LIFETIME OF SHORT-PERIOD BINARIES MEASURED FROM THEIR GALACTIC KINEMATICS

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ABSTRACT

As a significant fraction of stars are in multiple systems, binaries play a crucial role in stellar evolution. Among short-period (<1 day) binary characteristics, age remains one of the most difficult to measure. In this paper, we constrain the lifetime of short-period binaries through their kinematics. With the kinematic information from Gaia Data Release 2 and light curves from Wide-field Infrared Survey Explorer (WISE), we investigate the eclipsing binary fraction as a function of kinematics for a volume-limited main-sequence sample. We find that the eclipsing binary fraction peaks at a tangential velocity of \(10^{1.3-1.6}\) km s\(^{-1}\), and decreases towards both low and high velocity end. This implies that thick disk and halo stars have eclipsing binary fraction \(\gtrsim 10\) times smaller than the thin-disk stars. Using Galactic models, we show that our results are inconsistent with any known dependence of binary fraction on metallicity. Instead, our best-fit models suggest that the formation of these short-period binaries is delayed by 0.6-3 Gyr, and the disappearing time is less than the age of the thick disk. The delayed formation time of \(\gtrsim 0.6\) Gyr is too long for any pre-main sequence interaction alone and is more consistent with the three-body interaction through the Kozai-Lidov mechanism and magnetic winds. Because the main-sequence lifetime of our sample is longer than 14 Gyr, if the disappearance of short-period binaries in the old population is due to their finite lifetime, our results imply that most (\(\gtrsim 90\%\)) short-period binaries in our sample are destroyed during their main-sequence stage.

1. INTRODUCTION

Binaries are at the core of many exotic astronomical events in the Universe, including classical novae (Warner 1995), red novae (Tylenda et al. 2011), type Ia supernovae (Whelan & Iben, Icko 1973; Iben & Tutukov 1984; Webbink 1984), short gamma-ray bursts (Shibata & Taniguchi 2006; Fong & Berger 2013), binary black hole mergers (Abbott et al. 2016), and kilonovae (Abbott et al. 2017; Smartt et al. 2017; Cowperthwaite et al. 2017). A significant fraction of all stars are in binary and multiple systems (Duchêne & Kraus 2013). Therefore, binary evolution plays a crucial role in the understanding of the Universe.

All the stellar binaries are once a main-sequence (MS) binary. While thousands of short-period (<1 day) MS binaries have been found, they are not formed with such short separation because the radii of pre-MS stars are larger than the MS stars. In fact, the initial separation of binaries is believed to be \(\gtrsim 10\) AU because the radius of an initial hydrostatic stellar core is \(\sim 5\) AU (Larson 1969) and its fragmentation is unlikely (Bate 1998, 2011). Therefore, short-period binaries must have gone through orbital migration to shrink the separation from \(> 10\) AU (\(> 2000\) R\(_{\odot}\)) to a few R\(_{\odot}\).

Short-period binaries may have experienced several different processes to lose orbital angular momentum. At the pre-MS phase, the energy dissipation due to the interaction with the primordial gas may be able to produce binaries with separations down to \(\sim 0.1\) AU (Bate et al. 2002; Bate 2009, 2012). This process takes place on a free-fall timescale, typically \(\sim\)Myr, and may be able to explain the formation of pre-MS binary stars with periods >1 day (Mathieu 1994; Tohline 2002).

During the MS phase, if a binary has a distant tertiary companion, the angular momentum of the inner binary can exchange with the outer tertiary companion, the so-called Kozai-Lidov mechanism (Kozai 1962; Lidov 1962). The inner binary separation can be reduced to a few stellar radii at the pericenter passages due to the high eccentricity excited by the Kozai-Lidov mechanism, and at that point the tidal friction is able to remove the angular momentum and shrink the orbit (Harrrington 1968; Kiseleva et al. 1998; Eggleton & Kiseleva-Eggleton 2001; Fabrycky & Tremaine 2007). This process is often referred to as Kozai cycles with tidal friction (KCTF). If higher-order effects are taken into accounts, for example eccentric outer orbit and post-Newtonian effects, three-body interactions are more complicated and even chaotic (Naoz et al. 2013a,b; Naoz 2016). The Kozai-Lidov mechanism is supported by observations that a large fraction of MS close binaries are in triple systems (Tokovinin 1997; Pribulla & Rucinski 2006;
Tokovinin et al. 2006; Rucinski et al. 2007). Furthermore, Borkovits et al. (2016) find that the distribution of mutual inclination between the inner binaries and the outer secondaries shows a peak at $\sim 40^\circ$, consistent with the prediction from KCTF (Fabrycky & Tremaine 2007), although the other observed peak at $\sim 0^\circ$ is not expected. Depending on the configuration of the triple stars and the initial conditions, KCTF may operate on a wide range of timescales, from $\lesssim 0.1$ Gyr to several Gyr (Fabrycky & Tremaine 2007; Perets & Fabrycky 2009), until the orbits of the inner binaries are circularized.

