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EDITA STONKUTĖ

CHEMICAL COMPOSITION OF KINEMATICALLY IDENTIFIED GALACTIC STELLAR GROUP

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VILNIAUS UNIVERSITETAS

EDITA STONKUTĖ

CHEMINĖ KINEMATIŠKAI IDENTIFIKUOTOS GALAKTIKOS ŽVAIGŽDŽIŲ GRUPĖS SUDĖTIS

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Contents

Introduction

The history of our home Galaxy is complex and not fully understood. Observations and theoretical simulations have made much progress and provided us with tools to search for past accretion events in the Milky Way and beyond. The well-known current events are the Sagittarius (Ibata et al. 1994), Canis Major (Martin et al. 2004) and Segue 2 (Belokurov et al. 2009) dwarf spheroidal galaxies, merging into the Galactic disc at various distances. The Monoceros stream (Yanny et al. 2003; Ibata et al. 2003) and the Orphan stream (Belokurov et al. 2006) according to some studies are interpreted as tidal debris from the Canis Major and Ursa Major II dwarf galaxies, respectively (see Peñarrubia et al. 2005; Fellhauer et al. 2007; and the review of Helmi 2008). Accreted substructures are found also in other galaxies, such as the Andromeda galaxy (Ibata et al. 2001; McConnachie et al. 2009), NGC 5907 (Martínez-Delgado et al. 2008), and NGC 4013 (Martínez-Delgado et al. 2009).

Our understanding of the global star formation history of the Milky Way galaxy remains incomplete. We need to determine the detailed age and spatial distributions, space motions, and elemental abundances both globally and for every substructure. It is important to understand effects of accreted satellites, how they depend on the time of accretion, their initial orbits, masses and density profiles, since these factors impose different scenarios of the tidal disruption of satellites and the distribution of debris to different Galactic components (cf. Wyse 2009; van der Kruit & Freeman 2011, and references therein).

A number of stellar streams, moving and kinematic groups were identified in our Galaxy (cf. Zuckerman & Song 2004; Helmi 2008; Klement et al. 2009; Sesar et al. 2012, and references therein). Some of them are suspected to originate from accreted satellites. Can we also find such traces of ancient merger events in the solar neighbourhood? It is known that F- and G-type dwarf stars are particularly useful in studding Galactic evolution since they are numerous and long-lived and there atmospheres reflect their initial chemical composition. Using such stars, Helmi et al. (2006) investigated signatures of past accretions in the Milky Way disc from correlations between stellar orbital parameters, such as apocentre (A), pericentre (P), and z-angular momentum (L_z), the so-called APL space. They identified three new coherent groups of stars in the Geneva-Copenhagen survey (Nordström et al. 2004) and suggested that those might correspond to remains of disrupted satellites.

We investigate detailed elemental abundances in stars belonging to one of these groups, so-called Group 3.

Aims of the study

The main aim of the study is to perform a high-resolution spectroscopic analysis of the kinematic Group 3 and to compare the results with Galactic thin-disc dwarfs and thin-disc chemical evolution models. The aim is to investigate the homogeneity of the chemical composition of stars within the group and to look for possible chemical signatures that might give information about the formation history of this kinematic group of stars. With the detailed chemical composition analysis of the newly identified kinematic Group 3 we aim to contribute to the chemical composition, formation and evolution studies of the Galactic disc.

Tasks of the study

- High-resolution spectral observations of Group 3 stars and Galactic thin-disc comparison stars.
- Determination of the main atmospheric parameters (effective temperature, surface gravity, metallicity and microturbulence) in the kinemaicaly identified group of stars and Galactic thin-disc comparison stars.
- The detailed chemical abundance determination of oxygen, α-elements, iron group, and neutron capture chemical elements in Group 3 stars and comparison Galactic thin-disc stars.
- Interpretation of the results by comparing them with the Galactic disc dwarfs and chemical evolution models.

Scientific novelty

- For the first time, the detailed high-resolution spectroscopic analysis is performed for the stellar kinematic Group 3 of the Geneva-Copenhagen Survey identified in the Galactic disc and suspected to be a remnant of a disrupted satellite galaxy.

- It is shown that the detailed chemical composition of the kinematic Group 3 stars of the Geneva-Copenhagen Survey is similar to the thick-disc stars, which might suggest that their formation histories are linked. This study will contribute to our knowledges of the Milky Way and its thick-disc formation models.

Results and statements presented for defense

- The determined main atmospheric parameters (effective temperature, surface gravity, metallicity and microturbulence) and abundances of 22 chemical elements in twenty one Group 3 stars and in six comparison Galactic thin-disc stars from high-resolution spectra.

- The sample of kinematicaly identified group of stars is chemically homogeneous. The average [Fe/H] value of the 20 stars is $-\mathbf{0.69}\pm$ 0.05.

- All programme stars are overabundant in oxygen and α-elements compared with Galactic thin-disc dwarfs and this abundance pattern has similar characteristics as the Galactic thick disc.

- The abundances of chemical elements produced predominantly by the r-process are overabundant in comparison with Galactic thin-disc dwarfs of the same metallicity. The most prominent overabundances are seen for europium, samarium, and praseodymium.

- The abundances of iron-group elements and chemical elements produced mainly by the s-process are similar to those in the Galactic thin-disc dwarfs of the same metallicity.

- BD +35 3659 is not a member of Group 3, and BD +73 566 is an s-process-enhanced star.

- Group 3 consists of a 12-Gyr-old population.
- The chemical composition of stars in Group 3 is similar to the thick-disc stars, which might suggest that their formation histories are linked.
- The chemical composition together with the kinematic properties and ages of stars in the investigated Group 3 of the Geneva-Copenhagen survey support a gas-rich satellite merger scenario as the most suitable origin for Group 3.

Personal contribution

The author together with co-authors prepared observation programmes and observed spectra with the Nordic Optical Telescope. The author made the reduction of spectra of observed stars, determined the main atmospheric parameters (effective temperature, surface gravity, metallicity and microturbulence) and chemical composition of the programme stars. The author interpreted the chemical composition results, drew conclusions and together with co-authors prepared scientific publications.

Publications on the subject of the dissertation

1. **Stonkutė E.**, Nordström B. & Tautvaišienė G., 2010, *Investigation of ancient substructures in the Milky Way: chemical composition study*, IAU Symposium, Vol. 265, 376–377
2. **Stonkutė**, E., Tautvaišienė, G., Nordström, B. & Ženovienė, R., 2012, *Chemical Composition of a Kinematically Identified Stellar Group in the Milky Way*, The Astrophysics and Space Science series, JENAM 2010, 223–224
3. **Stonkutė E.**, Ženovienė R., Tautvaišienė G., Nordström, B., 2012, *Chemical analysis of ancient relicts in the Milky Way disk*, European Physical Journal Web of Conferences, Vol. 19, 05007 1–2
4. **Stonkutė E.**, Tautvaišienė G., Nordström B., Ženovienė R., 2012, *Stellar substructures in the solar neighbourhood. I. Kinematic group 3 in the Geneva-Copenhagen survey*, Astronomy & Astrophysics, Vol. 541, A157, 1–9

5. Nordström, B., **Stonkutė E.**, Tautvaišienė G., Ženovienė R., 2012, *Chemical tagging of kinematic stellar groups in the Milky Way Disk*, Astronomical Society of the Pacific Conference Series, Vol. 458, 235
6. **Stonkutė E.**, Tautvaišienė G., Nordström B., Ženovienė R., 2013, *Stellar substructures in the solar neighbourhoo. II. Abundances of neutron-capture elements in the kinematic Group 3 of the Geneva-Copenhagen survey*, Astronomy & Astrophysics, Vol. 555, A6, 1–8

