Comoving stars in the Gaia era

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Abstract

Comoving stars range from wide binaries to dense open clusters, and provide a unique window into the Milky Way. They are consequences of recent star formation which occurs highly clustered in giant molecular clouds, and the stellar and dynamical evolution that follows. Recent data releases from the Gaia astrometric mission together with the on-going large spectroscopic surveys provide an ideal playground to study the entire spectrum of comoving stars and illuminate the formation and disruption of these objects. This thesis contains a series of projects related to finding and characterizing comoving stars with the Gaia data. After a brief general introduction in Chapter 1, I develop a method to search for comoving pairs of stars using astrometric data based on a probabilistic model selection in Chapter 2. I apply the method to the first data release of the Gaia mission and find 13,085 pairs among 10,606 stars, which make up 4,555 comoving systems. I follow up two of these systems in detail. In Chapter 3, I study the metallicity and abundance differences of a wide binary, HD 240429 and HD 240430. I discuss the possible reasons for the significant and condensation temperature-dependent abundance differences between the two stars and argue that one of the stars has likely accreted a massive, rocky planetary system. In Chapter 4, I confirm and characterize the nearest and largest new comoving group discovered in Chapter 2 using the second data release of Gaia. I extend the candidate members and discuss its morphology in relation to its disruption.
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For my parents
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Chapter 1

Introduction

Stars form in clustered environments (Lada & Lada, 2003). Consequently, many young (age < 1 Gyr) stars reside in star clusters or loose associations (Zuckerman & Song, 2004). Most (∼70%) O-type stars are in young clusters or associations, and even the majority of the remaining O-type stars seemingly in the field are thought to be runaway stars having formed in star clusters (Gies, 1987; de Wit et al., 2005). Another consequence of this is that looking for comoving groups of stars is the best way to look for coeval populations of stars, which are important benchmarks for our understanding of stellar evolution. Having similar velocities with a small dispersion (≲ 2 km s⁻¹) is a tell-tale sign that a group of stars are coeval. Dense, massive open clusters such as the Pleiades cluster are on one extreme of the spectrum of comoving stars. They are dense enough to be gravitationally bound for hundreds of millions of years. On the other end of the spectrum are young local associations typically younger than 100 Myr.

However, the vast majority of stars that make up a galaxy including the Milky Way are not in clusters or associations. Embedded clusters, proto-cluster systems still buried in molecular clouds, have a high infant mortality rate, and only less than 10% of these systems eventually survive as something like the classical massive
open cluster like the Pleiades cluster (Lada & Lada, 2003). Within a few Myr after the star formation, outflows and jets from the very young stars drive gas outward, ceasing further star formation and making the gravitational potential much shallower. Formation of a small number of massive stars may greatly impact the star formation efficiency of the molecular clump core. It is also evident that even those that do emerge as comoving systems not only have a wide range of properties in their age, metallicity, size and velocity dispersion among other things but also have to be dynamically disrupted eventually. Simple evidence in support of the latter statement is the dearth of open clusters older than 1 Gyr. Thus, a detailed census of comoving stellar groups can be valuable for understanding both the star formation and the dynamics of their disruption.

Aside from understanding the statistical properties of the comoving star population, each individual cluster or moving group is an interesting subject of study for many reasons. Nearby systems in the Solar neighborhood are the most important laboratories to test and improve our knowledge of stellar physics. These systems are snapshots of stellar evolution across the stellar mass range at different times. They are the benchmarks to calibrate different methods to determine the fundamental properties of a star such as its age. They are testbeds for the chemical homogeneity of coeval stars from a single star formation event, which is the key underlying assumption of chemical tagging (Freeman & Bland-Hawthorn, 2002). Finally, members of young moving groups are also prime targets to study the formation and evolution of substellar objects such as exoplanets and brown dwarfs through direct imaging (e.g., Smith & Terrile, 1984; Lagrange et al., 2010; Zuckerman et al., 2001).

Even in the Solar neighborhood ($d \lesssim 200$ pc), our current census of these objects is likely still incomplete. Ever since it became evident that very young stars such as a pre-main sequence star TW Hya can exist outside of molecular clouds, many researchers have looked for young stars near the Sun for further studies of debris disks,
planet formation and substellar companions. Detecting stellar activities indicated by excess infrared emission or high X-ray to bolometric luminosity ratios is one way to filter down the number of candidates. The most effective, however, is to investigate whether a star has comoving companions in its Galactic space motion. Thus, the Hipparcos dataset was essential in identifying the members of local young associations. Still, confirming membership of faint low-mass stars has been hindered by the relatively bright magnitude limit \( V \approx 9 - 12 \) mag of the Hipparcos mission. It is also often the case that the search for comoving companions is for a particular set of seed stars that meet certain other criteria like their multi-wavelength properties mentioned above rather than a systematic search although there have been attempts at the latter approach as well (e.g., Platais et al., 1998).

We are at a special time in studying comoving stars amongst a flood of new data of unprecedented quantity and quality. The primary driver is, of course, the Gaia mission (Gaia Collaboration et al., 2016). Gaia is the successor space astrometric mission to Hipparcos and provides astrometric parameters for more than a billion sources down to \( G \) magnitude of 20. It also provides precise two-band photometry and, for sources brighter than \( G = 12 \), radial velocities with \( \approx 1 \) km s\(^{-1}\) precision. This data will be synergetic with the on-going and upcoming large stellar spectroscopic surveys such as APOGEE(-2) (Eisenstein et al., 2011), GALAH (Martell et al., 2017) and eventually SDSS-V (Kollmeier et al., 2017), which deliver precise chemical abundances of \( \gg 10 \) elements for more than a few hundreds of thousands of stars. These data promise to unveil the most detailed picture of the Milky Way and its components and make an ideal playground to study the entire spectrum of comoving stars.

This thesis contains a series of projects related to finding and characterizing comoving stars with Gaia data in combination with other observational data available.

In Chapter 2 I perform a systematic search for comoving pairs of stars using the Tycho-Gaia Astrometric Solution (TGAS), a component of the first data release of
Gaia. I use the marginalized likelihood ratio in order to select comoving pairs, which appropriately takes the uncertainties and covariances of the astrometric parameters into account. I find that looking for the widest comoving pairs naturally leads to discoveries of larger comoving groups and open clusters. Many of the larger systems correspond to known and well-studied systems but I also find quite a few new comoving systems that require further investigation. One of these new systems that stands out as the nearest and largest group in TGAS is revisited and confirmed in Chapter 4 with the updated Gaia astrometry in its second data release. Furthermore, I find a hint that there may be a population of very wide separation comoving pairs beyond the tidal limit of the Galactic potential.

This chapter has been published as "Comoving Stars in Gaia DR1: An Abundance of Very Wide Separation Comoving Pairs", Semyeong Oh, Adrian M. Price-Whelan, David W. Hogg, Timothy D. Morton and David N. Spergel, AJ 153, 257. I performed all of the analysis and wrote the paper. The method and the code were developed in collaboration with Adrian and David Hogg. All coauthors provided valuable feedback on the analysis and the draft.

In Chapter 3 I report and discuss the pattern of differential abundances in one particular pair of solar-type stars, HD 240429 and HD 240430, using the precise abundances measured from the Keck HIRES spectra by Brewer et al. (2016). The chemical abundances of HD 240430 show a significant enhancement in only the refractory elements relative to HD 240429 as well as a peculiarly high Li content in its atmosphere considering its old age (∼ 4 Gyr). Based on these data, I argue that the abundance differences may be due to past accretion of a massive, rocky planetary system in HD 240430.

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Justin Myles, ApJ 854, 138. I performed all of the analysis and wrote the paper. All coauthors contributed to the interpretation of the data and provided useful feedback on the draft. John provided the original normalized Keck high-resolution spectra used to measure the elemental abundances. Justin let us use his absolute Li abundance measurements prior to its publication.

In Chapter 4 I follow up the discovery of a new nearby large moving group that was Group 10 in the search using TGAS (Chapter 2) with the second data release of Gaia which became available in April, 2018. This second data release (DR 2) provides entirely independent astrometry based on the first 22 months of the Gaia mission unlike the TGAS which was anchored on the Tycho-2 catalogue. I confirm the existence of the group in DR 2 and extend the candidate members from 29 to 194 stars down to M dwarfs. I discuss the morphology of these members which features an under-density with two streams of stars on either side in the context of dynamical disruption of the group.

This chapter is a draft in preparation to be submitted to a refereed journal.

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Chapter 2

Co-moving stars in Gaia DR1: An abundance of very wide separation co-moving pairs

The primary sample of the Gaia Data Release 1 is the Tycho-Gaia Astrometric Solution (TGAS): \( \approx \) 2 million Tycho-2 sources with improved parallaxes and proper motions relative to the initial catalog. This increased astrometric precision presents an opportunity to find new binary stars and moving groups. We search for high-confidence co-moving pairs of stars in TGAS by identifying pairs of stars consistent with having the same 3D velocity using a marginalized likelihood ratio test to discriminate candidate co-moving pairs from the field population. Although we perform some visualizations using (bias-corrected) inverse-parallax as a point-estimate of distance, the likelihood ratio is computed with a probabilistic model that includes the covariances of parallax and proper motions, and marginalizes the (unknown) true distances and 3D velocities of the stars. We find 13,085 co-moving star pairs among 10,606 unique stars with separations as large as 10 pc (our search limit). Some of these pairs form larger groups through mutual co-moving neighbors: many of these pair networks correspond to
known open clusters and OB associations, but we also report the discovery of several new co-moving groups. Most surprisingly, we find a large number of very wide (> 1 pc) separation co-moving star pairs, the number of which increases with increasing separation and cannot be explained purely by false-positive contamination. Our key result is a catalog of high-confidence co-moving pairs of stars in TGAS. We discuss the utility of this catalog for making dynamical inferences about the Galaxy, testing stellar atmosphere models, and validating chemical abundance measurements.

2.1 Introduction

Stars that are roughly co-located and moving with similar space velocities (“co-moving stars”) are of special interest in many branches of astrophysics.

At small separations (0.001–1 pc), they are wide binaries (and multiples) that are either weakly gravitationally bound or slowly separating. Because they have low binding energies, a sample of wide binaries is valuable for investigating the Galactic dynamical environment. These systems must have both survived their dynamic birth environment and avoided tidal destruction along their orbit. Thus, the statistical properties of wide binaries provide a window into both star formation processes (e.g., Parker et al. 2009) and Galactic dynamics (Heggie 1975), including Galactic tides and other massive perturbers such as molecular clouds and MACHOs (Weinberg et al., 1987; Jiang & Tremaine 2010; Yoo et al. 2004; Allen & Monroy-Rodríguez, 2014).

Wide binaries are also good testbeds for stellar models and age indicators: the constituent stars were likely born at the same time with the same chemical compositions, but evolved independently because of their wide separation. These pairs are therefore useful for validating gyrochronology relations (e.g., Chanamé & Ramírez 2012) and may be valuable for testing consistency between stellar atmosphere models. Finally, calibration of stellar parameters of low-mass stars (e.g., M dwarfs), which dominate
the stellar content of the Galaxy by number, can benefit from a larger sample of widely
separated binaries containing a low mass star and a much brighter F/G/K star whose
stellar parameters are easier to measure (e.g., Rojas-Ayala et al., 2012).

At larger separations ($\gtrsim 1$ pc), co-moving stars are likely members of (potentially
dissolving) moving groups, associations, and star clusters or disrupted wide binaries.
The origin of moving groups is still under active debate (e.g., Bovy & Hogg 2010): are
they remnants of a coeval star formation event with similar chemical composition? Or
are they formed by dynamical effects of non-axisymmetric features of the Galaxy such
as spirals and bars? With the recent advances in measuring chemical abundances of a
large volume of stars using high and low resolution spectroscopy (e.g., Steinmetz et al.
2006; Majewski et al. 2015; Gilmore et al. 2012 to name a few), we can now start to
explore these questions with unprecedented statistics and in unexplored detail. The
dynamics of cluster dissolution provides important clues to understanding the star
formation history and the dynamical evolution of the Milky Way. In the halo, we know
of more than 20 disrupting globular clusters and dwarf galaxies (“stellar streams”;
see, e.g., Grillmair & Carlin 2016 for a summary of known streams). These tidal
streams are modeled to infer the parameters of the Galactic potential (e.g., Küpper
et al., 2015). Similar processes are at work with star clusters in the disk. However,
the dynamical time is much shorter, and the dynamics will be much more complex
because of the existence of other perturbers in the disk.

To date, thousands of candidate co-moving star pairs have been identified by
searching for stars with common proper motions (Poveda et al. 1994; Allen et al. 2000;
Chanamé & Gould 2004; Lépine & Bongiorno 2007; Shaya & Olling 2011; Alonso-
Floriano et al., 2015). Here, we use the recent first data release of Gaia which includes
precise distances, enabling us to ask whether two stars share the same physical (3D)
velocity rather than just the projections in the proper motion space.
This paper proceeds as follows: In Section 2.2 we briefly describe the data set used in this work. In Section 2.3 we develop a statistical method to identify high-confidence co-moving pairs in this catalog. In Section 2.4 we present and discuss our resulting catalog of co-moving pairs. We summarize in Section 2.5.

2.2 Data

The primary data set used in this Chapter is the Tycho-Gaia Astrometric Solution (TGAS), released as a part of Data Release 1 (DR1) of the Gaia mission (Gaia Collaboration et al., 2016; Lindegren et al., 2016). The TGAS contains astrometric measurements (sky position, parallax, and proper motions) and associated covariance matrices for a large fraction of the Tycho-2 catalog (Høg et al., 2000) with median astrometric precision comparable to that of the Hipparcos catalog (≈ 0.3 mas; van Leeuwen, 2007). In terms of parallax signal-to-noise ([S/N]_p = \varpi/\sigma_\varpi), the TGAS catalog contains 42385 high-precision stars with [S/N]_p > 32.

We construct an initial sample of star pairs to search for co-moving pairs as follows. We first apply a global parallax signal-to-noise cut, [S/N]_p > 8, to the TGAS, which leaves 619,618 stars. Then, for each star we establish an initial sample of possible co-moving partners by selecting all other stars that satisfy two criteria: separation less than 10 pc and difference in (point-estimate) tangential velocity less than |Δv_t| < 10 km s^{-1}. We ultimately build a statistical model that incorporates the covariances of the data, but for these initial cuts and for visualizations we use a point-estimate of the distance by applying a correction for the Lutz-Kelker bias (Lutz & Kelker, 1973):

\[ \hat{r} = 1000 \left[ \frac{\varpi}{2} \left( 1 + \sqrt{1 - \frac{16}{[S/N]_p^2}} \right) \right]^{-1} \text{pc} \]
where $\varpi$ is the parallax in mas. An estimate for the difference in tangential velocity between two stars is, then,

$$|\Delta v_t| = |\hat{r}_1 \mu_1 - \hat{r}_2 \mu_2|$$

(2.2)

where $\mu = (\mu_{\alpha_*}, \mu_\delta)$.

Figure 2.1 shows $|\Delta v_t|$ against the physical separation for the resulting 271,232 unique pairs in the initial sample. A few key observations can be made:

- At small separations ($< 1$ pc), there is a population of pairs with very small tangential velocity difference ($< 2$ km/s). Given that these pairs are very close in both 3D position and tangential velocities, it is highly probable that they are actually co-moving wide binaries.

