Chemical compositions of stars in two stellar streams from the Galactic thick disc

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ABSTRACT

We present abundances for 20 elements for stars in two stellar streams identified by Arifyanto & Fuchs: 18 stars from the Arcturus stream and 26 from a new stream, which we call the AF06 stream, both from the Galactic thick disc. Results show that both streams are metal poor and very old (10–14 Gyr) with kinematics and abundances overlapping with the properties of local field thick-disc stars. Both streams exhibit a range in metallicity but with relative elemental abundances that are identical to those of thick-disc stars of the same metallicity. These results show that neither stream can result from dissolution of an open cluster. It is highly unlikely that either stream represents tidal debris from an accreted satellite galaxy. Both streams most probably owe their origin to dynamical perturbations within the Galaxy.

Key words: stars: abundances – subdwarfs – Galaxy: disc – Galaxy: evolution – Galaxy: kinematics and dynamics – Galaxy: structure.

1 INTRODUCTION

The phase space of the Galaxy’s disc, as observed near the Sun, contains substructure within the larger structures known as the thin and the thick disc. Substructures include open clusters and stellar streams, also often referred to as moving groups. Moving groups, as promoted by Eggen (see e.g. Eggen 1998 and references therein), are considered to be stars having a common space motion and a common chemical composition, and originating from a dissolving open cluster. While some of the well-known moving groups do share a common composition (e.g. the HR 1614 group – De Silva et al. 2007) suggesting that they come from a tidally disrupted open cluster, other groups contain stars having very different compositions, a result demanding an origin more complex than disruption of an open cluster. The term ‘stream’ is now applied to some entities in Galactic phase space. Examples in the thin disc include the Hercules stream (Bensby et al. 2007) and the Hyades stream or supercluster (De Silva et al. 2011; Pompéia et al. 2011). For streams in the thick disc, a likely explanation involves dynamical interactions of disc stars with the central bar (Antoja et al. 2009) or spiral density waves (Minchev et al. 2010). Other possibilities arise for streams belonging to the thick disc including accretion from external galaxies.

In this paper, we present chemical compositions for subdwarfs belonging to two streams in the thick disc. Arifyanto & Fuchs (2006) undertook a search for fine structure in the phase space populated by subdwarfs from the large sample of F and G subdwarfs considered by Carney et al. (1994), for which Arifyanto & Fuchs (2006) refined data on stellar distances and kinematics. Two clumps in phase space were noted by Arifyanto & Fuchs (2006). One with \( V = -125 \, \text{km s}^{-1} \) and \( \sqrt{U^2 + V^2} = 185 \, \text{km s}^{-1} \) is referred to as the Arcturus stream. An Arcturus moving group had previously identified by Eggen (1971). The second stream AF06 with a stronger presence in phase space than the Arcturus stream is at \( V = -80 \, \text{km s}^{-1} \) and \( \sqrt{U^2 + V^2} = 130 \, \text{km s}^{-1} \).

Here, we report chemical compositions of stars from these two streams. We show that stars in both streams span a range in metallicity but with relative abundances which match closely the ratios reported for field thick-disc stars. This result serves to constrain greatly explanations for the origins of the two streams.

2 SAMPLE STARS AND OBSERVATIONS

Stars selected for observation came from membership lists of the Arcturus and AF06 streams given by Arifyanto & Fuchs (2006): 18 of the 22 stars in the former stream and 26 of the 44 stars in the latter stream were observed successfully with the Tull coudé spectrograph (Tull et al. 1995) at the 2.7 m Harlan J. Smith Telescope of the W.J. McDonald Observatory.

Spectra at a resolving power of 60,000 were obtained with spectral coverage from about 3800 to 10,000 Å with echelle orders incompletely recorded on the CCD beyond about 5800 Å. Wavelength calibration was provided by an exposure of a Th–Ar hollow cathode lamp. These two-dimensional data were reduced to one-dimensional relative flux versus wavelength spectra using the Image Reduction and Analysis Facility (IRAF). In a typical spectrum, the S/N ratio at
3 ANALYSIS

3.1 Stellar atmospheric parameters

Atmospheric parameters – effective temperature ($T_{\text{eff}}$), surface gravity ($\log g$) and metallicity ([M/H]) – have been derived from both photometric and spectroscopic data. In the former case, we relied on published catalogues of photometry and parallaxes, empirical calibrations and the theoretical stellar evolutionary models. In the latter case, our high-resolution spectra were used to derive the atmospheric parameters including microturbulence ($\xi_t$). Below, both the procedures are described in brief.

