Very wide companion fraction from *Gaia* DR2: A weak or no enhancement for hot Jupiter hosts, and a strong enhancement for contact binaries

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ABSTRACT

There is an ongoing debate on whether hot Jupiter hosts are more likely to be found in wide binaries with separations of $\gtrsim 100$ AU. In this paper, we search for comoving, very wide companions with separations of 10^3–10^4 AU for hot Jupiter hosts and main-sequence contact binaries in *Gaia* DR2, and compare the very wide companion fractions with their object-by-object-matched field star samples. We find that 11.9 ± 2.5 per cent of hot Jupiter hosts and 14.1 ± 1.0 per cent of contact binaries have companions at separations of 10^3–10^4 AU. While the very wide companion fraction of hot Jupiter hosts is a factor of 1.9 ± 0.5 larger than their matched field star sample, it is consistent, within $\sim 1\sigma$, with that of matched field stars if the matching is only with field stars without close companions (within ~ 50 AU) as is the case for hot Jupiter hosts. The very wide companion fraction of contact binaries is a factor of 3.1 ± 0.5 larger than their matched field star sample, suggesting that the formation and evolution of contact binaries are either tied to or correlated with the presence of wide companions. In contrast, the weak enhancement of very wide companion fraction for hot Jupiter hosts implies that the formation of hot Jupiters is not as sensitive to those environment properties. Our results also hint that the occurrence rates of dual hot Jupiter hosts and dual contact binaries may be higher than the expected values from random pairing of field stars, which may be due to their underlying metallicity and age dependence.

Key words: planets and satellites: formation – binaries:close – binaries: eclipsing.

1 INTRODUCTION

The discovery of the first exoplanet orbiting a sun-like star, 51 Pegasi b, presents a significant challenge to planet formation theories based on our Solar System (e.g. Mayor & Queloz 1995; Rasio et al. 1996). While the giant planets of the Solar System may have somewhat migrated (Morbidelli et al. 2012), they likely formed in the cooler outer regions of the protoplanetary disc where the icy material facilitated rapid core growth to accrete massive gaseous atmospheres before the disc dissipated. In contrast, 51 Pegasi b is the prototypical 'hot Jupiter', with a mass roughly half that of Jupiter but with an orbital separation from the host star of about seven times smaller than that of Mercury. 25 yr after the discovery of 51 Pegasi b, the formation of hot Jupiters remains an open question.

There are three main hot Jupiter formation theories: *in situ* formation, disc migration, and high-eccentricity tidal migration (Dawson & Johnson 2018). In the *in situ* formation scenario, hot Jupiters form at their current locations. This scenario was believed to be challenging because both gravitational instability and core accretion are difficult to operate at hot Jupiters' close-in locations (Rafikov 2005, 2006), but recent study suggests that *in situ* formation is still possible under certain conditions (Bodenheimer, Hubickyj & Lissauer 2000; Batygin, Bodenheimer & Laughlin 2016; Boley, Granados Contreras & Gladman 2016; Lee & Chiang 2016). In the disc migration scenario, hot Jupiters form at larger separations and migrate to their current location under the torque from the protoplanetary disc (Goldreich & Tremaine 1980; Lin & Papaloizou 1986; Lin, Bodenheimer & Richardson 1996; Nelson et al. 2000; Ida & Lin 2008).

In the high eccentricity migration scenario, the hot Jupiter forms at a large separation from the host star, is driven into a high-eccentricity orbit, and undergoes tidal circularization which leaves the planet in its small, circular orbit. The eccentricity excitation may be caused by planet–planet scattering (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Ford & Rasio 2006; Chatterjee et al. 2008; Jurić & Tremaine 2008), or Kozai-Lidov interactions (Kozai 1962; Lidov 1962) with an other planet (Naoz et al. 2011) and/or with a stellar companion (Wu & Murray 2003; Fabrycky & Tremaine 2007; Naoz, Farr & Rasio 2012).

The occurrence of stellar companions around hot Jupiter hosts provides a constraint on the formation of hot Jupiters. If Kozai-Lidov interactions with stellar companions represent a significant channel for hot Jupiter formation, then stellar companions should be common around hot Jupiter hosts. At an earlier evolutionary stage, the presence of stellar companions can affect the environment of the protoplanetary disc and the planet formation (Kraus et al. 2012).

There has been extensive work on measuring the incidence of stellar companions to hosts of hot Jupiters (Endl et al. 2014; Knutson et al. 2014; Piskorz et al. 2015; Bryan et al. 2016; Evans et al. 2016; Belokurov et al. 2020), but whether hot Jupiter hosts have a higher wide companion fraction is still an ongoing debate. Ngo et al. (2016) conduct a direct imaging search for companions to hot Jupiter systems and find that for companions with separations between 50 and 2000 AU, hot Jupiter hosts have a companion fraction 2.9 times higher than that of the field stars from Raghavan et al. (2010),

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with a significance of $4.4\,\sigma$. They argue that >80 per cent of these companions are not able to induce Kozai-Lidov oscillations because the oscillation time-scale is too long, and therefore the enhanced companion occurrence may instead be linked to the formation environment of the gas giants.

However, Moe & Kratter (2019) point out that such enhanced companion fraction of hot Jupiter hosts may be a consequence of several selection effects. First, they argue the field star sample from Raghavan et al. (2010) is not ideal for the hot Jupiter hosts used in Ngo et al. (2016) because these two samples have slightly different mass and metallicity, and the field star sample is not complete.

Secondly, observations have shown that fewer hot Jupiter hosts have close stellar companions at separations $\lesssim 50\,\mathrm{AU}$ compared to the field stars (Wang et al. 2014a,b; Kraus et al. 2016; Matson et al. 2018; Ziegler et al. 2019). This may be the result of the shorter lifetime of protoplanetary discs in binaries compared to those around single stars (Kraus et al. 2012, 2016). Specifically, hot Jupiter hosts have a very small companion fraction within 50AU – only 4 per cent$^{+4\ \mathrm{per\ cent}}_{-2\ \mathrm{per\ cent}}$ (Ngo et al. 2016). In contrast, field stars with a similar mass and metallicity have a companion fraction within 50 AU of 40 ± 6 per cent (Moe & Kratter 2019). In the absence of any other physical mechanisms, the lower close companion fraction of hot Jupiter hosts would result in a higher wide companion fraction compared to the field stars. After having accounted for this bias, Moe & Kratter (2019) argue that hot Jupiter hosts do not have an enhanced wide companion fraction compared to the field stars.

In this paper, we examine the very wide companion fraction at separations of 10^3–10^4 AU around hot Jupiter hosts and main-sequence contact binaries using *Gaia* data. We search for comoving and colocated companions to hot Jupiter hosts, contact binaries, and to field stars down to *Gaia*'s spatial resolution limit. By using *Gaia*, we are able to compare the companion fraction between different populations based on the same data set, without dependence on external data and models.