- A sample of co-moving stars also include stars that are part of, e.g., OB associations, moving groups, and open clusters. These astrophysical objects may be detected as a network of co-moving pairs, sharing some mutual co-moving neighbors. As the pair separation increases, the nature of co-moving pairs will change from binaries to those related to these larger objects, which generally subtend a larger angle in sky. Since the proper motions of two stars with the same 3D velocity are projections of this velocity onto the celestial sphere at two different viewing angles, the larger the difference in viewing angles is, the larger the difference in tangential velocities will be. Due to this projection effect, a population of genuine co-moving pairs will extend to larger $|\Delta v_t|$ at larger separation. This indeed can be seen in Figure 2.1 as an over-density in the lower right corner that gets thinner as $|\Delta v_t|$ increases.

- Finally, there is a population of “random” pairs of field stars that are not co-moving, but still have $|\Delta v_t| < 10$ km s$^{-1}$ by chance. As $|\Delta v_t|$ increases, this $\mu_{\alpha_*}$ is the proper motion component in the right ascension direction, $\mu_{\alpha_*} = \mu_{\alpha} \cos \delta$. 

---

$^1$
population will dominate. Figure 2.1 shows that there is an overlap between genuine co-moving pairs and “random” pairs.

In the following section, we construct a statistical model that propagates the non-trivial uncertainties in the data to our beliefs about the likelihood that a given pair of stars is co-moving.

Figure 2.1: Point estimates of tangential velocity and physical separation computed for all 271,232 unique pairs in the initial sample of pairs (black points). For this sample, we consider stars with separation < 10 pc and $|\Delta \mathbf{v}_t| < 10 \text{ km s}^{-1}$ computed relative to every other star in TGAS. The blue solid line shows the magnitude of the 3D orbital velocity as a function of semi-major axis for a $2 M_\odot$ binary system. Note the stream of points that starts at small separation ($\lesssim 0.01$ pc), small $|\Delta \mathbf{v}_t|$ ($\lesssim 2 \text{ km s}^{-1}$), but climbs to larger $|\Delta \mathbf{v}_t|$ at $|\Delta \mathbf{x}| \gtrsim 1$ pc, which eventually merges with random pairs of field stars dominating in the upper right corner (see Section 2.2 for details).
2.3 Methods

The abundance of pairs of stars with small velocity difference in Figure 2.1 suggests that there are a significant number of co-moving pairs in the TGAS data at a range of separations. Here, we develop a method to select high-confidence co-moving pairs that properly incorporates the uncertainties associated with the Gaia data. We make the following assumptions in order to construct a statistical model (a likelihood function with explicit priors on our parameters):

- We assume that the uncertainties in the data—parallax, \( \varpi \), and two proper motion components, \( \mathbf{\mu} = (\mu_\alpha^*, \mu_\delta^*)^T \)—are Gaussian with known covariances \( \mathbf{C} \). The values of covariances are provided as part of the Gaia data (Lindegren et al., 2012, 2016).

- We assume that the 3D velocities of stars in a given pair \( (\mathbf{v}_i, \mathbf{v}_j) \) (relative to the solar system barycenter) are either (1) the same with a small (Gaussian) dispersion \( s \) or (2) independent. In both cases, velocity is drawn from the velocity prior \( p(\mathbf{v}) \).

Under these assumptions, the likelihood of a proper motion measurement, \( \mathbf{\mu} \), for a star with true distance, \( r \), and true 3D velocity \( \mathbf{v} \) is

\[
L(\mathbf{\mu} | \mathbf{v}, r, s^2) = \left[ \det \left( \frac{\mathbf{C}^{-1}}{2\pi} \right) \right]^{1/2} \exp \left[ -\frac{1}{2} (\mathbf{\mu} - \mathbf{x}_\theta)^T \mathbf{C}^{-1} (\mathbf{\mu} - \mathbf{x}_\theta) \right]
\]

(2.3)

\[
\mathbf{x}_\theta = r^{-1} \mathbf{v}_i
\]

(2.4)
where the tangential velocity \( \mathbf{v}_t = (v_\alpha \ v_\delta)^T \) is related to the 3D velocity \( \mathbf{v} \) by projection matrix \( \mathbf{M} \) at the star’s sky position \((\alpha, \delta)\)

\[
\mathbf{v}_t = \mathbf{M} \mathbf{v}
\]

\[
= \begin{pmatrix}
-\sin \alpha & \cos \alpha & 0 \\
-\sin \delta & \cos \delta & -\sin \alpha & \cos \delta
\end{pmatrix}
\begin{pmatrix}
v_x \\
v_y \\
v_z
\end{pmatrix}
\tag{2.6}
\]

and the modified covariance matrix \( \hat{\mathbf{C}} \) is

\[
\hat{\mathbf{C}} = \mathbf{C} + \frac{(s/r)^2}{r} \mathbb{I}
\tag{2.7}
\]

where \( \mathbb{I} \) is the identity matrix. The parameter \( s \) is added to allow for small tolerance in velocities which we discuss below.

For a given pair, we compute the fully marginalized likelihood (FML) for the hypotheses (1) and (2), \( L_1 \) and \( L_2 \). We use the FML ratio \( L_1/L_2 \) as the scalar quantity to select candidate co-moving pairs, as described in Section 2.4.1 in more detail. To compute these FMLs, the likelihood functions for each star in a pair, \( L_i, L_j \), are marginalized over the (unknown) true distance and 3D velocity for each star in the pair \((i, j)\).

\[
L_1 = \int \int \, dr_i \, dr_j \, d^3v_i \, L_i(\mu_i \mid \mathbf{v}, r_i, s^2) \, L_j(\mu_j \mid \mathbf{v}, r_j, s^2) \, p(\mathbf{v}) \, p(r_i \mid \varpi_i) \, p(r_j \mid \varpi_j)
\tag{2.8}
\]

\[
L_2 = \int \int \, dr_i \, dr_j \, d^3v_i \, d^3v_j \, L_i(\mu_i \mid \mathbf{v}_i, r_i, s^2) \, L_j(\mu_j \mid \mathbf{v}_j, r_j, s^2) \, p(\mathbf{v}_i) \, p(\mathbf{v}_j) \, p(r_i \mid \varpi_i) \, p(r_j \mid \varpi_j).
\tag{2.9}
\]

Here, \( p(r_i \mid \varpi_i) \) is the posterior distribution of distance given parallax measurement \( \varpi_i \) and its Gaussian error \( \sigma_{\varpi,i} \). Note that the FML for the hypothesis (1) involves integration over one velocity \( \mathbf{v} \) that generates the likelihoods for both stars, \( L_i \) and
$L_j$. The marginalization integral for hypothesis (2) can be split into the product of two simpler integrals $L_2 = Q(\mu_i, \varpi_i) Q(\mu_j, \varpi_j)$ where

$$Q(\mu, \varpi) = \int dr d^3 v L(\mu \mid v, r, s^2) p(v) p(r \mid \varpi)$$

If the velocity prior $p(v)$ is also Gaussian, the integrals over velocity in both cases can be performed analytically: We use a mixture of three isotropic, zero-mean Gaussian distributions

$$p(v) = \sum_{m=1}^{3} w_m N(0, \sigma_{v,m}^2)$$

with velocity dispersions $(\sigma_{v,1}, \sigma_{v,2}, \sigma_{v,3}) = (15, 30, 50)$ km s$^{-1}$ and weights $(w_1, w_2, w_3) = (0.3, 0.55, 0.15)$ meant to encompass young thin disk stars to halo stars. These numbers are empirically chosen to account for the distribution of velocities of the TGAS stars. We derive the relevant expressions in Appendix 2.B. After marginalizing over velocity, the likelihood integrands only depend on distance; we numerically compute the integrals over the true distances of each star in a pair using Monte Carlo integration with $K$ samples from the distance posterior.

$$\int dr \tilde{L}(r) p(r \mid \varpi) \approx \frac{1}{K} \sum_{k} \tilde{L}(r_k)$$

where $\tilde{L}(r)$ is the velocity-marginalized likelihood function. In order to generate a sample of distances from the distance posterior $p(r_i \mid \varpi_i)$, we need to assume a distance prior. We adopt the uniform density prior (Bailer-Jones, 2015) with a maximum distance of 1 kpc. Through experimentation, we have found that $K = 128$ samples are sufficient for estimating the above integrals for stars with a wide range in parallax signal-to-noise.

For small-separation binaries, the assumption that the stars having the same 3D velocity for hypothesis (1) can break down for high-precision proper motion.
measurements because of the orbital velocity (blue solid line in Figure 2.1). To account for this, we set
\[ s^2 = \frac{2GM_\odot}{|\mathbf{x}_i - \mathbf{x}_j|}. \]
Because \( s^2 \) is much smaller than the velocity dispersions of the velocity prior \( p(\mathbf{v}) \), it has minimal effect on the hypothesis (2) FML.

2.4 Results

This section is divided into three parts. First, we discuss and justify a cut of the likelihood ratio to select candidate co-moving pairs. Second, we present the statistics and properties of our candidate co-moving pairs. Finally, we describe our catalog of candidate co-moving pairs, the main product of this study.

2.4.1 Selecting candidate co-moving pairs

In this section, we examine the distribution of (log-)likelihood ratios \( \ln \frac{\mathcal{L}_1}{\mathcal{L}_2} \), and come up with a reasonable cut for this quantity to select co-moving pairs from the initial sample.

Figure 2.2 shows the likelihood ratios for all \( \sim 271k \) pairs in the initial sample. As discussed in Section 2.2, we expect a correlation between the likelihood ratios of pairs, and their distribution on \( |\Delta \mathbf{v}_t| \) vs separation plane. Specifically, as we sweep through from small \( |\Delta \mathbf{v}_t| \) to large, we expect the population of pairs to change from genuinely co-moving to random. This becomes clear when we look at the distribution of the likelihood ratios of pairs in slices of \( |\Delta \mathbf{v}_t| \) (top row of Figure 2.2). Pairs with \( |\Delta \mathbf{v}_t| \in (0, 2.5) \) km s\(^{-1} \) are most likely actual co-moving pairs, and their likelihood ratio distribution is narrowly peaked at \( \gtrsim 5 \) (darkest pink histogram in the upper left panel of Figure 2.2). The distribution peaks at lower values and gets broader as \( |\Delta \mathbf{v}_t| \) increases, and the number of random pairs increasingly dominate. On the bottom row of Figure 2.2 we show how the distribution of pairs on \( |\Delta \mathbf{v}_t| \) vs separation plane changes with decreasing \( \ln \frac{\mathcal{L}_1}{\mathcal{L}_2} \) ratios. This is in agreement with our discussion in
Figure 2.2: Justification of the likelihood ratio cut. On the top row, we show how the distribution of \( \ln L_1/L_2 \) changes (left) in slices of \( |\Delta v_t| \) (sequentially color-coded in pink on the right panel). On the bottom row, we show how the distribution of pairs on \( |\Delta v_t| \) vs. separation changes (right) in slices of \( \ln L_1/L_2 \) (sequentially color-coded in blue on the left). The black dots in the upper right panel and the black line in the lower left panel correspond to the entire initial sample of pairs. For comparison, we also present the likelihood ratio distribution of random pairs of stars in the TGAS with parallax \( S/N > 8 \) in gray filled histogram. Based on this, we choose \( \ln L_1/L_2 > 6 \) as our high-confidence candidate co-moving pairs.
Section 2.2 Finally, as a test, we compute the likelihood ratios for 200,000 random pairs of stars with the same parallax signal-to-noise ratio cut as the initial sample \((S/N > 8)\). Shown as the gray filled histogram in Figure 2.2, this distribution peaks at a much lower value \((\approx 2)\), and is clearly separated from highly probable co-moving pairs.

Based on these comparisons, we select candidate co-moving pairs with \(\ln \mathcal{L}_1/\mathcal{L}_2 > 6\). Out of 271,232 pairs in the initial sample, 13,058 pairs \((4.8\%)\) satisfy this condition.

2.4.2 Statistics and properties of the identified co-moving pairs

![Histogram of the sizes of connected components.](image)

Figure 2.3: Histogram of the sizes of connected components.

Once we have identified candidate co-moving pairs from the initial sample, these pairs form an undirected graph where stars are nodes, and edges between the nodes
Figure 2.4: Visualizations of a few example connected components of co-moving pairs of stars. Each star (node) is marked as a red circle, and a line (edge) is drawn between two stars if they are co-moving by our selection criteria (see Section 2.4.1). On left, we show the largest network found in this study corresponding to the Pleiades star cluster. On right, we show four examples of connected components with varying sizes. The connected component on the upper left panel with a size of 58 corresponds to NGC 2632, also known as the Beehive cluster.

exist for co-moving pairs of stars. A star may have multiple co-moving neighbors, and two stars may either be directly or indirectly connected by a sequence of edges (“path”). We divide the graph into connected components and show the distribution of their sizes in Figure 2.3. The most common are connected components of size 2, which mean mutually exclusive co-moving pairs. However, it is clear that there are many aggregates of co-moving stars discovered by looking for co-moving pairs. These aggregates are likely moving groups, OB associations, or star clusters. In 13,058 co-moving pairs that we identified, there are 4,555 connected components among 10,606 unique stars. The maximum size of the connected components is 151. We show this largest connected component along with four other examples of varying sizes in Figure 2.4. The largest connected component corresponds to the Pleiades open cluster

---

2A connected component of an undirected graph $G$ is a subgraph of $G$ in which any two nodes are connected to each other by a path.
Figure 2.5: Panoramic view of co-moving pairs of stars around the Sun. This is a cylindrical projection of onto the Galactic plane with the Sun at the origin. Pairs in connected components of sizes less than 5 are connected by gray lines. Pair in connected components of size $\geq 5$ are plotted with a unique random color, and their nodes (stars) are highlighted with small black circles. We also show the positions of known Milky Way star clusters from Kharchenko et al. (2016) as light blue circles of 10 pc radius, and stars in OB associations from de Zeeuw et al. (1999) as blue crosses. Some of the larger connected components are clearly associated with known clusters, but we also discover quite a few new co-moving groups.
(left panel of Figure 2.4) while the upper left panel of the right column of Figure 2.4 is NGC 2632, another known Milky Way open cluster (Kharchenko et al., 2016).

We show the distribution of co-moving pairs in galactic longitude and distance in Figure 2.5. The connection between known co-moving structures and the larger connected components found in this work becomes immediately clear when we overplot the positions of known Milky Way star clusters (Kharchenko et al., 2016), and stars in OB associations (de Zeeuw et al., 1999). Many of the larger connected components are clearly associated with known star clusters: Melotte 22 (Pleiades) at \((l, d) \approx (167^\circ, 130 \text{ pc})\), Melotte 20 at \((l, d) \approx (147^\circ, 175 \text{ pc})\), Melotte 25 (Hyades) at \((l, d) \approx (180^\circ, 50 \text{ pc})\), and NGC 2632 (Beehive) at \((l, d) \approx (206^\circ, 187 \text{ pc})\) to name a few. Clumps of co-moving pairs at \((l, d) \approx (300 - 360^\circ, 100 - 200 \text{ pc})\) seem to strongly correlate with the locations of OB associations Upper Scorpius, Upper Centaurus Lupus, and Lower Centaurus Crux (de Zeeuw et al., 1999).

