CHEMICALLY TAGGING THE HR 1614 MOVING GROUP

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ABSTRACT

We present abundances for a sample of F, G, and K dwarfs of the HR 1614 moving group based on high-resolution, high signal-to-noise ratio spectra from the Anglo-Australian Telescope UCLES instrument. Our sample includes stars from Feltzing and Holmberg, as well as from Eggen. Abundances were derived for Na, Mg, Al, Si, Ca, Mn, Fe, Ni, Zr, Ba, Ce, Nd, and Eu. The α, Fe, and Fe-peak element abundances show a bimodal distribution, with four stars having solar metallicities, while the remaining 14 stars are metal-rich, [Fe/H] ≥ 0.25 dex. However, the abundances of these two groups converge for the heavier n-capture elements. Based on their photometry and kinematics, three of the four deviating stars are likely nonmembers or binaries. Although one star cannot be excluded on these grounds, we do expect low-level contamination from field stars within the HR 1614 moving group’s range of magnitude, color, and space velocities. Disregarding these four stars, the abundance scatter across the group members for all elements is low. We find that there is an 80% probability that the intrinsic scatter does not exceed the following values: Fe, 0.01 dex; Na, 0.08 dex; Mg, 0.02 dex; Al, 0.06 dex; Si, 0.02 dex; Ca, 0.02 dex; Mn, 0.01 dex; Ni, 0.01 dex; Zr, 0.03 dex; Ba, 0.03 dex; Ce, 0.04 dex; Nd, 0.01 dex; and Eu, 0.02 dex. The homogeneity of the HR 1614 group in age and abundance suggests that it is the remnant of a dispersed star-forming event. Its kinematical coherence shows that such a dispersing system need not be significantly perturbed by external dynamical influences such as Galactic spiral structure or giant molecular clouds, at least over a period of 2 Gyr.

Key words: Galaxy: evolution — open clusters and associations: individual (HR 1614 moving group) — stars: abundances

Online material: machine-readable table

1. INTRODUCTION

The concept of moving groups was first introduced by Olin Eggen in the 1960s. Basically, the stars form from a common progenitor gas cloud. As the cluster disperses around the Galaxy, it stretches into a tubelike structure around the Galactic plane, and after several Galactic orbits it will dissolve into the Galactic background. If the Sun happens to be inside this tube, the member stars will appear all over the sky but may be identified as a group through their common space velocities. A moving group is therefore the in-between step from bound clusters to field stars.

For this reason, moving groups are an important class of objects for the purpose of testing the chemical tagging technique put forward by Freeman & Bland-Hawthorn (2002). In summary, the long-term goal of chemical tagging is to reassemble the ancient star-forming aggregates in the Galactic disk by studying their chemical signatures, in order to unravel the sequence of events involved in the dissipative formation of the disk. One of the fundamental requirements for the viability of chemical tagging is chemical homogeneity within individual disk clusters. Since most bound open clusters are believed to be chemically homogeneous (e.g., Hyades [De Silva et al. 2006] and Cr 261 [De Silva et al. 2007]), establishing homogeneity in unbound moving groups that retain some kinematical identity is the next step for the chemical tagging technique. The final step is to chemically identify groups that have no dynamical identity.

Although the existence of many stellar moving groups has been suggested, the reality of most is yet to be verified. In the past, due to the lack of accurate parallaxes, it has been difficult to reliably identify the stellar members of moving groups. This has now been partly overcome by the observations from the Hipparcos satellite. The presence of a moving group associated with the star HR 1614, first advocated by Eggen (1978a), was verified by Feltzing & Holmberg (2000) using the new Hipparcos parallaxes and recent radial velocities (RVs), and provides an extended sample of stellar members.

Eggen’s initial identification of the moving group came from studying a sample of stars within ±10 km s⁻¹ of the Galactic rotational velocity (V) of star HR 1614. He used the high excess in b − y as a membership criterion for his stars to obtain a color-magnitude diagram (CMD; Eggen 1978b, Fig. 1a) resembling that of an old open cluster. Based on a few spectroscopic studies and positions in the Mᵥ versus R − I CMD, Eggen (1978b) concluded that the majority of stars he classified as members were as metal-rich as the Hyades.

Follow-up studies by Smith (1983) using DDO photometry showed enhanced cyanogen bands in the Eggen (1978a) sample stars. The derived metallicity confirmed Eggen’s estimate of a high metallicity, but two giants found to have significantly low
metallicity cast doubt over Eggen’s $b - y$ membership criteria. Enforcing a strict criterion using $UBV$, DDO, and $b - y$, Smith (1983) showed that many of Eggen’s original candidates did not belong to the group. Eggen (1992), using the CN-enhancement, provided a second sample of main-sequence dwarfs with the same $V$-velocity restrictions as applied earlier. With the accurate parallax measurements made available from the Hipparcos mission, Eggen (1998) showed that the group membership for his HR 1614 sample (Eggen 1992) is supported by Hipparcos parallaxes. However, for two stars for which the discrepancies were large, Eggen (1998) suggested errors in the Hipparcos parallaxes.

