Kronos and Krios: Evidence for Accretion of a Massive, Rocky Planetary System in a Comoving Pair of Solar-type Stars

Semyeong Oh1, Adrian M. Price-Whelan1, John M. Brewer2,3, David W. Hogg4,5,6,7, David N. Spergel1,4, and Justin Myles2

1 Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Princeton, NJ 08544, USA; semyeong@astro.princeton.edu
2 Department of Astronomy, Yale University, 260 Whitney Avenue, New Haven, CT 06511, USA
3 Department of Astronomy, Columbia University, 550 West 120th Street, New York, NY 10027, USA
4 Center for Computational Astrophysics, Flatiron Institute, 162 Fifth Avenue, New York, NY 10010, USA
5 Center for Cosmology and Particle Physics, Department of Physics, New York University, 726 Broadway, New York, NY 10003, USA
6 Center for Data Science, New York University, 60 Fifth Avenue, New York, NY 10011, USA
7 Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

Received 2017 September 14; revised 2018 January 25; accepted 2018 January 25; published 2018 February 21

Abstract

We report and discuss the discovery of a significant difference in the 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 ≈0.6 pc (∼0.01 pc projected) at a distance of r ≈ 100 pc with nearly identical 3D velocities, as inferred from Gaia TGAS parallaxes and proper motions, and high-precision radial velocity measurements. Stellar parameters determined from high-resolution spectra obtained with the High Resolution Echelle Spectrometer (HIRES) at the Keck Observatory indicate that the two stars are ∼4 Gyr old. The more metal-rich of the two, HD 240430, shows an enhancement of refractory (\( T_C \) > 1200 K) elements by ≈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 to date. 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, which is at odds with the observed differences in metallicity and abundance patterns. We therefore suggest that the star HD 240430, “Kronos,” accreted 15 \( M_x \) of rocky material after birth, selectively enhancing the refractory elements as well as lithium in its surface and convective envelope.

Key words: binaries: visual – planet–star interactions – stars: abundances – stars: formation – stars: individual (HD 240430, HD 240429)

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 (Yoo et al. 2004; Quinn et al. 2009; Allen & Monroy-Rodríguez 2014). 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 (Freeman & Bland-Hawthorn 2002). 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 through population studies to form more readily around inherently metal-rich stars (e.g., Santos et al. 2004; Fischer & Valenti 2005). 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; Teske et al. 2013, 2015, 2016a, 2016b; Liu et al. 2014; Mack et al. 2014, 2016; Tucci Maia et al. 2014; Biazzio et al. 2015; Ramírez et al. 2015, 2016; Saffe et al. 2015) have yielded varied results: while some systems appear to have undetectable differences (see also Gratton et al. 2001; Desidera et al. 2004), other studies have reported a \( T_C \)-dependent difference in abundance with higher-\( T_C \) elements showing larger differences. A possible explanation for the differences 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 (Biazzio et al. 2015; Ramírez 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 ≈0.05 dex, making them
challenging to detect even with a careful analysis of high-resolution spectra with high signal-to-noise ratios, and differential analyses of two stars that are very similar in their stellar parameters. We refer the readers to the Appendix 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; Kilic et al. 2006; Farihi et al. 2009). Some of the most dramatically polluted WDs show surface abundances closely matched by rocky planetary material with, e.g., bulk Earth composition, which is a strong argument that the disk formed from tidally disrupted minor planets (Zuckerman et al. 2007; Klein et al. 2010). Recently, transit signals from small bodies orbiting 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, which have unusual chemical abundance differences that strongly suggest accretion of rocky planetary material with, e.g., bulk Earth composition, which is a strong argument that the disk formed from tidally disrupted minor planets (Zuckerman et al. 2007; Klein et al. 2010). In Greek mythology, Kronos and Krios were sons of the gods Uranos and Gaia. Kronos notoriously devoured all of his children (except for Zeus) to prevent a prophecy from coming true, which predicted that he would be overthrown by them one day. We use the following convention for the 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, $[X/H] = \log_{10}(n_X/n_H)/\log_{10}(n_X/n_H,\odot))$. The absolute abundance of an element X is $A(X) = 12 + \log_{10}(n_X/n_H)$. In Section 2 we present the astrometric and spectroscopic data of the two stars that are relevant to the present discussion. In Section 3 we discuss possible interpretations of the abundance difference between the pair. We summarize our discussions in Section 4.