In this paper, we refer to companions with separations of $<50\,\mathrm{AU}$ as close companions, those of 50–2000 AU as wide companions, and those of 10^3–10^4 AU as very wide companions. This paper is structured as follows. Section 2 describes our sample selection and the search of comoving companions. Section 3 presents our main results. We discuss the results in Section 4 and conclude in Section 5.

2 SAMPLE SELECTION AND METHOD

2.1 Selection of hot Jupiter hosts

We use the sample of main sequence hot Jupiter hosts whose selection is described in Hamer & Schlaufman (2019). Briefly, hot Jupiters were selected from the confirmed planets table of the NASA Exoplanet Archive using the fiducial definition from Wright et al. (2012), planets having $P < 10\,\mathrm{d}$ and $M\sin i > 0.1\,M_{\mathrm{Jup}}$. Most ($\sim$90 per cent) of these hot Jupiters were discovered by transiting surveys and further confirmed by follow-up radial-velocity observations. Therefore, no contamination from false-positive eclipsing binaries is expected. This is important because an exoplanet sample from radial velocity surveys may be biased because exoplanet radial velocity surveys may exclude spectroscopic binaries (Moe & Kratter 2019). In transiting surveys, the presence of a close companion may dilute the transit depths and potentially bias an exoplanet sample, but Moe & Kratter (2019) show that hot Jupiters are relatively immune to this effect because of their deep and frequent transits. The *Gaia* DR2 designations of these hot Jupiter hosts were then obtained from SIMBAD. The sample was limited to hosts having

good astrometry using the quality cuts described in Appendix 1 of Hamer & Schlaufman (2019). Individual line-of-sight reddening values were calculated for each star by interpolating the 3D reddening map from Capitanio et al. (2017) and integrating the interpolated grid along the line of sight to calculate a total $E(B - V)$ reddening. $E(B - V)$ was converted to *Gaia* reddening $E(\mathrm{BP-RP})$ and extinction A_G, using the mean extinction coefficients from Casagrande & Vanden Berg (2018). Evolved hot Jupiter hosts were excluded by removing hosts which fall more than one magnitude above an empirical fit to the Pleiades in the $(\mathrm{BP - RP})$–M_G plane. Among the 338 main-sequence hot Jupiter hosts from Hamer & Schlaufman (2019), we further limit the sample to parallaxes >2.5 mas (distances <400 pc) for better companion completeness. As explained in the later sections, we remove targets where no matched field stars are found or in a comoving group, ending up with 193 hot Jupiter hosts.

2.2 Selection of main-sequence contact binaries

Short-period binaries are often compared to hot Jupiters because historically both their formations are speculated to be due to the Kozai-Lidov interactions (e.g. Fabrycky & Tremaine 2007). Furthermore, a direct comparison of wide companion fractions between short-period binaries and hot Jupiters (Moe & Kratter 2019) provides a probe of the different formation processes across the mass gap of 4–$9\,M_J$ (Schlaufman 2018). Therefore, in this paper we compare the companion fraction between main-sequence hot Jupiter hosts, main-sequence contact binaries, and field stars.

We use the sample of contact binaries whose selection is detailed in Hwang & Zakamska (2020). They used the fractional variability from *Gaia* Data Release 2 (DR2; Gaia Collaboration 2016, 2018) to select high-amplitude (>10 per cent) variables, which are dominated by contact binaries on the main sequence. They selected main-sequence objects using $|\Delta \mathrm{G}| < 1.5$ mag, where $\Delta \mathrm{G}$ is defined as the offset of absolute G magnitudes between the stars and Pleiades at the same BP−RP colours (Hamer & Schlaufman 2019). Other photometric and astrometric quality criteria employed in this work are the same as those used in Hwang & Zakamska (2020). By comparing with the Kepler eclipsing binary catalogue (Kirk et al. 2016), Hwang & Zakamska (2020) show that this method efficiently selects main-sequence contact binaries with orbital periods <0.5 d. In this paper, we use a colour cut of BP−RP = 0.5-1.5 mag to avoid blue pulsating stars and red M-dwarf flaring stars (Gaia Collaboration 2019).

With all selections discussed above, we further limit the main-sequence contact binary sample to parallaxes >2.5 mas (i.e. within 400 pc), remove targets if we cannot identify a matched field star, and remove targets in comoving groups explained in the later sections. We end up with 1333 main-sequence contact binaries.

2.3 Control field star sample

For each target sample (hot Jupiter host sample or main-sequence contact binary sample), we select a field star sample that matches object-by-object in several properties. Specifically, for each target star (hot Jupiter host or a contact binary), we search a field star such that: (1) it is >10 pc away from the target star (assuming the pair has the same parallax as the target star), and it is <20 deg from the target star; (2) the BP−RP colour difference is <0.05 mag; (3) the parallax difference with the target star is <10 per cent; (4) the tangential velocity difference with the target star is $<10\,\mathrm{km\,s^{-1}}$; (5) the field star satisfies the *Gaia* selections explained in Section 2.2. The tangential velocity used here has been corrected for the solar motion (Schönrich, Binney & Dehnen 2010) and the Galactic differential rotation using
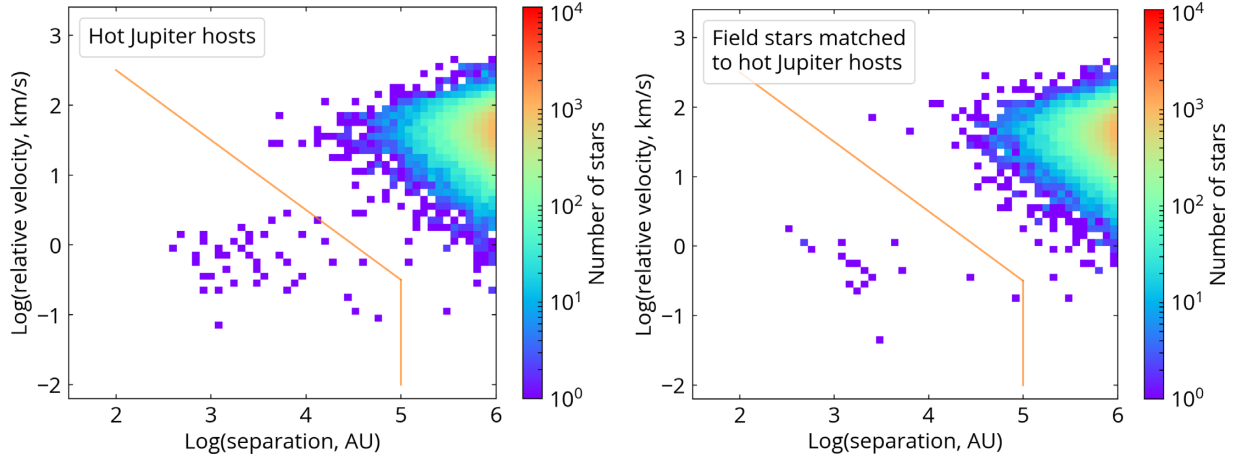
Figure 1. Search of comoving companions around hot Jupiter hosts (left-hand panel) and their matched field stars (right-hand panel). The x-axis is the physical separations projected on the sky assuming the mean of the two parallaxes, and the y-axis is the projected relative velocity. The upper-right distribution corresponds to the physically unrelated nearby stars, while the lower-left is the comoving companions. The solid line is the empirical demarcation line to isolate the comoving companions. Although four matched field stars are used for each hot Jupiter host, here we only show the same number of field stars and hot Jupiter hosts for better comparison.