Feltzing & Holmberg (2000, hereafter FH00) used Hipparcos parallaxes and RVs from several recent catalogs to perform an unbiased search for HR 1614 member stars over a large region of $U$-$V$ space. They conclude that there is a distinct stellar population of metal-rich stars centered at $U = 10$ km s$^{-1}$, $V = -60$ km s$^{-1}$ and tilted in the $U$-$V$ plane, which they associate with the HR 1614 moving group. Following simulations by Skuljan et al. (1997) and their own basic simulations, FH00 find the observed tilt in the $U$-$V$ plane to be a feature of a moving group. In contrast, the classical criteria used by Eggen (based on epicyclic theory) requires all member stars to lie at constant $V$ in the $U$-$V$ plane. FH00 state that such central clumping will only occur if the Sun is located very close to the center of the moving group, otherwise a tilt is to be expected.

With the past literature pointing toward its reality, the HR 1614 moving group is an attractive target for testing chemical tagging. The star cluster is quite distinctive due to its age of about 2 Gyr and high metallicity of $[Fe/H] = +0.25$. The stellar motions suggest that these stars formed in the inner disk. Dehnen (1999; see also Raboud et al. 1998) shows that there is an overdensity in the $U$-$V$ plane at $U = -20$ km s$^{-1}$ and $V = -45$ km s$^{-1}$ (earlier named the $U$-anomaly), which he associates with stars thrown out from the inner disk, an effect particularly strong close to the Galactic bars’ outer Lindblad resonance, where the Sun is located outside the outer Lindblad resonance. Its likely origin in the inner disk makes the HR 1614 moving group of particular interest. It gives us a unique chance to test chemical tagging precepts on stars that originated away from the solar circle. The HR 1614 moving group has never been subject to a high-resolution abundance study. We have now, for the first time, performed a detailed abundance analysis.

2. OBSERVATIONS

The original data were obtained at the 4 m Anglo-Australian Telescope, using UCLES, in 2003 August. Observations were done at two wavelength settings at the blue and red. The blue setting was centered at 4130 Å and covers the region from 3800 to 4700 Å, while the red setting was centered at 7040 Å, covering the spectral range from 5510 to 10200 Å. The 31.6 lines mm$^{-1}$ echelle grating was always used. The slit was opened to a width of 1.2$''$ on the sky, providing a resolving power of 48,000.

The observing routine included 10 bias frames and 5 quartz lamp exposures to provide data for flat-fielding, taken at the start of each night. A Th-Ar hollow cathode lamp spectra was taken before and after each stellar exposure. Two RV standards, one at the start and one at the end of each night, were also observed. The stellar exposures were taken in batches of at least three exposures per star, with each exposure typically around 200 s. All program stars have a total signal-to-noise ratio greater than 150 pixel$^{-1}$ at the central wavelengths.

The spectroscopic data were reduced using the IRAF packages IMRED, CCDRED, and ECHELLE. The preliminaries included biasing, flat-fielding, scattered-light removal, order extraction, wavelength calibration, and continuum fitting. Details of the final sample selected for abundance analysis are given in Table 1.

3. ABUNDANCE ANALYSIS

3.1. Model Atmospheres and Spectral Lines

The abundance analysis makes use of the latest version of the MOOG code (Sneden 1973) for LTE EW analysis and spectral syntheses. Interpolated Kurucz model atmospheres based on the ATLAS9 code (Castelli et al. 1997) with no convective overshoot were used throughout this study.

### Table 1

| HIP   | HD   | R.A.   | Decl. | $V$   | $B - V$ | $V - K^a$ | Source$^b$ |
|-------|------|--------|-------|-------|--------|----------|------------|
| 23311 | 32147| 05 00 48.68 | −05 45 03.5 | 6.22 | 1.05 | 2.51 | E, FH |
| 110996| 213042| 22 29 15.23 | −30 01 06.3 | 7.65 | 1.08 | 2.53 | E |
| 26834 | 37986| 05 41 53.54 | −15 37 48.9 | 7.36 | 0.80 | 1.73 | FH |
| 109378| 210277| 22 09 29.82 | −07 32 51.2 | 6.54 | 0.77 | 1.74 | E, FH |
| 22940 | 31452| 04 56 10.61 | +02 56 03.1 | 8.43 | 0.84 | 1.96 | FH |
| 116554| 222013| 23 37 15.31 | −45 28 30.8 | 9.22 | 0.81 | 1.88 | E, FH |
| 10599 | 13997| 02 16 27.60 | +12 22 49.1 | 7.99 | 0.79 | 1.76 | E, FH |
| 110843| 212708| 22 27 24.38 | −49 21 54.5 | 7.48 | 0.73 | 1.68 | FH |
| 17960 | 24040| 03 50 22.90 | +17 28 37.1 | 7.50 | 0.65 | 1.53 | FH |
| 22336 | 30562| 04 48 36.20 | −05 40 24.4 | 5.77 | 0.63 | 1.46 | E |
| 102393| 197623| 20 44 57.03 | +00 17 31.7 | 7.55 | 0.66 | 1.52 | FH |
| 11575 | 15590| 02 29 11.90 | −42 04 31.1 | 7.98 | 0.65 | 1.47 | E |
| 9353  | 12235| 02 00 09.16 | +03 05 49.2 | 5.89 | 0.61 | 1.40 | E, FH |
| 102010 | 196800| 20 40 23.23 | −24 07 04.9 | 7.21 | 0.61 | 1.42 | FH |
| 13513 | 18168| 02 54 02.78 | −35 54 16.8 | 8.23 | 0.93 | 2.36 | FH |
| 6762  | 8828 | 01 27 01.55 | −00 09 27.3 | 7.96 | 0.74 | 1.80 | E |
| 116970 | 22655| 23 42 42.22 | −41 14 51.3 | 9.57 | 0.76 | 1.74 | E |
| 25840 | 36379| 05 30 59.85 | −10 04 49.1 | 6.94 | 0.56 | 1.39 | E |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ $K$ magnitudes from 2MASS.