2. Data

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 method behind this search and only include a brief description here. For a given pair, we compute 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 $\ln L_1/L_2 = 8.52$, 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 High Resolution Echelle Spectrometer (HIRES) on the Keck I telescope, and analyzed (Brewer et al. 2016). The spectral resolution is $R \approx 70,000$ and the wavelength coverage is 5164–7799 Å. A typical 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, and 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 (J. Myles, in preparation). We list all relevant astrometric and spectroscopic measurements including the absolute abundances of Li for the two stars in Table 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 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 coordinates of the two stars. We start by generating posterior samples over the heliocentric distance, $r$, tangential velocities, $(v_r, v_t, v_\phi)$, and radial velocity, $v_r$, given the observed parallax, $\pi$, proper motions, $(\mu_\alpha^*, \mu_\delta^*)$, and radial velocity, $v_r$. We assume the noise is Gaussian, and the radial velocity measurements are uncorrelated with the astrometric measurements. If we define

$$\hat{y} = (\hat{\pi}, \hat{\mu_\alpha^*}, \hat{\mu_\delta^*}, \hat{v}_r)^T$$

and

$$y = (r^{-1}v_t, r^{-1}v_r, v_r)^T,$$

then the likelihood is

$$\hat{y} \sim \mathcal{N}(y, C),$$

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 $\sigma_v = 25$ km s$^{-1}$

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

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

For each of the two stars, we use emcee (Foreman-Mackey et al. 2013) to generate posterior samples in $(r, v_r, v_t, v_\theta)$ 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$^{-1}$ (e.g., Schönrich et al. 2010; Schönrich 2012).

Figure 1 shows differences in posterior samples converted into 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 ($\approx 60\%$; Figure 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 ($\approx 0.5$ dex) is the largest of all elements measured.

The validity of the measured abundance differences is further demonstrated in Figures 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 ($\Delta$[Fe/H] $\approx 0.2$), the ratio of data and model between the two stars shows 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 lower in amplitude (Figure 4). The Li doublet, analyzed in a separate work (J. Myles et al. 2017, in preparation), is clearly visible in the spectra of both stars, and is stronger in Kronos (Figure 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

| Name | Units | Kronos HD 240429 | Kronos HD 240430 | Uncertainties |
|------|-------|----------------|----------------|--------------|
| (1)  | Sp Type | ... | G0 | ... |
| (2)  | R.A.$^*$ | hh:mm:ss | 23:51:55.21 | 23:52:09.42 | ... |
| (3)  | Dec.$^*$ | dd:mm:ss | 59:42:48.16 | 59:42:26.08 | ... |
| (4)  | 2MASS $J^b$ | mag | 8.593 ± 0.023 | 8.415 ± 0.026 | ... |
| (5)  | $T_{\text{eff}}$ | K | 5878 | 5803 | 25 |
| (6)  | log $g$ | ... | 4.43 | 4.33 | 0.028 |
| (7)  | $v\sin i$ | km s$^{-1}$ | 1.1 | 2.5 | ... |
| (8)  | [Fe/H] | ... | 0.01 | 0.20 | 0.010 |
| (9)  | Age | Gyr | 4.00$^{+0.51}_{-0.36}$ | 4.28$^{+0.11}_{-0.01}$ | ... |
| (10) | $v_\star$ | km s$^{-1}$ | −21.2 | −21.2 | 0.2 |
| (11) | $\varpi^a$ | mas | 9.35 ± 0.24 | 9.41 ± 0.25 | ... |
| (12) | $\mu_\alpha^a$ | mas yr$^{-1}$ | 89.25 ± 0.66 | 89.41 ± 0.69 | ... |
| (13) | $\mu_\delta^a$ | mas yr$^{-1}$ | −29.68 ± 0.54 | −30.12 ± 0.52 | ... |

Notes. The listed quantities are the (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 (Spada et al. 2013; see Section 3.1), (10) radial velocity, (11) parallax, (12) proper motion in right ascension direction, and (13) proper motion in declination direction. All values are from Brewer et al. (2016) unless otherwise noted. The microturbulence parameter is fixed at 0.85 km s$^{-1}$ (Brewer et al. 2015).

$^a$ From TGAS.