the Oort's constants reported by Bovy (2017). To improve statistics, for each hot Jupiter host, we find four matched field stars, where the mutual separations of four matched field stars are all >10 pc (assuming the same parallax as the target star). We exclude hot Jupiter hosts from the sample if four matched field stars are not found. Because the contact binary sample is sufficiently large, only one field star is matched to one contact binary. Every control field star is matched to exactly one target.

By matching the properties described above, we ensure that the sample of the target stars (hot Jupiter hosts or contact binaries) and the corresponding matched field star sample have similar distributions of masses, sky distributions, Galactic latitudes, and kinematics. Since the stellar age is strongly correlated with the kinematics (Dehnen & Binney 1998; Nordström et al. 2004; Reid et al. 2009; Sharma et al. 2014), we expect that the kinematic ages of the target sample and the matched field star sample are also similar. This is important because the occurrence of both hot Jupiters and contact binaries has strong stellar age dependence (Hamer & Schlaufman 2019; Hwang & Zakamska 2020). Matching the Galactic latitudes is crucial because the contact binary fraction is much lower in the thick disc than in the thin disc (Hwang & Zakamska 2020).

The hot Jupiter occurrence rate is correlated with stellar metallicity (Gonzalez 1997; Santos, Israelian & Mayor 2004; Fischer & Valenti 2005). Therefore, ideally, we may also want to match metallicity for the control field stars. Although we match the masses, Galactic latitudes, and kinematics, which are all correlated with metallicity, there is no guarantee that the metallicity is exactly the same as the hot Jupiter host sample. However, in this paper we focus on the very wide companions (10^3–10^4 AU), and it has been shown that the solar-type binary fraction beyond >200 AU is independent of metallicity (El-Badry & Rix 2019; Moe, Kratter & Badenes 2019). Therefore, metallicity plays a relatively minor role in our investigation of very wide companions.

2.4 Comoving companion search

We search for very wide comoving companions with projected separations up to 10^6 AU (4.8 pc). We start with a selection of nearby stars, from which we further select the comoving companions.

For each target star (hot Jupiter host, contact binary, or field star), we select its nearby stars where (1) either the parallax difference <0.2 mas or the difference of line-of-sight distance (inverse of parallax) is <20 pc; (2) projected physical separations <20 pc assuming all nearby stars have the same parallaxes as the target star. Furthermore, we require that the candidate comoving companion meet all criteria in Section 2.2, except that we do not apply criteria on *Gaia* DR2 parameters `phot_rp_mean_flux_over_error`, `phot_bp_mean_flux_over_error`, `phot_bp_rp_excess_factor`, BP−RP, and ΔG since these criteria may exclude faint companions (like M dwarfs) and we are interested in identifying comoving companions of all stellar types.

For the nearby stars selected following this procedure, we then compute the projected relative velocity between two stars using their proper motion difference and their mean parallax. The projected physical separations are recomputed but now using the mean parallax of two stars. We use projected physical separations instead of 3D physical separations because the 3D physical separations are dominated by the parallax uncertainty.

We remove targets (hot Jupiter hosts, contact binaries, and their matched field stars) that are in clusters or comoving groups, because they may contaminate the comoving companion search. Specifically, we remove target stars that have ≥ 100 nearby stars within the separations of 10^{5-6} AU and relative velocities of <10 km s^{-1}. This only removes $\lesssim 1$ per cent of the samples and therefore does not affect the main results.

2.5 Selection of very wide comoving companions

Figs 1 and 2 show the distributions of relative velocity versus projected physical separation of nearby sources for hot Jupiter hosts and contact binaries, respectively. In these plots, the overdensity at the upper-right corner is the chance projection stars, and the overdensity at the lower-left corner is the comoving companions of the target stars. The triangular shape of the chance projections is because in the log–log space of relative velocity and physical separation, the number of chance projections increases as a power of 2 with respect to separation. The number of chance projections increases as a power of 2 with respect to the velocity in the low velocity
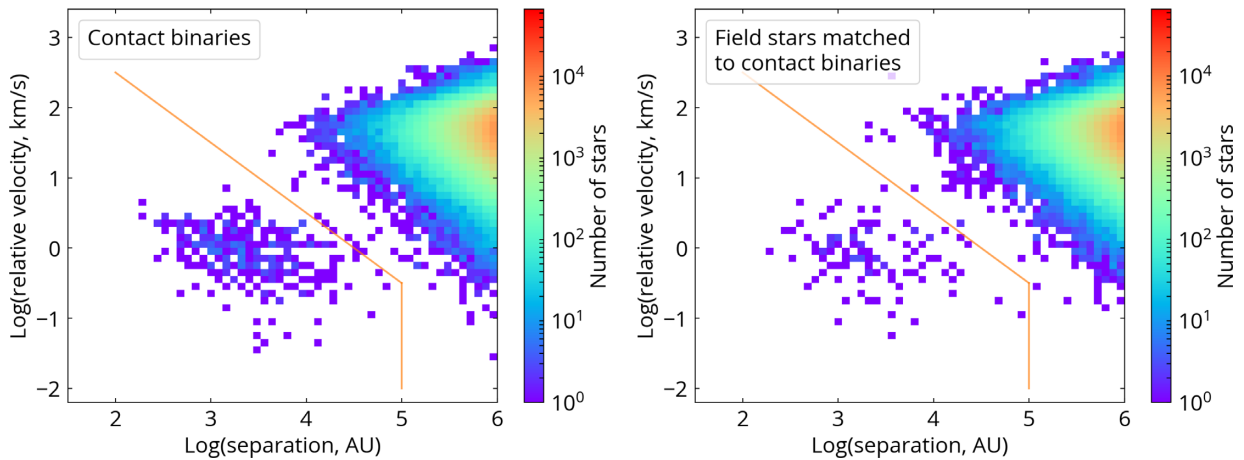
Figure 2. Similar to Fig. 1, but here for main-sequence contact binaries (left-hand panel) and their matched field stars (right-hand panel). Every contact binary has one matched field star.
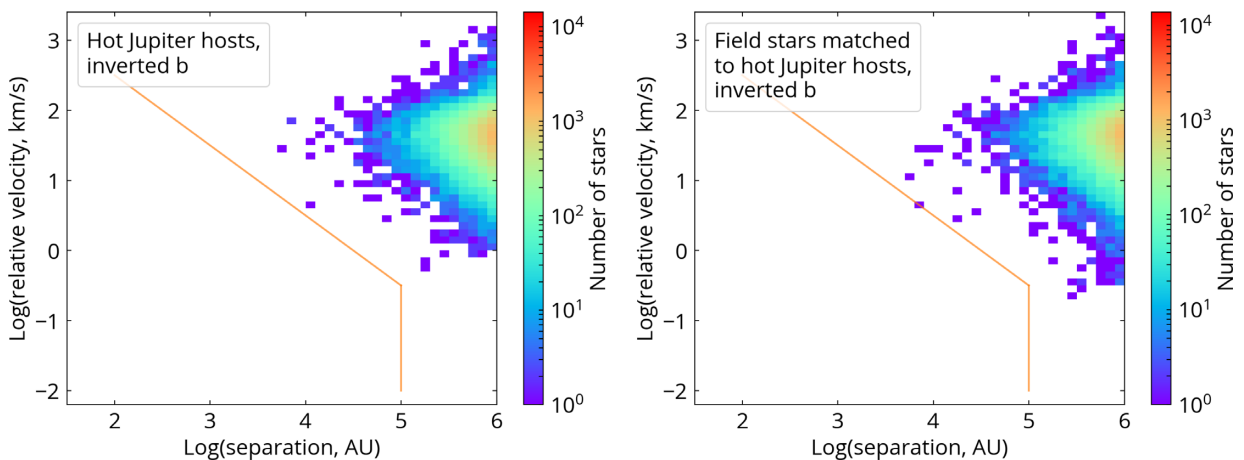