$^b$ FH, Feltzing & Holmberg (2000); E, Eggen (1998).
Now we focus on the lines of Na, Mg, Al, Si, Ca, Mn, Ni, Fe, Zr, Ba, Ce, Nd, and Eu. A full line list is given in Table 2, as well as EWs of the reference star. The $gf$ values for the detected lines of Na, Mg, Al, Si, Ca, Ni, and Zr were obtained from a combination of lines from Allende Prieto et al. (2004), Young et al. (2005), Reddy et al. (2003), and Paulson et al. (2003). For Mn, the $gf$ values were taken from Prochaska & McWilliam (2000) and include the effects of hyperfine splitting. The main sources of the Fe I line data are the laboratory measurements by the Oxford group (Blackwell et al. 1979a, 1979b, 1995, and references therein). This was supplemented by additional lines from Reddy et al. (2003). For Fe II we adopt the $gf$ values from Biemont et al. (1991), Paulson et al. (2003), and Allende Prieto et al. (2002). The only measurable Zr line data were obtained via the Vienna Atomic Line Database\(^2\) (VALD; Kupka et al. 2000, 1999; Ryabchikova et al. 1997; Piskunov et al. 1995) from the Bell heavy database (Kurucz 1995). Ba $gf$ values were adopted from Prochaska et al. (2000), as well as Allende Prieto et al. (2004). The Ce $gf$ values were obtained from the Database on Rare Earths At Mons University\(^3\) (DREAM; Biemont et al. 1999). The $gf$ values for Nd were taken from Den Hartog et al. (2003), and finally, the Eu $gf$ values were taken from Lawler et al. (2001), and we account for hyperfine splitting and isotopic shifts assuming a solar isotopic mix.

3.2 Stellar Parameters

Initially, $T_{\text{eff}}$ was estimated using the color-temperature relations of Alonso et al. (1996), equations (7) and (8), using $V - K$ values, where the $K$ magnitudes were obtained from the Two Micron All Sky Survey (2MASS) and $[\text{Fe/H}] = +0.2$ was adopted. These temperature estimates were used as an initial guess when deriving spectroscopic temperatures. An estimate of log $g$ was then obtained using the distances (from Hipparcos parallaxes), bolometric corrections, and stellar mass from Bertelli et al. (1994) isochrones. The best-fitting isochrone was found to be of age $\approx 2$ Gyr, consistent with the estimate obtained by FH00. Figure 1 shows our sample of stars overlaid with several isochrones for $Z = 0.05$.

Next we derived the stellar parameters based on spectroscopy. We computed abundances for all Fe I and Fe II lines based on the measured EW. The EWs were measured by fitting a Gaussian profile to each line using the interactive {	exttt{splot}} function in IRAF. The $T_{\text{eff}}$ was derived by forcing the Fe I abundances to be independent of excitation potential, i.e., excitation equilibrium. Microturbulence was derived from the condition that Fe I lines

\(^{2}\) See http://ams.astro.univie.ac.at/vald/

\(^{3}\) See http://w3.unihb.ac.be/~astro/dream.shtml.
show no abundance trend with EW. The log $g$ value was derived via ionization equilibrium, i.e., the abundance from Fe $i$ equals Fe $ii$. The photometric estimates of $T_{\text{eff}}$ and log $g$ were used as the initial guess model and iterated until a self-consistent set of model parameters were obtained. The spectroscopic estimates of $T_{\text{eff}}$ are hotter than the photometric estimates on average by 150 K. For our abundance analysis we adopt the spectroscopic stellar parameters. Table 3 lists the adopted parameters.

### 3.3. Elemental Abundances

Depending on the degree of blending of the spectral lines, abundances were derived either by EW measurements or by spectral synthesis. The EW measurements were used for abundance determinations for all elements, except the heavy elements from Ba to Eu, which required full spectral synthesis.

![Bertelli Isochrones](image)

Fig. 1.—Sample stars overlaid with Bertelli et al. (1994) isochrones. The best-fitting isochrone of $\approx$2 Gyr is highlighted. Note that all isochrones are for $Z = 0.05$.