However, there are still many new larger connected components that we discover. If we define a condition to associate a connected component to a known cluster as having more than 3 members within 10 pc from the nominal position of the cluster, for the 61 connected components with sizes larger than 5, we find that only 10 are associated with a cluster cataloged in Kharchenko et al. (2016). It is also worth noting that the positions of some of the known clusters are offset from those of the connected components associated with them, indicating that the TGAS data improves the distance estimates of these clusters. Finally, not all known star clusters are recovered in our search. This is primarily because of the non-uniform coverage and magnitude limit of the TGAS data.

Ultimately, any candidate co-moving pair found in this work needs to be verified using radial velocities. Here, we use 210,368 cross-matches of the TGAS with Radial Velocity Experiment fifth data release (RAVE DR 5; Kunder et al. 2017) to assess the false-positive rates of our selection. We have 283 pairs with both stars matched.
with RAVE. Figure 2.6 shows the difference in radial velocities between the two stars in a pair, Δ\(v_r\), as a function of their physical separation. We show Δ\(v_r\) in units of \(σ_{Δv_r}\), which we estimate as the quadrature sum of \(σ_{v_r}\) for each star. The fraction of pairs with good agreement in radial velocity decreases with increasing separation. This, after all, is not surprising because we are only using 2D velocity information (proper motions) with errors. However, the contamination becomes significant only at > 1 pc (which depends on the local stellar number density and velocity dispersion). Given the excellent correspondence between aggregates of co-moving pairs (connected components) and known genuine co-moving structures (Figure 2.5), we may expect that pairs in these larger connected components, which will often have separations > 1 pc, to have less contamination from false-positives. We divide the co-moving pairs into those mutually exclusively connected (i.e., in a connected component of size 2), and those in a larger group. We indeed find that many pairs in larger groups are at > 1 pc, yet the fraction of pairs that have identical radial velocities within 3\(σ\) is higher than the mutually exclusive pairs, and remains high (> 80%) to ∼ 10 pc. Finally, we note that the false-positive rate for mutually exclusive pairs with large angular separation may have been over-estimated due to projection.

We now examine the separation distribution of co-moving pairs in Figure 2.7. As expected, pairs in larger connected components are mostly found with separations larger than 1 pc. Surprisingly, however, we also find a large number of mutually exclusive co-moving pairs at > 1 pc as well. Even if we consider the increasing false-positive rate at large separations, the distribution is not significantly changed as the number of pairs at > 1 pc is in fact increasing much faster (as a power-law) than the decrease due to the false-positives (bottom panel of Figure 2.6). The nature of these very wide separation, mutually exclusive pairs, which cannot be gravitationally bound to each other, needs further investigation. Can they be remnants of escaped binaries that are drifting apart? In a study of the evolution of wide binaries including
Figure 2.6: Validation of candidate co-moving pairs using radial velocities from RAVE. Top: Radial velocity differences, $\Delta v_r$, of 283 pairs with RAVE measurements. $\Delta v_r$ is plotted in units of $\sigma_{\Delta v_r} = \sqrt{\sigma_{v_r,1}^2 + \sigma_{v_r,2}^2}$ as a function of physical separation. We highlight $3\sigma$ limit with two horizontal lines. Bottom: Fraction of pairs with $|\Delta v_r/\sigma_{\Delta v_r}| < 3$ as a function of physical separation. We calculate the fraction with a running bin containing 31 data points at a time. The median, and the minimum and maximum separation of pairs in each bin are indicated with a marker, and its errorbars. We separate pairs in connected components of size 2 (i.e., mutually exclusively connected) from those in larger connected components.
the Galactic tidal field as well as passing field stars, Jiang & Tremaine (2010) found that we expect to find a peak at $\sim 100 - 300$ pc in the projected separation due to stars that were once in a wide binary system, but are drifting apart with small relative velocities ($\sim 0.1$ km s$^{-1}$). In future work, we will increase the maximum search limit (in this work, 10 pc) to identify and study these large scale phase-space correlations.

Figure 2.7: Separation distribution of co-moving pairs of stars. As with Figure 2.6, we divide the pairs into those mutually exclusively connected (connected component size = 2), and those connected to larger connected components (size > 2).

Finally, we present the color-magnitude diagrams of co-moving pairs using the cross-matches with 2MASS. A more detailed study of stellar parameters using photometry from various sources will follow. Figure 2.8 and 2.9 show $G - J$ vs $G$ color-magnitude diagrams for stars in larger connected components (size > 2) and in mutually exclusive pairs, respectively. The connected components shown in Figure 2.8 correspond to those visualized in Figure 2.4. For stars in larger co-moving groups, there is a noticeable lack
of evolved, off-main sequence stars, in agreement with these kinematic structures being young. For mutually exclusive pairs, we divide the pairs by separation at 1 pc above which the false-positive rate due to random pairs starts to increase. While many pairs are located along the main sequence, we also find quite a few of main sequence-red giant pairs, which will be valuable to anchoring stellar atmospheric models together.

Figure 2.8: Color-magnitude diagrams of stars in larger connected components presented in Figure 2.4. Each panel shows the same group of stars visualized in the panel at the same position in Figure 2.4. We show a reference distribution of stars randomly drawn to have a matching distribution in distance as the stars in our co-moving pairs in blue.

2.4.3 Catalog of candidate co-moving pairs

In this section, we describe our catalog of candidate co-moving pairs of stars. For 13,058 pairs (10,606 unique stars) found in this work. The catalog is composed of three tables of stars, pairs, and groups. We summarize the content of each table in Table 2.1 and the relationships between the tables in Figure 2.10. The star table contains all 10,606 stars that have at least one co-moving neighbor by our selection. We provide the TGAS source id, which may be used to easily retrieve cross matches between Gaia and other surveys using the Gaia data archive. For each star, we also include the positional measurements from TGAS, Gaia G-band, 2MASS J-band magnitudes, and
Figure 2.9: Color-magnitude diagrams of stars in mutually exclusive co-moving pairs in two separation bins. We connect each pair by a line on the left for pairs with separations smaller than 1 pc. We show a reference distribution of stars randomly drawn to have a matching distribution in distance as the stars in our co-moving pairs in blue, same as Figure 2.8.
RAVE radial velocities where they exist. The co-moving relationship between the stars is described in the pair table. We also list the angular and physical separation of each pair, and the likelihood ratio, $\ln \frac{L_1}{L_2} (>6)$ (see Equation 2.8 and 2.9) computed in this work.

Finally, the information about the connected components found in these co-moving star pairs is in the group table. We assign a unique index to each group in descending order of its size. Thus, group 0 is the largest group that contains 151 stars. Each star or pair is associated with a group that it is a member of, listed in the group id column of the star and pair table.

We note a caveat on the completeness of a connected component of co-moving pairs found in our catalog. Because we applied a simple cut in the likelihood ratio ($\ln \frac{L_1}{L_2} > 6$), there is a possibility that, for example, a star in a mutually exclusive pair in our catalog may still have another possibly co-moving companion which has been dropped because the likelihood ratio is slightly less than 6.
Table 2.1: Candidate co-moving pairs catalog description

<table>
<thead>
<tr>
<th>Column Name</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>row id</td>
<td></td>
<td>Zero-based row index</td>
</tr>
<tr>
<td>TGAS source id</td>
<td></td>
<td>Unique source id from TGAS</td>
</tr>
<tr>
<td>Name</td>
<td></td>
<td>Hipparcos or Tycho-2 identifier</td>
</tr>
<tr>
<td>RA</td>
<td>deg</td>
<td>Right ascension from TGAS</td>
</tr>
<tr>
<td>DEC</td>
<td>deg</td>
<td>Declination from TGAS</td>
</tr>
<tr>
<td>parallax</td>
<td>mas</td>
<td>Unique source id from TGAS</td>
</tr>
<tr>
<td>distance</td>
<td>pc</td>
<td>Unique source id from TGAS</td>
</tr>
<tr>
<td>G</td>
<td>mag</td>
<td>Gaia G-band magnitudes</td>
</tr>
<tr>
<td>J</td>
<td>mag</td>
<td>2MASS J-band magnitudes</td>
</tr>
<tr>
<td>RAVE OBS ID</td>
<td></td>
<td>Unique id of the RAVE match</td>
</tr>
<tr>
<td>RV</td>
<td>km s(^{-1})</td>
<td>Radial velocity from RAVE</td>
</tr>
<tr>
<td>eRV</td>
<td>km s(^{-1})</td>
<td>Uncertainty of radial velocity from RAVE</td>
</tr>
<tr>
<td>group id</td>
<td></td>
<td>Id of the group this star belongs to</td>
</tr>
<tr>
<td>group size</td>
<td></td>
<td>Size of the group this star belongs to</td>
</tr>
</tbody>
</table>

Table: Pair (13,058 rows)

| star 1 | Index of star 1 in the star table |
| star 2 | Index of star 2 in the star table |
| angsep | arcmin | Angular separation |
| separation | pc | Physical separation |
| ln \(L_1/L_2\) | | Likelihood ratio |
| group id | Id of the group the pair belongs to |
| group size | Size of the group the pair belongs to |

Table: Group (4,555 rows)

| id | Unique group id |
| size | Number of stars in a group |
| mean RA | deg | Mean right ascension of members |
| mean DEC | deg | Mean declination of members |
| mean distance | pc | Mean distance of members |

2.5 Summary

In this Chapter, we searched for co-moving pairs of stars in the TGAS catalog released as part of the Gaia DR1. Our method is to compare the fully marginalized likelihoods between two hypotheses: (1) that a pair of stars shares the same 3D velocity, and (2) that the two stars have independent 3D velocities, in both cases incorporating the covariances of parallax and proper motions. We argued for a reasonable cut of the
likelihood ratio, and found 13,058 candidate co-moving pairs among 10,606 stars with separations ranging from 0.005 pc to 10 pc, the limit of our search.

We found that some co-moving pairs that we have identified are connected by sharing a common co-moving neighbor. This network of co-moving pairs, which forms an undirected graph, can be decomposed into connected components in which any two stars are connected by a path. The entire 13,058 candidate co-moving pairs are grouped into 4,555 connected components. The most common is a size-2 connected component, i.e., the two stars in these pairs are mutually exclusively linked. Many of the larger connected components naturally correspond to some of the known co-moving structures such as open clusters and stellar associations. Some of these co-moving groups of stars are newly discovered.

We have also found a large number of very wide separation (> 1 pc) mutually exclusive co-moving pairs, in which the stars are the only co-moving neighbor of each other and not part of large connected components. These are most likely remnants of dissolving wide binaries (Jiang & Tremaine 2010). The abundance of highly probable wide separation co-moving pairs conclusively shows that there is no strict cut-off semi-major axis for wide binary systems (e.g., Wasserman & Weinberg 1987). The presence of these pairs and similar separation distribution have already been noticed by Shaya & Olling 2011 using the Hipparcos data. If confirmed with radial velocity measurements, this population should still be relatively young compared to the general disk field population. Modeling the color-magnitude diagram distribution of these stars can shed some light on this issue. If they are remnants of dissolving systems that were born coeval, the sample of very wide separation co-moving pairs can potentially be used to measure the recent (≲ 1 Gyr) star formation history in the Solar neighborhood. Co-moving stars with separation less than 1 pc are very promising candidates for wide binaries. They are found to be pairs of stars of varying stellar types. Some of these pairs, such as main sequence-red giant or F/G/K-M dwarfs,
will be particularly valuable for testing theoretical stellar models and calibrating observational measurements of low mass stars.

We note that a similar search for wide binaries using the TGAS data is performed in a recent work by Oelkers et al. (2016). They find \( \approx 1,900 \) wide binaries with separation typically less than 1.5 pc, and 256 pairs with separation larger than \( \sim 1 \) pc. We emphasize that our method is based on a probabilistic model for the assumptions on the 3D velocities of the two stars in a pair, and that we marginalize over the (unknown) true distances and velocities of the stars in contrast to just applying a cut in the proper motion space.

Finally, we make our catalog of 13,058 candidate co-moving pairs available to the community. What we find using the TGAS is only a taste of what we will discover with the future releases of the Gaia mission.

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This work has made use of data from the European Space Agency (ESA) mission Gaia (http://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, http://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

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Science and Engineering (PICSciE) and the Office of Information Technology’s High Performance Computing Center and Visualization Laboratory at Princeton University.

This research additionally utilized: Astropy (Astropy Collaboration et al. 2013), IPython (Pérez & Granger 2007), matplotlib (Hunter 2007), and numpy (Van der Walt et al. 2011).

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van Leeuwen, F., ed. 2007, Astrophysics and Space Science Library, Vol. 350, Hipparcos, the New Reduction of the Raw Data
2.A Relevant properties of Gaussian integrals

In what follows, all vectors are column vectors, unless we have transposed them. A relevant exponential integral solution is

$$\ln \left[ \int \exp \left( -\frac{1}{2} [x - \nu]^T A^{-1} [x - \nu] - \Delta \right) dx \right] = \frac{1}{2} \ln ||2\pi A|| - \Delta ,$$

(2.13)

where $x$ and $\nu$ are $D$-dimensional vectors, $A$ is a positive definite matrix, $\Delta$ is a scalar, and the integral is over all of $D$-dimensional $x$-space. To cast our problem in this form, we will need to complete the square of the exponential argument. If we equate

$$\frac{1}{2} [x - \nu]^T A^{-1} [x - \nu] + \Delta = \frac{1}{2} x^T A^{-1} x + x^T B b + C ,$$

(2.14)

where $B b$ is a $D$-vector, and $C$ is a scalar, then we find

$$\nu = -A B b$$

(2.15)

$$\Delta = C - \frac{1}{2} \nu^T A^{-1} \nu .$$

(2.16)

We will identify terms in our likelihood functions with $A$, $B b$, and $C$, convert to $\nu$ and $\Delta$ and compute the marginalized likelihood using Equation \ref{eq:2.13}.

2.B Expressions for the marginalized likelihoods

At given distance $r$, the velocity-marginalized likelihood can be computed analytically using the expressions in Appendix 2.A. We will start by writing down expressions for the the likelihood multiplied by the prior pdf for the velocities. The likelihood for the data (proper motions of the two stars in a pair) is a Gaussian (Equation \ref{eq:2.3}). In order
to simplify our notation, we construct a velocity-space data vector \( \mathbf{y} \) as follows:

\[
\mathbf{y} = \begin{pmatrix} r_i \mu_{\alpha,i} & r_i \mu_{\delta,i} & r_j \mu_{\alpha,j} & r_j \mu_{\delta,j} \end{pmatrix}^T
\]  

(2.17)

where the subscripts \( i, j \) refer to the indices of each star in the pair and we have multiplied the observables (the proper motions) by the distances \( r_i, r_j \), which is permitted because we are conditioning on the distances. Fundamentally, our hypothesis 1 model (the stars have the same velocity with a small difference) is

\[
\mathbf{y} = \mathbf{M} \mathbf{v} + \text{noise}
\]

(2.18)

where now the \( 4 \times 3 \) transformation matrix \( \mathbf{M} \) is a stack of the transformation matrices for each star computed from the pair of sky positions and using Equation 2.6. The noise (in \( \mathbf{y} \)) is drawn from a \( 4 \times 4 \) Gaussian with block-diagonal covariance matrix, \( \Sigma \), constructed from the proper motion covariance matrix of each star, \( C_i, C_j \), and the distances \( r_i, r_j \):

\[
\Sigma = \begin{pmatrix} r_i^2 C_i & 0 \\ 0 & r_j^2 C_j \end{pmatrix}
\]

(2.19)

Given these definitions, the likelihood function for hypothesis 1 is

\[
p(\text{data} \mid \mathbf{v}, r_i, r_j) = r_i^2 r_j^2 N(\mathbf{y} \mid \mathbf{M} \mathbf{v}, \Sigma)
\]

(2.20)

\[
\ln p(\text{data} \mid \mathbf{v}, r_i, r_j) = 2 \ln r_i + 2 \ln r_j - \frac{1}{2} \ln ||2\pi \Sigma|| - \frac{1}{2} [\mathbf{y} - \mathbf{M} \mathbf{v}]^T \Sigma^{-1} [\mathbf{y} - \mathbf{M} \mathbf{v}],
\]

(2.21)

where the factor of \( r_i^2 r_j^2 \) is the Jacobian of the transformation from \( \mathbf{y} \) to the data space \((\mu_{\alpha,i}^* \mu_{\delta,i}^* \mu_{\alpha,j}^* \mu_{\delta,j}^*)^T\).

