to be observable. Such stars typically have a high enhancement in carbon, which, depending on the $T_{\text{eff}}$, may cause blending issues in the infrared, even for such metal-poor stars. A high resolution and S/N would be required to resolve the line, similar to in this study.

The high scatter at lower metallicities, below [Fe/H] < −2, in Fig. 5 does not solely originate from the uncertainties, which, according to the sources, span from 0.1 to 0.25 dex. It is instead a physical result of inhomogeneities in the Galactic interstellar medium at low metallicity combined with the fact that neutron-star mergers and the types of SNe (likely MRSSNe; Kobayashi et al. 2020) that host the r-process are rare, which creates isolated stellar groups of high and low r-process element abundances (see Sneden et al. 2008, and references therein). This behaviour of an r-process-dominated element at low metallicities has been reproduced in the stochastic chemical evolution models in Cescutti et al. (2015), which take inhomogeneous mixing into account. As we can see in this work in Fig. 5, the scatter decreases substantially at higher metallicities, a result of a more homogeneous stellar disk and regular enrichment.
The [Yb/Fe] trend with metallicity shows an enhancement in [Yb/Fe] for stars of subsolar metallicity, decreasing to solar values around solar metallicity, similar to elements produced in type II SNe (for example, the α elements), MRSNe, and likely neutron-star mergers (r-process; Cescutti et al. 2015; Grisoni et al. 2020; Kobayashi et al. 2020). The similarity of α- and r-process elemental trends originates from the timescales related to their formation, being a rapid and early onset of the enrichment of these elements in the Galaxy.

At super-solar metallicity the trend appears to flatten, with the exception of the highest-metallicity stars. The systematic uncertainties involved in determining abundances for these stars are likely to be high, so we draw no conclusions on the precise slope of the super-solar trend.

To ensure that the Yb abundances are in line with what is expected for neutron-capture elements and to examine the contribution from different production channels, we compared the [Yb/Fe] trend with those of [Ce/Fe] and [Eu/Fe] for the same stars. The Ce abundances were determined from the IGRINS spectra, as described in Sect. 3.2, while the Eu abundances are from the optical work in Forsberg et al. (2019), which has a 28 stellar overlap with our sample. The very tight abundance trend for Eu indicates a high precision in the analysis. The Eu abundances were determined using a similar method, although not the exact same stellar parameters. Nevertheless, this should limit systematic uncertainties in the comparison.

Since Yb is reported to have a contribution of somewhere between 40/60 and 50/50 from the s- and r-processes, respectively (e.g. Bisterzo et al. 2014; Kobayashi et al. 2020; Prantzos et al. 2020), the [Yb/Fe] trend should fit in between the s- and r-process trends of [Ce/Fe] and [Eu/Fe]. In Fig. 6, we plot running means of the full sample, the components of the disk and the s-enhanced stars for the neutron-capture elements. As can be seen, Yb indeed falls nicely in between the two comparison elements.

In Fig. 6 we see that the [Yb/Fe] trend with metallicity has a similar slope as [Eu/Fe], indicating an early enrichment from the Galactic disk.
processes with short timescales. This is indicative of type II SNe, MRRSNe, and possibly neutron-star mergers (Cescutti et al. 2015; Grisoni et al. 2020; Kobayashi et al. 2020). The [Ce/Fe] trend is much flatter than the [Yb/Fe] trend, although the thick disk s-enhanced star, marked with a yellow triangle in Fig. 6, clearly stands out in [Yb/Fe]. The other two s-enhanced stars (halo and thin disk, yellow star and filled circle, respectively) stand out too, but not to the same extent. This is expected since these two do not stand out as much in [Eu/Fe] either, once more highlighting the similarity between these two r-process-dominated elements. However, the fact that the s-enriched stars also show a similar pattern in [Yb/Fe] compared to [Ce, Eu/Fe] is a consequence of the precision in the determination of the Yb abundances and, to a lesser extent, of the s-process contribution to this element.

We can also consider the relative positions of the abundance ratios of the thin- and thick-disk stars in Fig. 6. The thick-disk stars (purple triangles) have lower [Ce/Fe] abundance ratios and higher [Eu/Fe] than what is typical for thin-disk stars (blue filled circles), as expected for s- and r-process-dominated elements (Forsberg et al. 2019). The [Yb/Fe] abundance ratios of the thick-disk stars are also found to be lower, although only slightly, than those of the thin-disk stars. This is a clear indication of the s-process contribution to this element. At the same time, the shape of the overall [Yb/Fe] trend, seen from the running mean, gives a clear indication of the r-process contribution, as expected from Galactic chemical evolution models of this ratio. Nonetheless, Kobayashi et al. (2020) report that the s-process has a significant contribution in producing Yb.