TABLE 3

| HIP     | Mass ($M_{\odot}$) | $M_{\text{bol}}$ | $T_{\text{eff}}$ (K) | log $g$ (cm s$^{-2}$) | $\xi$ (km s$^{-1}$) |
|---------|--------------------|------------------|----------------------|----------------------|------------------|
| 23311   | 0.80               | 6.34             | 4850                 | 4.4                  | 0.8              |
| 110996  | 0.78               | 6.34             | 4800                 | 4.3                  | 0.8              |
| 26834   | 0.95               | 5.33             | 5500                 | 4.3                  | 0.7              |
| 109378  | 0.97               | 5.25             | 5500                 | 4.3                  | 0.7              |
| 22940   | 0.93               | 5.50             | 5250                 | 4.5                  | 0.4              |
| 116554  | 0.92               | 5.50             | 5400                 | 4.7                  | 0.6              |
| 10599   | 0.95               | 5.33             | 5450                 | 4.5                  | 1.0              |
| 110843  | 1.00               | 5.00             | 5600                 | 4.3                  | 1.1              |
| 17960   | 1.12               | 4.32             | 5800                 | 4.4                  | 1.1              |
| 22336   | 1.25               | 3.70             | 5900                 | 4.4                  | 1.3              |
| 102393  | 1.20               | 3.80             | 5900                 | 4.4                  | 1.1              |
| 11575   | 1.30               | 3.20             | 5900                 | 4.1                  | 1.2              |
| 9355    | 1.30               | 3.45             | 6000                 | 4.2                  | 1.2              |
| 102018  | 1.20               | 4.14             | 6000                 | 4.4                  | 1.2              |
| 13513   | 0.87               | 5.90             | 5050                 | 4.5                  | 1.1              |
| 6762    | 0.95               | 5.17             | 5400                 | 4.6                  | 0.9              |
| 116970  | 0.97               | 5.17             | 5500                 | 4.7                  | 0.9              |
| 25840   | 1.25               | 3.85             | 6150                 | 4.5                  | 1.2              |

In our initial analysis, we derived absolute abundances, but for the purposes of testing chemical tagging we decided to use differential abundances, as these were found to have smaller systematic errors. The final differential abundances $\Delta [X/H]$ were derived by subtracting the absolute abundance of each individual line of the reference star HR 1614 from the same line in the sample stars and then taking the mean of the differences for each element. By using such a line-by-line differential technique we can identify and remove any problematic lines, reducing the errors due to the uncertainty in the line data, hence minimizing the star-to-star scatter. The differential Fe abundance $\Delta [\text{Fe/H}]$ is plotted in Figure 2. The differential abundances for all elements lighter than Fe are plotted in Figure 3, and those heavier than Fe are plotted in Figure 4. Note that the zero level in these plots does not correspond to the solar metallicity, as these are plots of the differential abundances relative to HR 1614. Also, note that four stars (HIP 13513, HIP 6762, HIP 25840, and HIP 116970) were found to have solar-level abundances for all elements except for the heavier $n$-capture elements. These stars are identified in the plots with different symbols. We discuss our results and these deviating stars in detail in § 5.2.

### 3.4. Error Analysis

The main sources of error in the present study are those of EW measurements, continuum placement, and stellar parameters. Because we are only interested in the differential abundances, external errors, such as uncertainties in the line data and model atmospheres, are the least sources of error. The number of lines used to calculate the final abundances also contributed to the total uncertainty for each element. The error in EWs was estimated by repeated measurements of each line. The measurement errors for the synthesized abundances were derived by changing the abundance until there was a clear visible deviation from the best fit. The errors in the
stellar parameters were estimated to be $\delta T_{\text{eff}} = 50$ K, $\delta \log g = 0.1$ cm s$^{-2}$, and $\delta$ = 0.1 km s$^{-1}$ based on our spectroscopic derivation. Table 5 summarizes the abundance sensitivities to each stellar parameter and methods of derivation for two stars at either end of the temperature range. Typical values of the final error are as follows: Fe, 0.05 dex; Na, 0.07 dex; Mg, 0.07 dex; Al, 0.07 dex; Si, 0.05 dex; Ca, 0.07 dex; Mn, 0.04 dex; Ni, 0.06 dex; Zr, 0.07 dex; Ba, 0.05 dex; Ce, 0.03 dex; Nd, 0.03 dex; and Eu, 0.03 dex.

The four stars that show solar-level metallicities in the lighter elements were reassessed to check whether the stellar parameters or other systematic parameters were at fault. However, this was not found to be the case, with large changes in the model parameters ($\delta T_{\text{eff}} \geq 300$ K, $\delta \log g \geq 2$, and $\delta$ $\geq 1$) needed to bring these star’s abundances in line with the other enriched stars. In conclusion, we find that systematic error is unlikely to explain the behavior of these four stars.

4. DYNAMICAL ANALYSIS

4.1. Membership Criteria

While open cluster members are easily determined from RVs with errors of less than a few kilometers per second, moving group membership is based on $U/VW$ space motion, but the exact criteria for selecting members remain somewhat uncertain.

Eggen’s method of isolating moving group members required all member stars to have the same $V$-velocity, i.e., in the direction of the Galactic rotation. In the epicycle approximation, as a star orbits around the Galaxy it travels on an epicycle about the circular guiding center of its Galactic orbit. If member stars, which would have originated from the one location, are now in the solar neighborhood, within the observable horizon, then this limits their guiding center radii to be very close to that of the Sun. Those member stars with longer and shorter guiding center radii would be either ahead or lag behind the Sun and therefore not be within a small locally defined volume. This means that HR 1614 group member stars located within a small volume should have a similar $V$-velocity. Any scatter in $V$ would reflect the scatter in the orbital radii. This variation cannot be large for stars within a small volume.