3.1.1 Photometry

$T_{\text{eff}}$ is derived using $(V-K_s)$ colour and Strömgren photometry ($uvby$) calibrations. The $K_s$ magnitude is taken from Two Micron All Sky Survey (2MASS) catalogue\(^2\) (Cutri et al. 2003)\(^3\). The subscript ‘$s$’ stands for the bandpass of the $K$ filter in the 2MASS survey, i.e. the $K_s$ filter is narrower than the Johnson $K$ filter. The $K_s$ magnitudes are converted to standard ‘$K$’ magnitudes using the relations given in Ramírez & Meléndrez (2005). The mean difference between the two magnitudes is only $K_s - K_{\odot} = -0.001 \pm 0.005$ and will have no effect when $K_s$ is used in place of $K$ magnitudes in the calibration between $(V-K)$ and $T_{\text{eff}}$. The $V$ magnitudes for all the stars were adopted from Kharchenko (2001). The $(V-K)$ colour and the empirical relations provided in Alonso, Arribas & Martinez-Roger (1996) are used for deriving $T_{\text{eff}}$. Strömgren colours and indices ($b-y, m_1, c_1$) are available for 26 out of 44 stars in the sample (Hauck & Mermilliod 1998). Values of metallicity and $T_{\text{eff}}$ were obtained using empirical calibrations of Strömgren colours and indices given in Schuster & Nissen (1989) and Alonso et al. (1996), respectively. Values of metallicity are quite sensitive to reddening as it makes observed $(b-y)$ more positive and $m_1$ values more negative than their intrinsic colours. However, we expect no significant reddening as the stars are nearby ($d < 130$ pc from the Sun). Using the methods given in Schuster & Nissen (1989), reddening values $E(b-y)$ have been estimated and, indeed, all reddening estimates are vanishingly small: $E(b-y) \leq 0.001 \pm 0.006$. Temperatures derived using $(V-K_s)$ and Strömgren colours are given in Table 1 as $(T_{\text{eff}})_{V-K_s}$ and $(T_{\text{eff}})_{b-y}$, respectively. The mean difference between the two temperatures, $(T_{\text{eff}})_{V-K_s} - (T_{\text{eff}})_{b-y} = 18 \pm 90$ K, excluding the outliers HIP 24030, HIP 53070, HIP 11952 and G192–21, for which the difference is large $245 \pm 24$ K, i.e. $T_{\text{eff}}$ derived from $(V-K_s)$ colour is hotter than those from $(b-y)$. The $(b-y)$ temperature of HIP 24030 and the $(V-K_s)$ temperature of G192–21 are much closer to the values obtained using spectroscopy. In the case of the other two, we suspect errors in one of the their colours.

The log $g$ value is derived from the trigonometric parallax, the $(B-V)$ colour, and theoretical isochrones (Demarque et al. 2004). (AURA) under cooperative agreement with the National Science Foundation.

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\(3\)Originally published in University of Massachusetts and Infrared Processing and Analysis Centre, IPAC/California Institute of Technology.

Errors in the parallax and $(B-V)$ colour are taken into account in estimating the uncertainty in the log $g$ value.

3.1.2 Spectroscopy

A full set of atmospheric parameters ($T_{\text{eff}}, \log g$, $\xi_t$, [M/H]) has been derived from spectral-line analysis by standard local thermodynamic equilibrium (LTE) techniques. In this exercise, the LTE Kurucz grid of ATLAS model atmospheres with the convective overshoot option was adopted (Kurucz 1998). The rationale for choosing overshoot models for solar-type dwarf stars was given in Reddy et al. (2003) and Reddy, Lambert & Allende Prieto (2006). Since we intend to compare our results with the results from the thin- and thick-disc studies of Reddy et al., we followed their analysis techniques. The LTE line analysis code MOOG (Sneden 1973) in its 2009 version was used throughout.

The effective temperature was set by the requirement that the Fe abundance provided by Fe I lines be independent of the lower excitation potential (LEP) of the selected lines. While deriving $T_{\text{eff}}$, caution was taken to minimize the effect of microturbulence by choosing, initially, very weak lines with a sufficient range in LEP. Later, microturbulence ($\xi_t$) was derived by adding Fe I lines of moderately strong equivalent width ($W_\lambda < 120$ mA) so that the abundance trend becomes sensitive to changes in $\xi_t$. The chosen value of $\xi_t$ is that for which the abundance is independent of equivalent width. The surface gravity log $g$ was obtained by requiring that, for the given $T_{\text{eff}}$ and $\xi_t$, Fe I and Fe II lines give the same Fe abundance.

The uncertainties in the derived parameters have been estimated by inspection of dependences for combinations of models of different sets of parameters. In the case of $T_{\text{eff}}$, we varied the best representative $T_{\text{eff}}$ in steps of 25 K for given log $g$, $\xi_t$ and [M/H]. For steps of 25 K changes, we found no significant changes in the slope as well as in abundances; however, we see (see Fig. 1) noticeable changes in abundance trends by increasing or decreasing 50 K from its mean model $T_{\text{eff}}$. Thus, we estimate $\pm 50$ K as an uncertainty in the best-fitting model atmosphere. Similarly, we found model uncertainties in log $g$ and $\xi_t$. In Fig. 1, estimation of uncertainties is illustrated for $T_{\text{eff}}$ and $\xi_t$. In this way, we found model uncertainties in $T_{\text{eff}}$, log $g$ and $\xi_t$: $\pm 50$ K, $\pm 0.20$ cm s$^{-1}$ and $\pm 0.20$ km s$^{-1}$, respectively. These individual uncertainties translate to an effective error of $\pm 0.05$ dex in metallicity [Fe/H].

Next, photometric and spectroscopic estimates of model atmospheric parameters are compared. Temperature, log $g$ and metallicity comparisons are given in Fig. 2. The mean difference between $(T_{\text{eff}})_{V-K_s}$ and spectroscopic $T_{\text{eff}}$ is just $-9 \pm 87$ K. There are a few outliers HIP 24030 and HIP 94931 (for which $(T_{\text{eff}})_{b-y}$ values are closer to spectroscopic $T_{\text{eff}}$), and G10–12 and HIP 9080 (for which $(T_{\text{eff}})_{b-y}$ values are not available) with a difference of $-77 \pm 174$ K. Excluding the outliers the mean difference becomes $-2 \pm 73$ K. The log $g$ values obtained from photometry are in good agreement with the spectroscopic values: the difference between the two methods is only $0.002 \pm 0.18$ cm s$^{-2}$ for 23 stars for which photometric gravities could be obtained, a difference within the combined uncertainties. The mean difference between the photometric metallicity from Strömgren photometry and the spectroscopic metallicity is $-0.03 \pm 0.11$ dex for 25 stars for which Strömgren photometry is available. Star G192–21 is an outlier whose spectroscopic metallicity is about 0.7 dex metal richer compared to the corresponding photometric value. The difference is probably due to erroneous Strömgren photometry. For the two metal-poor stars HIP 53070 and HIP 11952, too few lines are available for spectroscopic determination of parameters and, therefore, we have adopted photometric

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(\(T_{\text{eff}}\))\(b\rightarrow y\) and log g values. The microturbulent velocity \(\xi\), calculated using the relation given in Reddy et al. (2003) between \(\xi\), \(T_{\text{eff}}\) and log g was adopted for both stars. In the final calculations of abundances we adopt parameters derived from spectroscopy but no conclusions would be changed were the photometric parameters adopted.