If the binary separation is close enough (periods $\lesssim 5$ days), magnetic winds become important in extracting angular momentum of binaries. Specifically, stars with masses $\lesssim 1.3 \, M_\odot$ possess subphotospheric convection zones that generate magnetic winds which take away the (rotational) angular momentum of the star. Due to the synchronization between the rotational and orbital periods in short-period binaries, the loss of angular momentum shrinks the orbit. Over a timescale of a few Gyr, magnetic winds are able to bring binaries to the contact phase (Stepien 1995).

The relative contribution of each process to the formation of short-period (< 1 day) MS binaries is not yet clear. Hydrodynamical simulations show that pre-MS interaction is not able to produce binaries with separations $\lesssim 0.1$ AU, although it can be due to the simulation resolution limit (Bate et al. 2002; Bate 2009, 2012). The Kozai-Lidov mechanism encounters the difficulty that the majority of binaries with periods $< 10$ days have circular orbits (Latham et al. 2002; El-Badry et al. 2018), in which case the Kozai-Lidov mechanism is not able to excite eccentricity. The magnetic winds require small initial period ($\lesssim 5$ days) to be efficient.

If the ages of short-period binaries could be measured directly, ages could be used to constrain the mechanisms responsible for the orbital migration. By comparing with the MS lifetime, we can determine whether short-period binaries can survive for the entire MS lifetime. If the short-period binaries destruct or disappear at a particular age or at a particular stage of the stellar evolution, then we can constrain or identify the destruction process.

Age is notoriously difficult to measure for single stars. Furthermore, such methods, including isochrone fitting, stellar rotation, and chromosphere activity, are not valid anymore for short-period binaries because they may have undergone binary interaction and mass transfer. Kinematics is among the few reliable ways to probe the age of short-period binaries. The age-velocity dispersion relation has been well established for a variety of MS stars (Dehnen & Binney 1998; Nordström et al. 2004; Reid et al. 2009; Sharma et al. 2014). For disk stars, this relation may be the consequence of kinematic heating processes from giant molecular clouds, transient spiral arms, bars, and flyby satellite galaxies. Kinematics can also help separate the thin-disk, thick-disk, and halo stars. Because accelerations experienced by test particles are independent of their masses, we are able to directly compare the kinematics between single stars and binaries, and further infer their ages.

In this paper, we use Gaia Data Release 2 and the light curves from WISE to investigate the kinematics of short-period (< 1 day) eclipsing binaries. In Sec. 2, we describe the dataset, our sample selection, and our time-series analysis. In Sec. 3 we present our primary results of the relation between eclipsing binary fraction and kinematics. In Sec. 4, we investigate possible systematics and different sample selections. In Sec. 5, we use Galactic models and show that our results can be explained by a finite lifetime of eclipsing binaries. In Sec. 6, we discuss disk/halo difference, metallicity, and the implication from the lifetime of eclipsing binaries. We summarize in Sec. 7.

2. SAMPLE SELECTION AND MEASUREMENTS

2.1. The parent Gaia sample

Our sample is selected from Gaia Data Release 2 (DR2; Gaia Collaboration et al. 2016, 2018a). Gaia is an optical all-sky survey which is obtaining photometry and astrometry for stars with magnitudes down to $\sim 21$ mag and radial velocities for select bright stars. Gaia DR2 was released on 25 April 2018, based on data collected between 25 July 2014 and 23 May 2016. In Gaia DR2, broad-filter G-band magnitudes, blue-band BP magnitudes, red-band RP magnitudes, positions, parallaxes, and proper motions are available for $\sim 1.33$ billion objects and radial velocities for $\sim 7$ million stars, providing an unprecedented dataset on the phase-space distribution of stars in the Milky Way.

Our query for Gaia DR2 follows the one used in Gaia Collaboration et al. (2018b). Specifically, the mean flux divided by its error is is larger than 50 for G-band and larger than 20 for BP and RP bands. In Gaia DR2, BP and RP fluxes are not treated with deblending, so we apply a cut on $\text{phot_bp_rp_excess_factor}$ to reduce the effect of crowded fields which makes the BP and RP bands unreliable (Evans et al. 2018; Arenou et al. 2018). $\text{visibility_periods_used} > 8$ is used to ensure that there are sufficient observations for deriving the astrometric solutions (Lindegren et al. 2018), and $\text{parallax_over_error} > 10$ is adopted to have well-measured parallaxes. The criteria for the unit error introduced by Lindegren et al. (2018) are included to reduce spurious astrometric solutions. Because we obtain the light curves from WISE, we cross-match Gaia DR2 and WISE using the Gaia DR2 cross-match catalog.
(Marrese et al. 2019). Our Gaia DR2 query is included in the Appendix.