$^b$ Absolute abundances from J. Myles (2017, in preparation).
As shown in Figure 6, the differences in other pairs for all elements except for N and O, which are also the most uncertain (Table 1), are less than 0.05 dex, making the Kronos–Krios pair a significant outlier. The statistical uncertainties for each parameter presented in Table 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 that are 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 1.** Differences in posterior samples over Galactocentric phase-space coordinates for the two stars Krios and Kronos.

**Figure 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, and Y, but not in C, N, O, Na, and Mn.
3. Discussion

We discuss the possible origins of the peculiar abundance differences of Kronos and 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 3.5.

3.1. Stellar Ages and 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 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 \( 4.28^{+1.11}_{-1.00} \) Gyr and \( 4.00^{+1.51}_{-1.50} \) 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, the 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 a 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 than in other field stars of similar \( T_{\text{eff}} \). Given the overall higher metal

Figure 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](image-url)
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 Myr old, then they may have been part of a larger comoving group of stars. However, as we mention above (Section 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 (Adams et al. 1987; Feigelson & Montmerle 1999). We have compiled photometry from the Galaxy Evolution Explorer (GALEX), Tycho-2, the Two Micron All Sky Survey (2MASS), and WISE for these stars and found no evidence for indications of activity in their spectral energy distributions. The low \( v \sin(i) \) values (Table 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 the MWPotential2014 from Bovy 2015) using Gaia (Price-Whelan et al. 2017; Figure 7). The fiducial orbit of the pair 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, \( \sim 4 \) Gyr old main-sequence stars, and that the unusually high Li abundance of Kronos requires an alternative explanation.

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 merely happen to be comoving at such a small separation (\( \approx 0.6 \) 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 separations smaller than 2 pc among 119259 solar-mass primary stars. Of these pairs, we find none with small enough differences in the observed quantities such that \( \Delta \mu_\alpha < 2 \) mas yr\(^{-1} \), \( \Delta \mu_\delta < 2 \) mas yr\(^{-1} \), and

Figure 4. Same as Figure 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.

Figure 5. Lithium lines in the spectra of Kronos and Krios. This line is studied in J. Myles et al. (2017, in preparation), and the fitting shown here is from that work. Line legends are the same as in Figure 3.
usually show a similar enhancement in all other elements, unlike the pattern seen in the Kronos
Fe H 0. XH Fe H 0.175 Fe H 0.225 1 0.025 Fe H 0.02 is by construction. Random pairings of
and N 2 5 Na Fe 0 smaller than 0.02 Fe H 0. The distribution of the abundance differences between
(vi where Δ

Abundance difference in this pair and other twin-like
differences are smaller
the field stars with similar metallicity difference (Δ[Fe/H] ≈ 0.2) as blue shaded regions. The widths of the shaded
regions reflect the probability density as a function of Δ[X/H] for a given element, and the medians are indicated by the black line segments. These are random pairings of single stars in Brewer et al. (2016) at two metallicity bins, −0.025 < [Fe/H] < 0.025 (160 stars) and 0.175 > [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 Δ[Fe/H] is by construction. Random pairings of disk stars with similar Δ[Fe/H] usually show a similar enhancement in all other elements, unlike the pattern seen in the Kronos–Krios pair.

Figure 6. Abundance difference in this pair and other twin-like (Δ Teff ≤ 100 K) wide binaries in Brewer et al. (2016). The differences in other pairs are small (<0.05 dex) for all elements except for N and O, which are the most uncertain, making the difference of ≈0.2 dex seen in Kronos–Krios rare. Additionally, we show the distribution of the abundance differences between field stars with similar metallicity difference (Δ[Fe/H] ≈ 0.2) as blue shaded regions. The widths of the shaded regions reflect the probability density as a function of Δ[X/H] for a given element, and the medians are indicated by the black line segments. These are random pairings of single stars in Brewer et al. (2016) at two metallicity bins, −0.025 < [Fe/H] < 0.025 (160 stars) and 0.175 > [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 Δ[Fe/H] is by construction. Random pairings of disk stars with similar Δ[Fe/H] usually show a similar enhancement in all other elements, unlike the pattern seen in the Kronos–Krios pair.

\[ \Delta v_r < 2 \text{ km s}^{-1} \]
These are still with generous difference budgets in both positions and velocities, and the actual observed differences are smaller (Table 1). We find a single pair with a velocity difference smaller than 2 km s\(^{-1}\). Thus, while we cannot prove the binarity of 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 6) and Li abundance, which would make a chance pair like Kronos–Krios even more unlikely in a probabilistic sense.