Presentations at the international conferences

1. **Stonkutė E.**, Nordström B., Tautvaišienė G., *Investigation of ancient substructures in the Milky Way: chemical composition study*, „Chemical Abundances in the Universe – Connecting First Stars to Planets, IAU symposium 265", Rio de Janeiro (Brazil), 03–07 August, 2009
2. **Stonkutė E.**, Tautvaišienė G., Nordström B., Ženovienė R., *Chemical composition of a kinematically identified stellar group in the Milky Way*, „European Week of Astronomy and Space Science Science, JENAM 2010", Lisbon (Portugal), 06–10 September, 2010
3. **Stonkutė E.**, Tautvaišienė G., Nordström B., Ženovienė R., *Chemical composition of kinematically identified Galactic stellar groups*, „Seventh International Conference on Atomic and Molecular Data and Their Applications", Vilnius (Lithuania), 21–24 September, 2010
4. **Stonkutė E.**, Ženovienė R., Tautvaišienė G., Nordström B., *Chemical analysis of ancient relicts in the Milky Way disk*, „Assembling the Puzzle of the Milky Way", Le Grand Bornand (France), 17–22 April, 2011
5. Nordström B., **Stonkutė E.**, Tautvaišienė G., Ženovienė R., *Chemical tagging of kinematic stellar groups in the Milky Way Disk*, „The 3rd Subaru International Conference - Galactic Archaeology: Near – Field Cosmology and the Formation of the Milky Way", Shuzenji (Japan), 01–04 November, 2011
6. **Stonkutė E.**, Tautvaišienė G., Ženovienė R., Nordström B., *Satellite Remnants in the Milky Way Galaxy* „Science Innovation and Gender 2011", Vilnius

(Lithuania), 24–25 November, 2011

7. Ženovienė R., Tautvaišienė G., Nordström B., **Stonkutė E.**, *Chemical analysis of a new kinematically identified stellar group* „European Week of Astronomy and Space Science Science, EWASS 2012", Rome (Italy), 01–06 July, 2012
8. **Stonkutė E.**, Tautvaišienė G., Ženovienė R., Nordström B., *Chemical imprints of past accretion events in the Galaxy*, „SpS3 Galaxy evolution through secular processes, IAU GA 2012", Beijing (China), 20–31 August, 2012

Thesis outline

The dissertation summary consists of: introduction, three chapters, main results & conclusions, and references. Kinematic group of stars is presented in the first chaper, observations and methods of analysis are presented in the second chapter. The main atmospheric parameters and chemical composition of the Group 3 stars and comparison Galactic thin-disc stars are presented and discussed in the third chapter of this thesis summary. The main results and conclusions are presented at the end of this summary of dissertation.

Kinematic group of stars

The study of Galaxy formation and evolution attempts to answer a lot of questions. What fraction of stars located in the solar neighbourhood were formed *in situ*, what fraction originated during mergers? How many progenitor systems built up the Galaxy? What were their properties? Have gas-rich mergers played an important role in the Galaxy formation and evolution?

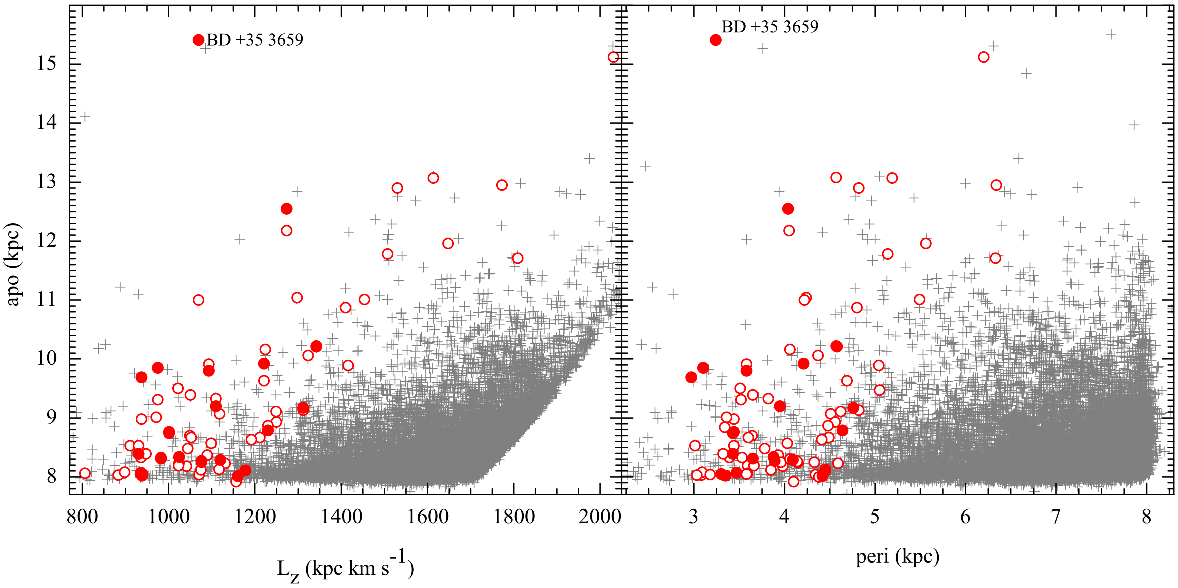
Large efforts were currently dedicated to explorations of the chemo-dynamical evolution of the Milky Way disc. The kinematic Group 3, which is investigated in this thesis work, was identified using the Geneva-Copenhagen Survey (Nordström et al. 2004).

1.1 Geneva-Copenhagen Survey

The Geneva-Copenhagen survey is complete, all-sky, magnitude limited and kinematically unbiased. Radial-velocity observations have been obtained by Nordström et al. (2004) which, together with published Strömgren $uvby\beta$ photometry, Hipparcos parallaxes, *Tycho*-2 proper motions and a few earlier radial velocities, complete the kinematic information. These high-quality velocity data are supplemented by effective temperatures and metallicities derived from revised calibrations. Spectroscopic binaries have been identified thanks to multi-epoch radial velocity measurements.

Space velocity components (U, V, W) have been computed in Nordström et al. (2004) catalogue for all the stars from their distances, proper motions, and mean radial velocities. (U, V, W) are defined in a right-handed Galactic coordinate system with U pointing towards the Galactic center, V in the direction of rotation, and W towards the north Galactic pole.

Before using the observed space motions Nordström et al. transformed them to the local standard of rest. For this, they have adopted a Solar motion of (10.0, 5.2, 7.2) km s^{-1}. For the orbit integrations Nordström et al. used the Galactic potential



1.1 Figure: Distribution for the stars in the APL space. Plus signs denote the Holmberg et al. (2009) sample, circles – Group 3, filled circles – investigated stars. Note that the investigated stars as well as all Group 3 stars are distributed in APL space along a line of constant eccentricity.

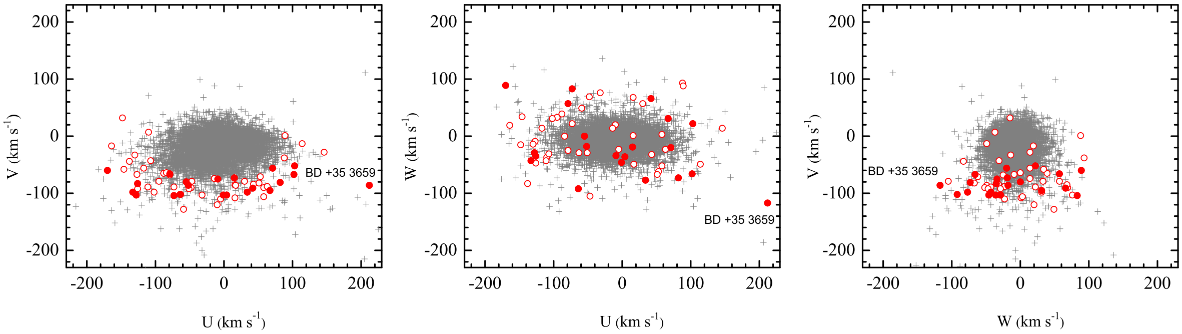
of Flynn et al. (1996), adopting a solar Galactocentric distance of 8 kpc.

Individual ages in Nordström et al. (2004) catalogue were determined by means of a Bayesian estimation method which compares a grid of theoretical isochrones with the location of stars in the Hertzsprung–Russell (HR) diagram, using the observed $T_{\rm eff}$, $M_{\rm v}$ and [Fe/H].

In the Nordström et al. (2004) catalogue they give the present radial and vertical positions (R_{gal}, z_{gal}) of each star as well as the computed mean peri- and apogalactic orbital distances (R_{min}, R_{max}), the orbital eccentricity e, and the maximum distance from the Galactic plane (z_{max}).