We compute tangential velocities from proper motions and parallaxes provided by Gaia DR2. We do not use the radial velocities in Gaia DR2 because the radial velocity sample is ~100 times smaller. Furthermore, Gaia DR2 does not report the radial velocities of double-line systems and objects having high radial velocity variations (Katz et al. 2019), which strongly biases the binary selection.

We correct the velocities by removing the solar motion and the differential rotation of the Galactic disk. We adopt the solar motion from Schönhrich et al. (2010) where \((U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25) \text{ km s}^{-1}\), with the convention that \(U_\odot, V_\odot, W_\odot\) are oriented towards the Galactic center, the direction of Galactic rotation, and the north Galactic pole. Our sample is within 500 pc with a median of 380 pc, the local shear approximation described by Oort’s constants is applicable. We remove the contribution from differential rotation of the Galactic disk using the Oort constants reported from Bovy (2017): \(A = 15.3 \text{ km s}^{-1} \text{kpc}^{-1}\), \(B = -11.9 \text{ km s}^{-1} \text{kpc}^{-1}\), \(C = -3.2 \text{ km s}^{-1} \text{kpc}^{-1}\), \(K = -3.3 \text{ km s}^{-1} \text{kpc}^{-1}\). While this correction is only valid for disk stars and not for halo stars because halo stars are not rotating with the disk, but since the velocity correction of differential rotation is \(< 10 \text{ km s}^{-1}\), this (incorrect) correction is small for halo stars where the typical velocities are \(>100 \text{ km s}^{-1}\). With the correction of the solar motion and the differential rotation of the Galactic disk, the tangential velocities \(V_t\) presented in this paper are the tangential components relative to the local Galactic rotation at the star’s location.

2.2. Eclipsing binary sample from WISE

Because Gaia DR2 has not released the time series and the catalog of eclipsing binaries, we construct the eclipsing binary sample using two other ways. One is from the light curves of WISE, and the second is from the variability information in Gaia DR2. These two samples are complementary: the WISE sample has less contamination, while the Gaia sample is more complete in terms of the sky distribution and is not affected by the limits of period-finding algorithms.

The WISE eclipsing binary sample is constructed using Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010). Our work requires a large sample and good cadences to recover short-period (< 1 day) eclipsing binaries, and WISE serves as an excellent dataset for this purpose. Since WISE is an all-sky survey, it provides a large cross match sample with Gaia. Furthermore, the orbital period of WISE satellite is ~1.6 hours, which is able to recover the MS eclipsing binaries, and this cadence is much better than most of the ground-based surveys. Its W1 (3.4 \(\mu\)m) and W2 (4.6 \(\mu\)m) bands have been collecting data since AllWISE in 2010 to NeoWISE in 2019, providing a long baseline to study the time series. In main-sequence regions and the color and parallax range of interest, we end up with ~1000 short-period eclipsing binaries in WISE, compared to only a few hundred targets in the Kepler eclipsing binary catalog (Kirk et al. 2016) and the Catalina Sky Survey (Drake et al. 2014) under the same criteria.

The AllWISE source catalog provides \(\text{var}_{\text{flag}}\) which is a measure of the probability that an AllWISE source is variable in each WISE filter. Specifically, \(\text{var}_{\text{flag}}\) is an integer ranging from 0 to 9 such that \(~10^{-\text{var}_{\text{flag}}}\) is the probability that the observed WISE light curve is drawn from a non-variable population (Hoffman et al. 2012). Therefore, \(\text{var}_{\text{flag}} = 0\) means non-variable and 9 indicates the highest probability of being variable. Out of the parent Gaia sample, we select targets where \(\text{var}_{\text{flag}} \geq 5\) in W1 band to further analyze their light curves, resulting ~20,000 variable candidates. We do not consider other WISE bands because W2 has worse sensitivity, and W3 and W4 do not have single-epoch exposures in NeoWISE.

We download complete W1 light curves from AllWISE Multiepoch Photometry Table and NEOWISE-R Single Exposure (L1b) Source Table through NASA/IPAC Infrared Science Archive and perform time series analysis for variable candidates where \(\text{var}_{\text{flag}} \geq 5\). The W1 light curves from AllWISE and NeoWISE provide a total baseline of ~9 years from 2010 to 2019. To ensure the photometric quality of single-epoch exposures, we follow the instruction of Cutri et al. (2011) to adopt the criteria of \(\text{saa}_{\text{sep}} > 0\), \(\text{moon}_{\text{masked}} = 0\), \(\text{q1}_{\text{fact}} > 0.9\) for AllWISE\(^1\), and \(\text{saa}_{\text{sep}} > 0\), \(\text{moon}_{\text{masked}} = 0\), \(\text{q1}_{\text{fact}} > 0.9\), and \(\text{qual}_{\text{frame}} > 0.9\) for NeoWISE\(^2\). AllWISE Multiepoch Photometry Database also contains some redundant photometric measurements, and we further exclude them by matching the source ID (source_id_mf) in AllWISE and NeoWISE\(^3\).