3.3. Exchange Scattering

Another possibility for two stars that were unrelated at birth to 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 semimajor axis \(a\) is

\[ \sigma_{\text{ex}} = \frac{640}{81} \pi a^2 \left( \frac{v_i}{v_c} \right)^{-6}, \]
where \(v_i\) is the incoming velocity, and \(v_c\) is the critical velocity, defined as

\[ v_c^2 = G \frac{m_1 m_2 (m_1 + m_2 + m_3)}{m_3 (m_1 + m_2)} \frac{1}{a}. \]

Equation (6) is appropriate when \(v_i/v_c \geq 1\) (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 km s\(^{-1}\), the rate of exchange scattering is

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

which is 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 [Fe/H] bins at [Fe/H] = 0 ± 0.025 and [Fe/H] = 0.2 ± 0.025, each similar to Krios and Kronos. In Figure 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] ≈ 0.2 dex, we generally expect [Na/Fe] > 0 and [Mn/Fe] > −0.1 (Bensby et al. 2003; Battistini & Bensby 2015), making the low [Na/Fe] and [Mn/Fe] seen in Kronos very unlikely to arise from variations in Galactic chemical evolution.

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] smaller than 0.02 dex (Gratton et al. 2001; Desidera et al. 2004). Even when a significant difference is detected with high-precision abundance measurements, the difference is typically ∼0.05 dex (see Figure 8 and the Appendix). Consistent with these results, none of the other seven similar wide binaries examined in Brewer et al. (2016) show such large differences in abundances, although there is generally a larger spread in C, N, and O, and some pairs show a difference in particular elements as large as ≈0.15 dex. The median and
maximum $\text{Fe/H}$ difference between component stars in the other seven pairs is 0.02 dex and 0.09 dex, respectively. The differences are even smaller ($\Delta \text{Fe/H} = 0.03$ dex) when we compare only twin-like ($\Delta T_{\text{eff}} \lesssim 100$ K) pairs (Figure 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.

3.5. 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 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 the 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 an 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 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, and WASP-94A/B in Figure 8. The metallicity difference of ≈0.2 dex observed in this pair is larger than the differences seen in any other pairs studied so far (see also the Appendix). 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 $T_C ≈ 1200$ K. This $T_C$-dependent trend of $Δ[X/H]$, 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 ≈0.2 dex? We carry out simple toy calculations of the expected $Δ[X/H]$ in a Sun-like star’s atmosphere by adding a certain mass of bulk Earth composition under these simplifying assumptions:

1. The material added is instantly and completely mixed throughout the star’s convective zone.
2. The atmospheric composition that we measure is identical throughout the star’s radiative and convective zone.
3. 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 into mass fraction as

$$f_{X,\text{photo}} = \frac{10^{[X/H]} \cdot m_X}{\sum_X 10^{[X/H]} \cdot m_X},$$

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

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

where $f_{CZ}$ is the fraction of the star’s mass in the convective envelope. We assume $f_{CZ} = 0.02$ (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) and Mack et al. (2014, 2016).

Figure 9 shows the expected change of surface abundances of metals in a Sun-like star after 15 $M_\oplus$ of material with the 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 Cl 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 $Δ[X/H]$, 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 (Baraffe et al. 2017; Thévenin 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 ($A(Li) = 1.05$), the accretion of 15 $M_\oplus$ of bulk Earth-like material would result in $Δ[Li/H] ≈ 1.65$ dex (see the inset of Figure 9). This closely matches what we find: the Li abundance of Kronos is $A(Li) = 2.75$ (Table 1, J. Myles 2017, in preparation), which is 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

![Figure 9](image_url)
element Mn varies from 800 to \(\approx 2000 \text{ ppm}\) (Lodders & Fegley 1998; McDonough 2001, 2003) mainly as a result of the uncertainty on the core composition of Earth. 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 decreases 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 \(f_{\text{c,z}}\), given the large metallicity enhancement (\(\approx 0.2 \text{ dex}\)), the accretion must have occurred 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 the 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 is theoretically expected to be absent (Pinsonneault 1997). However, an accretion of rocky material could have replenished \(^6\text{Li}\). Because the \(^6\text{Li}\) lines are slightly longer in wavelength, the presence of \(^6\text{Li}\) increases the asymmetry of the 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 spectra with a higher signal-to-noise ratio and higher resolution and a careful modeling effort (see, e.g., Israeli et al. 2001; Reddy et al. 2002). Such an investigation was not warranted by the current data (J. Myles 2017, in preparation).