1.2 Kinematic Group 3

Chemical and kinematical information is needed in order to understand and trace the formation history of the Milky Way Galaxy. In the homogeneous large sample of F- and G-type stars in the survey by Nordström et al. (2004), Helmi et al. (2006) found groups of stars with orbital parameters different from Galactic thin disc stars. Simulations of disrupted satellites showed that the groups have similar properties as infalling dwarf satellites would have after several gigayears. From correlations



1.2 Figure: Velocity distribution for all stars in the Holmberg et al. (2009) sample (plus signs), stars of Group 3 (circles) and the investigated stars (filled circles).

between orbital parameters, such as apocentre (A), pericentre (P), and z-angular momentum (L_z), the so- called APL space, Helmi et al. identified three new coherent groups of stars and suggested that those might correspond to remains of disrupted satellites. In Fig. 1.1, the stars are shown in the APL space.

In Fig. 1.2, we show the Galactic disc stars from Holmberg et al. (2009). Stars belonging to Group 3 in Helmi et al. are marked with open and filled circles (the latter are used to mark stars investigated in our work). Evidently, stars belonging to Group 3 have a different distribution in the velocity space in comparison to other stars of the Galactic disc.

In the U–V plane, the investigated stars are distributed in a banana-shape, whereas the disc stars define a centrally concentrated clump (see Fig.1.2). At the same time, in the U–W plane the investigated stars populate mostly the outskirts of the distributions. Both the U and W distributions are very symmetric. The investigated stars have a lower mean rotational velocity than the Milky Way disc stars, as we can see in the W–V plane. These characteristics are typical for stars associated with accreted satellite galaxies (Helmi 2008; Villalobos & Helmi 2009).

Stars in the identified groups cluster not only around regions of roughly constant eccentricity ($0.3 \leq \varepsilon < 0.5$) and have distinct kinematics, but have also distinct metallicities [Fe/H] and age distributions. One of the parameters according to which the stars were divided into three groups was metallicity. Group 3, which we investigate in this work, is the most metal-deficient and consists of 68 stars. According to the Nordström et al. (2004) catalogue, its mean photometric metallicity, [Fe/H], is about -0.8 dex and the age is about 14 Gyr. Group 3 also differs from the other two groups by slightly different kinematics, particularly in the vertical (z) direction.

Observations and analysis

2.1 Observations

Echelle spectra of the programme and comparison stars were obtained with the high-resolution FIbre-fed Echelle Spectrograph (FIES) on the Nordic Optical 2.5 m telescope. This spectrograph gives spectra of resolving power $R \approx 68\,000$ in the wavelength range of 3680–7270 Å.

The spectra were exposed to reach a signal-to-noise ratio higher than 100. Reductions of CCD images were made with the FIES pipeline FIESTOOL, which performs a complete reduction: calculation of reference frame, bias and scattering subtraction, flat-field dividing, wavelength calibration and other procedures.

Twenty-one programme and six comparison stars (thin-disc dwarfs) were observed. A list of the observed stars and some of their parameters are presented in Table 3.1.

2.2 Differential analysis

The spectra were analysed using a differential model atmosphere technique. We performed the differential abundance analysis for all Group 3 and comparison Galactic thin-disc stars relative to the Sun as a standard star. The differential analysis helps to eliminate systematic uncertainties.

2.2.1 Software packages and models of stellar photosphere

The EQWIDTH and BSYN program packages, developed at the Uppsala Astronomical Observatory, were used to carry out the calculation of abundances from measured equivalent widths and synthetic spectra, respectively.

EQWIDTH is a package for the calculation of chemical elemental abundances from measured equivalent widths. Abundances of α-elements and iron group chemical elements were determined using equivalent widths of their lines. All lines used for calculations were carefully selected to avoid blending. The equivalent widths of the lines were measured by fitting of a Gaussian profile using the 4A software package (Ilyin 2000).

BSYN is a program package for synthetic spectra modeling. BSYN calculates profiles of lines according to the input data and constructs a superposition of theoretical line profiles for all spectral lines presented in the wavelength range of the analysis. Calibrations to the solar spectrum Kurucz (2005) were made for all the spectral regions used for synthetic spectra modeling. For this purpose we used the solar model-atmosphere from the set calculated in Uppsala with a microturbulent velocity of 0.8 km s^{-1}, as derived from Fe I lines.

A set of plane-parallel, line-blanketed, constant-flux local thermodynamical equilibrium (LTE) model atmospheres (Gustafsson et al. 2008) were taken from the MARCS stellar model atmosphere and flux library (http://marcs.astro.uu.se/).

2.2.2 Atomic data

The Vienna Atomic Line Data Base (VALD, Piskunov et al. 1995) was extensively used in preparing input data for the calculations. Atomic oscillator strengths for the main spectral lines analysed in this study were taken from an inverse solar spectrum analysis performed in Kiev (Gurtovenko & Kostyk 1989).

In addition to thermal and microturbulent Doppler broadening of lines, atomic line broadening by radiation damping and van der Waals damping were considered in calculating abundances. Radiation damping parameters of lines were taken from the VALD database. In most cases the hydrogen pressure damping of metal lines was treated using the modern quantum mechanical calculations by Anstee & O'Mara (1995), Barklem & O'Mara (1997), and Barklem et al. (1998). When using the Unsöld (1955) approximation, correction factors to the classical van der Waals damping approximation by widths (Γ_6) were taken from Simmons & Blackwell (1982). For all other species a correction factor of 2.5 was applied to the classical Γ_6 ($\Delta \log C_6 = +1.0$), following Mäckle et al. (1975).

For lines stronger than $W = 100$ mÅ in the solar spectrum the correction factors were selected individually by inspecting the solar spectrum.

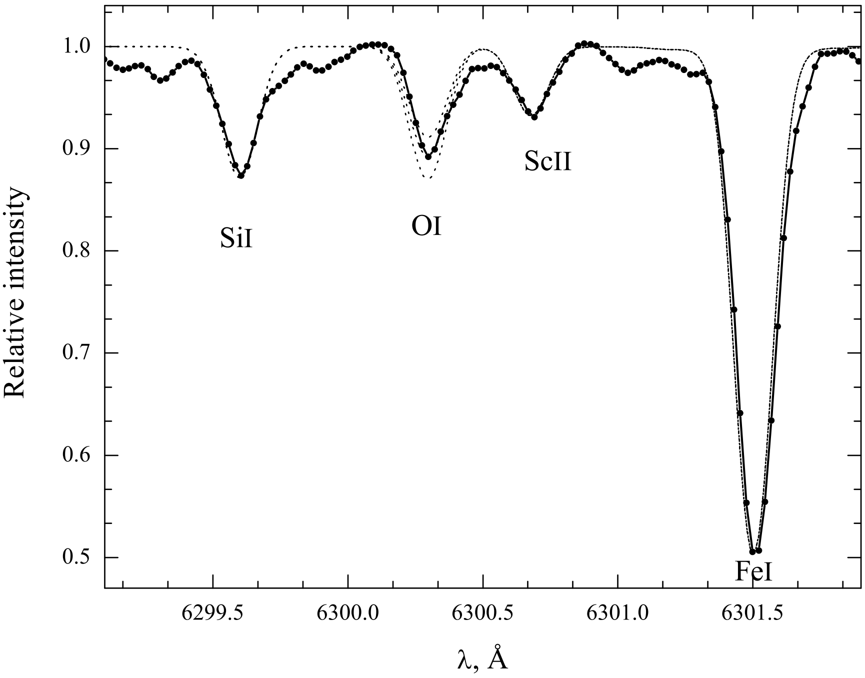
Non-local thermodynamical equilibrium. Abundances of Na and Mg were determined with non-local thermodynamical equilibrium (NLTE) taken into account, as described by Gratton et al. (1999). The calculated corrections did not exceed 0.04 dex for Na I and 0.06 dex for Mg I lines. Abundances of sodium were determined from equivalent widths of the Na I lines at 5148.8, 5682.6, 6154.2, and 6160.8 Å; magnesium from the Mg I lines at 4730.0, 5711.1, 6318.7, and 6319.2 Å.

2.2.3 Synthetic spectra

For some programme stars it was difficult to measure equivalent widths of some spectral lines with high precision. This was the case when lines were blended or had hyperfine splitting and/or isotopic shifts. The spectral synthesis was performed for the abundance determinations of [O I], Y II, Zr I, Zr II, Ba II, La II, Ce II, Pr II, Nd II, Sm II, and Eu II spectral lines.