We use the periodogram of Multi-Harmonic Analysis of Variance (MHAOV; Schwarzenberg-Czerny 1996) to determine the periodicity in the light curves. MHAOV has good performance compared to other period-finding algorithms in terms of the accuracy against magnitude, sampling rates, quoted period, S/N ratios, number of observations, and different variability classes (Graham et al. 2013). We run MHAOV with three harmonics on the WISE variable candidates from \(f_{\text{min}} = 0.1 \text{ day}^{-1}\) to

1 http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/sec3_1.html
2 http://wise2.ipac.caltech.edu/docs/release/neowise/expsup/sec2_3.html
3 http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/sec3_2.html
\( f_{\text{max}} = 20 \text{day}^{-1} \) with \( \Delta f = 1 \times 10^{-4} \text{day}^{-1} \), or equivalently periods ranging from 0.05 day (1.2 hour) to 10 days. Chen et al. (2018) also measure the periods for WISE variables, but their minimum period in the periodogram is set to 0.143 day (3.4 hours). While this minimum period is safer because it is above the classical Nyquist period of 3.2 hours (i.e. two times of the WISE satellite’s orbital period), it misses most of short-period MS eclipsing binaries. The Nyquist sampling theorem applies when the sampling is uniform, whereas WISE satellite does not observe targets uniformly due to the size of the field of view and the drift of the satellite’s orbital plane (Mainzer et al. 2014). Thus WISE’s slightly irregular sampling may help to recover periods below the classical Nyquist limit (VanderPlas 2018). If the aliasing does happen, it results in an aliased peak in the periodogram. Therefore, aliasing only makes the measured period inaccurate but does not affect the fact that such source is a periodic variable. Since our main interest is in selecting short-period (< 1 day) eclipsing binaries but not their exact periods, aliasing does not affect our sample selection. Therefore, we adopt a minimum period in the periodogram smaller than the classic Nyquist limit to recover short-period MS eclipsing binaries. A more detailed investigation of the short-period WISE periodic variables will be presented in Petrosky et al. (in prep.).

For some eclipsing binaries, particularly contact binaries (W UMa binaries), their primary and secondary eclipses have similar depths so period-searching algorithms may not be able to distinguish the primary from secondary eclipses. Therefore, the period-searching algorithm may report a period that is two times smaller than the orbital period. We do not attempt to apply this factor of 2 correction, and we refer to the measured periods from periodograms as ‘apparent periods’, and keep in mind that the apparent periods may be two times smaller than the orbital periods of the binaries.

After time series analysis of the WISE variables, we use the following criteria to select the WISE eclipsing binary sample: (1) the peak in the MHAOV periodogram (\( \Theta \) statistics) is larger than 200, meaning that a strong periodic signal is detected in the light curves; (2) there is at least one observation in every 0.05 phase in the phase-folded light curves, ensuring that the light curve is well-sampled; (3) even with the previous two criteria, there is an overdensity in the apparent periods at \( \sim 0.067 \) day, the orbital period of the WISE satellite. Therefore, we limit our sample to apparent periods > 0.07 day to avoid these spurious period measurements. These three criteria result in 2994 periodic variables from the parent Gaia sample. We inspect their phase-folded light curves and confirm that these criteria provide a robust eclipsing binary sample.

Fig. 2 shows the apparent periods of the WISE periodic variables with respect to the Gaia BP–RP colors. The red line is the theoretical minimum possible period for contact, equal-mass MS binaries. The red line is derived using PARSEC isochrone (Bressan et al. 2012) with an age of 9 Gyr and solar metallicity. The simple theoretical minimum possible apparent period is computed by

\[
P_{\text{apparent}} = 0.5 P_{\text{orbital}} = \pi \sqrt{a^3/G(M_1 + M_2)},
\]

where \( a \) is the semi-major axis of the binary, \( G \) is the gravitational constant, and \( M_1 \) and \( M_2 \) are the masses of the stars. We consider equal-mass binaries (\( M_1 = M_2 \)) and use the Roche-lobe volume radius \( R_L = 0.38a \) (Eggleton 1983), where \( R_L \) is the volume radius of a star. By definition, the volume radius \( R_L \) equals to the radius of an undistorted star which is provided in the PARSEC isochrone. The overall trend of the solid red line in Fig. 2 represents the periods limited by the sizes of stars: bluer, larger stars have larger minimum periods while redder, smaller stars can have smaller periods.

Fig. 2 shows that our period measurements are in excellent agreement with the period limit of contact binaries, meaning that our WISE variable sample, if not all, is dominated by eclipsing binaries. Fig. 2 also emphasizes the need to search apparent periods below the classical Nyquist limit of 0.13 day, otherwise most of the eclipsing binaries having BP–RP > 1 would be missed. Some narrow gaps in apparent periods at multiples of the WISE’s orbital period (0.13 day and 0.2 day) can be seen in the black points because the sampling is not sensitive to their periods. While aliasing can potentially downgrade our period accuracy, Fig. 2 shows that our results pass through the classic Nyquist limit at 0.13 day quite smoothly and recover a large number of low-mass eclipsing binaries below this limit. The blue end (BP–RP < 0.5) overlaps the instability strip, so some of them may be \( \delta \) Scuti variables (Gaia Collaboration et al. 2018c). Type-II Cepheids are also located at the blue end (BP–RP < 0.5), but their periods typically are longer than 1 day and are not seen in this plot.