To further investigate the contribution from the s- and r-processes, we plotted [Yb/Ce] and [Yb/Eu] versus metallicity (see Fig. 7). A flat trend in these types of plots indicates a similar production rate of the two elements, whereas a decrease or increase indicates discrepancies.

The so-called pure r-process line is also indicated in the plot, which is calculated using the solar r-process contributions of the elements. As such, the pure r-process is the value of the r-process contribution in both elements, for instance [r-process(Yb)/r-process(Ce)]. The closer to the pure-r-process line, the more of the elements originate from the r-process.

Considering [Yb/Ce] in Fig. 7, it becomes clear that the r-process component is stronger in Yb than in Ce. The r-process dominates the production of neutron-capture elements at lower metallicities, also producing the s-process-dominated elements, such as Ce and, to a greater extent, Yb. The onset of s-production in AGB stars, originating from low- to intermediate-mass stars, has a time delay in enriching the Galactic interstellar medium. This can be seen at around [Fe/H] approximately −0.3, where the [Yb/Ce] trend starts decreasing due to an increase in s-process production and a higher Ce enrichment compared to Yb.

The [Yb/Eu] trend clearly indicates a significant contribution from the r-process in the production of Yb, similar to what is seen when comparing the trends in Fig. 6. We also note that the thick-disk stars tend to all lie around the pure r-process line, indicating a large r-process contribution in the thick disk.

Because of potential issues with finding local continuum points and the risk of stronger molecular blends for super-solar metallicities, we refrain from drawing any conclusion about the possible upturns we see in this metallicity region. Hotter stars with less significant molecular blends could possibly clarify the trend for these metallicities.

The above comparisons with other neutron-capture elements strengthen the validity of the Yb abundances presented in this work and assure us that we can correctly model the CO blend in the Yb II line.

5. Conclusions

In this work we have presented Yb abundances for 30 K giants, with metallicities in the −1.1 < [Fe/H] < 0.3 range, which, to the best of our knowledge, is the largest disk sample with Yb abundances to date. Our typical (random) uncertainties in [Yb/Fe] are approximately 0.1 dex.

The derived abundances align well with previous studies of low-metallicity stars. Although the Yb II line is not useful in the solar spectrum at this resolution, the measured trend obtained from abundance determinations in our K giants passes through the solar value at [0,0], which is reassuring. Via comparisons with the abundances of two other neutron-capture elements, namely Ce and Eu, we find the cosmic origin of Yb to be dominated by the r-process, which is supported by the [Yb/Eu] comparison. It is, however, clear from the s-enhanced stars and the precise alignment between the thin and thick disk that the s-process plays a part in producing Yb, as expected from theoretical models. Additionally, we find the Yb abundances to be of high quality since they reproduce the s-enhancement previously observed for the same stars in optical spectra, confirming that the CO blend in the Yb II line is modelled properly.

Previous measurements of neutron-capture elements in stars from the infrared H and K bands are dominated by Ce, which has a number of usable lines (Cunha et al. 2017). Two other elements have been measured in small samples, Yb and Nd (Hasselquist et al. 2016). Like Ce, Nd is thought to be produced predominately in the s-process for stars of solar metallicity (see e.g. Kobayashi et al. 2020), but at a higher uncertainty (Böcek Topcu et al. 2019, 2020).

Elements created in the r-process offer clear signatures of events that led to element formation on short timescales, such
as neutron-star mergers. The ability to determine abundances of the \( r \)-process-dominated element Yb from near-infrared spectra for a wide range of metallicities up to super-solar values opens an additional Galactic chemical evolution channel from near-infrared spectra. This is significant both for the readily available near-infrared spectrographs and upcoming versatile instruments, such as the HIRES spectrograph for the ELT (Marconi et al. 2018).

Regarding the usefulness of having a wide range of neutron-capture elements in galactochemical research, we can consider our comparison of Yb to Ce and Eu: it becomes evident that the thick disk has a stronger enrichment by the \( r \)-process compared to the thin disk. The reverse holds for the thin disk, being more enriched by the \( s \)-process compared to the thick disk.

We have shown that with high enough spectral resolution and a careful analysis, the territory of the \( r \)-process can thus now be reached in the near-infrared. This will help to unravel regions previously obscured by dust, such as the Milky Way bulge. For future large near-infrared spectroscopic surveys, the Yb II line could therefore allow the \( r \)-process to also be studied in obscured stellar populations. Here, Yb can contribute a lot in deciphering the star formation history and assembly of the bulge.

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