The oxygen abundance was determined from the forbidden [O I] line at 6300.31 Å (see Fig. 2.1). The oscillator strength values for ^{58}Ni and ^{60}Ni, which blend the oxygen line, were taken from Johansson et al. (2003). The [O I] $\log gf = -9.917$ value was calibrated by fitting to the solar spectrum (Kurucz 2005) with $\log A_{\odot} = 8.83$ taken from Grevesse & Sauval (2000).

Abundances of the investigated chemical elements were determined from up to seven Y II lines at 4883.7, 4982.1, 5087.4, 5200.4, 5289.8, 5402.8, and 5728.9 Å; from the Zr I lines at 4687.8, 4772.3, 4815.6, 5385.1, 6134.6, 6140.5, and 6143.2 Å and Zr II lines at 5112.3 and 5350.1 Å; from the Ba II line at 5853.7 Å with the hyperfine structure (HFS) and isotopic composition adopted from McWilliam (1998). The lanthanum abundance was determined from the La II lines at 4662.5, 4748.7, 5123.0, and 6390.5 Å. To analyse the 4662.5, 5123.0, and 6390.5 Å lines, we adopted the $\log gf$ from Lawler et al. (2001a) and HFS patterns from Ivans et al. (2006). The HFS patterns were not provided for the La II line at 4748.7 Å. This line is very weak, so the broadening by hyperfine splitting can be neglected. Up to five Ce II lines at 5274.2, 5330.5, 5512.0, 5610.3, and 6043.4 Å were used to determine the abundance of cerium. The praseodymium abundance was determined from the Pr II lines at 5259.7 and 5322.8 Å with the information on HFS taken from Sneden et al. (2009). We investigated Nd II lines at 4811.3, 5130.6, 5255.5, 5276.9, 5293.2, 5319.8, and 5385.9 ; Sm II lines at 4467.3, 4577.7, and 4791.6 Å. For the Sm II line at 4467.3 Å the $\log gf$ was taken from Lawler et al. (2006), and the HFS patterns from Roederer et al.



2.1 Figure: Fit to the forbidden [O I] line at 6300.3 Å in the programme star HD 204848. The observed spectrum is shown as a solid line with black dots. The synthetic spectra with $[\mathrm{O/Fe}] = 0.52 \pm 0.1$ are shown as dashed lines.

(2008). For the remaining two lines a hyperfine structure was not taken into account since these lines are very weak and their hyperfine splitting can be neglected (cf. Mishenina et al. 2013).

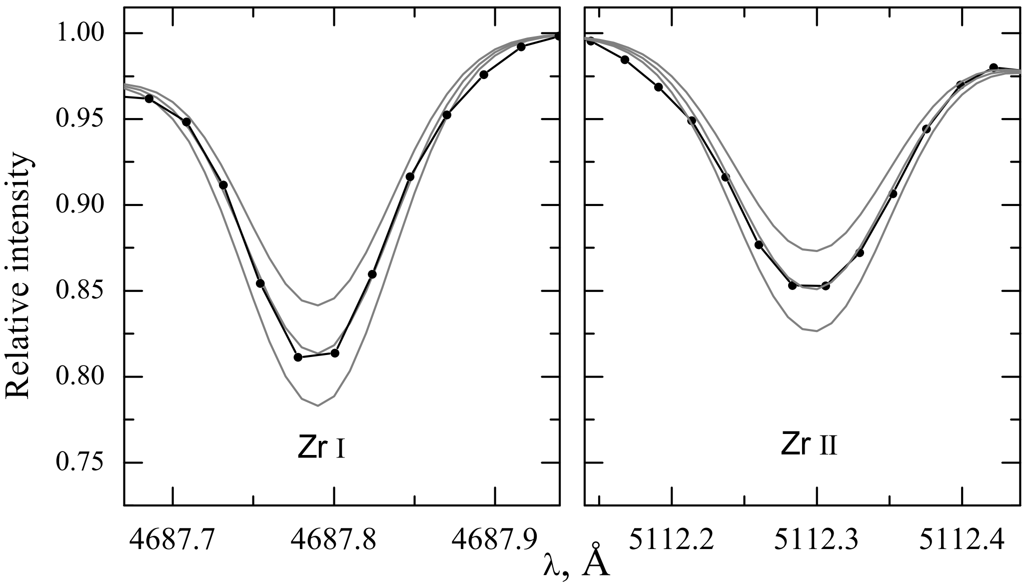
The abundance of europium was determined from the Eu II lines at 4129.7 and 6645.1 Å. The $\log gf$ values for the Eu II lines and isotope fractions were adopted from Lawler et al. (2001b). An information on the HFS pattern for the Eu II line at 4129.7 Å was taken from Ivans et al. (2006), and for the line at 6645.1 Å from Biehl (1976). A partial blending of the Eu II line 6645.1 Å with weak Si I and Cr I lines at 6645.21 Å was taken into account.

Several fits of the synthetic line profiles to the observed spectra are shown in Figs. 2.1, 2.2, and 2.3. The best-fit abundances were determined by eye.

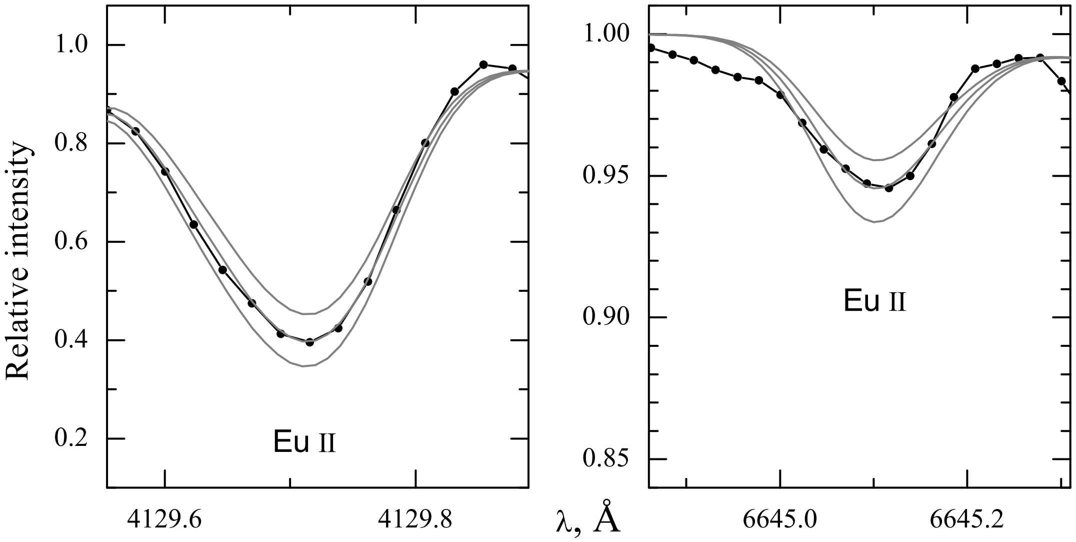
2.2.4 Determination of main atmospheric parameters

Main atmospheric parameters (effective temperature T_{eff}, surface gravity $\log g$, metallicity $[\mathrm{Fe/H}]$, and microturbulence velocity v_{t}) were determined using spectroscopic methods.

Effective temperature T_{eff}. Initial values of the effective temperatures for the



2.2 Figure: Synthetic spectrum fit to the Zr I line at 4688 and Zr II line at 5112 . The grey lines are synthetic spectra with [Zr I/Fe] = 0.40 ± 0.10 and [Zr II/Fe] = 0.38 ± 0.10, respectively. The observed spectrum for the programme star HD 204848 is shown as dots.



2.3 Figure: Synthetic spectrum fit to the Eu II lines at 4129 and 6645 . The grey lines are synthetic spectra with [Eu/Fe] = 0.33 ± 0.10 and [Eu/Fe] = 0.37 ± 0.10 for these two lines, respectively. The observed spectrum for the programme star HD 170737 is shown as dots.

programme stars were taken from Holmberg et al. (2009) and then carefully checked and corrected if needed by forcing Fe I lines to yield no dependency of iron abundance on excitation potential by changing the model effective temperature.