Now we multiply this likelihood with the velocity prior. As described in Section 2.3 we use an isotropic, mixture-of-Gaussians prior on velocity (Equation 2.11). For
simplicity here let us work out the marginalization for one component of the mixture so that $\mathbf{v} \sim \mathcal{N}(\mathbf{0}, \mathbf{V}_m)$. Then,

$$\ln p(\mathbf{v}) = -\frac{1}{2} \ln ||2\pi \mathbf{V}_m|| - \frac{1}{2} \mathbf{v}^T \mathbf{V}_m^{-1} \mathbf{v} \quad (2.22)$$

We can identify $\nu$ and $\Delta$ in $\ln p(\mathbf{v}) + \ln p(\text{data} \mid \mathbf{v}, r_i, r_j)$ using Equation 2.15 and 2.16 as

$$A = \left[ \mathbf{M}^T \mathbf{\Sigma}^{-1} \mathbf{M} + \mathbf{V}_m^{-1} \right]^{-1} \quad (2.23)$$

$$\mathbf{\nu} = -A \mathbf{M}^T \mathbf{\Sigma}^{-1} \mathbf{y} \quad (2.24)$$

$$\Delta = -2 \ln r_i - 2 \ln r_j + \frac{1}{2} \ln ||2\pi \mathbf{\Sigma}|| + \frac{1}{2} \ln ||2\pi \mathbf{V}_m|| + \frac{1}{2} \mathbf{y}^T \mathbf{\Sigma}^{-1} \mathbf{y} - \frac{1}{2} \mathbf{\nu}^T A^{-1} \mathbf{\nu} \quad , \quad (2.25)$$

which we plug in to Equation 2.13 to get the marginalized likelihood conditioned on the two distances $r_i, r_j$.

The marginalized likelihood for the hypothesis 2 model (the stars have independent velocities) is very similar. In this case, the marginalized likelihood is a product of two independent integrals $Q$, composed in the same way as the hypothesis 1 model but now for each star individually, where

$$\mathbf{y} = \begin{pmatrix} r \mu^x_{\alpha} \\ r \mu^0 \end{pmatrix}^T \quad (2.26)$$

$$\mathbf{\Sigma} = r^2 \mathbf{C} \quad (2.27)$$

$$\quad (2.28)$$
and $M$ is now the transformation matrix for one star. Then,

$$
A = [M^T \Sigma^{-1} M + V_m^{-1}]^{-1}
$$

(2.29)

$$
\nu = -A M^T \Sigma^{-1} y
$$

(2.30)

$$
\Delta = -2 \ln r + \frac{1}{2} \ln ||2\pi \Sigma|| + \frac{1}{2} \ln ||2\pi V_m|| + \frac{1}{2} y^T \Sigma^{-1} y - \frac{1}{2} \nu^T A^{-1} \nu ,
$$

(2.31)

and

$$
Q = \frac{1}{2} \ln ||2\pi A|| - \Delta .
$$

(2.32)
We report and discuss the discovery of a significant difference in chemical abundances of a comoving pair of bright solar-type stars, HD 240430 and HD 240429. The two stars have an estimated 3D separation of $\approx 0.6$ pc ($\approx 0.01$ pc projected) at a distance of $r \approx 100$ pc with nearly identical three-dimensional velocities, as inferred from Gaia TGAS parallaxes and proper motions, and high-precision radial velocity measurements. Stellar parameters determined from high-resolution Keck HIRES spectra indicate that both stars are $\sim 4$ Gyr old. The more metal-rich of the two, HD 240430, shows an enhancement of refractory ($T_C > 1200$ K) elements by $\approx 0.2$ dex and a marginal enhancement of (moderately) volatile elements ($T_C < 1200$ K; C, N, O, Na, and Mn). This is the largest metallicity difference found in a wide binary pair yet. Additionally, HD 240430 shows an anomalously high surface lithium abundance ($A$(Li) = 2.75),
higher than its cooler companion by 0.5 dex. The proximity in phase-space and ages between the two stars suggests that they formed together with the same composition, at odds with the observed differences in metallicity and abundance patterns. We therefore suggest that the star HD 240430, “Kronos”, accreted 15 $M_\odot$ of rocky material after birth, selectively enhancing the refractory elements as well as lithium in its surface and convective envelope.

### 3.1 Introduction

Wide binary stars are valuable tools for studying star and planet formation as well as Galactic dynamics and chemical evolution. In the context of studying the evolution of the Milky Way, they are useful for two main reasons. First, because wide binaries are weakly bound systems that may be tidally disrupted by, e.g., field stars, molecular clouds, or the Galactic tidal field, their statistics can be informative of the Galactic mass distribution. For example, the separation distribution of halo binaries has been used to constrain the mass of massive compact halo objects \cite{Yoo+2004,Quinn+2009,Allen&MonroyRodriguez2014}. They can also be used to test the “chemical tagging” hypothesis that stars from the same birthplace may be traced back using detailed chemical abundance patterns as birth tags \cite{Freeman&BlandHawthorn2002}. While any multiple-star system, including massive open clusters, can be used to test the hypothesis, wide binaries have the advantage of being extremely abundant, rendering their statistics a meaningful indication of whether the hypothesis works.

Binary stars that form from the same birth cloud start with nearly identical composition. A differential analysis of the chemical composition of binary stars can reveal their history through the chemical signatures related to planet formation or accretion regardless of Galactic chemical evolution. Giant planets on short period orbits have been shown, via population studies, to form more readily around inherently
metal rich stars (e.g., Fischer & Valenti 2005; Santos et al. 2004). However, the post-formation accretion of rocky planets can still alter the photospheric abundances. If host stars are polluted after their birth by rocky planetary material with a high refractory-to-volatile ratio, the convective envelope of the stars may be enhanced in refractory elements (e.g., Fe) compared to their initial state (e.g., Pinsonneault et al. 2001). Thus, differences in planet formation or accretion in two otherwise identical stars may imprint differences in chemical abundances that depend on the condensation temperature ($T_C$).

High resolution spectroscopic studies of binary star systems hosting at least one planet (Ramírez et al. 2011; Tucci Maia et al. 2014; Teske et al. 2013; Mack et al. 2014; Liu et al. 2014; Teske et al. 2015; Saffe et al. 2015; Ramírez et al. 2015; Biazzo et al. 2015; Mack et al. 2016; Teske et al. 2016a,b) have yielded varied results: while some systems appear to have undetectable differences in metallicities (see also Desidera et al. 2004; Gratton et al. 2001), other studies have reported a $T_C$-dependent difference in abundance with higher-$T_C$ elements showing larger differences. A possible explanation for the difference is that forming more gas giants or rocky planets leads to an overall or $T_C$-dependent depletion of metals in gas that eventually accretes onto the host star (Ramírez et al. 2015; Biazzo et al. 2015). Alternatively, late time accretion of refractory-rich planetary material can also produce the trend by enhancing the abundance of high-$T_C$ elements in one of the two stars. The observed differences are $\lesssim 0.1$ dex even in the most dramatic case, and often at a level of $\approx 0.05$ dex, making them challenging to detect even with a careful analysis of high-resolution, high signal-to-noise ratio spectra, and differential analyses of two stars that are very similar in their stellar parameters. We refer the readers to Appendix 3.A for a review of a handful of individual pairs studied in their detailed chemical abundances (see also Melendez & Ramirez 2016).
Spectral analysis of polluted white dwarfs (WDs) currently provides the strongest evidence for accretion of planetary material by a host star (Zuckerman et al. 2003, 2010; Koester et al. 2014; see Farihi 2016 for review). Because the gravitational settling times of elements heavier than He in the WD atmosphere is much shorter than the WD cooling time (Paquette et al. 1986), detection of metals likely indicates the presence of a reservoir of dusty material around the WD. Indeed, many of the polluted WDs host a dusty debris disk detected in the infrared (Zuckerman & Becklin 1987; Graham et al. 1990; Reach et al. 2005; Farihi et al. 2009; Kilic et al. 2006). Some of the most dramatically polluted WDs show surface abundances closely matched by rocky planetary material with, e.g., bulk Earth composition, strongly arguing that the disk formed from tidally disrupted minor planets (Zuckerman et al. 2007; Klein et al. 2010). Recently, transit signals from small bodies orbiting around a polluted WD have been detected by Kepler adding further support to the picture (Vanderburg et al. 2015).

Here, we report and discuss the discovery of a comoving pair of G stars, HD 240430 and HD 240429, with unusual chemical abundance differences that strongly suggest accretion of rocky planetary material by one of the two stars, HD 240430. Throughout the Chapter, we nickname the two stars Kronos (HD 240430) and Krios (HD 240429). In Greek mythology, Kronos and Krios were sons of Uranos and Gaia. Kronos notoriously devoured all of his children (except Zeus) to prevent the prophecy that one day he will be overthrown by them. We use the following convention for chemical abundances of stars: $[X/H]$ is the log ratio of the number density of an element X to H relative to the solar value, $[X/H] = \log_{10}(n_X/n_H)/n_{H,\odot}/n_{H,\odot})$. The absolute abundance of an element X is $A(X) = 12 + \log_{10}(n_X/n_H)$. In Section 3.2 we present the astrometric and spectroscopic data about the two stars relevant to the present discussion. In Section 3.3 we discuss possible interpretations of the abundance difference between the pair. We summarize our discussions in Section 3.4.
3.2 Data

Figure 3.1: Differences in posterior samples over Galactocentric phase-space coordinates for the two stars Krios and Kronos.

Krios and Kronos were identified as a candidate comoving star pair in our recent search for comoving stars using the proper motions and parallaxes from the Tycho-Gaia Astrometric Solution catalog (TGAS), a component of Gaia DR1. We refer the readers to this previous work (Oh et al., 2017) for a full explanation of the methodology behind this search and only include a brief description here. For a given pair, we compute
Table 3.1: Astrometric and spectroscopic measurements of the pair

<table>
<thead>
<tr>
<th>Name</th>
<th>Units</th>
<th>Krios HD 240429</th>
<th>Kronos HD 240430</th>
<th>Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Sp Type</td>
<td>G0</td>
<td>G2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) R.A. (^a)</td>
<td>hh:mm:ss</td>
<td>23:51:55.21</td>
<td>23:52:09.42</td>
<td></td>
</tr>
<tr>
<td>(4) 2MASS (^a)</td>
<td>J mag</td>
<td>8.593 ± 0.023</td>
<td>8.415 ± 0.026</td>
<td></td>
</tr>
<tr>
<td>(5) (T_{\text{eff}})</td>
<td>K</td>
<td>5878</td>
<td>5803</td>
<td>25</td>
</tr>
<tr>
<td>(6) (\log g)</td>
<td></td>
<td>4.43</td>
<td>4.33</td>
<td>0.028</td>
</tr>
<tr>
<td>(7) (v \sin i)</td>
<td>km s(^{-1})</td>
<td>1.1</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>(8) [Fe/H]</td>
<td></td>
<td>0.01</td>
<td>0.20</td>
<td>0.010</td>
</tr>
<tr>
<td>(9) Age</td>
<td>Gyr</td>
<td>(4.00^{+1.51}_{-1.56})</td>
<td>(4.28^{+1.11}_{-1.03})</td>
<td></td>
</tr>
<tr>
<td>(10) (v_r)</td>
<td>km s(^{-1})</td>
<td>−21.2</td>
<td>−21.2</td>
<td>0.2</td>
</tr>
<tr>
<td>(11) (\varpi) (^a)</td>
<td>mas</td>
<td>9.35 ± 0.24</td>
<td>9.41 ± 0.25</td>
<td></td>
</tr>
<tr>
<td>(12) (\mu_\alpha^*) (^a)</td>
<td>mas yr(^{-1})</td>
<td>89.25 ± 0.66</td>
<td>89.41 ± 0.69</td>
<td></td>
</tr>
<tr>
<td>(13) (\mu_\delta) (^a)</td>
<td>mas yr(^{-1})</td>
<td>−29.68 ± 0.54</td>
<td>−30.12 ± 0.52</td>
<td></td>
</tr>
</tbody>
</table>

\(T_c < 1200\) K

| \(A(\text{Li})\) \(^b\) | | 2.25 | 2.75 | 0.05 |
| [C/H] | | 0.00 | 0.09 | 0.026 |
| [N/H] | | −0.06 | −0.01 | 0.042 |
| [O/H] | | 0.01 | 0.09 | 0.036 |
| [Na/H] | | −0.06 | −0.04 | 0.014 |
| [Mg/H] | | −0.03 | 0.00 | 0.020 |

\(T_c > 1200\) K

| [Mg/H] | | 0.01 | 0.19 | 0.012 |
| [Al/H] | | 0.01 | 0.21 | 0.028 |
| [Si/H] | | 0.00 | 0.16 | 0.008 |
| [Ca/H] | | 0.02 | 0.23 | 0.014 |
| [Ti/H] | | 0.02 | 0.20 | 0.012 |
| [V/H] | | 0.02 | 0.20 | 0.034 |
| [Cr/H] | | 0.01 | 0.17 | 0.014 |
| [Fe/H] | | 0.01 | 0.20 | 0.010 |
| [Ni/H] | | −0.01 | 0.21 | 0.014 |
| [Y/H] | | 0.04 | 0.26 | 0.030 |

The listed quantities are: (1) spectral type (2) right ascension (3) declination (4) 2MASS identifier (5) effective temperature (6) surface gravity (7) rotational velocity (8) metallicity (9) stellar age derived in this work by isochrone fitting using the Yale-Yonsei model isochrones \(^{[\text{Spada et al. 2013}]\) see Section 3.3.1 (10) radial velocity (11) parallax (12) proper motion in right ascension direction (13) proper motion in declination direction. All values are from \(^{[\text{Brewer et al. 2016}]\) unless otherwise noted. The microturbulence parameter is fixed at 0.85 km s\(^{-1}\) \(^{[\text{Brewer et al. 2015}]\).\(\)

\(^a\) From TGAS.