Work by FH00 and Skuljan et al. (1997) shows that such a clump in the $U-V$ space is not necessary for all members of the moving group. Their modeling shows that a small $\text{tilt}$ in the $U-V$ space is the dynamical signature of the moving group. This seems to be in contradiction to the above mentioned concept and is primarily due to the limitations of the epicyclic approximation,

Fig. 3.—Differential abundances relative to HR 1614 for elements up to Mn. The symbols are the same as those for Fig. 2. The bimodality seen in Fig. 2 is clearly present in these elements as well.
Fig. 4.—Differential abundances relative to HR 1614 for elements heavier than Fe. The symbols are the same as those for Fig. 2. While a clear bimodality is observed for Ni and Zr, the two groups tend to converge for the heavier s- and r-process elements.

| HIP ID     | Na  | Mg  | Al  | Si  | Ca  | Mn  | Fe  | Ni  | Zr  | Ba  | Ce  | Nd  | Eu  |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 23311      | 6.56| 7.86| 6.77| 7.78| 6.65| 5.79| 7.77| 6.63| 2.72| 2.52| 1.75| 1.58| 0.74|
| 110996     | 6.61| 7.83| 6.73| 7.77| 6.67| 5.79| 7.75| 6.57| 2.65| 2.51| 1.68| 1.53| 0.71|
| 26834      | 6.62| 7.98| 6.72| 7.90| 6.71| 5.82| 7.83| 6.69| 2.77| 2.67| 1.74| 1.56| 0.71|
| 109378     | 6.50| 7.92| 6.65| 7.83| 6.60| 5.72| 7.76| 6.55| 2.77| 2.61| 1.73| 1.56| 0.76|
| 22940      | 6.41| 7.87| 6.60| 7.79| 6.60| 5.76| 7.75| 6.63| 2.94| 2.59| 1.73| 1.58| 0.73|
| 116554     | 6.35| 7.78| 6.52| 7.77| 6.55| 5.73| 7.75| 6.54| 2.73| 2.56| 1.73| 1.62| 0.71|
| 10599      | 6.54| 7.82| 6.68| 7.88| 6.59| 5.73| 7.77| 6.64| 2.83| 2.52| 1.72| 1.57| 0.68|
| 110843     | 6.55| 7.84| 6.65| 7.83| 6.59| 5.76| 7.79| 6.58| 2.73| 2.51| 1.71| 1.55| 0.71|
| 179690     | 6.49| 7.87| 6.64| 7.78| 6.58| 5.72| 7.72| 6.59| 2.72| 2.55| 1.75| 1.56| 0.74|
| 22336      | 6.48| 7.78| 6.59| 7.83| 6.56| 5.74| 7.76| 6.57| 2.77| 2.62| 1.73| 1.56| 0.73|
| 102393     | 6.57| 7.80| 6.64| 7.88| 6.61| 5.76| 7.82| 6.63| 2.79| 2.60| 1.74| 1.53| 0.76|
| 11575      | 6.58| 7.80| 6.57| 7.81| 6.55| 5.73| 7.77| 6.56| 2.75| 2.60| 1.68| 1.56| 0.76|
| 9353       | 6.61| 7.76| 6.61| 7.87| 6.57| 5.74| 7.73| 6.57| 2.72| 2.53| 1.67| 1.56| 0.74|
| 102018     | 6.51| 7.76| 6.51| 7.76| 6.59| 5.73| 7.72| 6.53| 2.73| 2.51| 1.64| 1.55| 0.78|
| 13513      | 6.17| 7.61| 6.34| 7.59| 6.38| 5.39| 7.55| 6.31| 2.44| 2.33| 1.55| 1.43| 0.61|
| 6762       | 6.06| 7.47| 6.24| 7.53| 6.25| 5.32| 7.47| 6.21| 2.51| 2.41| 1.61| 1.41| 0.61|
| 116970     | 6.20| 7.63| 6.27| 7.61| 6.38| 5.38| 7.55| 6.32| 2.50| 2.46| 1.67| 1.44| 0.65|
| 25840      | 6.16| 7.61| 6.24| 7.47| 6.27| 5.36| 7.44| 6.21| 2.51| 2.42| 1.59| 1.42| 0.65|
RVs were determined by Fourier transform cross-correlation of template spectra with observed spectra, making use of the packages RVSAO and XCSAO (Kurtz & Mink 1998; Kurtz et al. 1992), which are run under IRAF. From the available spectra, RVs were estimated using the blue region from 4200 to 4400 Å, which are run under IRAF. From the available spectra, RVs were determined by Fourier transform cross-correlation of the observed echelle spectra has interorder gaps in the red region, while the high-noise regions are removed. The sample selected for our chemical analysis includes stars selected from Eggen (via the Y-clump criteria), as well as from the FH00 sample (selected via the tilted criteria). As establishing accurate membership is a key component of our study, obtaining reliable velocity information is essential. While some velocity information is available from the FH00 sample (selected via the tilted criteria), as well as from the FH00 sample (selected via the tilted criteria), we have decided to undertake our own measurements in order to obtain a consistent set of velocities.

### 4.2. Radial Velocities

RVs were determined by Fourier transform cross-correlation of template spectra with observed spectra, making use of the packages RVSAO and XCSAO (Kurtz & Mink 1998; Kurtz et al. 1992), which are run under IRAF. From the available spectra, RVs were estimated using the blue region from 4200 to 4400 Å, which are run under IRAF. From the available spectra, RVs were determined by Fourier transform cross-correlation of the observed echelle spectra has interorder gaps in the red region, while the high-noise regions are removed. The sample selected for our chemical analysis includes stars selected from Eggen (via the Y-clump criteria), as well as from the FH00 sample (selected via the tilted criteria). As establishing accurate membership is a key component of our study, obtaining reliable velocity information is essential. While some velocity information is available from the FH00 sample (selected via the tilted criteria), we have decided to undertake our own measurements in order to obtain a consistent set of velocities.