Surface gravity $\log g$. We used the ionization equilibrium method to find surface gravities of the programme stars by forcing neutral and ionized iron lines to yield the same iron abundances.

Microturbulence velocity v_t. The derived abundance should be the same regardless of which line (strong or weak) was used for the analysis. Microturbulence velocity values corresponding to the minimal line-to-line Fe I abundance scattering were chosen as correct values.

Metallicity [Fe/H]. If all the above mentioned main atmospheric parameters are determined correctly, then the final metallicity [Fe/H] value is well-determined.

2.2.5 Uncertainties

The uncertainties in abundances are due to several sources: uncertainties caused by analysis of individual lines, including random errors of atomic data and continuum placement and uncertainties in the stellar parameters. The sensitivity of the abundance estimates to changes in the atmospheric parameters by the assumed errors Δ[El/H] are illustrated in the dissertation for the star HD 224930. The possible parameter errors do not affect the abundances seriously; the element-to-iron ratios, which we use in our discussion, are even less sensitive. The scatter of the deduced abundances from different spectral lines, σ, gives an estimate of the uncertainty due to the random errors. The mean value of σ is 0.05 dex, thus the uncertainties in the derived abundances that are the result of random errors amount to approximately this value.

Results and discussion

3.1 Main atmospheric parameters and detailed elemental abundances

The effective temperature T_{eff}, surface gravity $\log g$, metallicity [Fe/H], and microturbulent velocity v_{t} values of the programme and comparison stars were derived using spectroscopic methods. The atmospheric parameters and metallicity for 21 Group 3 stars are presented in Table 3.1.

The effective temperatures of Group 3 stars are in the range between 5100 and 5900 K. The metallicities (except BD +35 3659) are quite homogeneous: [Fe/H] = −0.69 ± 0.05.

The element-to-iron abundance ratios were derived for Na I, Mg I, Al I, Si I, Ca I, Sc II, Ti I, Ti II, V I, Cr I, Fe I, Fe II, Co I, Ni I spectral lines using measured equivalent widths. For all other species investigated in this study ([O I], Y II, Zr I, Zr II, Ba II, La II, Ce II, Pr II, Nd II, Sm II, and Eu II) we used the spectral synthesis method.

A list of the observed stars and some of their parameters are presented in Table 3.1. The determined elemental abundance ratios of stars in the investigated stellar group and comparison thin disc stars are presented in the thesis appendix (Table A1 and Table A2).

3.2 Comparison with previous studies

Effective temperatures for all stars investigated are also available in Holmberg et al. (2009) and Casagrande et al. (2011). Casagrande et al. provide astrophysical parameters for the Geneva-Copenhagen survey by applying the infrared flux method for the effective temperature determination. In comparison to Holmberg et al., stars in the Casagrande et al. catalogue are on average 100 K hotter. For the stars investigated here, our spectroscopic temperatures are on average 40 ± 70 K hotter than

3.1 Table: Parameters of Group 3 stars.

Star	$T_{\rm eff}$ K	log g	v_t km s^{-1}	[Fe/H]	Age[*] Gyr	M_v[*] mag	d[*] pc	e[*]
HD 967	5570	4.3	0.9	−0.62	9.9	5.23	43	0.34
HD 17820	5900	4.2	1.0	−0.57	11.2	4.45	61	0.39
HD 107582	5600	4.2	1.0	−0.62	9.4	5.18	41	0.41
BD +73 566[a]	5580	3.9	0.9	−0.91	...	5.14	67	0.36
BD +19 2646	5510	4.1	0.9	−0.68	...	5.53	74	0.38
HD 114762	5870	3.8	1.0	−0.67	10.6	4.36	39	0.31
HD 117858	5740	3.8	1.2	−0.55	11.7	4.02	61	0.32
BD +13 2698	5700	4.0	1.0	−0.74	14.2	4.52	93	0.40
BD +77 0521	5500	4.0	1.1	−0.50	14.5	5.27	68	0.42
HD 126512	5780	3.9	1.1	−0.55	11.1	4.01	45	0.40
HD 131597	5180	3.5	1.1	−0.64	...	3.06	119	0.52
BD +67 925	5720	3.5	1.2	−0.55	13.0	4.14	139	0.53
HD 159482	5730	4.1	1.0	−0.71	10.9	4.82	52	0.51
HD 170737	5100	3.3	1.0	−0.68	...	2.88	112	0.40
BD +35 3659[b]	5850	3.9	0.9	−1.45	0.9	5.32	96	0.65
HD 201889	5700	3.8	0.9	−0.73	14.5	4.40	54	0.46
HD 204521	5680	4.3	1.0	−0.72	2.1	5.18	26	0.29
HD 204848	4900	2.3	1.2	−1.03	...	1.98	122	0.36
HD 212029	5830	4.2	0.9	−0.98	13.1	4.66	59	0.44
HD 222794	5560	3.7	1.1	−0.61	12.1	3.83	46	0.42
HD 224930	5470	4.2	0.9	−0.71	14.7	5.32	12	0.29

[*] Parameters were taken from the Holmberg et al. 2009 catalogue.
[a] The star is rich in chemical elements produced by s- and r-processes.
[b] Probably not a member of Group 3.

in Holmberg et al. and 60 ± 80 K cooler than in Casagrande et al. (BD +35 3659, which has a difference of 340 K, was excluded from the average).

[Fe/H] values for all investigated stars are available in Holmberg et al. (2009) as well as in Casagrande et al. (2011). A comparison between Holmberg et al. and Casagrande et al. shows that the latter gives [Fe/H] values that are on average by 0.10 dex more metal-rich. For our programme stars we obtain a difference of 0.10 ± 0.10 dex in comparison with Holmberg et al., and no systematic difference but a scatter of 0.10 dex in comparison with Casagrande et al.

Some stars from our sample have been previously investigated by other authors. We compare the results with Nissen & Schuster (2010), Reddy et al. (2006), and with Ramírez et al. (2007). Ramírez et al. determined only the main atmospheric parameters. We compare the mean differences and standard deviations of the main parameters and abundance ratios [El/Fe] for four stars of Group 3 that are in common with Nissen & Schuster (2010), seven stars in common with Reddy et al. (2006), and ten stars in common with Ramírez et al. (2007).

The thin-disc stars we have investigated in our work for a comparison have been analysed previously by Edvardsson et al. (1993) and by Thévenin & Idiart (1999). We compare the mean differences and standard deviations of the main parameters and abundance ratios for six thin-disc stars that are in common with Edvardsson et al. (1993) and five stars with Thévenin & Idiart (1999).