### 2.3. Main sequence selection

Our MS selection is made to satisfy several purposes: (1) the binary fraction is a strong function of mass and therefore color (Duchêne & Kraus 2013). Using a narrow color range reduces such mass dependence in our results. (2) On the blue end (BP–RP < 0.5), there is contamination from pulsating stars like \( \delta \) Scuti. (3) Stars may leave the MS phase because of stellar evolution, so selecting long-lived (i.e. redder) MS helps to interpret kinematic results. (4) Because binaries are brighter than single stars, we aim to construct a volume-limited sample instead of a magnitude-limited sample to avoid systematics. For this reason, we cannot use MS stars that are too red because they are faint and the sample
size would be very small in a volume-limited sample.

To address all these points, we select an MS sample with absolute magnitude offsets $|\Delta G| < 1.5$ mag and with $0.9 < BP-RP < 1.4$, shown as the colored region in Fig. 1. The black dashed line in Fig. 1 is the spline fit to Pleiades, following Hamer & Schlaufman (2019). Pleiades is a young, solar-metallicity open cluster with age $10^{8.04}$ years and $[\text{Fe/H}] = -0.01$ (Netopil et al. 2016), and $\Delta G$ is defined as the offset of absolute G magnitudes between the stars and Pleiades at the same BP–RP colors, where $\Delta G < 0$ means that the star is brighter than Pleiades at the same color. Objects are defined as MS if they have $|\Delta G| < 1.5$ mag. The 1.5 magnitude range is motivated by the fact that we want to include binaries, which are 0.75 mag brighter than single stars assuming equal luminosities and no occultations, and we also want to keep thick-disk and halo stars which are $\lesssim 1$ mag fainter than Pleiades at the color range considered.

The color selection of $0.9 < BP-RP < 1.4$ is chosen to avoid the pulsating stars at BP-RP $< 0.5$, and to include most of the eclipsing binaries concentrated around BP-RP $\sim 1$ in Fig. 2. Furthermore, from the PARSEC isochrone, we ensure that the selection of BP-RP $> 0.9$ has an MS lifetime longer than 14 Gyr.

We now determine the parallax (distance) cut to construct a volume-limited WISE eclipsing binaries sample with the MS selection of $|\Delta G| < 1.5$ mag and $0.9 < BP-RP < 1.4$. Fig. 3 shows the fraction of stars that are short-period WISE eclipsing binaries as a function of parallax. If a star is too far so that it is not well detected in a single-exposure in WISE and therefore the periods cannot be well determined, we expect a steep drop in eclipsing binary fraction at a certain parallax. While we do see a slightly decreased binary fraction in the parallax bin of 2.5–3 mas, it is not due to the sensitivity limit because otherwise we should expect an even greater reduction of the binary fraction in the parallax bin of 2–2.5 mas, which is not seen. Therefore, the overall flat trend of WISE eclipsing binary fraction with respect to parallax suggests that the detectability of eclipsing binaries remains the same across the entire range of parallax. We are not aiming for a perfectly flat relation in Fig. 3 because the thick-disk and halo stars may have different eclipsing binary fractions and they have larger contributions at larger distances.

With the criteria of $|\Delta G| < 1.5$ mag, $0.9 < BP-RP < 1.4$, and parallax $> 2$ mas, we end up with 1081 WISE eclipsing binaries. All of them have apparent periods $< 0.5$ day. We do not correct for dust extinction because the Galactic models we use for comparisons with data includes the effects of extinction. At the limiting distance of 500 pc of our sample, the level of reddening ($E(B-V) = 0.2$ mag) is small compared to the color range of our selection, and the level of extinction $(A_V < 0.8$ mag) does not affect the completeness of the volume-limited sample in our chosen magnitude range.

2.4. Eclipsing binary sample from Gaia DR2

Here we construct another eclipsing binary sample using Gaia DR2 alone. While Gaia DR2 does not release the catalog and the light curves of eclipsing binaries, we can construct an indirect eclipsing binary sample from Gaia DR2. The variability information can be obtained from the photometric errors of Gaia DR2 (Gaia Col-
The photometric errors are calculated by

\[ \text{phot}_G\text{ mean flux error} = \sigma_G / \sqrt{\text{phot}_G\text{ n obs}}, \]