#### TABLE 5

**Abundance Sensitivities**

| Model Parameter | Na  | Mg  | Al  | Si  | Ca  | Mn  | Fe  | Ni  | Zr  | Ba  | Ce  | Nd  | Eu  |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| HR 1614 (T\(_\text{eff} = 4850\) K) |     |     |     |     |     |     |     |     |     |     |     |     |     |
| T\(_\text{eff} \pm 50\) | ±0.04 | ±0.01 | ±0.03 | ±0.02 | ±0.03 | 0.00 | ±0.02 | ±0.01 | ±0.01 | ±0.01 | ±0.01 | ±0.01 | ±0.01 |
| log g \pm 0.1 | ±0.05 | ±0.02 | ±0.04 | ±0.01 | ±0.04 | 0.00 | ±0.01 | ±0.01 | ±0.01 | ±0.01 | ±0.01 | ±0.01 | ±0.01 |
| ξ \pm 0.1 | ±0.01 | ±0.02 | ±0.02 | ±0.01 | ±0.04 | ±0.02 | ±0.04 | ±0.03 | ±0.05 | ±0.05 | ±0.01 | ±0.02 | 0.00 |
| Δ EW/synth | ±0.03 | ±0.06 | ±0.05 | ±0.04 | ±0.03 | ±0.03 | ±0.03 | ±0.02 | ±0.02 | ±0.02 | ±0.02 | ±0.02 | ±0.02 |
| HIP 9353 (T\(_\text{eff} = 6000\) K) |     |     |     |     |     |     |     |     |     |     |     |     |     |
| T\(_\text{eff} \pm 50\) | ±0.02 | ±0.02 | ±0.02 | ±0.01 | ±0.02 | ±0.01 | ±0.04 | ±0.01 | 0.00 | ±0.01 | ±0.01 | ±0.01 | ±0.01 |
| log g \pm 0.1 | ±0.02 | ±0.01 | ±0.01 | 0.00 | ±0.01 | 0.00 | ±0.01 | ±0.01 | ±0.01 | ±0.01 | ±0.01 | ±0.01 | ±0.01 |
| ξ \pm 0.1 | ±0.02 | ±0.02 | ±0.01 | ±0.03 | ±0.04 | ±0.02 | ±0.03 | ±0.04 | ±0.05 | 0.00 | 0.00 | ±0.01 | ±0.01 |
| Δ EW/synth | ±0.04 | ±0.05 | ±0.06 | ±0.04 | ±0.02 | ±0.03 | ±0.01 | ±0.04 | ±0.02 | ±0.02 | ±0.02 | ±0.02 | ±0.02 |

### TABLE 6

**Radial Velocities**

| HIP ID | This Study (km s\(^{-1}\)) | N04 (km s\(^{-1}\)) | FH00 Sources\(^\text{a}\) (km s\(^{-1}\)) |
|--------|--------------------------|-------------------|----------------------------------|
| 26331 | 21.6                      | 21.0              | 27.0                             |
| 110996| 5.3                       | 4.8               | 7.4                              |
| 26834 | 59.1                      | ...               | 67.0                             |
| 109378| −21.3                     | ...               | −24.1                            |
| 22940 | 15.2                      | ...               | 14.3                             |
| 116554| −16.5                     | −15.1             | −2.6                             |
| 10599 | −21.5                     | −21.3             | −23.6                            |
| 110843| 4.7                       | 4.9               | −7.3                             |
| 17960 | −10.1                     | ...               | −7.6                             |
| 22336 | 76.7                      | 77.0              | 78.6                             |
| 102393| −69.2                     | ...               | −71.0                            |
| 11575 | 37.0                      | 36.9              | 36.8                             |
| 9353  | −18.1                     | −18.5             | −18.4                            |
| 102018| −63.5                     | −63.8             | −61.2                            |
| 13513 | 3.5/−46.9                 | 4.0               | 3.0                              |
| 6762  | 13.7                      | 13.2              | 3.5                              |
| 116970| 27.7                      | ...               | 26.9                             |
| 25840 | 22.9                      | 22.8              | ...                              |

* Turon et al. (1993); Barbier-Brossat & Figon (2000); Grenier et al. (1999).

### TABLE 7

**Radial Velocities of RV Standards**

| RV Standards | This Study (km s\(^{-1}\)) | Maurice et al. (1984) (km s\(^{-1}\)) |
|--------------|-----------------------------|--------------------------------------|
| HD 6677      | 19.7                        | 19.6                                 |
| CPD 432527   | 20.0                        | 19.1                                 |
HIP 13513, our results agree better with the measurements by Nordström et al. (2004), where the average difference is about 0.4 km s\(^{-1}\), than with FH00, where the average difference is about 4 km s\(^{-1}\), although they agree within the given error bars of the FH00 sources. Our RVs for all sample stars and RV standards, with corresponding literature values, are given in Tables 6 and 7, respectively. Our errors as calculated by XCSAO are less than 1 km s\(^{-1}\).

### 4.3. UVW Velocities

Using the above computed RVs, and proper motions and parallaxes from Hipparcos, we calculated UVW space velocities, making use of the conversion code obtained from M. Williams (2006, private communication). The resulting velocities are with respect to the LSR, adopting the standard solar motion of \(U = 10\) km s\(^{-1}\), \(V = 5\) km s\(^{-1}\), and \(W = 7\) km s\(^{-1}\) (Dehnen & Binney 1998). Table 8 lists our derived velocities, as well as those from FH00. Overall, our velocities are in good agreement with FH00, with mean differences of about 1.7, 0.6, and 2.1 km s\(^{-1}\) in \(U\), \(V\), and \(W\), respectively.