### 3.2 Abundances

Elemental abundances have been derived using measured equivalent widths and synthetic spectra with LTE model atmospheres for the adopted stellar parameters taken from Kurucz grid (Kurucz 1998) and the 2009 version of the LTE line analysis code MOOG. The line list compiled by Reddy et al. (2006) was adopted. Solar abundances derived by Reddy et al. (2003) have been used as reference values, except Eu abundance. The solar Eu abundance (log \(\epsilon(Eu) = 0.55\)) has been derived, for this study, using the Atlas solar spectrum (Hinkle et al. 2000) and two \(\text{Eu} II\) lines (6645.13, 4129.72 Å). For transitions with significant hyperfine structure (HFS) data were taken from the Kurucz HFS data base (Kurucz 1998). The lines of Mn, V, Cu and Eu with HFS were analysed by computing synthetic spectra. In the case of vanadium, the line at 6216.36 Å, one of

### Table 1. The atmospheric parameters – photometry & spectroscopy.

| Star     | \((T_{\text{eff}})_{b\rightarrow y}\) (K) | \((T_{\text{eff}})_{b\rightarrow y}\) (K) | \(\log g \pm \text{error}\) (cm s\(^{-1}\)) | \([\text{M/Hi}]_{b\rightarrow y}\) (dex) | \(T_{\text{eff}}\) (K) | \(\log g\) (cm s\(^{-1}\)) | \([\text{Fe/H}]_{\text{model}}\) (dex) | \(\xi\) (km s\(^{-1}\)) | \(N\) |
|----------|----------------------------------------|----------------------------------------|-----------------------------------------|--------------------------------------|----------------|-----------------|-----------------------------|-----------------|------|
| HIP 10588 | 5798                                   | 5665                                   | 4.05 ± 0.05                             | −0.81                                | 5790           | 4.30            | −0.55                        | 1.08 (42.7)      |
| HIP 36710 | 5301                                   | −                                       | −                                       | −0.37                                | 5340           | 4.63            | −0.45                        | 0.48 (46.6)      |
| HIP 77637 | 5478                                   | 5550                                   | 4.31 ± 0.08                             | −0.95                                | 5580           | 3.73            | −0.85                        | 0.90 (30.7)      |
| G103+53  | 5435                                   | 5340                                   | 4.16 ± 0.09                             | −0.66                                | 5290           | 4.40            | −0.65                        | 0.52 (42.5)      |
| G72+12   | 5041                                   | 5094                                   | −0.27                                   | 5060                                | 4.64            | −0.40                        | 0.67 (43.5)      |
| G4+2     | 5258                                   | 5238                                   | −0.61                                   | 5160                                | 4.64            | −0.70                        | 0.48 (37.4)      |
| HIP 53070 | 5962                                   | 5719                                   | 4.23 ± 0.04                             | −1.30                                | −              | −                            | −1.40                        | 1.36 (4.3)      |
| G204+30  | 5610                                   | −                                       | −                                       | −5550                              | 4.42            | −0.80                        | 0.69 (27.5)      |
| G139+49  | 5331                                   | −                                       | −                                       | −5380                              | 4.12            | −0.75                        | 0.47 (30.5)      |
| G241+7   | 5446                                   | −                                       | −                                       | −5320                              | 4.00            | −0.95                        | 0.91 (25.4)      |
| HIP 40613 | 5723                                   | 5670                                   | 4.16 ± 0.03                             | −0.64                                | 5670           | 4.02            | −0.55                        | 0.90 (45.6)      |
| G42+34   | 4858                                   | −                                       | −                                       | −4920                              | 4.22            | −0.60                        | 0.44 (47.4)      |
| HIP 36491 | 5741                                   | 5681                                   | 4.41 ± 0.05                             | −0.96                                | 5760           | 4.20            | −0.85                        | 1.10 (25.6)      |
| HIP 94931 | 4964                                   | 5118                                   | 4.56 ± 0.01                             | −0.35                                | 5120           | 4.58            | −0.40                        | 0.55 (48.6)      |
| HIP 74033 | 5647                                   | 5574                                   | 4.02 ± 0.04                             | −0.92                                | 5690           | 4.04            | −0.70                        | 1.06 (42.7)      |
| G5+1     | 5562                                   | −                                       | 4.37 ± 0.08                             | −5470                                | 4.25            | −1.05                        | 0.45 (24.5)      |
| G102+44  | 5253                                   | −                                       | −                                       | −5260                              | 4.43            | −0.63                        | 0.44 (45.5)      |
| HIP 58253 | 5359                                   | 5351                                   | −0.37                                   | 5280                                | 4.38            | −0.35                        | 0.52 (41.4)      |

For the AF06 stream, the parameters were taken from the Kurucz HFS data base (Kurucz 1998). The lines of Mn, V, Cu and Eu with HFS were analysed by computing synthetic spectra. In the case of vanadium, the line at 6216.36 Å, one of the

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Uncertainties in abundances can also be gauged by comparing results for stars that are common in this and other studies. For seven stars that are common with thick-disc sample study by Reddy et al. (2006), differences in the derived abundance ratios $[X/Fe]$ between the studies are given in Table 5. The differences are quite small and less than measured uncertainty ($\sigma_{\text{model}}$). The good agreement between the two studies implies that the results of the two streams in this study can be compared directly with the results of the thick-disc sample study from Reddy et al. (2006). This is akin to a differential analysis with respect to the thick disc.