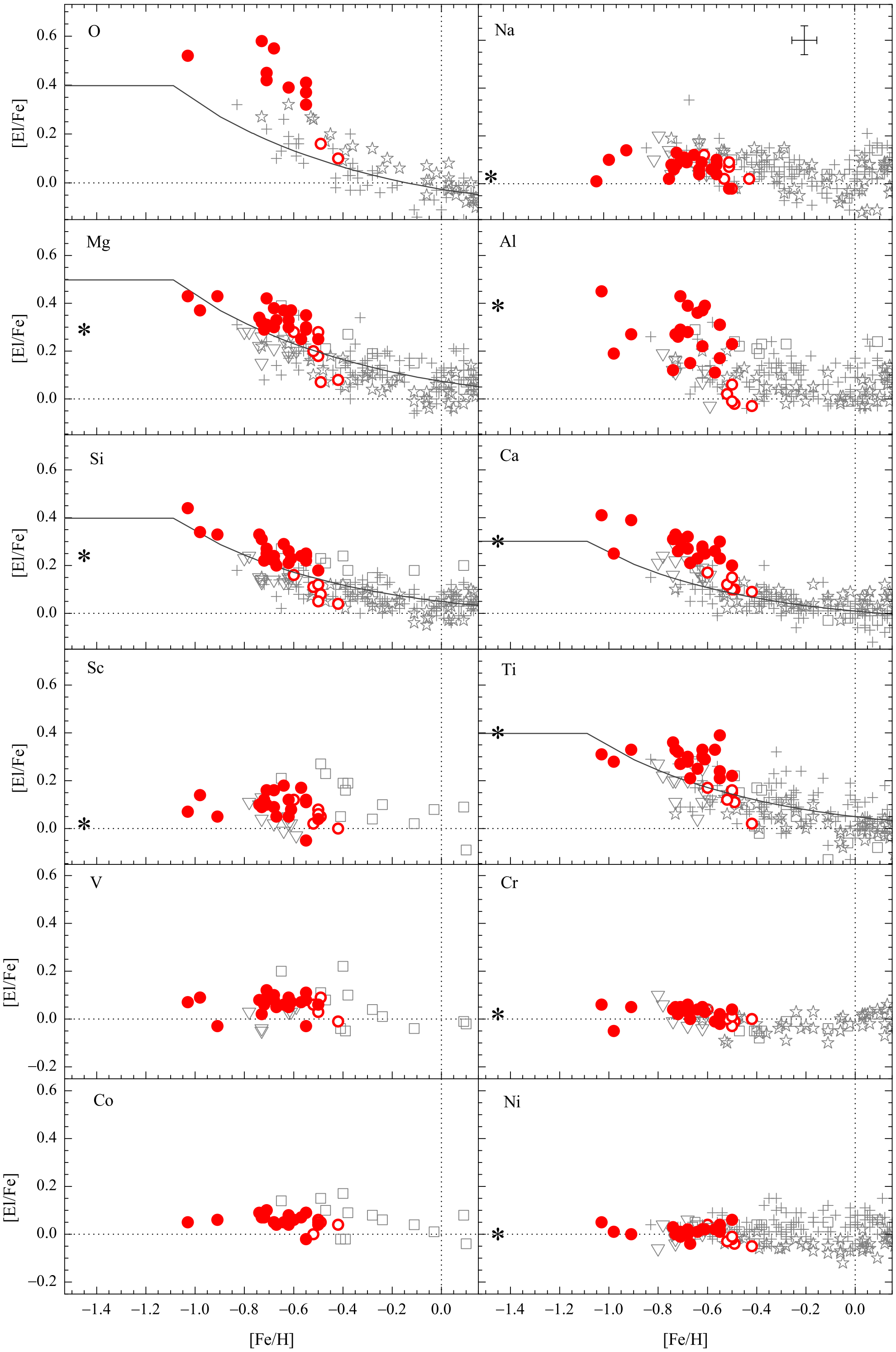
Our [El/Fe] for the stars in common agree very well with other studies. Slight differences in the $\log g$ values lie within errors of uncertainties and are caused mainly by differences in determination methods applied. In our work we see that titanium abundances determined using Ti I and Ti II lines agree well and confirm the $\log g$ values determined using iron lines.

3.3 The detailed elemental abundances

In Fig. 3.1 we present our results of α-elements and iron-group elements, and compare them with the Galactic thin-disc pattern. The data for Galactic thin-disc dwarfs are taken from Edvardsson et al. (1993), Bensby et al. (2005), Reddy et al. (2006), Zhang & Zhao (2006), and the chemical evolution model from Pagel & Tautvaišienė (1995).

The thin-disc stars taken from Edvardsson et al. and Zhang & Zhao were selected by using the membership probability evaluation method described by Trevisan et al. (2011), since their lists contained stars of other Galactic components as well. The same kinematical approach in assigning Galactic thin-disc membership was used in Bensby et al. (2005) and Reddy et al. (2006), so the thin-disc stars used for the comparison are uniform in that respect.

The α-element-to-iron ratios are very sensitive indicators of galactic evolution (Pagel & Tautvaišienė 1995; Fuhrmann 1998; Reddy et al. 2006; Tautvaišienė et al. 2007; Tolstoy et al. 2009 and references therein). If stars that formed in different environments they normally have different α-element-to-iron ratios for a given metallicity.



3.1 Figure: Comparison of elemental abundance ratios of stars in the investigated stellar group (filled circles) and data for Milky Way thin-disc dwarfs from Edvardsson et al. (1993, plus signs), Bensby et al. (2005, stars), Reddy et al. (2006, squares), Zhang & Zhao (2006, triangles), and Galactic thin disc chemical evolution models by Pagel & Tautvaišienė (1995, solid lines). Results obtained for thin-disc dwarfs analysed in our work are shown by open circles. Average uncertainties are shown in the box for Na. The star BD +35 3659, which was removed from Group 3, is marked by an asterisk.

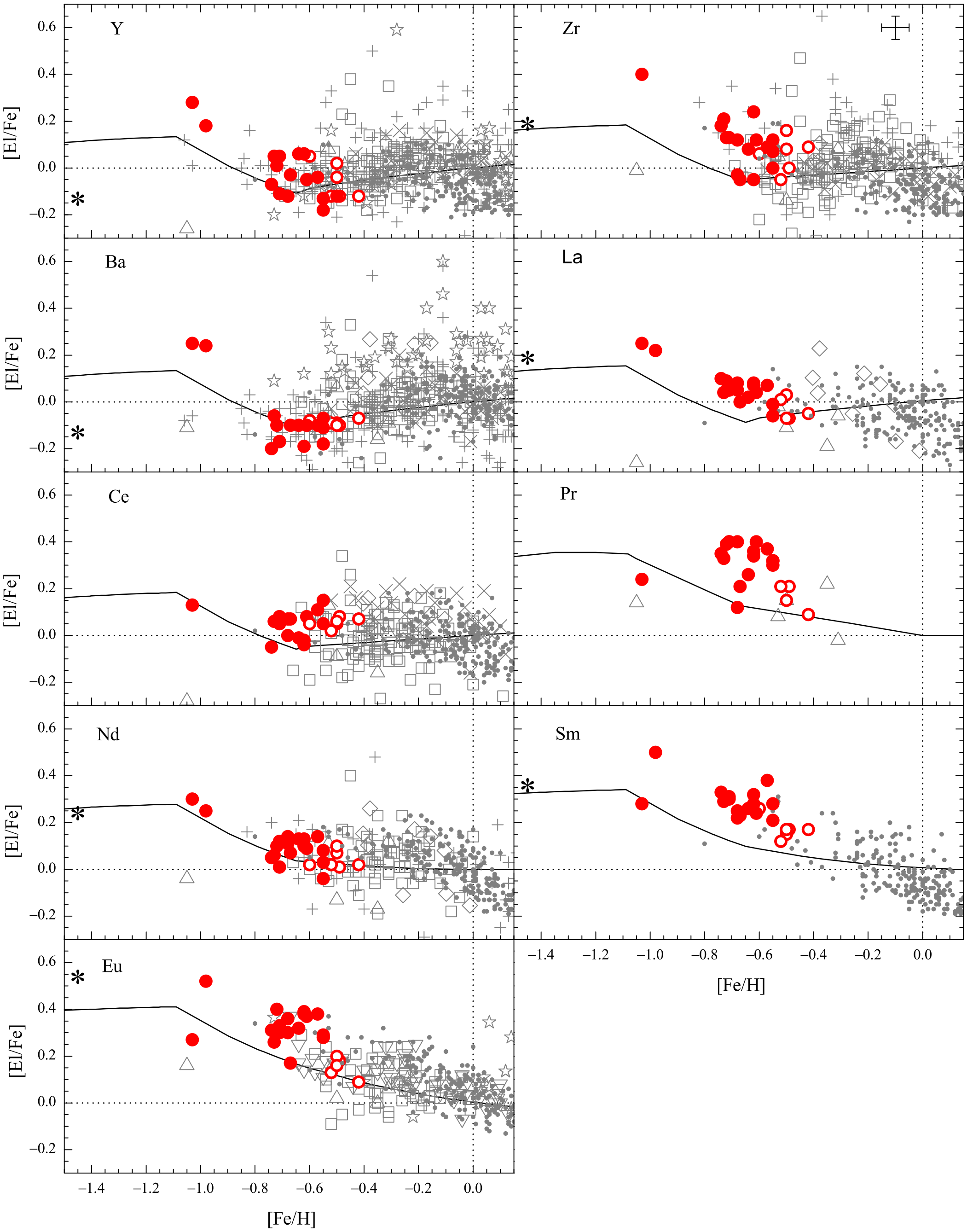
In Fig.3.1 we see that the abundances of α-elements in the investigated stars are overabundant compared with the Galactic thin-disc dwarfs. A similar overabundance of α-elements is exhibited by the thick-disc stars (Fuhrmann 1998; Prochaska et al. 2000; Tautvaišienė ir al. 2001; Bensby et al. 2005; Reddy & Lambert 2008; and references therein). Helmi et al. (2006), based on the isochrone fitting, have suggested that stars in the identified kinematic groups might be α-rich. Our spectroscopic results qualitatively agree with this. However, based on metallicities and vertical velocities, Group 3 cannot be uniquely associated to a single traditional Galactic component (Helmi et al. 2006).