Figure 5 shows the position of our stars in the \(U-V\) plane using the new velocities obtained in this study. The presence of a slight slope seems to support the tilted membership criterion argued by FH00. By fitting a least-squares regression line of the form \(V = a + b U\), we find \(a = -55.06\) and \(b = 0.18\). The significance of this slope depends on the measurement errors. Taking into account errors in RVs and Hipparcos parallaxes, our typical errors are \(<2\) km s\(^{-1}\) for \(U\), \(<10\) km s\(^{-1}\) for \(V\), and \(<5\) km s\(^{-1}\) for \(W\). Considering the uncertainty in \(V\)-velocity to be on average 6 km s\(^{-1}\) and disregarding the small uncertainty in \(U\)-velocity, we derive the uncertainty in the gradient \((b)\) of the best-fitting line to be \(\pm 0.05\). Therefore, the slight tilt in Figure 5 is marginally significant and lends support to FH00’s tilted membership criterion in the \(U-V\) plane. We discuss the issue of membership in detail in § 5.2.

### 5. Discussion

#### 5.1. Chemical Homogeneity

We have studied a total of 18 stars that were thought to be members following the kinematical criteria of FH00 and Eggen (1998). Out of this sample, four stars are found to deviate from the cluster mean in all elements except the \(n\)-capture elements. Disregarding these four stars for the moment, our abundance analysis demonstrates that the moving group is chemically enriched, with mean \([\text{Fe}/\text{H}] = 0.25\), adopting a solar value of 7.52 (Sneden et al. 1992), comparable to the result obtained by FH00 using photometric techniques given the estimated errors. Table 9 summarizes the cluster mean abundances for all studied elements and the rms scatter, both including and excluding the four deviating stars.

Disregarding the four deviating stars, Table 10 summarizes the intrinsic star-to-star scatter \(\sigma_{\text{int}}\) within the HR 1614 moving group. By examining the uncertainties in our abundance error analysis we also calculate the uncertainty of the estimated intrinsic scatter. Assuming that our abundance measurements follow a Gaussian distribution, we estimate the confidence interval for the uncertainty

![Figure 5](image-url)
intrinsic scatter. Taking into account the sampling error in the observed scatter and a 10% uncertainty in our adopted measurement errors, we find that the stated uncertainty limits in Table 10 are approximately 80% confidence limits for \( \sigma_{\text{int}} \). Furthermore, based on a \( \chi^2 \) analysis we derive the probability of finding the observed scatter given the measurement errors and zero intrinsic scatter. Figure 6 plots this probability for the different elements.

The above analysis does not include the four deviating stars. Since our aim is to obtain an estimate of the level of chemical homogeneity in all the moving group members, it is important for us to determine the nature of the deviating stars. If they are found to be nonmembers or peculiar in some way (including binary systems, in which the original birth abundance level may have been modified), then the level of homogeneity observed is indeed very high. If there is a reason to include the deviating stars, the mean level of homogeneity will rise to well over 0.1 dex. However, given the clear bimodality of the results, it seems likely that these stars have a different origin.

### 5.2. Stellar Membership

Following the bimodal nature of the chemical analysis results, one immediately wonders whether the deviating stars are nonmembers of the group. This is much harder to establish for a moving group than for a bound cluster system. Putting aside any chemical knowledge, space velocities and color-magnitude criteria are the key to establishing membership. If we are to use the tilted criteria of FH00, we see in Figure 5 that the deviating star HIP 25840 lies outside their tilted boundary. Also adopting Eu's criteria, this star is below the \( V \)-velocity clump. This velocity deviation would be sufficient to class this star as a nonmember of the moving group. So we feel justified in excluding this star from further discussion.

Our RV measurements found HIP 13513 to have a variable RV. The red and blue spectra were observed a few weeks apart, and the derived RVs were greatly different. This prompted a search for established binarity for these four deviating stars. Searching the Hipparcos catalog confirmed that stars HIP 13513 and HIP 6762 were binary stars. This would be a valid reason for us to discard these stars in our search for chemical homogeneity.

The stars' position in the CMD also helps identify possible nonmembers. Figure 7 shows the CMD of our sample stars, with the deviating stars marked with their respective symbols. HIP 13513 and HIP 6762 happen to lie on the main sequence; however, given our earlier discussion on its variability, its positioning on the CMD is likely to be by chance.

Our investigation fails to identify star HIP 116970 as a nonmember or peculiar in any way. It satisfies both FH00 and Eggen's velocity criteria, lies in the middle of the main sequence in the CMD, and has no variability or binary observed in other surveys. A plausible scenario is that this star is a field star unassociated with the HR 1614 moving group, but lies within the group's kinematical and photometric interval simply by chance. Out of our total sample of 18 stars, we discover only one star (if we disregard the other three stars, assuming they are "confirmed" nonmembers or binaries) to be contaminating the HR 1614 moving group. We are not aware of any literature calculations of the expected rate of contamination of moving groups.