### 3.3 Kinematics

Both streams were identified by Arifyanto & Fuchs (2006) as overdensities of stars in phase space. To represent stars in phase space one requires information such as coordinates, radial velocities, distance (parallaxes) and proper motions. In the calculation of Galactic motions Arifyanto & Fuchs (2006) used Hipparcos data (Perryman et al. 1997) and radial velocities from Carney et al. (1994). Recently, Hipparcos observations were re-reduced by van Leeuwen (2007). Consequently, we have rederived the Galactic velocities ($U, V, W$) for stream members using the revised Hipparcos parallaxes and proper motions, and including the radial velocities derived from our McDonald spectra. Radial velocities obtained in this study are in very good agreement with the velocities given in Arifyanto & Fuchs (2006). The mean difference between the two studies is $0.15 \pm 0.50$ km s$^{-1}$.

The $U, V$ and $W$ velocities with respect to the Sun were calculated using the method given in Johnson & Soderblom (1987). A right-handed coordinate system is used throughout where $U$ is positive towards the Galactic centre, $V$ is positive in the direction of Galactic rotation and $W$ is positive towards the North Galactic Pole. Velocities ($U, V, W$) are in good agreement with values given by Arifyanto & Fuchs (2006), differences between the two studies are mainly due to the updated parallaxes. None of the stars identified as members by Arifyanto & Fuchs (2006) lost their membership in either stream. Derived radial velocities ($R_*$) and Galactic velocities ($U_{\text{LSR}}, V_{\text{LSR}}, W_{\text{LSR}}$) relative to Local Standard of Rest (LSR) are given in Table 6. In conversion to the LSR frame, the solar motion of $(U_\odot, V_\odot, W_\odot) = (+10.0, +5.3, +7.2)$ km s$^{-1}$ is used (Dehnen & Binney 1998).

The mean motion ($U_{\text{LSR}}, V_{\text{LSR}}, W_{\text{LSR}}$) of the Arcturus stream based on the 18 member stars observed by us is $(-6.48 \pm 49.29, -124.79 \pm 8.92, -11.5 \pm 49.59)$ and for the AF06 stream the mean motion is $(-41.55 \pm 47.45, -87.35 \pm 7.83, 3.82 \pm 54.34)$. These values are in good agreement with the streams’ central values given in Arifyanto & Fuchs (2006).

To compute orbital parameters, the ($U, V, W$) of each star is integrated over the Galactic potential provided by D. Lin (private communication). Orbital parameters – mean of apogalactic and perigalactic distance ($R_*$), eccentricity ($e$) and maximum distance of the star away from the Galactic plane ($Z_{\text{max}}$) – have been derived and are given in Table 6. A distance of 8.5 kpc between the Sun and the Galactic centre is used in the calculation.

The ($U, V, W$) of both the streams, as Arifyanto & Fuchs (2006) appreciated, suggests that the streams are part of the thick disc. Probabilities that a particular star belongs to the halo, the thick and the thin disc are calculated using the definitions and recipes
given in Reddy et al. (2006). The percentage probability (P) that a star belongs to the thick disc is given in Table 6. All the Arcturus stream members in our sample are thick-disc stars with a probability $P_{\text{thick}} \geq 80$ per cent, while 15 out of the 26 AF06 stream members have a probability that would qualify them as thick-disc members with the remaining 11 stars having probabilities placing them in either the thin or thick discs.

In Fig. 3, sample stars of the two streams along with the representative members of the thick disc, the thin disc and the halo are shown in the space of angular momentum per unit mass components $J_z$ and $J_\perp = \sqrt{J_x^2 + J_y^2}$, the azimuthal and perpendicular components, respectively. In angular momentum space, stars are clustered in a small region compared to their distribution in the velocity space (see Helmi & Zeeuw 2000). Values are calculated in the right-handed coordinate system and the LSR velocity is assumed to be 220 km s$^{-1}$.

The value $J_z = 0$ implies no rotational velocity in the direction of the Galactic rotation and increasing values mean higher rotational velocities. $J_\perp$ represents the extent of the tilt of the star’s orbit with respect to the Galactic plane. Obviously, for the thin disc it is quite small. The Arcturus stream and AF06 stream have a mean $J_z$ of $-811 \pm 77$ and $-1130 \pm 63$ km pc kpc$^{-1}$, respectively.

The presence of the Arcturus stream was detected by Navarro, Helmi & Freeman (2004) in catalogues of metal-poor stars by Beers et al. (2000) and Gratton et al. (2003). They found the Arcturus stream lagging the LSR by 120 km s$^{-1}$ but with a large dispersion of $\sigma_v \sim 50$ km s$^{-1}$. Their detected structure has angular momentum
Arcturus stream and AF06 stream