4. Summary

We report and discuss very different metallicities (\(\Delta [\text{Fe/H}] \approx 0.2 \text{ dex}\)) and condensation temperature (\(T_C\))-dependent abundance differences in a comoving pair of the 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 10 elements with \(T_C > 1200 \text{ K}\) including Fe, while it is underenhanced in the five elements C, N, O, Na, and Mn with \(T_C < 1200 \text{ K}\) relative to HD 240429 (Krios). It also has an anomalously high surface Li abundance for its age of \(\sim 4 \text{ Gyr}\) and its effective temperature, which is 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 3.2) or in an exchange scattering event (Section 3.3), or that there may be chemical inhomogeneity in the birth cloud (Section 3.4) to find all three hypotheses 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 3.5). We argue that an accretion of 15 \(M_\odot\) of bulk Earth composition to Kronos after its thin convective zone is in place can explain the enhancement in both refractory elements and lithium. It remains unclear what triggered the planet engulfment in one of the two comoving stars. One possibility is that a fly-by interaction with a field star could have triggered an 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 that might be detectable with future data releases of the Gaia mission.

Despite the arguments presented above for the physical association of the two stars based on phase-space coordinates and a physically interesting explanation for their metallicity and abundance differences, we cannot completely rule out the very rare possibility that the two stars, one of which has an uncommon abundance pattern, including a high Li abundance, are not coeval but merely 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 might have recently been disrupted. This skepticism may be based on or amplified by the large metallicity differences. Another recent study, however, has reported a comoving pair of solar-type stars in which one shows a 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 conclude that the seemingly exotic explanation of rocky planet engulfment in one of the stars is the simpler and more natural explanation 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.

We thank Andy Casey for bringing \(^6\text{Li}\) into our attention. We thank Megan Bedell and Andy Casey for valuable discussions, and Keith Hawkins, Nathan Leigh, and Josh Winn for comments on the early version of the draft. The Flatiron Institute is supported by the Simons Foundation.

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. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

Software: This research used 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).

Appendix

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 Meléndez & Ramírez (2016).

16 Cygni A/B. The chemical composition of this well-known pair of solar-type stars (G1.5/53) has been studied many times. The hotter star 16 Cyg A has no detected planets, but has an M-dwarf companion $\sim$70 au away in projected separation that is probably physically associated (Patience et al. 2002), and may have affected a planet formation process around the star (Jensen et al. 1996; Mayer et al. 2005). The other star, 16 Cyg B, hosts a giant planet on an eccentric orbit ($\epsilon = 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 the abundance differences show a correlation with $T_C$, and the interpretation is likewise debated. Tucci Maia et al. (2014) suggested that formation of a 1.5–6 $M_\odot$ 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$9000 au (corresponding to 4.2 sky separation) and solar metallicity host close-in giant planets. HD 20782 hosts a Jupiter-mass planet on a very eccentric ($\epsilon \approx 0.97$) orbit with a pericenter distance of 1.4 au, while HD 20781 hosts two Neptune-mass planets within 0.3 au with moderately high eccentricity ($\epsilon \approx 0.1–0.3$). The measured abundances of 15 elements between the two stars are consistent with each other (Mack et al. 2014). However, Mack et al. (2014) argued that there is a moderately significant ($\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, Cu, Ti, Al, and 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 $M_\oplus$ of H-depleted rocky material during giant planet migration.

HAT-P-1. This pair of G0 stars separated by 11$^\circ$ 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 a mean error of 0.013 dex (Liu et al. 2014). Thus, it seems that the presence of close-in giant planets 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 hosts a very eccentric ($\epsilon = 0.94$) giant planet, and HD 80607 has no detected planets (Saffe et al. 2015; Mack et al. 2016).

$^{10}$ Note that the condensation temperature $T_C$ used is for solar system composition gas, which can differ from that of higher metallicity gas.
0.03 ± 0.017 dex in refractory elements in A relative to B without any conclusive interpretation.