Figure 3. Contamination tests for hot Jupiter hosts (left-hand panel) and their matched field stars (right-hand panel) by inverting their Galactic latitudes. The axes are the same as Fig. 2. Although four matched field stars are used for each hot Jupiter host, here we only show the same number of field stars and hot Jupiter hosts for better comparison.

limit of the Maxwellian-like velocity distribution (the velocity difference in Figs 1 and 2 contains two dimensions of velocity). At the high velocity limit of the Maxwellian-like distribution, the number of chance projections decreases exponentially. Therefore, the constant number of chance projection follows a slope of -1 at low velocities.

The orange solid line in Figs 1 and 2 is an empirical demarcation line that isolates the comoving companions from the chance projection stars. Specifically, this demarcation line has a relative velocity of $10^{1.5}$ km s^{-1} at a projected separation of 10^3 AU and a slope of -1 in the log–log space, and removes objects beyond 10^5 AU. The slope of the demarcation line ensures that it is parallel to the chance projection stars so that the contamination level is not a strong function of the separation.

Given the *Gaia* DR2 sensitivity down to $\sim$20 mag in *G*-band, our search for comoving companions is complete down to an absolute *G*-band magnitude of 12 mag within 400 pc. When selecting comoving companions, we adopt a conservative cut that the comoving companions have *G*-band absolute magnitudes brighter than 11.5 mag. Therefore, we should detect most of the stellar objects, except for late M dwarfs and old white dwarfs. Since the hot Jupiter hosts in wide binaries and wide solar-type binaries have statistically

consistent stellar mass-ratio distributions (Moe & Kratter 2019), the incompleteness at the faintest end does not affect our result.

In Figs 3 and 4, we test the level of contamination from the random background stars by flipping the sign of the Galactic latitudes of the targets (Shaya & Olling 2011; Jiménez-Esteban, Solano & Rodrigo 2019). In addition, we flip the sign of the proper motion in the direction of galactic latitudes after removing the solar motion and the differential rotation from the Galactic disc. The tests show that 0, 1, 0, 1 chance projection stars fall into our selection (below the orange demarcation line and a separation between 10^3 and 10^4 AU) for hot Jupiter hosts, the field stars matched for hot Jupiter hosts, contact binaries, and the field stars matched for the contact binaries, respectively. The contamination from the chance projection stars is mainly due to the targets at low Galactic latitudes. This level of contamination does not significantly affect our main results.

Fig. 5 shows the separation distribution of the comoving companions selected using the demarcation line. The comoving companion fraction on the vertical axis is computed from the number of comoving companions in each separation bin divided by the total number of the sample. We remove targets (field stars) and their corresponding field stars (targets) if more than one comoving companions are found. Specifically, none of hot Jupiter hosts and the field star
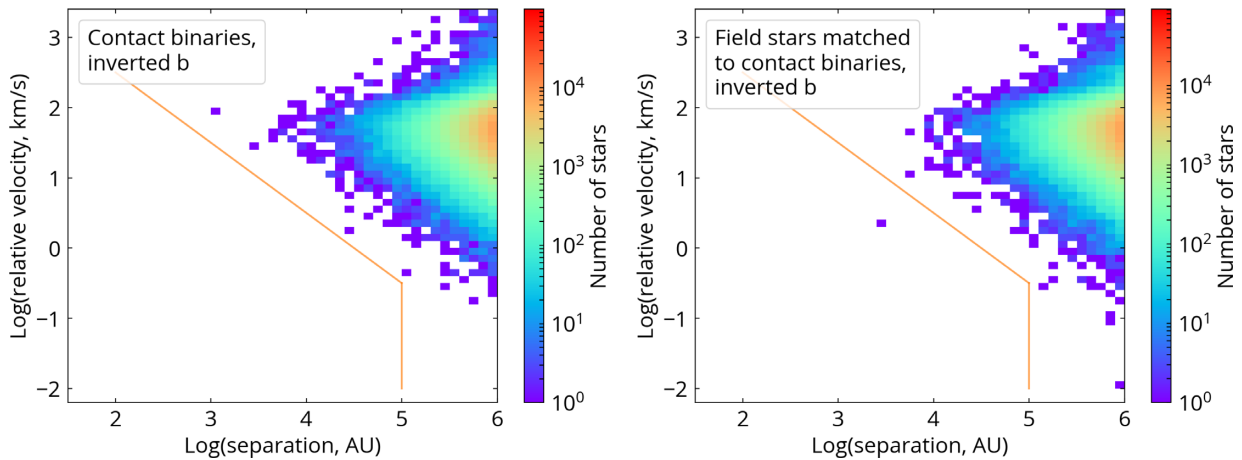
Figure 4. Contamination tests for main-sequence contact binaries (left-hand panel) and their matched field stars (right-hand panel) by inverting their Galactic latitudes.
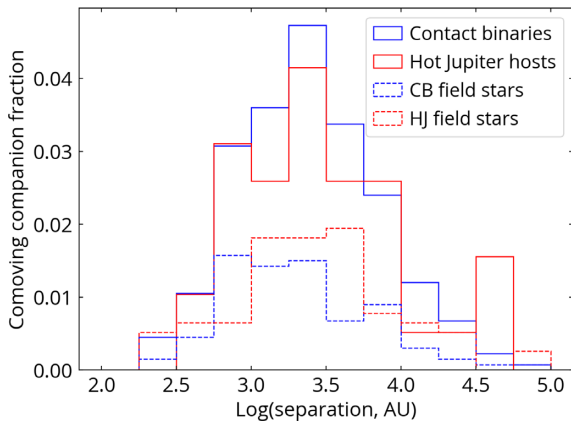