| Star          | [Cr/Fe] | [Cr/Fe] | [Mn/Fe] | [Co/Fe] | [Ni/Fe] | [Cu/Fe] | [Zn/Fe] | [Y/Fe] | [Ba/Fe] | [Ce/Fe] | [Nd/Fe] | [Eu/Fe] |
|---------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| HIP 105888    | −0.10   | 0.02    | −0.34   | 0.13    | −0.01   | −0.05   | 0.30    | 0.02    | −0.17   | −0.02   | 0.16    | 0.36    |
| HIP 36710     | −0.17   | −0.04   | −0.28   | 0.09    | −0.04   | 0.07    | 0.21    | −0.08   | −0.22   | 0.15    | −        | 0.41    |
| HIP 77637     | −0.17   | −0.06   | −0.37   | −0.01   | −0.09   | −0.20   | 0.26    | 0.09    | 0.01    | −0.11   | 0.18    | 0.21    |
| G103−53       | −0.14   | −0.10   | −0.35   | 0.16    | −0.05   | 0.13    | 0.26    | −0.11   | −0.19   | 0.14    | 0.26    | 0.10    |
| G72−12        | −0.11   | −0.04   | −0.24   | 0.10    | −0.06   | 0.09    | 0.17    | −0.01   | −0.19   | 0.10    | 0.38    | 0.16    |
| G4−2          | −0.14   | 0.04    | −0.31   | 0.09    | −0.07   | 0.06    | 0.12    | −0.15   | −0.24   | −        | −        | 0.49    |
| HIP 53070     | −0.17   | −0.27   | 0.05    | −0.05   | 0.14    | 0.05    | −0.09   | −        | −        | 0.37    |         |         |
| G139−49       | −0.14   | −0.37   | 0.05    | −0.14   | 0.05    | 0.36    | −0.15   | −0.15   | −        | −        | −        | −        |
| G241−7        | −0.05   | 0.06    | −0.48   | 0.07    | 0.01    | 0.01    | 0.43    | 0.05    | −0.20   | 0.02    | −        |         |
| HIP 40613     | −0.18   | 0.00    | −0.32   | 0.06    | −0.04   | −0.01   | 0.28    | −0.07   | −0.15   | −0.26   | 0.03    | 0.24    |
| G42−34        | −0.11   | −0.31   | 0.21    | −0.10   | 0.16    | 0.02    | −0.14   | −0.23   | 0.33    | 0.05    | 0.47    |
| HIP 36491     | −0.14   | −0.06   | −0.37   | 0.24    | 0.02    | −0.12   | 0.20    | −0.03   | −0.17   | 0.15    | 0.46    | 0.34    |
| HIP 94931     | −0.14   | 0.04    | −0.20   | 0.06    | −0.05   | 0.17    | 0.16    | 0.05    | −0.21   | 0.17    | 0.16    | 0.43    |
| HIP 74033     | −0.12   | 0.01    | −0.30   | 0.10    | −0.03   | −0.02   | 0.32    | 0.11    | −0.08   | −0.04   | 0.16    | 0.33    |
| G5−1          | −0.18   | −0.05   | −0.43   | 0.07    | −0.07   | −0.40   | 0.08    | −0.08   | −0.22   | 0.13    | −        | 0.29    |
| G102−44       | −0.10   | 0.02    | −0.35   | 0.04    | −0.07   | −0.05   | 0.20    | −0.09   | −0.14   | 0.11    | 0.40    | −0.01   |
| HIP 58253     | −0.14   | −0.01   | −0.31   | 0.23    | −0.00   | 0.01    | 0.13    | −0.02   | −0.09   | −        | −        | 0.13    |

Arcturus stream

(A) in the range of 700−1100 km s$^{-1}$ kpc. It appears to us that this structure detected by Navarro et al. (2004) is the combined structure of the Arcturus and the AF06 stream, but this structure was separated into two different streams by Arifyanto & Fuchs (2006) using the wavelet transform technique. By combining the samples taken for this study, we get the mean values $V_{LSR}$ and $J_z$ ($−102.67 \pm 20.34$, $−1000 \pm 173$) very similar to what Navarro et al. (2004) found for the structure that they thought to be the single structure labelled the Arcturus stream. The Arcturus stream has been identified in recent studies (Klement, Fuchs & Rix 2008) as a significant overdensity in phase space. The Klement et al. (2008) study is based on more than 7000 stars within a distance of 500 pc taken from the Radial Velocity Experiment (RAVE) survey. They have identified stars with high orbital eccentricities having overdensities at about $V = −120$ km s$^{-1}$ and $V = −95$ km s$^{-1}$ which coincide with phase-space coordinates of the Arcturus and AF06 streams, respectively, as given in Arifyanto & Fuchs (2006). Williams et al. (2009) examined a data set of 16000 giants from the RAVE survey and showed pronounced overdensity of stars at velocities overlapping with the Arcturus stream in the solar circle.

3.4 Ages

Determination of stellar ages from the location of a star in a colour–magnitude diagram is an uncertain procedure because the majority of the stars in both streams fall very close to the zero-age main
sequence. For the few stars that appear relatively evolved off the main sequence ages were estimated. Mean ages with upper and lower limits are given in Table 6. Errors in $B - V$ and parallaxes are used to estimate the limits. In Fig. 4, the stars are shown in the Hertzsprung-Russell diagram of $M_V$ versus $(B - V)$ colour along with isochrones of ages 10, 12 and 16 Gyr for the metallicities $[\text{Fe/H}] = -0.70$ and $-0.51$ dex, for the Arcturus stream and AF06 stream, respectively. Ages of the stream members range from 10 to 14 Gyr. The stellar ages, therefore, are very similar to the ages of thick-disc field stars which are all older than about 10–11 Gyr (Reddy et al. 2006). The derived ages are in good agreement with previous studies of the Arcturus group (cf. Navarro et al. 2004; Helmi et al. 2006; Williams et al. 2009) based on different selections of stream members.
Table 6. The kinematical parameters of the sample.