\(^b\) Absolute abundances from \(^{[\text{Myles 2017 in prep}]\).
Figure 3.2: Abundances of the comoving pair, Krios (blue) and Kronos (red). Lines are drawn for each star only to guide the eye. Kronos is enhanced in Fe by $\approx 0.2$ dex relative to Krios along with Mg, Al, Si, Ca, Ti, V, Cr, Ni, Y yet not in C, N, O, Na, and Mn.

the marginalized likelihood ratio between the hypotheses (1) that a given pair of stars share the same 3D velocity vector, and (2) that they have independent 3D velocity vectors, using only the astrometric measurements from TGAS (parallaxes and proper motions). We then select a sample of high-confidence comoving pairs by making a conservative cut on this likelihood ratio. In the resulting catalog of comoving pairs (Oh et al. 2017), the pair presented in this paper was assigned a group id of 1199, and the marginalized likelihood ratio (Bayes factor) between the two hypotheses is $\ln \mathcal{L}_1/\mathcal{L}_2 = 8.52$, well above the adopted cut value of 6. While we independently identified this pair as described above, the pair has also been previously recognized as a common proper motion pair by Halbwachs 1986 and listed as a visual double star system in the Washington Double Star catalog (Mason et al. 2001). We have checked that we do not find any possible additional comoving companions by lowering the likelihood ratio cut for the stars around this pair.

In a separate effort to study detailed chemical abundances of potential planet-hosting stars, high-resolution spectra of both stars were obtained using the HIRES spectrograph on the Keck I telescope, and analyzed (Brewer et al., 2016). The spectral resolution is $R \approx 70000$ and the wavelength coverage is 5164–7799 Å. A typical
Figure 3.3: Selective segments of the spectra of Krios and Kronos. Alternating sets of two rows show the continuum-normalized data and model in the upper panel, and the ratio (Kronos/Krios) of data (gray) and model (black) in the lower panel.
Figure 3.4: Same as Figure 3.3 but for smaller portions of spectra at longer wavelengths that are not dominated by Fe. We mark elements that give rise to strong absorption lines. Note that the lines of Na and O, which are under-enhanced in Kronos relative to Fe or other refractory elements, show weaker residuals.

The signal-to-noise ratio in the spectral continuum is > 200 per pixel. The resulting measurements include elemental abundances for 15 chemical species (C, N, O, Na, Mg, Al, Si, Ca, Ti, V, Cr, Mn, Fe, Ni, Y) as well as stellar parameters and high precision radial velocities. For the details of the spectral analysis, we refer the readers to Brewer et al. 2016. Additionally, the Li doublet at 6707.6 Å for this sample was investigated in a separate work (Myles 2017 in prep). We list all relevant astrometric and spectroscopic measurements including the absolute abundances of Li for the two stars in Table 3.1.

The projected separation between the pair is 1.9′ (≈ 0.01 pc), and the 3D separation is ≈ 0.6 pc. Although selected based only on their astrometry, the two stars have identical radial velocities within their uncertainties (Table 3.1), confirming that they are truly comoving. Combining these precise radial velocities with the Gaia TGAS astrometry, we can compare differences between the inferred 6D phase-space
Figure 3.5: Lithium lines in the spectra of Kronos and Krios. This line is studied in Myles et al. (in prep.), and the fitting shown here is from that work. Line legends are the same as in Figure 3.3.
Figure 3.6: Abundance difference in this pair and other twin-like ($\Delta T_{\text{eff}} \lesssim 100$ K) wide binaries in [Brewer et al. 2016]. The differences in other pairs are small ($< 0.05$ dex) for all elements except N and O which are the most uncertain, making the difference of $\approx 0.2$ dex seen in Kronos-Krios rare. Additionally, we show the distribution of abundance differences between field stars with similar metallicity difference ($\Delta [\text{Fe}/H] \approx 0.2$) as violins with medians indicated by black line segments. These are random pairings of single stars in [Brewer et al. 2016] at two metallicity bins, $-0.025 < [\text{Fe}/H] < 0.025$ (160 stars) and $0.175 > [\text{Fe}/H] > 0.225$ (137 stars), similar to Kronos and Krios. The difference is always taken to be higher [Fe/H] − lower [Fe/H]. Thus, the narrower range of $\Delta [\text{Fe}/H]$ is by construction. Random pairings of disk stars with similar $\Delta [\text{Fe}/H]$ usually show similar enhancement in all other elements unlike the pattern seen in Kronos-Krios pair.
coordinates of the two stars. We start by generating posterior samples over the Heliocentric distance, \( r \), tangential velocities, \((v_{\alpha^*}, v_\delta)\), and radial velocity, \( v_r \), given the observed parallax, \( \hat{\pi} \), proper motions, \((\hat{\mu}_{\alpha^*}, \hat{\mu}_\delta)\), and radial velocity, \( \hat{v}_r \). We assume the noise is Gaussian, and the radial velocity measurements are uncorrelated with the astrometric measurements. If we define

\[
\hat{y} = \begin{pmatrix} \hat{\pi} & \hat{\mu}_{\alpha^*} & \hat{\mu}_\delta & \hat{v}_r \end{pmatrix}^T
\]

\[
y = \begin{pmatrix} r^{-1} & r^{-1} v_{\alpha} & r^{-1} v_\delta & v_r \end{pmatrix}^T
\]

then the likelihood is

\[
\hat{y} \sim N(y, C)
\]

where \( C \) is the covariance matrix. We adopt a uniform space density prior for the distance and an isotropic Gaussian for any velocity component, \( v \), with a dispersion \( \sigma_v = 25 \text{ km s}^{-1} \).

\[
p(r) = \begin{cases} \frac{3}{r_{\text{lim}}^2} r^2 & \text{if } 0 < r < r_{\text{lim}} \\ 0 & \text{otherwise} \end{cases}
\]

\[
p(v) = \frac{1}{\sqrt{2\pi} \sigma_v} \exp \left[ -\frac{1}{2} \frac{v^2}{\sigma_v^2} \right].
\]

For each of the two stars, we use \textit{emcee} (\textit{Foreman-Mackey et al.} 2013) to generate posterior samples in \((r, v_{\alpha}, v_\delta, v_r)\) by running 64 walkers for 4608 steps and discarding the first 512 steps as the burn-in period. For each sample, we convert the heliocentric phase-space coordinates into Galactocentric coordinates assuming that the Sun’s position and velocity are \( x_\odot = (-8.3, 0, 0) \) kpc and \( v_\odot = (-11.1, 244, 7.25) \) km s\(^{-1}\) (\textit{e.g., Schönrich et al.} 2010, Schönrich 2012).

\(^1\alpha^*\) denotes the projection in right ascension direction, i.e., \( \mu_{\alpha^*} = \dot{\alpha} \cos \delta \).
Figure 3.1 shows differences in posterior samples converted to Galactocentric phase-space coordinates for the two stars. The differences in velocities are consistent with zero. For a 2 M\(_\odot\) binary system, the Jacobi radius in the Solar neighborhood is 1.2 pc (Jiang & Tremaine 2010). Thus, Kronos and Krios are likely a bound system that formed coevally, and we expect the two stars to have identical metallicities and abundance patterns. However, one of the stars, Kronos is significantly more metal rich than the other by 0.2 dex (≈ 60%; Figure 3.2). Moreover, not all elements are equally enhanced: the abundances of Kronos show selective depletion in C, N, O, Na, and Mn relative to Fe. Kronos also has a high surface Li abundances, and the difference in Li abundance (≈ 0.5 dex) is the largest among all elements measured.

The validity of the measured abundance differences is further demonstrated in Figure 3.3, 3.4, and 3.5 where we show segments of the spectra and models of the two stars used to measure their abundances (Brewer et al. 2016). As expected from their reported metallicity difference (\(\Delta\text{[Fe/H]} \approx 0.2\)), the ratio of data and model between the two stars show significant residuals for almost all metal line features, largely dominated by Fe. However, for lines of elements that are not as enhanced in Kronos the residuals are much smaller in amplitude (Figure 3.4). The Li doublet, analyzed in a separate work (Myles et al. in prep.), is clearly visible in the spectra of both stars, and is stronger in Kronos (Figure 3.5).

We stress that none of the other four twin-like (\(\Delta T_{\text{eff}} \lesssim 100\) K) wide binary pairs examined by Brewer et al. 2016 show discrepancies in abundances between the stars at this level. As shown in Figure 3.6, the differences in other pairs for all elements except N and O, which are also the most uncertain (Table 3.1), are less than 0.05 dex, making Kronos-Krios pair a significant outlier. The statistical uncertainties for each parameter presented in Table 3.1 from Brewer et al. 2016 are estimated from repeated measurements of multiple spectra of the same stars. We note that while there may be systematic uncertainties (bias) in the elemental abundances of these two stars.
unconstrained by this procedure, the systematic uncertainties, if any, for these two solar-type “twin-like” stars with small differences in $T_{\text{eff}}$ and $\log g$ are unlikely to wash out the observed abundance differences of $\approx 0.2$ dex.

Figure 3.7: Left panel: Galactic orbits computed for Krios (black) and the Sun (grey). For Krios, the initial conditions are set to the median of the posterior samples over the phase-space coordinates. The orbits are computed by integrating backwards from the present-day positions for 2.5 Gyr with a time step of 0.5 Myr using the Leapfrog integration scheme implemented in Gala [Price-Whelan et al. 2017]. Right panel: distribution of maximum $z$-heights for orbits computed from all posterior samples.

3.3 Discussion

We discuss the possible origins of the peculiar abundance differences of Kronos & Krios. We first discuss the ages and coevality of the stars in this pair, and consider both possibilities in which the two stars are or are not coeval. Our favored scenario is discussed in the last subsection, Section 3.3.5.

3.3.1 Stellar Ages & Coevality

Apart from their closeness in phase-space coordinates, we can constrain the ages of the two stars given the precise measurements of $\log(g)$ and $T_{\text{eff}}$ by comparing these
Figure 3.8: Abundance differences of the Kronos-Krios pair ranked by the condensation temperature of elements for solar composition gas from [Lodders 2003]. The condensation temperature may be read from the gray line and right y-axis. We show three wide binary systems selected from the literature: HD 20782/1 ([Fe/H] ≈ 0), XO-2N/S ([Fe/H] ≈ 0.35), and WASP-94AB ([Fe/H] ≈ 0.3). Locations of elements with at least one measurement from any study are indicated by a vertical line and its symbol. Note that often multiple values are reported for one element corresponding to different ionization states in equivalent width analyses. No other pair studied so far were shown to have such large difference in metallicity or sharp contrast between (moderately) volatile and refractory elements as Kronos-Krios.

Values to theoretical isochrones. We use the distances (inferred from Gaia parallaxes), V-band magnitudes, and B – V colors to obtain bolometric luminosities of the two stars ([VandenBerg & Clem 2003]). We then combine the luminosities with effective temperature, [Fe/H], and [Si/H] in order to interpolate the age, mass, and radius of each star using a grid of Yale-Yonsei model isochrones ([Spada et al. 2013]). The best-fit isochrone ages of Kronos and Krios are $4.28^{+1.11}_{-1.03}$ Gyr and $4.00^{+1.51}_{-1.56}$ Gyr, respectively, consistent with them being coeval.

The surface lithium abundance in a Sun-like star decreases with its age due to mixing induced by convection or rotation, which brings the lithium into the interior
$(T > 2.5 \times 10^6 \text{ K})$ where it will be destroyed by proton capture burning. In hotter stars with thin convective zones on the main sequence, most of this mixing occurs in the pre-main sequence phase when the star is fully convective. Thus, surface lithium abundance can be an indicator of stellar ages, especially whether the star is very young ($\lesssim 1 \text{ Gyr}$). The absolute Li abundance of solar-type stars also correlates steeply with the effective temperature (e.g., Chen et al. 2001; Ramírez et al. 2012). Generally, cooler stars with larger convective envelope have lower Li abundances. The absolute Li abundance of 2.25 dex for Krios is typical for its $T_{\text{eff}}$. On the other hand, the lithium abundance ($A(\text{Li}) = 2.75$) of Kronos, which has lower $T_{\text{eff}}$ than Krios, is not only higher than that of Krios but also much higher compared to other field stars of similar $T_{\text{eff}}$. Given the overall higher metal abundances and the peculiar abundance patterns in Kronos, it is unclear, however, whether this higher Li abundance means a younger age or something else. For example, Casey et al. 2016 attributes the presence of Li-rich red giant stars to the engulfment of substellar companions such as gas giant planets or brown dwarfs which may replenish Li.

The surface lithium abundance of Kronos is the only indicator of a younger age. If the two stars were only several hundred Myrs old, then they may have been part of a larger comoving group of stars. However, as we mention above (Section 3.2), there is no evidence in our search of comoving pairs using TGAS that the two stars belong to a larger group of young stars. Very young stars often show signs of activity such as X-ray emission from magnetic activity, emission lines, or infrared excess due to circumstellar disks (Feigelson & Montmerle 1999; Adams et al. 1987). We have compiled GALEX, Tycho-2, 2MASS, and WISE photometry for these stars, and found no evidence for indications of activity in their spectral energy distributions. The low $v \sin(i)$ values (Table 3.1) also argue against very young ages that would be inferred from the surface lithium abundance. Finally, we computed the Galactic orbit of the pair using the median of the posterior sample over the phase-space coordinates of
Krios, in a Milky Way-like gravitational potential (similar to MWPotential2014 from Bovy [2015]) using Gala (Price-Whelan et al. [2017]). The pair’s fiducial orbit has a vertical action larger than the Sun, favoring an older age (Wielen [1977]; Aumer et al. [2016]). We therefore conclude that the two stars are most likely coeval, ~4 Gyr old main sequence stars, and that the unusually high Li abundance of Kronos requires an alternative explanation.

### 3.3.2 Chance pair of unassociated single field stars?

Given that their metallicities and abundance patterns are significantly different, one may simply conclude that the two stars are not physically associated but they merely happen to be comoving at such a small separation (~0.6 pc) by chance. An estimate of this probability requires an assumption about the distribution function of single stars in the Milky Way. We used the Gaia Universe Mock Simulation (GUMS; Robin et al. [2012]), a mock end-of-mission Gaia catalog with the Besançon Galaxy model (Robin et al. [2003]), and looked for a chance pair of solar-mass (0.9 \( M_\odot \) < \( M \) < 1.1 \( M_\odot \)) primary stars ignoring any companions to the primary. Within 200 pc from the Sun, there are 7061 pairs with separation less than 2 pc among 119259 solar-mass primary stars. Of these pairs, we find zero with small enough differences in observed quantities such that \( \Delta \mu_\alpha^* < 2 \text{ mas yr}^{-1} \), \( \Delta \mu_\delta < 2 \text{ mas yr}^{-1} \) and \( \Delta v_r < 2 \text{ km s}^{-1} \). These are still with generous difference budgets in both positions and velocities, and the actual observed differences are smaller (Table 3.1). We find a single pair with velocity difference less than 2 km s\(^{-1}\). Thus, while we cannot prove the binarity this pair by resolving its orbit, it seems more natural to assume that they are physically associated rather than a chance pair of unrelated single stars. This does not take into account the fact that one of the stars, Kronos, is genuinely atypical in its abundance pattern (Figure 3.6) and Li abundance, which would make a chance pair like Kronos-Krios even more unlikely in a probabilistic sense.
3.3.3 Exchange Scattering

Another possibility that two stars unrelated at birth may end up in a binary system is via a binary-single scattering event that results in an exchange of binary members. In order to estimate the rate at which any binary-single event will produce a wide binary system such as Krios and Kronos, we may consider the rate at which this wide binary will scatter with a field star to result in an exchange reaction. The cross-section of exchange scattering for a binary with semi-major axis $a$ is

$$\sigma_{\text{ex}} = \frac{640}{81} \pi a^2 \left( \frac{v_i}{v_c} \right)^{-6} \quad (3.6)$$

where $v_i$ is the incoming velocity, and $v_c$ is the critical velocity, defined as

$$v_c^2 = \frac{G m_1 m_2 (m_1 + m_2 + m_3) 1}{m_3 (m_1 + m_2) a} \quad (3.7)$$

Equation (3.6) is appropriate when $v_i/v_c \gg 1$ (Hut & Bahcall 1983; Hut 1983), which is the case for wide binaries scattering with field (disk) stars. If we assume that field stars are made of solar-mass stars with a constant number density $n = 1 \text{ pc}^{-3}$, and the incoming velocity of field stars is $10 \text{ km s}^{-1}$, the rate of exchange scattering is

$$n \sigma_{\text{ex}} v_i = 6.82 \times 10^{-8} \text{ Gyr}^{-1} \frac{n}{\text{pc}^{-3}} a \left( \frac{10 \text{ km s}^{-1}}{v_i} \right)^5 \quad (3.8)$$

low enough to be negligible.