Figure 5. The distributions of projected separations for the comoving companions around hot Jupiter hosts, main-sequence contact binaries, and their matched field stars. For separations $<10^3$ AU, the sample starts to suffer from incompleteness due to *Gaia* photometry. The separations of 10^3–10^4 AU is secure for the investigation of wide comoving companions.

samples has two resolved comoving stars. In contrast, a significantly higher fraction (7/1333) of contact binaries have two comoving stars, providing further constraints on the formation of contact binaries and their wide companions. Overall, multiple comoving systems are rare so removing them does not affect the results.

We find one known dual hot Jupiter host, WASP-94 A and B (Neveu-Vanmalle et al. 2014; Teske, Khanal & Ramírez 2016), and one known dual contact binary, BV Dra and BW Dra (Batten & Hardie 1965), and one newly discovered dual binary. In our procedure, we count the separations of these dual systems twice, but it does not change the main result if we exclude them or count their separations once.

We provide two machine-readable tables, one for the hot Jupiter hosts and the other one for the contact binaries, with their corresponding wide companions that are used in Fig. 5. The tables contain (1) the *Gaia* DR2 `source_id` of hot Jupiter hosts and contact binaries; (2) the *Gaia* DR2 `source_id` of their companions; (3) their physical separations in AU. Dual systems appear two times in the table.

Since we require reliable BP−RP colours for the targets (not for the companions), our spatial resolution is limited by *Gaia*'s BP- and RP-band photometry because *Gaia* DR2 uses a window of

3.5×2.1 arcsec^2 to measure the total flux in *BP*- and *RP*-bands, i.e. applies no deblending. For pairs with separations $\lesssim 2$ arcsec, their BP and RP fluxes may be affected by the companion and may be excluded by the `phot_bp_rp_excess_factor` criteria. Therefore, our secure spatial resolution is 2 arcsec, and because we limit our sample to be within 400 pc, we are able to probe the very wide comoving companions with separations >800 AU.

The contact binary sample and two field star samples all show a steady decline of the companion fractions towards larger separations, but the hot Jupiter sample has an enhanced comoving companion fraction at ~$10^{4.5}$ AU. While it may be due to the contamination from chance projection, the contamination test (Fig. 3) shows that <1 contamination is expected at this separation. However, there are only three sources in the bin at ~$10^{4.5}$ AU, and therefore it suffers from small-number statistics and its significance requires a larger sample to confirm.

We conclude that separations of 10^3–10^4 AU is the secure separation range to investigate in *Gaia* DR2, and we define the very wide companion fraction as the fraction of a sample that have comoving companions at separations of 10^3–10^4 AU. In the next section, we investigate the very wide comoving fraction in hot Jupiter hosts and contact binaries.

3 RESULTS

In this section, we start with the presentation of the observed very wide companion fractions in Section 3.1. We then compute how the lack of close companions may affect the very wide companion fractions in Section 3.2. We compare the observed quantities with the enhancement due to the lack of close companions in Section 3.3.

3.1 Observed very wide companion fractions

Table 1 presents the very wide comoving companion fractions for hot Jupiter hosts, contact binaries, and their matched field stars. Specifically, 11.9 ± 2.5 per cent (23/193) of hot Jupiter hosts and 6.3 ± 0.9 per cent (49/772) of their matched field stars have companions at separations of 10^3–10^4 AU. For main-sequence contact binaries and their matched field stars, 14.1 ± 1.0 per cent (188/1333) and 4.5 ± 0.6 per cent (60/1333) have very wide comoving companions. The ratios of the observed comoving fraction to the field value

Table 1. Very wide companion fraction (10^3–10^4 AU) for hot Jupiter hosts and contact binaries.

	Hot Jupiter hosts	Contact binaries
Very wide companion fraction (10^3–10^4 AU)	11.9 ± 2.5 per cent (23/193)	14.1 ± 1.0 per cent (188/1333)
Field star values	6.3 ± 0.9 per cent (49/772)	4.5 ± 0.6 per cent (60/1333)
Enhancement compared to the field values	1.9 ± 0.5	3.1 ± 0.5
Enhancement expected from the lack of close companions	1.4 ± 0.3	1.0

is 1.9 ± 0.5 and 3.1 ± 0.5 for the hot Jupiter hosts and main-sequence contact binaries, respectively.

3.2 Expected enhancement of very wide companion fraction due to the lack of close companions

Moe & Kratter (2019) point out that the seemingly enhanced wide companion fraction of hot Jupiter hosts compared to the field stars may be the consequence of the lack of close companions (<50 AU) to the hot Jupiter hosts. As an extreme example, if all the stars were in stellar binary systems with a wide range of separations and hot Jupiters could not form in binaries with separations <1000 AU, then we would find that all hot Jupiter hosts have wide stellar companions at separations >1000 AU, i.e. an enhanced very wide companion fraction compared to the field stars. Therefore, an ideal comparison sample of the field stars for the hot Jupiter hosts would be those field stars that do not have close companions within ~ 50 AU. Unfortunately, it is not possible to select such a sample at the present time: such stellar pairs are too close to be spatially resolved, photometric selection on the colour–magnitude diagram is rarely precise enough to distinguish a single from a binary with a high mass ratio, and the use of high-precision radial velocity surveys strongly reduce the sample size. Therefore, there is no way to evaluate the fraction that have a companion within ~ 50 AU in our field star samples.

As we are unable to find comparison objects without close companions, we test the hypothesis that the hot Jupiter hosts are a random sampling of the field stars except that hot Jupiter hosts avoid systems with close companions. If there were no triple systems, this statement is equivalent to having the same companion separation distribution for hot Jupiter hosts and for the field stars at separations $\gtrsim 50$ AU. If there are triples, the companion separation distributions of hot Jupiter hosts and field stars are not the same, because avoiding systems with close separations also affects the companions at large separations.