| Star          | \( R_e \) (pc) | \( U_{LSR} \pm 1\sigma \) (km s\(^{-1}\)) | \( V_{LSR} \pm 1\sigma \) (km s\(^{-1}\)) | \( W_{LSR} \pm 1\sigma \) (km s\(^{-1}\)) | \( R_m \) (kpc) | \( e \) | \( Z_{max} \) (kpc) | Age (Gyr) | \( P \) (per cent) | \( J_z \) (kpc km s\(^{-1}\)) | \( J_\perp \) (kpc km s\(^{-1}\)) |
|---------------|-----------------|------------------------------------------|------------------------------------------|------------------------------------------|-----------------|-----|-----------------|---------|-----------------|-----------------|-----------------|
| HIP 105888    | –84.3           | –23.9 ± 0.7                             | –122.4 ± 4.8                             | –40.0 ± 6.5                              | 5.42 ± 0.57     | 0.35 | 10.8±0.8       | 97 ± 0   | –825            | 338             |
| HIP 36710     | –70.8           | +45.8 ± 1.3                             | –107.3 ± 6.9                             | +45.3 ± 7.0                              | 5.82 ± 0.51     | 0.42 | –97 ± 1        | 965 ± 38 |
| HIP 77637     | –51.0           | –26.9 ± 1.2                             | –134.0 ± 17.7                            | +15.8 ± 6.1                              | 5.21 ± 0.63     | 0.14 | –96 ± 0        | 724 ± 131|
| G103–53       | +10.0           | +10.0 ± 1.8                             | –125.4 ± 19.1                            | –55.4 ± 9.6                              | 5.44 ± 0.58     | 0.54 | –96 ± 3        | 813 ± 476|
| G72–12        | –33.4           | –13.3 ± 6.7                             | –118.7 ± 15.0                            | –62.9 ± 12.7                             | 5.55 ± 0.65     | 0.65 | –96 ± 2        | 866 ± 538|
| G4–2          | +38.8           | –11.1 ± 1.2                             | –117.2 ± 19.8                            | –76.0 ± 8.1                              | 5.60 ± 0.54     | 0.90 | –95 ± 4        | 880 ± 650|
| HIP 53070     | +65.8           | –23.6 ± 0.71                            | –124.8 ± 4.8                             | +22.9 ± 2.1                              | 5.41 ± 0.59     | 0.19 | –95 ± 1        | 811 ± 194|
| G204–39       | –69.7           | +58.9 ± 11.5                            | –130.4 ± 12.0                            | +6.9 ± 10.7                              | 5.62 ± 0.44     | 0.95 | –95 ± 3        | 763 ± 399|
| G139–49       | –94.1           | –25.9 ± 5.5                             | –131.7 ± 11.8                            | –6.7 ± 1.9                               | 5.24 ± 0.62     | 0.06 | 95 ± 1         | 742 ± 57 |
| G241–7        | –113.6          | –45.5 ± 14.1                            | –134.1 ± 5.3                             | –20.4 ± 1.5                              | 5.34 ± 0.64     | 0.16 | 95 ± 0         | 729 ± 175|
| HIP 40613     | –112.5          | –31.6 ± 1.7                             | –139.0 ± 3.3                             | –32.7 ± 3.5                              | 5.21 ± 0.66     | 0.27 | 95 ± 1         | 692 ± 279|
| G42–34        | +36.9           | +8.4 ± 2.7                              | –126.5 ± 17.6                            | –7.1 ± 6.5                               | 5.37 ± 0.59     | 0.08 | 94 ± 6         | 799 ± 60 |
| HIP 36491     | –118.5          | –47.7 ± 1.8                             | –118.9 ± 6.1                             | +1.2 ± 2.6                               | 5.60 ± 0.57     | 0.01 | 91 ± 4         | 865 ± 10 |
| HIP 94931     | –121.4          | +65.9 ± 2.7                             | –120.7 ± 12.2                            | –79.2 ± 1.8                              | 5.70 ± 0.58     | 0.95 | 91 ± 1         | 845 ± 672|
| HIP 74033     | –59.8           | –111.7 ± 7.5                            | –132.7 ± 11.5                            | +42.3 ± 7.2                              | 5.83 ± 0.68     | 0.40 | 89 ± 5         | 738 ± 351|
| G5–1          | –22.4           | +44.8 ± 2.4                             | –125.7 ± 15.5                            | –85.7 ± 13.2                             | 5.56 ± 0.59     | 1.07 | 89 ± 8         | 810 ± 737|
| G102–44       | –29.2           | +73.6 ± 5.4                             | –130.5 ± 21.3                            | +8.1 ± 11.7                              | 5.68 ± 0.63     | 1.15 | 82 ± 14        | 769 ± 759|
| HIP 58253     | –29.3           | –62.5 ± 7.5                             | –106.2 ± 10.8                            | –3.4 ± 4.2                               | 5.89 ± 0.52     | 0.08 | 80 ± 16        | 96  ± 34 |

4 RESULTS AND DISCUSSION

4.1 Chemical signatures

Since their discovery (cf. Eggen 1957), various theories have been put forward to explain the substructures in phase space known variously as moving groups or stellar streams. The most prominent theories identify a stellar stream as either (a) a dissolved open cluster, (b) debris from an accreted satellite galaxy or (c) the result of dynamical perturbations within the Galaxy.

4.2 The streams

In establishing the correct explanation for a particular stream, the importance of the chemical signatures or chemical tagging of stream members has been recognized (Freeman & Bland-Hawthorn 2002; Bensby et al. 2007; De Silva et al. 2007; Williams et al. 2009) not only to pinpoint their origin but also to understand the formation and evolution of the disc.