where \( \sigma_G \) is the standard deviation of the G-band fluxes. When a star passes through the field of view of the Gaia satellite, it goes through 9 astrometric field CCDs where each CCD has one G-band photometric measurement. This \( \sigma_G \) is the standard deviation of each CCD photometric measurement, which are obtained within the crossing time of a source over one CCD is \( \sim 4.4 \) seconds. Furthermore, as the Gaia satellite spins with a period of 6 hours, a source passes its two field of views separated by \( \sim 1.8 \) (or 4.2) hours. Therefore, \( \sigma_G \) also contains the information on variability on timescales of hours. Depending on the location of the sky, Gaia scans through the same target after several weeks (Evans et al. 2018; Riello et al. 2018). In our selection, we require that \textit{visibility\_periods\_used} > 8, ensuring that there are enough visits to derive reliable astrometric solutions but also enough observations to measure photometric variability. In our Gaia sample with the MS cut, the median \textit{visibility\_periods\_used} is 13 and the median \textit{phot\_G\_n obs} (number of CCD photometric measurements contributing to G photometry) is 254.

Based on the photometric errors in the Gaia DR2, we compute \( \sigma_G \) and further \( f_{G,\text{raw}} = \sigma_G / F_G \) for all the sources, where \( F_G \) is the mean flux in the G band. We refer to the dimensionless \( f_{G,\text{raw}} \) as ‘raw fractional variability’ in the G band. While \( f_{G,\text{raw}} \) contains the information about the variability of stars, it has to be corrected for the magnitude-dependent instrumental errors (Evans et al. 2018). The instrumental fractional variability, \( f_{G,\text{inst}} \), is computed from the running modes of \( f_G \) for our entire sample across the observed G-band magnitudes. Then the instrumentally corrected fractional variability is \( f_{G,\text{inst}}^2 = f_{G,\text{raw}}^2 - f_{G,\text{inst}}^2 \). In this definition, \( f_{G,\text{inst}}^2 \) may be negative, which means that such stars do not have significant variability compared to the instrumental level. 95% of our MS sample is brighter than 14.8 mag in G-band, where the instrumental correction is \( f_{G,\text{inst}} \sim 0.8\% \).

We use \( f_{G,\text{inst}}^2 \) to identify eclipsing binaries in Gaia DR2. Fig. 4 shows the distribution of \( \log(f_{G,\text{inst}}^2) \) for the eclipsing binaries identified from WISE and for all MS stars located in the same region in the H-R diagram. The distribution of MS stars has a small excess at \( \log(f_{G,\text{inst}}^2) \sim -3 \) and an enhanced tail at \( \log(f_{G,\text{inst}}^2) > -2 \), suggesting two different origins for variability. By comparing with the WISE eclipsing binaries, we select stars having \( \log(f_{G,\text{inst}}^2) > -2 \) (dashed line) as the eclipsing binary candidates. The excess at \( \log(f_{G,\text{inst}}^2) \sim -3 \) is likely due to stellar rotation and the spots. Particularly, we find that stars having \( -2.5 < \log(f_{G,\text{inst}}^2) < -2 \) are significantly kinematically cooler than other stars, suggesting that they may be young stars where the spots are more active. A similar method has been used to obtain Gaia variability information to identify RR Lyrae stars (Belokurov et al. 2017) and sub-kpc dual quasar candidates (Hwang et al. 2019).

With the criteria of \( |\Delta G| < 1.5\text{mag} \) and \( 0.9 < \text{BP–RP} < 1.4 \), we end up with 1545 eclipsing binaries from Gaia DR2. This selection of eclipsing binaries is based on the assumption that eclipsing binaries are the dominant sources of variability on the MS in the color range considered. Although we do not have the information of periods for eclipsing binaries selected from Gaia DR2, we expect that short-period binaries dominate the sample because systems having shorter orbital periods have a higher probability of being eclipsing systems. While it is still possible that some variability can be due to stellar rotations and flares, we argue that eclipsing binaries still dominate the number. One reason is that our criteria select objects with large variation amplitudes of \( f_{G,\text{inst}}^2 > 0.01 \) (i.e. \( > 10\% \)), which is unlikely to be due to spots. Furthermore, Fig. 3 shows that the Gaia eclipsing binary fraction is more or less consistent with WISE eclipsing binary sample. The difference between WISE and Gaia eclipsing binary fractions in Fig. 3 may be due to the Gaia eclipsing binary cut at \( \log(f_{G,\text{inst}}^2) > -2 \) that misses the lower-amplitude eclipsing binaries.

While we refer to our sample as eclipsing binaries, the variability may not only come from eclipses. The variability can also be the ellipsoidal modulation due to the strongly distorted stars. For WISE eclipsing binaries, we do not attempt to classify eclipsing binaries into subclasses based on their light curves, but Paczynski et al. (2006) show that eclipsing binaries with peri-
ods $< 1$ day consist of mostly contact binaries and some semi-detached binaries, and very few detached binaries.