We also present n-capture element abundances (specifically Y, Zr, Ba, La, Ce, Pr, Nd, Sm, and Eu) for 21 stars of Group 3 and 6 comparison stars and compare them with the Galactic disc pattern.

The n-capture elements are produced through both slow (s-) and rapid (r-) n-capture processes (Burbidge et al. 1957). The s- and r-processes are believed to occur at different sites. The r-process, which requires a high neutron flux level (with many n-captures over a timescale of a fraction of a second), is believed to occur in supernova explosions. The s-process, which in contrast requires a lower neutron flux (with a typical n-capture taking many years), is generally thought to occur during the double-shell burning phase of low- ($1-3\ M_{\odot}$) or intermediate-mass ($4-7\ M_{\odot}$) thermally pulsing asymptotic giant branch (AGB) stars.

[El/Fe] ratios for the programme and comparison stars are plotted in Fig. 3.2. For the comparison we use six comparison stars of the Galactic thin-disc observed in our work as well as data from other studies of thin-disc (Mishenina et al. 2013; Mashonkina et al. 2007; Reddy et al. 2006, 2003; Brewer & Carney 2006; Bensby et al. 2005; Koch & Edvardsson 2002; Gratton & Sneden 1994; Edvardsson et al. 1993). The comparison was made also with the Galactic thin disc chemical evolution models by Pagel & Tautvaišienė (1997).

In Fig. 3.2 we see that the abundances of yttrium and barium which are produced mainly in the s-process are the same as in the thin-disc stars. The abundances of chemical elements for which the r-process contribution is larger or dominating are larger than in the thin disc. This is seen for europium, samarium and praseodymium. The element-to-iron ratios for these elements in the Group 3 stars are higher than in the investigated comparison stars and other thin-disc stars. In case of zirconium, lanthanum, cerium, and neodymium, the Group 3 and comparison stars



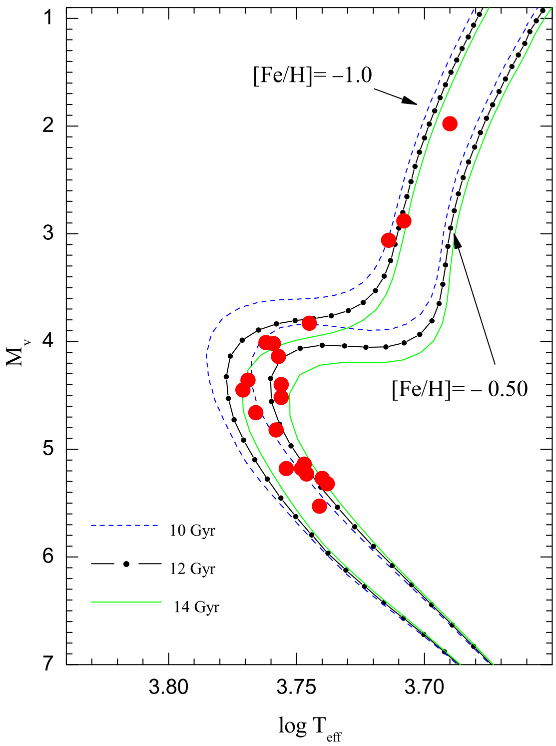
3.2 Figure: Elemental abundance ratios of stars in Group 3 (filled circles) and comparison stars (open circles). The star BD +35 3659, which was removed from Group 3, is marked by an asterisk. For this comparison the data for Milky Way thin-disc dwarfs are plotted: Mishenina et al. (2013, dots), Mashonkina et al. (2007, crosses), Reddy et al. (2006, 2003, squares), Brewer & Carney (2006, diamonds), Bensby et al. (2005, stars), Koch & Edvardsson (2002, upside down triangles), Gratton & Sneden (1994, triangles), Edvardsson et al. (1993, plus signs). Solid lines show the Galactic thin-disc chemical evolution models by Pagel & Tautvaišienė (1997). Average uncertainties are shown in the box for zirconium.

have approximately similar element-to-iron ratios. The similar pattern of n-capture element-to-iron ratios is observed in the thick-disc stars (e.g. Mashonkina & Gehren 2000; Prochaska et al. 2000; Tautvaišienė ir al. 2001; Bensby et al. 2005; Reddy et al. 2006; Reddy & Lambert 2008; Mishenina et al. 2013).

3.4 Members of the Group 3 and age distribution

One star in Group 3 is rich in elements produced in s- and r-processes. The star BD +73 566 has much stronger lines of elements produced in s- and r-processes and consequently much higher abundances of such elements. We recall that BD +73 566 is not plotted in Fig. 3.2. According to the definition of Beers et al. (2005), BD +73 566, with its [Ba/Fe] =1.62 and [Ba/Eu] =0.98, falls in the category of the s-process-enhanced stars.

The metallicities of all programme stars except one (BD +35 3659) are quite homogeneous: [Fe/H] = −0.69 ± 0.05. The star BD +35 3659 is much younger



3.3 Figure: HR diagram of the Group 3 stars. Yi et al. (2001) isochrones representing three different ages and metallicities are shown. The filled circles correspond to the investigated stars with the spectroscopic effective temperatures taken from Stonkutė et al. (2012). Isochrones are with [α/Fe]= 0.4 dex.

(0.9 Gyr), has $[\mathrm{Fe/H}] = -1.45$, its eccentricity, velocities, distance, and other parameters differ as well. We recall that BD +35 3659 is not a member of Group 3 and can be considered as a comparison star.

The age distribution of Group 3 stars was evaluated using the Hertzsprung-Russell (HR) diagram. An initial age evaluation for Group 3 was 14 Gyr (Holmberg et al. 2007). In Fig. 3.3 we plotted the investigated stars of Group 3 with our spectroscopic effective temperatures and absolute magnitudes M_v taken from Holmberg et al. (2009). We have used the Yonsei-Yale single stellar population library by Yi et al. (2001), and its updated version by Demarque et al. (2004). We have plotted isochrones of three ages (10, 12, and 14 Gyr) and two metallicities [Fe/H] (-1.0 and -0.50). These two metallicities represent the minimum and maximum values of Group 3 stars. The overall features of the HR diagram seem to be well reproduced by the 12 Gyr isochrone.

3.5 Connection between the Group 3 and Galactic thick disc

A similar chemical composition of stars in Group 3 and thick-disc stars might suggest that their formation histories are linked.

We compare the mean [El/Fe] values of Group 3 and thick-disc stars at the same metallicity interval $-0.8 < [\mathrm{Fe/H}] < -0.5$. In this metallicity interval lie almost all stars of Group 3. The comparison was made with stars from three thick-disc studies: ten stars lying in the mentioned metallicity interval were taken from Bensby et al. (2005), 44 stars from Reddy et al. (2006), and six stars from Mishenina et al. (2013). Clearly, Group 3 stars and thick-disc stars are of similar chemical composition. The deviations do not exceed the uncertainties of chemical composition determinations.

What does the similarity of α-element and neutron-capture elements abundances in the thick-disc and the investigated kinematic group mean? It would be easier to answer this question if the origin of the thick disc of the Galaxy was known (see van der Kruit & Freeman 2011 for a review).

There are several competing models that aim to explain the nature of a thick disc. Stars may have appeared at the thick disc through: orbital migration because of heating of a pre-existing thin disc by a varying gravitational potential in the thin disc (e.g. Roškar et al. 2008; Schönrich & Binney 2009); heating of a pre-existing thin disc by minor mergers (e.g. Kazantzidis et al. 2008; Villalobos & Helmi 2008, 2009); accretion of disrupted satellites (e.g. Abadi et al. 2003), or gas-rich satellite mergers when thick-disc stars form before the gas completely settles into a thin disc (see Brook et al. 2004, 2005).