Under such hypothesis, we compute the expected enhancement of companion fraction at separations between s_0 and s_1 due to the lack of close companions, denoted as $\mathcal{E}^{\mathrm{HJ}}(s_0, \ s_1)$:

$$\mathcal{E}^{\mathrm{HJ}}(s_0, \ s_1) = \frac{F^{\mathrm{HJ}}(s_0, \ s_1)}{F^{\mathrm{field}}(s_0, \ s_1)} = \frac{B^{\mathrm{HJ}}(s_0, \ s_1) + T^{\mathrm{HJ}}(s_0, \ s_1)}{B^{\mathrm{field}}(s_0, \ s_1) + T^{\mathrm{field}}(s_0, \ s_1)}, \quad (1)$$

where $F^{\mathrm{HJ}}(s_0, s_1)$ is the companion fraction of hot Jupiter hosts at separations between s_0 and s_1; $B^{\mathrm{HJ}}(s_0, s_1)$ is the fraction of hot Jupiter hosts that are in binary systems with separations between s_0 and s_1; and $T^{\mathrm{HJ}}(s_0, s_1)$ is the companion fraction with separations between s_0 and s_1 contributed by triple systems. For field stars, similar definitions are used for $F^{\mathrm{field}}(s_0, s_1)$, $B^{\mathrm{field}}(s_0, s_1)$, and $T^{\mathrm{field}}(s_0, s_1)$.

We first calculate the expected enhancement of companion fraction ($\mathcal{E}^{\mathrm{HJ}}_{\mathrm{no\ triple}}$) in the case with no triples, i.e. $T^{\mathrm{HJ}} = T^{\mathrm{field}} = 0$. We use

close to denote the separations smaller than 50 AU, *wide* to denote the separations between 50 and 2000 AU, and *very wide* to denote the separations between 10^3 and 10^4 AU. From equation (1), we have $\mathcal{E}^{\mathrm{HJ}}_{\mathrm{no\ triple}}(wide) = B^{\mathrm{HJ}}(wide)/B^{\mathrm{field}}(wide)$. We further define a function $\mathcal{S}^{\mathrm{HJ}}(s_0, s_1) \equiv B^{\mathrm{HJ}}(s_0, s_1)/(1 - B^{\mathrm{HJ}}(close))$ and similarly for $\mathcal{S}^{\mathrm{field}}(s_0, s_1)$. Then under the hypothesis that the shapes of the companion separation distributions of hot Jupiter hosts and field stars are the same beyond 50 AU, we have $\mathcal{S}^{\mathrm{HJ}}(wide) = \mathcal{S}^{\mathrm{field}}(wide)$. Therefore, $\mathcal{E}^{\mathrm{HJ}}_{\mathrm{no\ triple}}(wide) = B^{\mathrm{HJ}}(wide)/B^{\mathrm{field}}(wide) = [\mathcal{S}^{\mathrm{HJ}}(wide)(1 - B^{\mathrm{HJ}}(close))]/[\mathcal{S}^{\mathrm{field}}(wide)(1 - B^{\mathrm{field}}(close))] = (1 - B^{\mathrm{HJ}}(close))/(1 - B^{\mathrm{field}}(close))$. With $F^{\mathrm{HJ}}(close) = B^{\mathrm{HJ}}(close) = 0.04$ (Ngo et al. 2016) and $F^{\mathrm{field}}(close) = B^{\mathrm{field}}(close) = 0.40$ (Moe & Kratter 2019), the expected enhancement for very wide companion fractions is $\mathcal{E}^{\mathrm{HJ}}_{\mathrm{no\ triple}}(wide) = (1 - 0.04)/(1 - 0.40) = 1.6$. Thus in the case of no triples, there is an apparent enhancement of companion fraction which is independent of the chosen separation range once it is >50 AU, and therefore $\mathcal{E}^{\mathrm{HJ}}_{\mathrm{no\ triple}}(wide) = \mathcal{E}^{\mathrm{HJ}}_{\mathrm{no\ triple}}(very\ wide)$. This is an example that the (very) wide companion fraction of hot Jupiter hosts may be enhanced compared to that of the field star sample due to the lack of close companions in hot Jupiter hosts which are common in the comparison sample of field stars.

The contribution of companion fraction from triples can be written as

$$T^{\mathrm{HJ}}(s_0, \ s_1) = T^{\mathrm{HJ}}_{\mathrm{in},0}(s_0, \ s_1) + T^{\mathrm{HJ}}_{\mathrm{in},1}(s_0, \ s_1) + T^{\mathrm{HJ}}_{\mathrm{out},1}(s_0, \ s_1), \quad (2)$$

where $T^{\mathrm{HJ}}_{\mathrm{in},0}(s_0, \ s_1)$ is the fraction of hot Jupiter hosts that are in the inner binary of triples with inner separations between s_0 and s_1; $T^{\mathrm{HJ}}_{\mathrm{in},1}(s_0, \ s_1)$ is the fraction of hot Jupiter hosts that are in the inner binary of triples with outer separations between s_0 and s_1; and $T^{\mathrm{HJ}}_{\mathrm{out},1}(s_0, \ s_1)$ is the fraction of hot Jupiter hosts that are in the outer tertiary of triples with outer separations between s_0 and s_1. Similar definitions apply to $T^{\mathrm{field}}_{\mathrm{in},0}(s_0, \ s_1)$, $T^{\mathrm{field}}_{\mathrm{in},1}(s_0, \ s_1)$, and $T^{\mathrm{field}}_{\mathrm{out},1}(s_0, \ s_1)$ for field stars.

Triples tend to make the enhancement of companion fraction ($\mathcal{E}$) smaller than the case without triples. For example, if there is a triple with inner separation <50 AU and an outer separation of 5000 AU, then this system would contribute a very wide companion to field stars through $T^{\mathrm{field}}_{\mathrm{in},1}(very\ wide)$, but not to hot Jupiter hosts through $T^{\mathrm{HJ}}_{\mathrm{in},1}(very\ wide)$ because its small inner separation prevents the formation of a hot Jupiter. An accurate estimate of $T^{\mathrm{HJ}}(s_0, s_1)$ is challenging because it requires a good understanding of the distributions of inner and outer separations and their correlation.

By taking the contribution of triples into account, Moe & Kratter (2019) estimate the expected enhancement of companion fraction due to the lack of close companions to be $\mathcal{E}^{\mathrm{HJ}}(wide) = 1.32 \pm 0.25$ ($0.37 \pm 0.07/0.28 \pm 0.05$) for wide binaries. For very wide companions investigated in this paper, $\mathcal{E}^{\mathrm{HJ}}(very\ wide)$ may not be

exactly the same as $\mathcal{E}^{\mathrm{HJ}}$(wide), depending on difference of the triple contribution in these two separation ranges. However, with current limited understanding of the correlation between inner and outer separations, we estimate that $\mathcal{E}^{\mathrm{HJ}}$(very wide) $\sim \mathcal{E}^{\mathrm{HJ}}$(wide) to leading order.