2.5. Summary of the sample selection

Here we summarize our sample selection. Each of the WISE and Gaia samples has a parent MS sample and an eclipsing binary sample. The parent MS samples have the same selection as their corresponding eclipsing binary samples except without requiring variability or eclipses. For the WISE sample, the selection criteria are:

1. $\text{parallax\_over\_error} > 10$.
2. $\text{phot\_g\_mean\_flux\_over\_error} > 50$.
3. $\text{phot\_rp\_mean\_flux\_over\_error} > 20$.
4. $\text{phot\_bp\_mean\_flux\_over\_error} > 20$.
5. $\text{visibility\_periods\_used} > 8$.
6. Cuts on $\text{phot\_bp\_rp\_excess\_factor}$ following Gaia Collaboration et al. (2018b).
7. Cuts on unit errors following Gaia Collaboration et al. (2018b).
8. $\text{parallax}> 2\text{mas}$ (i.e. within 500 pc).
9. MS selection so that the absolute G-band magnitude relative to Pleiades is smaller than $1.5\text{mag}$ ($|\Delta G| < 1.5$).
10. A color selection of $0.9 < \text{BP}-\text{RP} < 1.4$.
11. Every object has an AllWISE cross match.
12. AllWISE $\text{cc\_flags} = 0000$, indicating no spurious signals in WISE images.
13. For the WISE eclipsing binary selection, we require that the peak in the MHAOV periodograms is larger than 200, at least one observation in every 0.05 phase in the phase-folded light curves, and apparent periods between 0.07 and 0.5 day.

The Gaia parent MS sample is selected using criteria (1)-(10), and the Gaia eclipsing binaries are selected further using $\log(f_G^2) > -2$.

3. ECLIPSING BINARY FRACTIONS AS A FUNCTION OF KINEMATICS

Fig. 5 presents the eclipsing binary fraction as a function of tangential velocity in the MS sample. Because WISE eclipsing binaries are easier to identify with more WISE scans and therefore may have different sky distribution as the WISE parent sample, we weigh the WISE result based on the sky distribution of WISE eclipsing binaries. Specifically, we bin the WISE eclipsing binaries by the galactic coordinates with steps of $\Delta l = 15\deg$ and $\Delta b = 10\deg$, and assign weights to each bin such that the parent sample has the same sky distribution as the WISE eclipsing binary sample while the total number of sources (i.e. the sum of the weights) remain unchanged. The error bars in Fig. 5 are estimated using the Poisson statistics assuming no errors from the weights. The difference between the unweighted and weighted result is small, within 0.4 of the error bars.

The WISE and Gaia eclipsing binary samples are in excellent agreement in Fig. 5: they show that the eclipsing binary fraction peaks at an intermediate tangential velocity ($\sim 10^{1.1} \text{km s}^{-1}$), and decreases towards both low and high velocity end. With smaller error bars, the Gaia eclipsing binary sample constrains the peak to be in the bin of $10^{1.3-1.6} \text{km s}^{-1}$. This is the primary result of this paper: the fraction of short-period binaries is a strong function of kinematics.

We perform the Kolmogorov-Smirnov (K-S) test to quantify the significance of the difference in the distributions of tangential velocity between the sample of short-period eclipsing binaries and the comparison MS sample. For WISE eclipsing binary sample, the p-value, the probability that two distributions are sampled from the same parent distribution, is 0.06. For Gaia eclipsing binary sample, the p-value is 0.02. Therefore, the kinematic difference is statistically significant.

In principle, different velocity components ($U$, $V$, and $W$) may provide different kinematic information for eclipsing binaries. For example, the velocity component in the direction of galactic rotation ($V$ component) would lag behind the disk as a result of asymmetric
Figure 5. The fraction of short-period eclipsing binaries as a function of tangential velocity. The blue crosses use the eclipsing binaries selected from WISE, and the orange crosses are from Gaia DR2. The horizontal bars indicate the size of the bins, and the vertical bars are errors estimated using Poisson statistics. Both eclipsing binary samples show that the eclipsing binary fraction peaks at tangential velocity of $\sim 10^{1.3\pm0.6}$ km s$^{-1}$, and decreases toward both lower and higher velocities.

drift (Dehnen & Binney 1998; Reid et al. 2009). However, since only tangential velocities are available for our sample, we find that decomposing the tangential velocity into $U$, $V$, and $W$ component suffers strongly from the projection and does not provide statistically meaningful constraints. Therefore, we focus on the results of tangential velocities in this paper.

4. POTENTIAL SYSTEMATICS

Because binaries are brighter than single stars, using magnitude cut could bias the sample. We use a volume-limited sample without any explicit magnitude cut, and in Fig. 3 we show that the binary fractions remain fairly flat over the entire range of parallax considered, meaning that eclipsing binaries within this distance range are well recovered. Furthermore, 95% of our MS sample are brighter than 14.8 mag in G-band while the limiting magnitude of Gaia DR2 is $\sim 21$ mag, our criteria for the mean flux divided by its error do not imply any implicit magnitude cut.