ORCID iDs

Semyeong Oh https://orcid.org/0000-0001-7790-5308
Adrian M. Price-Whelan https://orcid.org/0000-0003-0872-7098
John M. Brewer https://orcid.org/0000-0002-9873-1471
David W. Hogg https://orcid.org/0000-0003-2866-9403

References

Adams, F. C., Lada, C. J., & Shu, F. H. 1987, ApJ, 312, 788
Allen, C., & Monroy-Rodríguez, M. A. 2014, ApJ, 790, 158
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Aumer, M., Binney, J., & Schönrich, R. 2016, MNRAS, 462, 1697
Baraffe, I., Pratt, J., Goffrey, T., et al. 2017, ApJL, 845, L6
Battistini, C., & Bensby, T. 2015, A&A, 577, A9
Bensby, T., Feltzing, S., & Lundström, I. 2003, A&A, 410, 527
Biazzo, K., Gratton, R., Desidera, S., et al. 2015, A&A, 583, A135
Bovy, J. 2015, ApJS, 216, 29
Brewer, J. M., Fischer, D. A., Basu, S., Valenti, J. A., & Farihi, J. 2014, ApJ, 805, 126
Brewer, J. M., Fischer, D. A., Valenti, J. A., & Piskunov, N. 2016, ApJS, 225, 32
Casey, A. R., Ruchti, G., Masseron, T., et al. 2016, MNRAS, 461, 3336
Chambers, J. E. 2010, ApJ, 724, 92
Chen, Y. Q., Nissen, P. E., Benoni, T., & Zhao, G. 2001, A&A, 371, 943
Cochran, W. D., Hatze, A. F., Butler, R. P., & Marcy, G. W. 1997, ApJ, 483, 457
Desidera, S., Gratton, R. G., Scuderi, S., et al. 2004, A&A, 420, 683
Eiroa, C., Fedele, D., Maldonado, J., et al. 2010, A&A, 518, L131
Farihi, J. 2016, NewAR, 71, 9
Farihi, J., Jura, M., & Zuckerman, B. 2009, ApJ, 694, 805
Feigelson, E. D., & Montmerle, T. 1999, ARA&A, 37, 363
Fischer, D. A., & Valenti, J. 2005, ApJ, 622, 1102
Foreman-Mackey, D. 2016, JOSS, 1, 24
Freeman, K., & Bland-Hawthorn, J. 2002, ARA&A, 40, 487
Freeman, K., & Bland-Hawthorn, J. 2002, ARA&A, 40, 487
Graham, J. R., Matthews, K., Neugebauer, G., & Soifer, B. T. 1990, ApJ, 357, 216
Gratton, R. G., Bonanno, G., Caldui, R. U., et al. 2001, A&A, 377, 123
Hallwachs, J. L. 1986, A&AS, 66, 131
Hunter, J. D. 2007, CSE, 9, 21
Hut, P. 1983, ApJ, 268, 342
Hut, P., & Bahcall, J. N. 1983, ApJ, 268, 319
Israelian, G., Santos, N. C., Mayor, M., & Rebolo, R. 2001, Natur, 411, 163
Jensen, E. L. N., Mathieu, R. D., & Fuller, G. A. 1996, ApJ, 458, 312
Jiang, Y.-F., & Tremaine, S. 2010, MNRAS, 401, 977
Kalec, M., Van Hille, T., Leggett, S. K., & Winget, D. E. 2006, ApJ, 646, 474
Klein, B., Jura, M., Koester, D., Zuckerman, B., & Melis, C. 2010, ApJ, 709, 950
Koester, D., Günsethe, B. T., & Farihi, J. 2014, A&A, 566, A34
Laws, C., & Gonzalez, G. 2001, ApJ, 553, 405
Liu, F., Asplund, M., Ramírez, I., Yong, D., & Meléndez, J. 2014, MNRAS, 442, L51
Lodders, K. 2003, ApJ, 591, 1220
Lodders, K., & Fegley, B. 1998, The Planetary Scientist’s Companion (Oxford: Oxford Univ. Press)
Mack, C. E., III, Schuler, S. C., Stassun, K. G., & Norris, J. 2014, ApJ, 787, 98
Mack, C. E., III, Stassun, K. G., Schuler, S. C., Hebb, L., & Pepper, J. A. 2016, ApJ, 818, 54