The unresolved inner binaries of triples may also enhance the (very) wide companion fractions. Unresolved binaries have two times higher probability of having a hot Jupiter than single stars, simply because there are two stars in an unresolved binary. If there exists a significant number of triples with unresolved inner separations ($\lesssim$1000 AU in our case) and resolved outer separations ($>$1000 AU in our case), then hot Jupiter hosts may have an enhanced wide companion fraction because they are more likely to be found in the inner binaries of triples. With some realistic binary fraction and triple fraction, we estimate that this effect would result in an enhancement of companion fraction of 10–20 per cent, and may be smaller if hot Jupiter hosts tend to have fewer close companions. Combined with the effect of the lack of close companions, the expected enhancement of very wide companion fraction is $\mathcal{E}^{\mathrm{HJ}}$(very wide) $= 1.4 \pm 0.3$ for hot Jupiter hosts, and we tabulate this number in the bottom row of Table 1.

Unlike hot Jupiter hosts where a lack of close companions is observed within $\sim$50 AU, close binaries only show a lack of companions within $\sim$1 AU (Tokovinin et al. 2006; Gies et al. 2012; Tokovinin 2014). Therefore, while the lack of close companions enhances the wide companion fraction for hot Jupiter hosts, such effect is negligible for contact binaries (Moe & Kratter 2019), and we tabulate $\mathcal{E}^{\mathrm{CB}}$(very wide) $= 1.0$ in the bottom row of Table 1 for the contact binaries.

3.3 A weak or no enhancement for hot Jupiters, and a significant enhancement for contact binaries

Compared to $\mathcal{E}^{\mathrm{HJ}}$(*very wide*) $= 1.4 \pm 0.3$, our measured enhancement factor of 1.9 ± 0.5 for hot Jupiter hosts suggests that there is no or a weak enhancement at $\sim$1σ significance. Therefore, the enhanced very wide companion fraction from hot Jupiter hosts is consistent, within $\sim$1σ, with the fact that they lack close companions. Confirming the weak enhancement requires a larger hot Jupiter host sample in the future.

Compared to $\mathcal{E}^{\mathrm{CB}}$(*very wide*) $= 1.0$, our measured enhancement factor of 3.1 ± 0.5 for main-sequence contact binaries shows that there is a significant enhancement at a 4σ significance. This enhancement cannot be explained by the lack of close companions, and therefore some other physical mechanisms are needed to explain the connection between contact binaries and their very wide companions.

4 DISCUSSION

4.1 Very wide companions play a minor role in the orbital migration

Close binary fraction increases with decreasing metallicity, but (very) wide binary fraction with separations $\gtrsim$200 AU is weakly dependent on the metallicity (El-Badry & Rix 2019; Moe et al. 2019). Therefore, the enhanced very wide companion fraction around contact binaries is not due to their metallicity.

The very wide companions investigated in this paper are not able to induce significant orbital migration in the proto-contact binaries and proto-hot Jupiter systems through the classical Kozai-Lidov mechanism. For a companions at a separation of 10^3 AU, it can induce the Kozai-Lidov oscillation only when the inner binaries

have a separation $\gtrsim$5 AU, which is set by the requirement that the oscillation time-scale needs to be shorter than the time-scale of the relativistic pericentre precession (Fabrycky & Tremaine 2007). Therefore, these very wide companions are not able to bring the inner proto-hot Jupiter system and proto-contact binaries to their current separations ($<$0.1 AU).

When the outer orbit is eccentric, it can trigger a higher order octuple effect, called the eccentric Kozai-Lidov effect (Naoz et al. 2013; Naoz 2016). The eccentric Kozai-Lidov effect typically enhances the efficiency of forming hot Jupiters (Naoz et al. 2012) and close binaries (Naoz & Fabrycky 2014). Although the octuple time-scale is not well quantified due to the chaotic nature of the eccentric Kozai-Lidov effect, it is typically longer than the classical Kozai-Lidov effect (Naoz 2016). Therefore, the very wide companions are not able to contribute much to the orbital migration through the eccentric Kozai-Lidov effect either.

Another possibility is that the very wide companions were initially located at a smaller separation where they can induce strong Kozai-Lidov oscillations, and they migrated outward at a later time. This scenario is also suggested by El-Badry et al. (2019) where they find an excess of equal-mass stellar binaries out to separations of $\sim$10^3 AU. Because equal-mass binaries are mainly formed from disc fragmentation at close separations ($\lesssim$100 AU), they argue that the observed equal-mass wide binaries are formed with close separations and further widened by dynamical interactions in their birth environments. However, such excess of equal-mass binaries at $\sim$10^3 AU is only $\sim$5 per cent in the field. It is not yet clear if this outward migration is a dominant path for the very wide companions around contact binaries. Further investigation on the mass ratios between the contact binaries and their very wide companions may be able to constrain this scenario.

If the Kozai-Lidov mechanism is a dominant formation channel for contact binaries, we would expect them to have companions with smaller separations to trigger the Kozai-Lidov oscillations. Then following the same argument as Section 3.2, we would expect a lower very wide companion fraction for contact binaries because of their enhanced close companion fraction. Instead, our result shows that contact binaries have an enhanced very wide companion fraction, suggesting that either the Kozai-Lidov mechanism is not a dominant formation channel for contact binaries, or there is another mechanism producing a significant number of very wide companions around contact binaries that compensate for the effect of the enhanced close companion fraction.

To sum up, these very wide companions play a minor role in the orbital migration of the inner systems unless they have undergone a significant outward orbital migration. Therefore, the very wide companions are more likely to be indicative of their formation environment.

4.2 Formation environment of very wide companions, hot Jupiter hosts, and contact binaries

Because the binding energy of very wide binaries is small, they are sensitive to the environment of their birth place. Several mechanisms have been proposed for the formation of wide binaries. Turbulent core fragmentation may be able to form binaries with separations from a few hundred to a few thousand AU (Offner et al. 2010; Lee et al. 2017). Binaries with separations of 10^3–10^5 AU can form through the dissolution of star clusters (Kouwenhoven et al. 2010; Moeckel & Clarke 2011), the disintegration of unstable compact triples (Reipurth & Mikkola 2012), and pairing of adjacent pre-stellar cores (Tokovinin 2017). In terms of time-scales, turbulent

core fragmentation and the paring of adjacent cores take place at an age of $\lesssim 1$ Myr during the pre-stellar phase. It takes a longer time (from 10 to a few hundred Myr) for a cluster to dissolve and for a compact triple to unfold.