An exchange scattering scenario is unlikely to be able to explain the observed abundance difference pattern of Kronos and Krios. We test this by randomly drawing pairs of stars in the sample of Brewer et al. 2016 from two $[\text{Fe/H}]$ bins at $[\text{Fe/H}] = 0 \pm 0.025$ and $[\text{Fe/H}] = 0.2 \pm 0.025$, each similar to Krios and Kronos. In Figure 3.6 we compare the observed abundance difference of Kronos-Krios with the distribution of abundance differences from 300 random pairs. We see that when a star is enhanced
in Fe by 0.2 dex, all other elements are typically enhanced at a similar level, with some variations. Specifically, for a typical star with [Fe/H] \approx 0.2 dex, we generally expect [Na/Fe] > 0 and [Mn/Fe] > -0.1 (Battistini & Bensby 2015; Bensby et al. 2003) making the low [Na/Fe] and [Mn/Fe] seen in Kronos very unlikely to arise from variations in Galactic chemical evolution.

### 3.3.4 Chemical Inhomogeneity in Star Formation

In this subsection, we explore the hypothesis that chemical inhomogeneity within the birth cloud is the source of the observed abundance difference. There is ample evidence against this scenario as most wide binaries show a difference in [Fe/H] less than 0.02 dex (Desidera et al. 2004; Gratton et al. 2001). Even when a significant difference is detected with high-precision abundance measurements, the difference is typically \sim 0.05 dex (see Figure 3.8 and Section 3.A). Consistent with these results, none of the other seven similar wide binaries examined in Brewer et al. 2016 show such large differences in abundances though there is generally a larger spread in C, N and O, and some pairs show a difference in particular elements as large as \approx 0.15 dex.

The median and maximum [Fe/H] difference between component stars in the other seven pairs is 0.02 dex and 0.09 dex, respectively. The differences are even smaller (maximum \Delta[Fe/H] = 0.03 dex) if we compare only twin-like (\Delta T_{\text{eff}} \lesssim 100 K) pairs (Figure 3.6 black lines). Thus, a difference of \approx 0.2 dex seen in Kronos-Krios pair is unlikely to be due to chemical inhomogeneity in the birth cloud.

### 3.3.5 Accretion of rocky planetary material

Another possibility that two coeval stars may end up with different surface abundances is accretion of planetary material after birth. In a multi-planet system, dynamical instabilities triggered by planet-planet scattering (Rasio & Ford 1996; Weidenschilling & Marzari 1996) or encounters with a field star (Malmberg et al. 2011) can lead to
Figure 3.9: Comparing the observed abundance difference (Kronos − Krios; blue circles) to the expected change in solar surface abundance after adding 15 $M_\oplus$ of material with bulk Earth composition [McDonough 2003] (black open and filled circles). The assumed mass fraction in the convective zone is 0.02. All astronomical metals are ordered by their $T_C$ for solar composition gas on the $x$-axis. For the predictions, we highlight elements measured for Kronos-Krios pair in filled circles, while those without a measurement are left open. The close match with the observed abundance difference in Kronos-Krios pair suggests that the abundance difference may be due to accretion of 15 $M_\oplus$ of rocky planetary material. The element Li is off the plot and indicated in the inset.

Planet ejection or accretion. Indeed, it is an important goal of many exoplanet studies to detect chemical signatures of planet formation or accretion, distinguish them from Galactic chemical evolution, and connect them to theories of evolution of planetary systems. One approach that is free from confusion with Galactic chemical evolution is to compare two almost identical stars in a wide binary system. Assuming that the component stars were born together with identical initial composition, we may see a difference in their surface abundances if the two stars then accreted different amounts of planetary material. The resulting abundance difference may depend on the condensation temperatures of elements in the protoplanetary disks from which the accreted planets formed, as their compositions depend on the radial temperature gradient in the disk.
In Figure 3.8, we show the abundance difference between Kronos and Krios ordered by the rank of $T_C$ of each element. The equilibrium condensation temperatures for the composition of solar system are taken from Lodders 2003 (Table 8). The difference seen in Kronos-Krios is compared to HD 20781/2, XO-2N/S, WASP-94A/B in Figure 3.8. The metallicity difference of $\approx 0.2$ dex observed in this pair is larger than the differences seen in any other pairs studied so far (see also Appendix 3.A). The five under-enhanced elements in Kronos relative to Krios are the five most volatile in all elements measured. The difference in Mn ($T_C = 1158$ K) and Cr ($T_C = 1296$ K) suggests a break in $T_C \approx 1200$ K. This $T_C$-dependent trend of $\Delta[X/H]$, combined with the enhanced Li abundance ($A$(Li) = 2.75), strongly suggests that accretion of rocky material has occurred in Kronos.

How much mass of rocky material is needed to explain an increment of $\approx 0.2$ dex? We carry out simple toy calculations of the expected $\Delta[X/H]$ in a Sun-like star’s atmosphere by adding a certain mass of bulk Earth composition under these simplifying assumptions:

- The material added is instantly and completely mixed through the star’s convective zone.
- The atmospheric composition that we measure is identical throughout the star’s radiative and convective zone.
- The surface abundance of the star has been altered only by the accretion event(s).

We take the solar abundances, $[X/H]$, of element X (Asplund et al. 2009) which can be converted to mass fraction as

$$f_{X,\text{photo}} = \frac{10^{[X/H]} m_X}{\sum_X 10^{[X/H]} m_X} \quad (3.9)$$
where \( m_X \) is the mass of each element in, e.g., atomic mass unit. Assuming that the accreted material has a total mass \( M_{\text{acc}} \), and the mass fraction in each element \( f_{X,\text{acc}} \), the abundance difference is

\[
\Delta[X/H] = \log_{10} \frac{f_{X,\text{photo}} f_{\text{CZ}} M_{\text{star}} + f_{X,\text{acc}} M_{\text{acc}}}{f_{X,\text{photo}} f_{\text{CZ}} M_{\text{star}}}
\]  

(3.10)

where \( f_{\text{CZ}} \) is the fraction of the star’s mass in the convective envelope. We assume \( f_{\text{CZ}} = 0.02 \) (Spada et al. 2013), and take the composition of bulk Earth from a chondritic model of the Earth (McDonough 2003). Similar calculations have been performed by, e.g., Chambers (2010), Mack et al. (2014, 2016).

Figure 3.9 shows the expected change of surface abundances of metals in a Sun-like star after 15 \( M_\oplus \) of material with composition of bulk Earth is added. A volatility trend such that more volatile (low \( T_C \)) elements are more depleted in the Earth relative to CI or other carbonaceous chondrites has long been known (McDonough 2001). This trend is presumed to be closely related to the formation of terrestrial planets and, in particular, to the radial temperature gradient in a protoplanetary disk. The trend resulting from adding 15 \( M_\oplus \) of bulk Earth provides an overall good match to the observed \( \Delta[X/H] \), suggesting that the refractory-enhanced star, Kronos accreted 15 \( M_\oplus \) more of rocky planetary material than Krios.

What about Li? The element Li is worth special attention in the context of the accretion scenario. Because Li is present in either carbonaceous chondrites or bulk Earth with a concentration of 1 – 1.5 ppm in mass (McDonough 2003), but is depleted quickly within the first Gyr on the surface of a Sun-like star (Thévenin et al. 2017; Baraffe et al. 2017), accretion of either material at later times will significantly replenish the lithium on the star’s surface. For the present-day Sun (\( A(\text{Li}) = 1.05 \)), the accretion of 15 \( M_\oplus \) of bulk Earth-like material would result in \( \Delta[\text{Li/H}] \approx 1.65 \) dex (see the inset of Figure 3.9). This closely matches what we find: the Li abundance of
Kronos is $A(\text{Li}) = 2.75$ (Table 3.1 Myles 2017 in prep) approximately 1.7 dex higher than the solar value.

We stress that while the calculation carried out is useful in an order-of-magnitude sense, further investigation of each of the simplifying assumptions made is warranted. In addition, the composition of bulk Earth has some uncertainties. For example, the reported bulk Earth concentration of the siderophile element Mn, varies from 800 to $\approx 2000$ ppm (Lodders & Fegley 1998, McDonough 2001, 2003) mainly due to the uncertainty of the Earth’s core composition. Given these limitations, the level of agreement for $\Delta[X/H]$ and Li for Kronos is remarkable.

The fractional mass in the convective zone of solar-type stars decrease dramatically in the first Gyr, and then stays nearly constant at $\approx 2\%$ (Spada et al. 2013). Because the accreted mass $M_{\text{acc}}$ is proportional to $f_{\text{CZ}}$, given the large metallicity enhancement ($\approx 0.2$ dex), the accretion must have happened after a thin convective envelop is established. Otherwise, the accreted mass would be unreasonably high. Thus, it is plausible that a dynamical process after the planet formation ended is responsible for pushing rocky planets in.

Finally, we mention that detection of $^6\text{Li}$ provides a strong test for this scenario. This isotope of Li is destroyed at even lower temperatures than $^7\text{Li}$, and theoretically expected to be absent (Pinsonneault 1997). However, an accretion of Rocky material could have replenished $^6\text{Li}$. Because $^6\text{Li}$ lines are slightly longer in wavelengths, presence of $^6\text{Li}$ increases the asymmetry of Li 6707.6 feature. Depending on how recent the accretion was and how fast $^6\text{Li}$ is depleted on the main sequence, this feature may be detectable. This is a very subtle effect that requires a higher signal-to-noise, higher resolution spectra and careful modelling effort (see e.g., Israeli et al. 2001, Reddy et al. 2002). Such investigation was not warranted by the current data (Myles 2017 in prep).
3.4 Summary

We report and discuss very different metallicities ($\Delta [\text{Fe/H}] \approx 0.2$ dex), and condensation temperature ($T_C$)-dependent abundance differences in a comoving pair of bright solar-type stars HD 240430 and HD 240429 (G0 and G2). The more metal-rich of the two stars, HD 240430 (Kronos), shows enhancement in all ten elements with $T_C > 1200$ K including Fe, while under-enhanced in the five elements, C, N, O, Na, and Mn with $T_C < 1200$ K relative to HD 240429 (Krios). It also has an anomalously high surface Li abundance for its age of $\sim 4$ Gyr, and its effective temperature very close to that of the Sun. We consider that the comoving pair may have formed from two stars of different birth origins by chance (Section 3.3.2) or in an exchange scattering event (Section 3.3.3), or that there may be chemical inhomogeneity in the birth cloud (Section 3.3.4) to find all unlikely.

In order to explain the $T_C$-dependent enhancement and high Li abundance of Kronos, we consider the accretion of planetary material as the most plausible cause (Section 3.3.5). We argue that an accretion of 15 $M_\oplus$ of bulk Earth composition to Kronos after its thin convective zone is in place can explain the enhancement in both refractory elements and lithium. What triggered the planet engulfment in one of the two comoving stars remains unclear. One possibility is that a fly-by interaction with a field star could have triggered eccentricity excitation of outer planets, which may have propagated inward through planet-planet scattering, leading to the accretion of inner rocky planets (Zakamska & Tremaine 2004; Malmberg et al. 2011). If this is the case, there may be surviving, highly-eccentric giant planets potentially detectable with future data releases of the Gaia mission.

Despite the arguments presented above for the two star’s physical association based on phase-space coordinates and a physically interesting explanation for their metallicity and abundance differences, we can never completely rule out a very rare possibility that the two stars, in which one has an uncommon abundance pattern including high
Li abundance, are not coeval but happen to be so close in phase-space coordinates. Indeed, we do not resolve the orbital motions of the system, and cannot know whether they are gravitationally bound or, possibly, they have recently been disrupted. Such skepticism may be based on or amplified the large metalicity differences. Yet, another recent study has reported a comoving pair of solar-type stars in which one shows similarly disparate metallicity ($\Delta [\text{Fe/H}] \approx 0.1 \text{ dex}$) and $T_C$-dependent abundance patterns as well as higher Li, leading to a similar conclusion [Saffe et al. 2017]. From the possibilities that we have considered, we think that, in fact, the seemingly exotic explanation of rocky planet engulfment in one of the stars is the simpler and more natural scenario for all of the observed properties of the two stars.

The two stars have not been included in any publicly released data from planet search programs. We have begun a precision radial velocity campaign for the two stars and early indications are that there are no close in giant planets. If both stars have accreted planetary material, it would be very interesting to search for the existence and architectures of the planetary systems left behind.

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This research utilized: Astropy (Astropy Collaboration et al. 2013), corner.py (Foreman-Mackey 2016), emcee (Foreman-Mackey et al. 2013), IPython (Pérez & Granger 2007), matplotlib (Hunter 2007), numpy (Van der Walt et al. 2011), and pandas (McKinney 2010).

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3.A Review of Detailed Chemical Abundance Studies of Stars in Comoving Pairs

We review and summarize a handful of wide binary systems that have been studied in their detailed chemical abundances so far with high-resolution spectroscopy. These systems are 16 Cygni A/B, HD 20782/HD 20781, HD 80606/HD 80607, XO-2N/XO-2S, HAT-P-1, WASP-94A/WASP94-B, and HD 133131A/HD 133131B. We focus on key characteristics of stars and planets, and interpretations of any trend in $\Delta[X/H]$ with $T_C$. Interested readers may also consult Melendez & Ramirez 2016.