Quantitative abundances of 20 elements have been extracted here for members of the two streams. There are three main groups of elements: iron peak (V, Cr, Mn, Fe, Ni, Co), α elements (O, Mg, Si, Ca, Ti) and heavy elements such as s-process (Ba, Nd) and r-process...
streams. Results shown in Fig. 8 and Table 2 show that stellar metallicities span a wide range for both streams. For the Arcturus stream, \([\text{Fe/H}]\) runs from \(-1.40\) to \(-0.37\). For the AF06 stream, the range is from \(-1.69\) to \(+0.22\) but the range is from \(-1.69\) to \(-0.17\) for those 15 members with a high probability of belonging to the thick disc. For strictly homogeneous populations such as open and globular clusters, the degree of chemical homogeneity is quite high, and it is about 0.05 dex (De Silva et al. 2006; Pancino et al. 2010) for a number of elements. In the case of \([\text{Fe/H}]\), dispersions are found to be in the range 0.02–0.1, and in some extreme cases dispersions are of the order of 0.2 dex (Paunzen et al. 2010). The wide range in metallicity clearly shows that the systems from which the stream members originated had a relatively long history with multiple episodes of star formation.

We have also inspected the sample for evidence of a subgroup with chemical homogeneity. Results shown in Figs 5–7 indicate that no such group exists in the Arcturus stream sample; however, in the stream AF06, we find a hint of clustering of stars at \([\text{Fe/H}] = -0.4\) dex. About 8 stars (out of total 26) show metallicity \([\text{Fe/H}] = -0.4\) within the dispersion of 0.04 dex. Does it mean that part of the sample stars originated from the disrupted cluster? Probably not, this may be a manifestation of the thick-disc metallicity distribution which peaks at about \(-0.6\) dex, and to some extent due to a smaller sample size. Thus, neither the Arcturus nor the AF06 stream, as shown by the metallicity distribution of the member stars of the two streams (see Fig. 8), is a dissolved open cluster. This conclusion about the Arcturus stream was also reached by Williams et al. (2009) who selected 134 stream members by selection criteria different from those used by Arifyanto & Fuchs (2006) and applied to stellar catalogues other than that compiled by Carney et al. (1994). Their analyses of high-resolution spectra led to a \([\text{Fe/H}]\) range similar to that quoted above (see also Navarro et al. 2004).

4.3 Are the streams chemically identical to thick-disc field stars?

Among thick-disc field stars in the solar neighbourhood, there is a strikingly very small dispersion in elemental abundance ratios, i.e. \([\text{X/Fe}]\) at a given \([\text{Fe/H}]\). Indeed, Reddy et al. (2006) found \([\text{X/Fe}]\) to be Gaussian-like with a dispersion \(\sigma\) of less than 0.10 dex for the most of the elements except for V, Y and Zr for which \(\sigma\) is slightly more than 0.1 dex. Furthermore, such dispersions were uncorrected for measurement uncertainties so the intrinsic or ‘cosmic’ dispersion must be very small.

In sharp contrast to the very similar \([\text{X/Fe}]\) ratios at a given \([\text{Fe/H}]\) for local field stars, element ratios reflecting different contributions from major processes of stellar nucleosynthesis do vary from one stellar system to another. For example, ratios in the Galactic bulge are not uniformly identical at a given \([\text{Fe/H}]\) to those among local...
Figure 5. The abundance plots of the elements O, Na, Mg, Al, Si and Ca for the Arcturus stream (left-hand column) and AF06 stream (right-hand column). The grey symbols represent the field thick-disc members from Reddy et al. (2006).

Figure 6. Same as Fig. 4 but for the elements Sc, Ti, V, Cr, Mn, Co and Ni.
thick- or thin-disc field stars. Similarly, ratios of $\alpha$ elements ($[\alpha/Fe]$) at a given [Fe/H] among stars of dwarf spheroidal galaxies differ appreciably from those of local stars and from one galaxy to another (Venn et al. 2004; Tolstoy, Hill & Tosi 2009; Kirby 2010). This has been illustrated in Fig. 9 where the ratio [$\alpha$/process/Fe] (mean of $\alpha$-process elements Mg, Si, Ca and Ti) is compared with that of the thick disc (Reddy et al. 2006) and a number of dwarf spheroidal galaxies for which data were taken from Venn et al. (2004) and Monaco et al. (2005).

Therefore, the chemical signatures or tags in the form of $[X/Fe]$ for those key elements from the major processes of nucleosynthesis may test some proposed origins for the streams. To address the question ‘Are these two streams chemically identical to thick-disc field stars?’, we show plots of $[X/Fe]$ versus [Fe/H] in Figs 5–7 with field stars from Reddy et al. (2006) shown by grey symbols, and the Arcturus and AF06 stream members shown as black filled circles. To quantify possible systematic offsets between the field thick disc and stream members, we compute mean values and dispersions for the Arcturus and AF06 streams over the [Fe/H] interval $-0.30$ to $-1.0$. Dispersions about the trends are a combination of both the cosmic scatter and errors associated with the model parameters. The values ($\sigma_{AF06}$, $\sigma_{Arcturus}$) are computed as the standard deviation of the residuals from straight line fits to abundance trends of $[X/Fe]$ against [Fe/H]. Similarly, $\sigma_{thick\ disc}$ for the thick-disc abundance trends of Reddy et al. (2006) are computed over the same interval. All results are provided in Table 7. In Fig. 10, we make a comparison of $\sigma_{thick\ disc}$ with those of the Arcturus and AF06 streams. Dispersion values about the abundance trends of the Arcturus stream show very good agreement with that of the thick disc within about 0.02. However, for the AF06 stream, in most cases, dispersions are lower by 0.01–0.03 compared to thick-disc dispersions. With the current limited sample it would be far fetching to attribute this to the different chemical evolution for the AF06 stream and hence the external origin to it. The mean abundances of the Arcturus and AF06 streams are quite similar, and the differences are within 0.05 dex except three elements (O, Cu, Eu) for which the difference is 0.06–0.07 dex. Dispersions about the trends for all the elements are

Figure 7. Same as Fig. 4 but for the elements Cu, Zn, Y, Ba, Ce, Nd and Eu.