Wide binaries may be disrupted over time through the gravitational interaction with closely passing stars, molecular clouds, invisible objects, and the Galactic tides (Heggie 1975; Bahcall, Hut & Tremaine 1985; Weinberg, Shapiro & Wasserman 1987; Chaname & Gould 2004; Jiang & Tremaine 2010). Such disruption takes place on time-scales of several Gyr, and most binaries with separations $<10^4$ AU are not disrupted within the age of the Milky Way (Weinberg et al. 1987; Andrews et al. 2012). Even if the wide binaries are disrupted, two stars can still stay in an unbound comoving pair at separations of ~ 100 pc for several Gyr because of the small relative velocity (Jiang & Tremaine 2010; Oh et al. 2017). Therefore, most of the very wide companions investigated here are stable over the age of the Milky Way and the disruption events play a relatively minor role.

The enhanced very wide companion fraction around contact binaries suggests that (proto-)contact binaries are more likely to form in the environments that produce wide systems. For the scenario where wide companions are formed from the dissolution of star clusters, it means that the formation of contact binaries is sensitive to the cluster properties (Kouwenhoven et al. 2010). If wide companions are formed from the disintegration of compact triples, then it implies that (proto-)contact binaries may be the product of such formation. If the very wide companions are formed from the enhanced turbulent core fragmentation due to certain environmental properties (which may also tend to produce compact multiples), then it suggests contact binaries are also more likely to form in such environment.

In contrast, the weak or no enhancement of very wide companion fraction around hot Jupiter hosts suggests that hot Jupiter formation has different dependence on the formation environment as the contact binaries. Moe & Kratter (2019) use the different wide companion enhancements between hot Jupiter hosts and close binaries to support the idea that hot Jupiters are formed from core accretion and (sub-)stellar objects are formed from gravitational instability, coinciding with the mass gap of $4–9\,M_J$ found by Schlaufman (2018). The very wide companions investigated here are more sensitive to the birth environment, and the weak or no enhancement of very wide companion fraction around hot Jupiter hosts indicates that hot Jupiter host formation may be insensitive to larger-scale properties of the birth environment, including the cluster properties and the efficiency of turbulent core fragmentation.

4.3 The frequency of dual hot Jupiter hosts and double contact binaries

The probability of finding a hot Jupiter host (contact binary) in the companion of a hot Jupiter host (contact binary) seems to be higher than the occurrence rate of hot Jupiters (contact binaries) in the field. Although the sample is small, we find one dual hot Jupiter host (two hot Jupiter hosts) among 22 hot Jupiter hosts that have very wide companions. This ~ 9 per cent of hot Jupiter occurrence rate (we double count the dual hot Jupiter host because that preserves correct statistical properties for inference) in the comoving companions of hot Jupiter hosts is much higher than the 0.5–1 per cent occurrence rate in the field (Mayor et al. 2011; Wright et al. 2012; Fressin et al. 2013; Santerne et al. 2016; Zhou et al. 2019). Similarly, we find two double contact binaries out of 188 contact binaries that have very wide companions. This ~ 2 per cent

occurrence in the very wide companions is also significantly higher than the 0.1 per cent occurrence in the field using the same selection method (Hwang & Zakamska 2020). Our results hint that the occurrence rate of hot Jupiters and contact binaries in the comoving companions may be about one order-of-magnitude higher than that in the field. In other words, the occurrence rates of dual systems are higher than the expected values from random pairing of field stars. However, the current sample size of dual systems is still very small so future larger samples are needed to further confirm these results.

Tokovinin (2014) also finds an enhanced occurrence rate of $2 + 2$ systems (quadruples consisting of two close stellar binaries) and suggests that these systems were formed by some special process. The disintegration of dynamically unstable compact multiples (Reipurth & Mikkola 2012) may also help the formation of double contact binaries, but not for dual hot Jupiter hosts. Here we propose another scenario where the enhanced occurrence rate of dual systems is due to the co-chemical (components have similar metallicities) and the co-eval (components have similar ages) nature of the components of wide binaries. Andrews, Chanamé & Agüeros (2018) show that the components of wide binaries with separations $<4 \times 10^4$ AU have similar metallicities and elemental abundances within measurement uncertainties (see Kamdar et al. 2019 for larger separations). Therefore, if we find a wide companion around a hot Jupiter host, then because hot Jupiter hosts tend to have higher metallicities (Gonzalez 1997; Santos et al. 2004; Fischer & Valenti 2005) and the components of wide binaries have similar metallicities (Andrews et al. 2018), we would expect that the wide companion of a hot Jupiter host also has a higher metallicity and therefore a higher chance of hosting a hot Jupiter, resulting in an enhanced occurrence rate of dual hot Jupiter hosts. The close binary fraction is dependent on the metallicity (Moe et al. 2019), and the contact binary fraction is also a function of the stellar age due to their orbital migration and merger (Hwang & Zakamska 2020), and therefore such metallicity and age dependence of contact binaries can also result in the higher occurrence rate of dual contact binaries.

5 CONCLUSIONS

In this paper we investigate the very wide comoving fractions with separations of $10^3–10^4$ AU around hot Jupiter hosts and main-sequence contact binaries using *Gaia* DR2. We further compute the enhancement of very wide companion fractions by comparing with their matched field star samples. We present the following findings:

(i) 11.9 ± 2.5 per cent of hot Jupiter hosts and 14.1 ± 1.0 per cent of contact binaries have companions at separations of $10^3–10^4$ AU. Compared to the matched field star samples, the very wide companion fractions are enhanced by a factor of 1.9 ± 0.5 and 3.1 ± 0.5 for hot Jupiter hosts and contact binaries, respectively (Table 1).

(ii) The measured fraction of very wide companions for hot Jupiter hosts is consistent, within $\sim 1\sigma$, with that for matched field stars once we take into account the observational bias in the comparison sample introduced by the lack of close companions to hot Jupiter hosts. In contrast, the strong enhancement of very wide companions around contact binaries is highly statistically significant, and there must be a physical mechanism connecting the inner short-period binary with its very wide companion.

(iii) We argue that the very wide companions are indicative of the formation environments. The enhanced very wide companion fraction around contact binaries suggests that contact binary forma-

tion is sensitive to their formation environment, e.g. the star cluster properties, the efficiency of fragmentation, and/or compact multiples. The weak or no enhancement of very wide companion fraction around hot Jupiters implies that the formation of hot Jupiters is more tied to their host-star properties instead of large-scale formation environments.

(iv) The probability of finding a hot Jupiter host (contact binary) in the companion of a hot Jupiter host (contact binary) seems to be about an order of magnitude larger than the occurrence rate of hot Jupiters (contact binaries) in the field, which may be due to the underlying metallicity and age dependence of hot Jupiters and contact binaries. Larger samples are needed to better quantify such occurrence rates.

ACKNOWLEDGEMENTS

DATA AVAILABILITY

The data underlying this article are available in the article and in its online supplementary material.

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