In an attempt to estimate possible contamination, we obtained a synthetic stellar population based on Besancon models (Robin et al. 2003), with stars limited to the magnitude, color, and velocity criteria of the HR 1614 group stars. The stellar sample was restricted to stars lying along the main sequence in Figure 7 with \( 4 < M_V < 7, 0.5 < B - V < 1.2 \), and a width of \( \Delta(B - V) = \pm 0.2 \). The velocity space was restricted to stars lying along the tilt in

### TABLE 9

**MEAN ABUNDANCES AND SCATTER**

| Element | \( (\text{Members}) \) | \( \sigma \) | \( (\text{All Stars}) \) | \( \sigma \) |
|---------|-------------------------|-------------|--------------------------|-------------|
| Fe      | 7.77                    | 0.033       | 7.71                     | 0.117       |
| Na      | 6.53                    | 0.078       | 6.44                     | 0.178       |
| Mg      | 7.83                    | 0.063       | 7.77                     | 0.125       |
| Al      | 6.63                    | 0.075       | 6.55                     | 0.169       |
| Si      | 7.82                    | 0.047       | 7.76                     | 0.126       |
| Ca      | 6.60                    | 0.046       | 6.53                     | 0.130       |
| Mn      | 5.75                    | 0.030       | 5.67                     | 0.169       |
| Ni      | 6.59                    | 0.046       | 6.52                     | 0.148       |
| Zr      | 2.76                    | 0.067       | 2.70                     | 0.129       |
| Ba      | 2.56                    | 0.051       | 2.52                     | 0.085       |
| Ce      | 1.71                    | 0.034       | 1.69                     | 0.059       |
| Nd      | 1.56                    | 0.022       | 1.53                     | 0.062       |
| Eu      | 0.73                    | 0.027       | 0.71                     | 0.051       |

**TABLE 10**

**INTRINSIC SCATTER**

| Element | \( \sigma_{\text{int}} \) | Uncertainty |
|---------|---------------------------|-------------|
| Fe      | 0.000                     | 0.010       |
| Na      | 0.034                     | 0.050       |
| Mg      | 0.000                     | 0.020       |
| Al      | 0.017                     | 0.040       |
| Si      | 0.000                     | 0.017       |
| Ca      | 0.000                     | 0.020       |
| Mn      | 0.000                     | 0.010       |
| Ni      | 0.009                     | 0.010       |
| Zr      | 0.000                     | 0.030       |
| Ba      | 0.000                     | 0.025       |
| Ce      | 0.016                     | 0.020       |
| Nd      | 0.000                     | 0.010       |
| Eu      | 0.000                     | 0.018       |
The clear bimodal abundance pattern seen for the $\alpha$, Fe, Fe-peak, and light $s$-process elements is interesting. As discussed above, of the four deviating stars, only one cannot be classed as a nonmember, a binary, or an otherwise peculiar star based on its kinematics or photometric properties. Although we are not aware of any prior calculation of the expected rate of contamination from field stars that are not part of the group, our simple estimate based on Besancon stellar population models shows that some contamination (15%) is to be expected. It is likely that there are other such contaminating stars in this (and other) moving groups that are not yet identified due to the lack of detailed chemical information. Our results are a clear demonstration of the necessity and importance of obtaining detailed chemical information, and that chemical probing is essential to see the true story behind the history of any stellar stream in the Galactic disk.

Our results support the conclusion of Feltzing & Holmberg (2000) regarding the reality of the HR 1614 moving group. Several authors have argued that at least some moving stellar groups are not the dispersed remnants of star-forming events, but rather are dynamical in origin, resulting from the dynamical effects of the Galactic bar or spiral structure (e.g., Dehnen 1999; De Simone et al. 2004; Famaey et al. 2005). We would not expect such dynamical groups to be coeval and chemically homogeneous. The homogeneity of the HR 1614 group in age and abundance supports the view that this group is indeed the remnant of a dispersed star-forming event. Its kinematical coherence shows that such a dispersing system need not be significantly perturbed by external dynamical influences such as Galactic spiral structure or giant molecular clouds, at least over a period of order 2 Gyr.

Finally, the high level of chemical homogeneity observed across the confirmed HR 1614 moving group members is a major step forward for chemical tagging. Earlier, De Silva et al. (2006) reported chemical homogeneity in the Hyades, which is a younger bound star cluster. Our study on the very old open cluster Cr 261 (De Silva et al. 2007) also shows similar levels of homogeneity, and in it we further explore the implications of our combined results on chemical tagging. Here we have shown that an unbound, intermediate-aged cluster is also chemically identifiable. Although much work is yet to be done, the chemical tagging technique and the prospect of unravelling the dissipative history of the Galactic disk now seems viable.

5.3. Implications for Chemical Tagging

The clear bimodal abundance pattern seen for the $\alpha$, Fe, Fe-peak, and light $s$-process elements is interesting. As discussed above, of the four deviating stars, only one cannot be classed as a nonmember, a binary, or an otherwise peculiar star based on its kinematics or photometric properties. Although we are not aware of any prior calculation of the expected rate of contamination from field stars that are not part of the group, our simple estimate based on Besancon stellar population models shows that some contamination (15%) is to be expected. It is likely that there are other such contaminating stars in this (and other) moving groups that are not yet identified due to the lack of detailed chemical information. Our results are a clear demonstration of the necessity and importance of obtaining detailed chemical information, and that chemical probing is essential to see the true story behind the history of any stellar stream in the Galactic disk.

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