**16 Cygni A/B:** The chemical composition of this well know pair of solar-type stars (G1.5/G3) has been studied many times. The hotter star 16 Cyg A has no detected planets, but has an M dwarf companion $\sim 70$ AU away in projected separation which is probably physically associated (Patience et al. 2002), and may have affected planet formation process around the star (Jensen et al. 1996; Mayer et al. 2005). The other star, 16 Cyg B, hosts a giant planet on an eccentric orbit ($e = 0.63$, Cochran et al. 1997). While past measurements of metallicity and abundance difference between the two stars reported conflicting results (Laws & Gonzalez 2001; Schuler et al. 2011), recent studies using high quality spectra (Ramírez et al. 2011; Tucci Maia et al. 2014) consistently reported that A is more metal rich than B by $\approx 0.04 \pm 0.005$ dex. However, there is still a disagreement between studies on whether abundance differences shows a correlation with $T_C$ as well as its interpretation. Tucci Maia et al. 2014 suggested that formation of $1.5 - 6$ $M_\oplus$ rocky core for the giant planet around 16 Cyg B can explain the offset and the positive correlation between $\Delta[X/H](A - B)$ and $T_C$. On the other hand, Ramírez et al. 2011 who found no correlation, argued that forming giant planets results in an overall shift in all elements.

**HD 20782/HD 20781:** Two common proper motion G dwarf stars (G2/G9.5) with a projected separation of $\sim 9000$ AU (corresponding to 4.2′ sky separation) and
solar metallicity host close-in giant planets. HD 20782 hosts a Jupiter-mass planet on
a very eccentric \((e \approx 0.97)\) orbit with a pericenter distance of 1.4 AU while HD 20781
hosts two Neptune-mass planets within 0.3 AU with moderately high eccentricity
\((e \approx 0.1 - 0.3).\) The measured abundances of 15 elements between the two stars
are consistent with each other \cite{Mack2014}. However, \cite{Mack2014} argued
that there is a moderately significant \((\sim 2\sigma)\) positive slope of \(\approx 10^{-5}\) dex K\(^{-1}\) with
increasing \(T_C\) for \(T_C > 900\) K elements (namely, Na, Mn, Cr, Si, Fe, Mg, Co, Ni, V,
Ca, Ti, Al, Sc leaving out C and O of their measurements) in the abundances of each
star individually. They suggest that this slope is evidence that the stars accreted
10 – 20 \(M_{\odot}\) of H-depleted rocky material during giant planet migration.

**HAT-P-1:** This pair of G0 stars separated by 11" with [Fe/H] \(\approx 0.15\) has different
planetary systems: the secondary star is known to host one transiting giant planet
while no planet has been discovered around the primary star. The two stars are
identical in metallicities and abundances for 23 elements measured with the mean
error of 0.013 dex \cite{Liu2014}. Thus, it seems that the presence of close-in giant
planet does not necessarily lead to atmospheric pollution of its host star.

**HD 80606/HD 80607:** Similar to HAT-P-1, no significant chemical difference
is found between two common proper motion G5 stars with super-solar metallicity
([Fe/H] \(\approx 0.35\)). HD 80606 which hosts a very eccentric \((e \approx 0.94)\) giant planet and
HD 80607 which has no detected planets \cite{Saffe2015, Mack2016}.

**XO-2N/XO-2S:** A few independent studies have investigated this pair of G9
stars with super-solar metallicity ([Fe/H] \(\gtrsim 0.35\)). XO-2N hosts a giant planet while
XO-2S is known to host two giant planets with masses 0.26\(M_{\text{Jup}}\) and 1.37\(M_{\text{Jup}}\) on
moderately eccentric \((\approx 0.15)\) orbits at \(< 0.5\) AU. A significant difference of metallicity
\((\gtrsim 0.05\) dex) is detected between the two stars with a possible correlation with \(T_C\)

\(^{2}\) The two stars were monitored by HARPS campaign, and it has recently been reported by \cite{Udry2017} that HD 20781 hosts four planets between \(M \sin(i) \approx 0.006 - 0.04 \ M_{\text{Jup}}\) with \(e \leq 0.11\) within \(\approx 0.35\) AU.
At low $T_C$, the difference $(N - S)$ in volatile elements differ by $\sim 0.01$ dex while the range of difference spans up to $0.1$ dex at $T_C > 1600$ K.

Ramírez et al. (2015) suggested that the small overall depletion ($\approx 0.015$ dex) of metals in XO-2S compared to XO-2N is plausibly due to the presence of more gas giant planets around XO-2S, following a similar interpretation of Meléndez et al. (2009) of the trend between solar twins and the Sun. In this scenario, forming planets in the protoplanetary disk locks heavier elements to the core of gas giant planets. The positive correlation of $\Delta[X/H](N - S)$ with $T_C$ requires a scenario involving rocky planets. Both forming more rocky planets in XO-2S and accreting more rocky planets to XO-2N at later stage were discussed (Ramírez et al. 2015; Biazzo et al. 2015). The estimated mass of rocky material required to explain the observed trend is a few tens of $M_\oplus$.

**WASP-94A/B**: Each star in this pair of F8 and F9 stars with super-solar metallicity ([Fe/H] $\approx 0.3$) hosts a hot Jupiter. The planet around WASP-94A is transiting with a misaligned, probably retrograde circular ($e < 0.13$) orbit, while that hosted by WASP-94B is a little more massive by $\sim 0.15$ $M_{\text{Jup}}$ and closer in, aligned with the host star. WASP-94A shows a depletion of $0.02$ dex in volatile and moderately volatile elements ($T_C < 1200$ K) and an enhancement of $0.01$ dex in refractory elements ($T_C > 1200$ K) relative to WASP-94B, with a median uncertainty of $0.006$ dex among all elements resulting in a statistically significant non-zero slope between $\Delta[X/H]$ and $T_C$ (Teske et al. 2016a). Multiple possibilities related to the formation and evolution of planetary systems around each star as well as causes unrelated to planets such as dust cleansing during the fully convective phase or different rotation and granulation between the stars were considered, but none was favored.

$^3$ Note that the condensation temperature $T_C$ used is for solar system composition gas, which can differ from that of higher metallicity gas.
\(\zeta^1/\zeta^2\) Reticuli (HD 20807/HD 20766): With a projected separation of \(\approx 3700\) AU, both solar-type stars in this pair have no detected planets. However, \(\zeta^2\) hosts a debris disk detected via infrared excess (Trilling et al. 2008) as well as direct imaging (Eiroa et al. 2010). Both stars have super-solar metallicity of \(\approx 0.2\) dex. A differential abundance analysis using high-resolution spectra shows that \(\zeta^1\) is more metal rich than \(\zeta^2\) by \(\sim 0.02 \pm 0.003\) dex, and that there is a positive slope between the abundance differences of 24 species and \(T_C\). A possible explanation proposed is that the relative lack of refractory elements in \(\zeta^2\) is because they are locked up in rocky bodies that make up its debris disk (Saffe et al. 2016).

HD 133131A/B: For this metal-poor ([Fe/H] \(\approx -0.3\)), old \((\sim 9.5\) Gyr) pair of solar-type stars, high-precision radial velocity monitoring recently revealed several planets (Teske et al. 2016b): star A hosts two eccentric giant planets at \(\approx 1.4\) and \(\approx 5\) AU while star star B hosts a longer period giant planet at \(\approx 6.5\) AU. Teske et al. 2016b measured a deficit of \(0.03 \pm 0.017\) dex in refractory elements in A relative two B without any conclusive interpretation.
Chapter 4

Rediscovery of a nearby young, coeval moving group

We confirm and characterize a recently discovered, nearby ($d \approx 100$ pc), young (age $\approx 250$ Myr) moving group using astrometric and photometric data from Gaia DR 2 combined with spectroscopic data compiled from the literature. This group, which notably includes two A-type stars, 81 Uma (HIP 66198) and and 84 Uma (HIP 67231), spans a large area on the sky, ($\Delta R.A., \Delta Decl.$) $\approx (39, 18)$ deg, thus allowing for a well-constrained astrometric radial velocity that agrees with spectroscopic radial velocities for a subset of members. The morphology of the group in the Galactic $X-Y$ coordinates shows an interesting gap while it is highly concentrated in $Z$ direction. We discuss possible origins of the gap in relation to the disruption of the group.

4.1 Introduction

Comoving, coeval stars in the solar neighborhood are valuable astrophysical laboratories for studying stellar properties, stellar evolution, and galactic dynamics (e.g., Gaia Collaboration et al., 2018b; Montes et al., 2018). Multiple stars form in each molecular cloud, often in kinematically coherent groups. Galactic dynamics determines how
and when these groups eventually dissolve into the field population. Thus, a detailed census of these objects traces both the recent star formation history in the local volume as well as the dynamics of their disruption. Individual star clusters or coeval moving groups are also interesting dynamical entities themselves as their dynamical evolution is intimately tied to their internal structures and external perturbations from the Galactic tides or giant molecular clouds. Finally, within ≈ 100 pc, members of young stellar groups represent the best samples to study dusty debris disks, exoplanets and brown dwarfs through direct imaging.

The second data release from the \textit{Gaia} mission (DR 2; Gaia Collaboration et al. 2018a) marks a new era for charting the kinematic substructure and stellar populations in the solar neighborhood. \textit{Gaia} DR 2 provides parallaxes, proper motions, and precise two-band photometry of stars brighter than $G \lesssim 20.7$ as well as radial velocities for stars brighter than $G \lesssim 12.5$. Previously, we performed a search for comoving pairs using the Tycho-Gaia Astrometric Solution (TGAS), a subset of \textit{Gaia} DR 1 which provides astrometric measurements for 2 million sources in the Tycho-2 catalog ($G < 12$ mag; Oh et al., 2017). This comoving-pair search both recovered many of the large known nearby comoving stellar groups, ranging from loose associations to open clusters, and identified several previously unknown large and small groups (see also Faherty et al. 2018). Since DR 2 goes much deeper and provides more precise parallaxes and proper motions, it is worth revisiting these new groups with the new data in order to better characterize their memberships and properties.

Here, we focus on one of the most interesting of the coeval moving groups discovered in Oh et al. (2017), Group 10, which stands out as the largest and nearest new group from the search with little prior discussion in the literature. We use the \textit{Gaia} DR 2 data to extend the candidate membership in Section 4.2, discuss the ages, kinematic modelling and morphology of the group in Section 4.3, and summarize in Section 4.4.
4.2 Data & Sample

Before extending the membership with Gaia DR 2, we briefly summarize how the group was initially discovered in Oh et al. (2017) using the TGAS data. We calculate the marginalized likelihood ratio between the model in which two stars in a pair have the same three-dimensional velocity vector and the model in which they have two independent velocity vectors based on probabilistic models that connect velocities to the astrometric parameters of the stars and their uncertainties. We do not make any pre-positioned cuts to exclude known comoving systems, and find that by looking for
comoving pairs we can naturally detect larger comoving groups as connected comoving pairs. Many of these groups correspond to known open clusters and associations, but even quite a few of the large groups containing more than 10 members are new. We refer the readers to Oh et al. (2017) for details. An independent assessment of the correspondence of these groups to 27 known associations within 150 pc from the Sun is performed by Faherty et al. (2018). Group 10 stands out as the largest and nearest among the new groups.

We search for candidate members of Group 10 in Gaia DR 2 based on the angular and parallactic spread of this group from the previous discovery using TGAS. We go out to 20 degrees and 9 degrees from the mean position \((\alpha, \delta) = (215.32, 56.133)\) in R.A. and Decl. direction respectively, and a nominal 20 pc in distance around the median parallax of 9.94. The exact query executed on the Gaia Archive is

```
select *
from gaiadr2.gaia_source
where
  ra between 195.320 and 235.320
  and dec between 47.134 and 65.134
  and parallax between 8.3 and 12.4
```

There are 3413 Gaia sources within these cuts. Figure 4.1 shows the distribution of these sources on sky and in proper-motion space. While there is no discernable concentration of sources on sky (Figure 4.1a), a clear overdensity is found in proper-motion space at \((\mu_\alpha^*, \mu_\delta) \approx (-16.8, -3) \text{ mas yr}^{-1}\) in agreement with the previous identification using TGAS. Of course, the sources in this overdensity do not have exactly the same proper motion due to geometric projection. The span of this overdensity in Figure 4.1b mainly corresponds to the spread in parallaxes: sources with larger parallaxes have larger proper motions.
In order to select candidate members of the group, we fit a Gaussian mixture model to the zoom-in box indicated in Figure 4.1b in \((v^*_\alpha, v_\delta)\) space with two components: one for the overdensity corresponding to the group and one broad component for the background. The zoom-in box in \((v^*_\alpha, v_\delta)\) space is shown in Figure 4.1c. We select 194 sources with higher probability (> 0.5) of belonging to the overdensity component as candidate members of the group. These sources, along with 1σ ellipse of each component of the mixture model, are indicated in Figure 4.1c. We expect this selection to be neither complete nor without contamination. However, given the clear overdensity in proper-motion space within this parallax slice of the group, we expect the contamination to be low.

Table 4.1 summarizes all the relevant Gaia and other photometric data from 2MASS, allWISE, and PanSTARRS compiled for the candidate members for further analysis. We used the cross-match identifier tables in the Gaia Archive to retrieve the cross-matches to 2MASS, allWISE, and PanSTARRS. We note that 95% of the selected candidate members have parallax signal-to-noise ratios above 24 with the median signal-to-noise ratio of 170. From the propagation of uncertainties ignoring covariances, formal velocity uncertainties in the R.A. and Decl. directions span 0.25–0.79 km s\(^{-1}\) and 0.05–0.17 km s\(^{-1}\) (25–75 percentiles). Of 194 sources selected, there are 31 sources that have radial velocities (RVs) measured from Gaia DR 2. The RV uncertainties are similarly small spanning 0.46–0.95 km s\(^{-1}\). The median and standard deviation of the velocities of the 31 sources with RVs in the Galactic coordinates are \((U, V, W) = (-3.6, -9.1, -1.6)\) km s\(^{-1}\) and \((\sigma_U, \sigma_V, \sigma_W) = (0.60, 0.88, 1.23)\) km s\(^{-1}\).

In Section 4.3.3, we derive the isotropic velocity dispersion of the candidate members with forward modelling.
4.2.1 Previous identifications

Moving group identifications are often scattered throughout the literature (e.g., Gagné et al., 2018). We reviewed the bibliography associated with all TGAS sources in Group 10 from our previous selection (Oh et al., 2017) using the Simbad database, and note previous identifications of this group.

Latyshev (1977) had identified three of the A-type stars in Group 10, HIP 66198 (81 Uma), HIP 67231 (84 Uma), and HIP 67005, as part of a possible open cluster composed of 7 A-type stars (HIP 66198, HIP 67231, HIP 67005, HIP 67848, HIP 66738, TYC 3851-606-1, TYC 3469-497-1) dubbed Latyshev 2 by Archinal & Hynes (2003).

In a recent review, Mamajek (2016) doubts the physical reality of this putative cluster based on the lack of a convergent point and deviances in the kinematics. However, we show here that some of these stars are clearly part of a distinct kinematic structure.

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<td>mag</td>
<td>allWISE W1, W2, W3, W4 magnitudes</td>
</tr>
<tr>
<td>obj_id</td>
<td></td>
<td>PanSTARRS source identifier</td>
</tr>
<tr>
<td>g, r, i, z, y</td>
<td>mag</td>
<td>PanSTARRS photometry</td>
</tr>
</tbody>
</table>
4.3 Analysis

4.3.1 Color-magnitude diagrams and isochrone ages

Figure 4.2a shows the color-magnitude diagram of the candidate group members (black and red circles) and all stars within 100 pc (blue background) using the Gaia
The absolute $G$ magnitude, $M_G$, is calculated as $G + 5 \log(\varpi) - 10$ where $\varpi$ is the parallax in milliarcseconds. The group is at a high galactic latitude (median $b = 55$ degrees), and the extinction is very low: We checked the dust maps of Schlegel et al. (1998) and Lenz et al. (2017) at the location of candidate members and found the median reddening to be $E(B-V) \lesssim 0.012$ mag although there are some variations across the region with the maximum reddening of 0.025 mag. We apply no correction for dust to the data or the isochrone models.