Dierickx et al. (2010) analysed the eccentricity distribution of thick-disc stars that has recently been proposed as a diagnostic to differentiate between these mechanisms (Sales et al. 2009). Using SDSS data release 7, they have assembled a sample of 31,535 G-dwarfs with six-dimensional phase-space information and metallicities and have derived their orbital eccentricities. They found that the observed eccentricity distribution is inconsistent with that predicted by orbital migration only. Also, the thick disc cannot be produced predominantly through heating of a pre-existing thin disc, since this model predicts more high-eccentricity stars than observed. According to Dierickx et al., the observed eccentricity distribution fits well with a gas-rich merger scenario, where most thick-disc stars were born *in situ*.

In the gas-rich satellite merger scenario, a distribution of stellar eccentricities peak around e = 0.25, with a tail towards higher values belonging mostly to stars originally formed in satellite galaxies. The group of stars investigated in our work fits this model with a mean eccentricity value of 0.40. This scenario is also supported by the RAVE survey data analysis made by Wilson et al. (2011) and the numerical simulations by Di Matteo et al. (2011). In this scenario, Group 3 can be explained as a remnant from stars originally formed in a merging satellite.

Clearly, all formation mechanisms made influence in the Galactic thick-disc formation. The similar chemical composition of stars in Group 3 and thick-disc stars suggest that their formation histories are linked. Thus, as was pointed out by Helmi et al. (2006) and by us, Group 3 can not be uniquely associated to a single traditional Galactic component. The chemical composition, together with the kinematic properties and ages of stars in the investigated Group 3 of the Geneva-Copenhagen survey, support a gas-rich satellite merger scenario as most suitable for Group 3 origin. A gas-rich satellite merger may be responsible for the formation of the Galactic thick-disc as well (Brook et al. 2004, 2005; Dierickx et al. 2010; Wilson et al. 2011; Di Matteo et al. 2011).

The identification of such kinematic groups and the exploration of their chemical composition will be a key in understanding the formation and evolution of the Galaxy.

Main results and conclusions

Using high-resolution spectra, we performed the detailed chemical analysis of 21 stars attributed to Group 3 of the Geneva-Copenhagen survey and six comparison Galactic thin disc stars. The main atmospheric parameters (effective temperature, surface gravity, metallicity and microturbulence) and abundances of oxygen, α-elements, iron-group chemical elements, and neutron-capture chemical elements, have been determined. The results we compared with the Galactic disc dwarfs and chemical evolution models. Our study of Group 3 stars shows the following:

1. The sample of stars in the kinematicaly identified group is chemically homogeneous. The average [Fe/H] value of the 20 stars is -0.69 ± 0.05 dex.
2. All programme stars are overabundant in oxygen and α-elements compared with Galactic thin-disc dwarfs and the Galactic evolution model used. This abundance pattern has similar characteristics to those of the Galactic thick disc.
3. The abundances of chemical elements produced predominantly by the r-process are overabundant in comparison with Galactic thin-disc dwarfs of the same metallicity. The most prominent overabundances are seen for europium, samarium, and praseodymium.
4. The abundances of iron-group elements and chemical elements produced mainly by the s-process are similar to those in the Galactic thin-disc dwarfs of the same metallicity.
5. BD +73 566 is an s-process-enhanced star and BD +35 3659 is not a member of Group 3.
6. Group 3 consists of a 12-Gyr-old population.

7. The chemical composition of stars in Group 3 is similar to the thick-disc stars, which might suggest that their formation histories are linked.
8. The chemical composition together with the kinematic properties and ages of stars in the investigated Group 3 of the Geneva-Copenhagen survey support a gas-rich satellite merger scenario as the most suitable origin for Group 3.

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Santrauka

Paukščių Tako galaktikoje yra identifikuota žvaigždžių srautų, kinematinių grupių, kurių kilmė siejama su įkritusių galaktikų liekanomis (Zuckerman ir Song 2004; Helmi 2008; Klement ir kt. 2009; Sesar ir kt. 2012). Aktualu ištirti, ar yra tokių senųjų substruktūrų pėdsakų mūsų Saulės aplinkoje?

Helmi ir kt. (2006), panaudoję Nordström ir kt. (2004) Ženevos – Kopenhagos apžvalgos (ŽKA) katalogą, kuriame yra pateikta daugiau nei 14 tūkstančių F ir G spektrinių klasių nykštukių kinematiniai duomenys, temperatūra bei metalingumas, identifikavo tris naujas koherentines žvaigždžių grupes, kurios pasižymi išskirtiniais kinematiniais parametrais. Helmi ir kt. teigimu, šios žvaigždės yra užgalaktinės kilmės.

Šiuo disertacijos darbu siekiama prisidėti prie Galaktikos substruktūrų tyrimų, pasinaudojant detalia aukštos skiriamosios gebos spektrų chemine analize. Siekiama išsiaišknti, ar ŽKA kinematinės grupės žvaigždžių detali atmosferų cheminė sudėtis skiriasi nuo Galaktikos disko žvaigždžių, ar identifikuotoji kinematinė grupė yra homogeniška, ar ŽKA kinematinė žvaigždžių grupė galėjo atsirasti mūsų Galaktikoje, įkritus nykštukinei galaktikai dar Paukščių Tako galaktikos evoliucijos pradžioje. Darbe tiriama detali cheminė vienos iš Helmi ir kt. (2006) identifikuotų žvaigždžių grupių sudėtis.

Nustatėme 21 3–osios ŽKA kinematinės grupės bei 6 palyginamųjų Galaktikos plonojo disko žvaigždžių atmosferų pagrindinius parametrus (efektinę temperatūrą, gravitacijos pagreitį žvaigždė paviršiuje, metalingumą bei mikroturbutencijos greitį) bei 22 cheminių elementų gausas.

Kinematinės žvaigždžių grupės deguonies ir α elementų gausos yra padidėjusios lyginant su plonuoju Galaktikos disku ir yra panašios į Galaktikos storojo disko žvaigždžių atmosferų cheminę sudėtį. Geležies grupės elementų gausos sutampa su Galaktikos plonojo disko žvaigždžių atmosferų chemine sudėtimi bei cheminės evoliucijos modeliais. 3–osios ŽKA grupės žvaigždžių cheminių elementų gausos, daugiausia pagaminamos *s*-procese, yra panašios į plonojo Galaktikos disko nykštukių su tuo pačiu metalingumu cheminių elementų gausas, o cheminių elementų gausos, daugiausia pagaminamos *r*-procese, yra padidėjusios lyginant su plonuoju Galaktikos disku.

Remiantis kinematika bei mūsų darbe nustatyta detalia chemine sudėtimi, nustatėme kad žvaigždė BD +35 3659 nėra 3–osios ŽKA kinematinės grupės narė, o žvaigždė BD +73 566 yra praturtinta *s*-proceso elementais.

Naudojant HR diagramą ir teorines Yonsei – Yale izochronas nustatėme, kad 3–osios ŽKA grupės žvaigždžių amžius yra apie 12 mlrd. metų.

Panaši cheminė tirtos kinematinės grupės bei storojo Galaktikos disko sudėtis rodo, kad kinematinės žvaigždžių grupės ir storojo Galaktikos disko žvaigždžių formavimo scenarijai yra galimai susiję.

3–osios ŽKA kinematinės grupės žvaigždžių atmosferų cheminė sudėtis, kinematika ir amžiaus pasiskirstymas palaiko scenarijų, kuriame Paukščių Tako galaktika evoliucijos pradžioje susijungė su praturtinta dujomis nykštukinė galaktika.

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B.Sc. in Theoretical Physics at Vytautus Magnus university, 2002 – 2006.

M.Sc. in Theoretical Physics and Astronomy at Vilnius Pedagogical university, 2006 – 2008.

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Professional improvement:

Technical Engineer at Vilnius University, Institute of Theoretical Physics and Astronomy, 2006 – 2008.

Junior Researcher at Vilnius University, Institute of Theoretical Physics and Astronomy, 2008 – to present.

Research Visit at Nils Bohr Institute, Copenhagen, Denmark, January 2011 – February 2011.

Observing Experience:

Optical High Res. Spectroscopy (Nordic Optical Telescope).

Optical Imaging (35/51 cm Maksutov telescope, Nordic Optical Telescope).

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LOC Member of international summer schools at the Molėtai Astronomical observatory: Nordic-Baltic Research school 2012; NEON summer school 2011.

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