Figure 8. The metallicity distribution of (a) the Arcturus stream, binsize = 0.25 dex, and (b) the AF06 stream, binsize = 0.3 dex.
Figure 9. The [α/Fe] versus [Fe/H] plot. Red triangles: Arcturus stream, blue squares: AF06 stream, cyan open circles: thick disc, magenta filled circles: dSph satellite galaxies (Draco, Sculptor, Sextans, Ursa Minor, Carina, Fornax, Leo I) from Venn et al. (2004), black crosses: Sgr dSph from Monaco et al. (2005) with [α/Fe] = (Mg/Fe)+[Ca/Fe]+[Ti/Fe]/3.

Table 7. Mean elemental abundance ratios and dispersions.

| Element | Arcturus Mean | Arcturus σ | AF06 Mean | AF06 σ | Thick disc Mean | Thick disc σ | σ_model |
|---------|--------------|------------|-----------|--------|-----------------|-------------|---------|
| [O/Fe]  | 0.54         | 0.13       | 0.48      | 0.08   | 0.60            | 0.12        | 0.07    |
| [Na/Fe] | 0.03         | 0.09       | 0.07      | 0.04   | 0.10            | 0.06        | 0.04    |
| [Mg/Fe] | 0.21         | 0.11       | 0.21      | 0.09   | 0.30            | 0.07        | 0.05    |
| [Al/Fe] | 0.18         | 0.04       | 0.21      | 0.03   | 0.26            | 0.08        | 0.04    |
| [Si/Fe] | 0.14         | 0.06       | 0.15      | 0.04   | 0.22            | 0.06        | 0.02    |
| [Ca/Fe] | 0.14         | 0.05       | 0.16      | 0.04   | 0.16            | 0.06        | 0.06    |
| [Sc/Fe] | 0.07         | 0.09       | 0.07      | 0.07   | 0.14            | 0.09        | 0.09    |
| [Ti/Fe] | 0.20         | 0.05       | 0.23      | 0.04   | 0.19            | 0.07        | 0.06    |
| [V/Fe]  | 0.07         | 0.08       | 0.11      | 0.06   | 0.11            | 0.08        | 0.07    |
| [Cr/Fe] | –0.13        | 0.03       | –0.07     | 0.04   | –0.03           | 0.04        | 0.06    |
| [Cu/Fe] | –0.01        | 0.05       | –0.03     | 0.08   | –               |            | 0.12    |
| [Zn/Fe] | –0.32        | 0.05       | –0.27     | 0.05   | –0.26           | 0.07        | 0.06    |
| [Ni/Fe] | –0.04        | 0.05       | 0.02      | 0.02   | 0.02            | 0.04        | 0.04    |
| [Co/Fe] | 0.10         | 0.07       | 0.09      | 0.05   | 0.10            | 0.05        | 0.05    |
| [Sc/Fe] | 0.01         | 0.08       | 0.08      | 0.08   | –0.02           | 0.07        | 0.07    |
| [Zn/Fe] | 0.22         | 0.09       | 0.17      | 0.07   | 0.12            | 0.06        | 0.07    |
| [Y/Fe]  | –0.03        | 0.08       | –0.02     | 0.08   | 0.00            | 0.11        | 0.09    |
| [Ba/Fe] | –0.15        | 0.06       | –0.13     | 0.08   | –0.14           | 0.09        | 0.13    |
| [Ce/Fe] | 0.06         | 0.15       | 0.08      | 0.11   | 0.06            | 0.13        | 0.16    |
| [Nd/Fe] | 0.22         | 0.14       | 0.19      | 0.14   | 0.20            | 0.16        | 0.19    |
| [Eu/Fe] | 0.29         | 0.15       | 0.22      | 0.13   | 0.36            | 0.12        | 0.12    |

Figure 10. The dispersions in [X/Fe] of the members of the Arcturus stream, the AF06 stream and the field thick-disc sample.

5 CONCLUSIONS

The outstanding results of our abundance analyses are that the subdwarfs comprising the Arcturus stream and AF06 stream identified as overdensities in phase space by Arifyanto & Fuchs (2006) have (i) a considerable spread in metallicity and (ii) relative abundance [X/Fe] identical to those of the Galactic thick disc. The metallicity spread excludes the hypothesis that either stream represents a dissolved open cluster. The high degree of similarity between [X/Fe] at a given [Fe/H] for these streams and the field stars of the thick disc greatly strains a proposal that these streams represent the tidal debris of an accreted satellite galaxy. By exclusion, the likely origin of these streams is that they are the product of dynamical interactions within the Galaxy.

However, chemical identity with the thick disc and the non-similarity of the chemistry of these streams with the satellite galaxies within the Local Group alone may not suffice to rule out the possibility of these streams being a result of disrupted satellites (Minchev et al. 2009; Gómez et al. 2012). It is still a matter of debate how perturbation can create streams with such a very high velocity drag and exhibit very tight abundance trends. It would be important to know from the models the extent of regions that get affected due to bar/spiral perturbations and their effect on the abundance trends of clumped stars in phase space. Astrometry from GAIA will provide unprecedented sample size as well as accuracy to map the Galaxy precisely which would decipher the Galaxy formation and evolution.

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