The candidate members resemble a clean, single-age population that lies on a very narrow main-sequence compared to the “field” stars within 100 pc. The field sample was constructed by querying all stars with parallax $\varpi > 10$ mas, parallax signal-to-noise ratio over 50 and good BP – RP colors filtered by phot_bp_rp_excess_factor according to quality cuts in the Appendix of Gaia Collaboration et al. (2018b).

How old is Group 10? In order to estimate an approximate age of the group, we compared the distribution of candidate members in the color-magnitude diagram to MIST (Choi et al., 2016 with rotation) and PARSEC isochrones (v1.2S; Bressan et al.)
of solar metallicity visually, and found $\log(\text{age/yr}) \approx 8.4$ (250 Myr) to be a good fit. A range of $\log(\text{age/yr}) = (8.2 - 8.55)$ encapsulates the plausible age of the group judging from the disagreement in lower-main sequence for the even younger ages (with PARSEC models) and the main-sequence turn-off for the even older ages. Isochrones of $\log(\text{age/yr}) = 8.4$ from the MIST (black) and PARSEC (blue) models are plotted in Figure 4.2a for comparison. The discrepancy between the MIST models and the data for low-mass ($M \lesssim 0.6 \, m_\odot$) stars is a well-known problem seen in many young open clusters or associations and generic in many stellar models. This is attributed to incomplete atomic and molecular line opacity data (Choi et al., 2016). This is remedied in the PARSEC models by revising and calibrating the boundary conditions to match the observations of star clusters (Chen et al., 2014), leading to a better agreement with the data. A more careful modelling is required to properly infer the age and metallicity of the group.

At the very faint end, the Gaia BP-RP colors may be incorrect due to contamination from nearby sources as no deblending was performed for BP and RP bands in DR 2 (Evans et al., 2018). Following Gaia Collaboration et al. (2018b), we use the empirical cuts to the phot_bp_rp_excess_factor as a function of BP-RP color in order to flag these sources which are marked as ‘x’ in all panels of Figure 4.2. In order to illuminate the nature of these sources, we use four other deeper survey magnitudes (2MASS J, allWISE W1 and PanSTARRS r and y) with Gaia G band magnitudes. Figure 4.2c-e show the color-magnitude diagrams using these photometry. Many of these sources seem to be lower-mass stars further down the main-sequence with even redder colors.

For five Hipparcos stars of the candidate members, an independent age determination by David & Hillenbrand (2015) exists. The stars were treated as field stars and modelled individually. We use the cross-match to the Tycho-2 catalog provided in the Gaia Archive in order to retrieve the Hipparcos identifiers. Figure 4.3 shows the posterior distributions of their age estimates. Except for one star, HIP 69275,
with a notable disagreement with the rest, four out of five stars have a consistent most-probable age of $202 - 214$ Myr (mode of the posterior distribution) and overlapping posterior distributions. This is in good agreement with the visually-determined isochrone age.

4.3.2 Stellar activity in UV and X-ray emission

Young low-mass stars with a substantial convective layer stand out from field stars in their enhanced UV and X-ray emission as a result of strong internal magnetic dynamo coupled with rapid rotation enhancing chromospheric and coronal activity (Zuckerman & Song 2004; Torres et al. 2008; Shkolnik et al. 2011; Rodriguez et al. 2013). Thus, the UV and X-ray photometry can provide an independent indication of youth for young stars in a coeval moving group. We checked the UV and X-ray detection of the candidate members by cross-matching to the GALEX source catalog (Martin et al. 2005) and the ROSAT all-sky survey (2RXS; Boller et al. 2016). We used 2" and 20"
search radii for GALEX and 2RXS respectively. When there are multiple GALEX matches to a source, we choose the one with the smallest NUV magnitude error. We find that 62 of our candidate members (~ 30%) have corresponding GALEX UV detection, of which 10 are also X-ray sources. There are 4 additional X-ray detected candidate members without UV detection. The NUV – G colors of the candidate members tend to be at the edge of the distribution of field stars at fixed BP – RP colors towards brighter NUV magnitudes or show UV excess (Figure 4.4). This is commonly seen in young stars upto ages of a few hundred Myrs old, providing an independent qualitative confirmation of the the isochrone age.

4.3.3 Mean velocity and velocity dispersion

In this section, we derive the mean velocity and velocity dispersion of the group using either only parallaxes and proper motions or full 6D information including radial velocities. Although the original selection was done by selecting comoving pairs, we can also model the proper motions of the stars in the group as drawn from a distribution with a mean velocity and a dispersion around that mean. Historically, the basic assumption of a group of stars having the same velocity has been used to derive a distance to the group (moving cluster method). However, given the exquisite measurements of parallaxes and proper motions in Gaia DR 2, a forward modeling of the same basic model may yield interesting inference of a geometric radial velocity of the group or other residual velocity patterns beyond the simple isotropic dispersion (Dravins et al., 1999; Madsen et al., 2002).

Here, we fit the simplest model in which the velocities of stars in the group are drawn from a single Gaussian. The components of the model are:

\[ M_G < 3(BP - RP + 0.5) + 7.5 \text{ if } BP - RP < 2 \]
• We assume that the velocity $v_i$ of the star $i$ is drawn from a single Gaussian component with mean (group) velocity $u$ and an isotropic dispersion $\sigma_u$:

$$v_i \sim \mathcal{N}(u, \sigma_u).$$

Then, the proper motion of star $i$ is $(\mu_{\alpha,*}, \mu_\delta)^T = M_i(\alpha_i, \delta_i) v_i/r_i$ where $M_i$ is the rotation matrix that transforms the equatorial rectangular coordinates to the tangential coordinates at the location $(\text{R.A.}, \text{Decl.}) = (\alpha_i, \delta_i)$ and $r_i$ is the distance to star $i$.

• We assume that the noise model for the Gaia data is Gaussian, and the covariance matrix $C_i$ is fixed as given by the Gaia catalog:

$$(\tilde{\omega}_i, \tilde{\mu}_{\alpha,i}^*, \tilde{\mu}_{\delta,i}) \sim \mathcal{N}((\omega_i, \mu_{\alpha,i}^*, \mu_{\delta,i}), C_i)$$

• **Priors:** We assume an uninformative uniform prior in distance and a broad Gaussian prior $u \sim \mathcal{N}(0, 100 \text{ km s}^{-1})$ and $\sigma_u \sim \mathcal{N}(0, 50 \text{ km s}^{-1})$ for the mean velocity $u$ and velocity dispersion $\sigma_u$. Given that the parallax signal-to-noise is very high (median of 170), the distance prior has little effect on the fit.

This can be naturally extended to include radial velocity of each star. In this case, the radial velocity is just $v_{r,i} = \hat{u}_r(\alpha_i, \delta_i) \cdot v_i$ where $\hat{u}_r(\alpha_i, \delta_i)$ is the unit radial vector and the covariance of the noise model is extended as $\text{diag}(C_i, \sigma_{v_r}^2)$. We refer the model using proper-motions only of all candidate member stars as ‘PM only’ and the model using a subset of 38 stars with RVs as ‘PM+RV’ respectively. For each case, we first do an optimization using L-BFGS algorithm starting from the initial values $r_{i,0} = 1/\tilde{\omega}_i$, a random mean velocity $u_0$ and $\sigma_u = 10 \text{ km s}^{-1}$. We then sample the posterior distribution of $r_i$, $u$ and $\sigma_u$ starting from this optimum.
This fitting achieves two main goals. First, it properly deconvolves the uncertainty of each measurement taking covariances between parallax and proper motions into account when inferring the intrinsic dispersion of velocities from the data. Secondly, for ‘PM only’ case, this derives the geometric (astrometric) velocity of the group, which can be compared to the spectroscopic RVs from Gaia DR 2 for a subset of stars. This may be particularly interesting as Group 10 has a large angular span ((ΔR.A., ΔDecl.) ≈ (39, 18) deg) and the precisions of the astrometric parameters are generally excellent.

Figure 4.5 summarizes and compares the fit result for the two cases. Because this group spans a large area on sky, all three components of the mean velocity are well-constrained geometrically using proper-motions only (black density and contours). The mean and standard deviation of the posterior samples of the mean velocity \( \mathbf{u} \) are \((u_x, u_y, u_z) = (-3.82 \pm 0.19, 6.84 \pm 0.14, -4.00 \pm 0.34)\) in the equatorial coordinates. The velocity dispersion is very small with the mean of the posterior samples at \( \approx 0.73 \) km s\(^{-1}\). The fit result of ‘PM only’ is in good agreement with ‘PM+RV’ case with the mean velocity of \((-3.02 \pm 0.13, 7.41 \pm 0.14, -5.89 \pm 0.13)\) and the mean dispersion of \(0.82\) km s\(^{-1}\)(orange density and contours). While the differences between the two models is significant formally, the difference is very small < 1 km s\(^{-1}\).

4.3.4 Morphology

Figure 4.6 shows the spatial distribution of candidate members of Group 10: The spatial distribution shows no discernible center or concentration in Galactic X-Y coordinates, while it seems highly concentrated in Z direction around the median height of \(\approx 82\) pc above the Galactic plane. The empirical standard deviation in X, Y, and Z coordinates is 6.7, 10, and 4.3 pc respectively. Furthermore, the candidate members seem to be divided in their X-Y distribution, with a visible banded under-density or gap that is tilted with respect to the direction of Galactic rotation (+Y).
Figure 4.5: Fitting mean velocity and isotropic velocity dispersion of Group 10 using astrometric parameters only (black) and including RVs for a subset of stars (orange). Geometric constraints on all three components of the velocities are in good agreement with those determined by including spectroscopic RVs. The velocities are in equatorial coordinates.
Figure 4.6: Distribution of candidate members in Group 10 in the Galactic coordinates (top row) and the orbit of the group integrated backwards in a fiducial Milky Way potential (bottom row). On top row, stars are colored by their BP – RP color, and the mean velocity is marked by an arrow in each projection.
The bottom panels of Figure 4.6 show the nearly-circular orbit of the group integrated backwards for 300 Myr in a Milky Way potential (Bovy, 2015) using the mean velocity derived from ‘PM+RV’ model fitting in Section 4.3.3 and the median position marked by a black ‘x’ in the top panels of the same Figure.

We estimate the total mass of the group using BP-RP colors and a model isochrone assuming an initial mass function (IMF). We interpolate the BP-RP color-initial mass relation of a PARSEC isochrone of solar metallicity and log age/yr = 8.4. We select stars in a color range $0 < BP - RP < 3$ which corresponds to initial masses of $2.1 \, M_\odot$ and $0.24 \, M_\odot$. For the Kroupa initial mass function (Kroupa, 2001), the total mass is 2.4 times the mass within this color (mass) range. Since the total mass of 124 candidate members within this color range is $70 \, M_\odot$, the total mass is estimated to be $\approx 167 \, M_\odot$. This is likely a lower limit because the membership selection may not be complete while the contamination is expected to be low, and because binaries are not taken into account.

The morphological asymmetries are peculiar and reminiscent of tidal tails, but other plausible explanations are consistent with the data at hand. One possible explanation is that this group formed this way and has not had time to disperse. Unlike the classical open clusters, for the smaller local associations of young stars with typical ages less than 100 Myr, it is often assumed that the gravitational interaction between member stars is not important, and their dynamics is governed by the initial conditions and the Galactic potential (Brown et al., 1997; Miret-Roig et al., 2018). Based on these assumptions, tracing back the orbits of the stars to a converging point can result in a dynamical estimate of their ages. However, simple expansion does not offer any explanation for the presence of the gap nor the highly anisotropic stretch of the morphology of Group 10. In addition, Group 10 is significantly older than most local associations to which such analysis is commonly applied, which are typically tens of Myr old. Given the velocity dispersion of $0.6 \, \text{km s}^{-1}$ and an age of 200 Myr, if the
group has been expanding shortly after the star formation, it should now be spread over > 120 pc. While it is possible that there are more potential members of the group beyond the search region defined here, the majority of the group is contained within the extent of Figure 4.6.

Star clusters that survive the infant mortality are thought to be eventually disrupted by the Galactic tidal field or encounters with Giant Molecular Clouds (GMCs). As stars in a cluster gain energy from external perturbations, they escape primarily through $L_1$ and $L_2$ Lagrange points (Heggie, 2001), which are separated by $2r_J$ where $r_J$ is the tidal (or Jacobi) radius of the cluster. For a cluster like Group 10 in the Solar neighborhood with a nearly circular orbit, the tidal radius due to the Galactic tides is (Portegies Zwart et al., 2010)

$$r_J = \left( \frac{GM}{2(V_G/R_G)^2} \right)^{1/3}$$

$$= 8.5 \text{ pc} \left( \frac{M}{200 M_\odot} \right)^{1/3} \left( \frac{8.3 \text{ kpc}}{R} \right)^{2/3} \left( \frac{V}{220 \text{ km s}^{-1}} \right)^{2/3} \quad (4.1)$$

where $V_G$ and $R_G$ are the circular orbital speed around the Galactic center and the Galactocentric distance. Thus, the size of the gap between two streams of stars is roughly consistent with $2r_J$. The stars that leave the cluster potential through the two Lagrange points, which are always aligned with the Galactic center, will then move away with velocities close to the mean velocity of the cluster. However, as indicated by the arrows in Figure 4.6, the stretch of the group in $X - Y$ coordinates is significantly tilted from the mean velocity although it does agree in $X - Z$ coordinates. Furthermore, it is unclear whether a small cluster under the influence of the Galactic tides throughout its lifetime of $\gtrsim 200$ Myr should still be detectable as an overdensity in velocity space. Regardless of whether the disruption was solely driven by the Galactic tides or was also affected by passing GMCs, it is unclear why there is no clear
progenitor overdensity unless this is the final stage of disruption. Further investigation is needed to illuminate the significance and origin of this morphology.

4.4 Summary

We confirm and characterize a new nearby coeval comoving group first detected in the Tycho-Gaia Astrometric Solution (TGAS) of Gaia DR 1 with the independent and much improved data of Gaia DR 2. We select a total of 194 candidate members with DR 2 astrometry vastly improving the census of the group which was originally detected as interconnected comoving pairs of 29 stars. The age of the group is estimated to be $\approx 200 - 250$ Myr from matching the Gaia color-magnitude diagram with theoretical isochrones. Some of the candidate members show an independent sign of youth in their UV and X-ray properties. The group, which stands out from our previous search as the largest nearby coeval moving group with little prior discussion in the literature, shows an interesting morphology in their Galactic $X - Y$ distribution which looks like broad tidal tails separated by an underdensity. While we speculate on the possibility that the morphology may be related to the disruption of a small star cluster, not all features are easily explained and further observational and theoretical investigation is needed. This work is one step forward towards completing the census of coeval moving groups in the solar neighborhood.

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France, NASA’s Astrophysics Data System, and data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national
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