The excellent agreement between the WISE sample and Gaia sample in Fig. 5 means that our results are not affected by the WISE cross-match nor the limit of period-finding algorithms. Furthermore, the difference in the observing strategies of WISE and Gaia (and the resulting differences in the sky distribution of binaries) does not appear to affect our result. The dependence of the binary fraction on $V_t$ cannot be explained by the covariance between velocity measurements and the variability. First of all, the tangential velocities are computed from proper motions and parallaxes with corrections from solar motions and the Galactic differential rotation, and there is no direct link to the photometry. If the observed dependence were due to the covariance between velocity and variability measurements, we would expect to see a monotonic relation in Fig. 5, which is not the case.

Gaia DR2 uses the standard deviation of individual flux measurements to estimate the flux errors, so variable sources like eclipsing binaries may have lower phot$_g$mean_flux_over_error (also depends on the number of observations). Therefore, if a stricter cut for the mean flux divided by its error is used, the eclipsing binary sample may be reduced. However, this only affects the completeness level but not the kinematics, so it is not expected to change the observational trend in Fig. 5. To verify, we test a selection with the mean flux divided by its error only larger than 10 for G, BP and RP bands (instead of 50, 20, and 20), resulting in $\sim 10\%$ more eclipsing binaries but not affecting the conclusion in Fig. 5. The binaries in our sample only have separations of a few solar radii. For a solar-like contact binary at 100 pc, the maximum angular separation of the binary is $\sim 0.1$ mas, and the observed angular separation is even smaller due to the orbital motion and the viewing angle. Therefore, the resulting astrometric noise is $\ll 0.1$ mas, which is below Gaia’s astrometric precision (Lindegren et al. 2018).
In Fig. 6, we establish the robustness of results to differences in sample selection. In the top panel, we use the Gaia eclipsing binary sample to test with a different MS selection of $|\Delta G| < 2$ mag (blue crosses) and parallax $> 3$ mas (orange crosses), using the Gaia eclipsing binary sample. Bottom panel: Different color selections. BP-RP=0.4-0.9 (blue crosses) and BP-RP=0.9-1.4 (black crosses) from the Gaia eclipsing binary sample agree with each other very well. BP-RP=1.4-2 from the WISE eclipsing binary sample also shows a similar trend but with a lower eclipsing binary fraction compared to the bluer color ranges, which may be due to the combination of lower (eclipsing) binary fraction in low-mass stars (Duchêne & Kraus 2013), the faintness of these stars, and their short periods below the classic Nyquist limit. The eclipsing binary fraction from the Gaia eclipsing binary sample with BP-RP=1.4-2 (purple crosses) peaks at the lowest velocity bin, with perhaps a slightly flattened trend at $V_t \sim 10^{1.6} \text{km s}^{-1}$. Because our Gaia eclipsing binary selection is based on the flux standard deviation but not the light curves, it is likely that this selection ends up with many actively flaring, young late-type stars. Due to the likely low completeness and high contamination of the reddest bin, we do not use it in our subsequent modeling. Further analysis of this red sample will be discussed in Petrosky et al.

5. THE LIFETIME OF ECLIPSING BINARIES FROM THE GALACTIC MODEL

The kinematics in Fig. 5 may be linked to the age of the stars. When stars form in the disk, they have similar circular velocity (with some offset, Reid et al. 2009) as the disk initially. As time goes by, stars are perturbed by structures like giant molecular clouds, transient spiral arms, bars, and flyby satellite galaxies, resulting in a higher velocity dispersion when stars age. The age-velocity dispersion relation has been widely studied in literature (e.g. Nordström et al. 2004; Holmberg et al. 2009; Sharma et al. 2014; Cheng et al. 2019), and this relation is crucial for converting the kinematics into stellar ages.

Because the velocity dispersion monotonically increases with the stellar age, the average age of the stars in each tangential velocity bin in Fig. 5 is older with increasing velocities. Because the eclipsing binary fraction peaks at $10^{1.3-1.6} \text{km s}^{-1}$ and drops at both lower and higher velocity ends, it means that the eclipsing binary fraction peaks at a certain stellar age, and is lower for younger and older populations. As a first-order approximation, we parameterize the eclipsing binary fraction as a function of stellar age using three parameters: intrinsic eclipsing binary fraction (IEBF), the time when the eclipsing binaries form ($t_0$), and the time when the eclipsing binaries disappear ($t_1$). $t_0$ and $t_1$ determine the overall trend of eclipsing binary fraction versus kinematics, and IEBF adjusts the normalization but does not affect the trend.
Fully modeling Fig. 5 requires a complete description from the Galactic model, including the Galactic star formation rate history, number densities and kinematics for different stellar populations. We use the Gaia DR2 mock catalog produced by Rybizki et al. (2018). The Gaia DR2 mock catalog is generated using Galaxia (Sharma et al. 2011) that samples stars from a Besançon Galactic model (Robin et al. 2003) with a realistic 3D dust extinction map (Drimmel et al. 2003; Marshall et al. 2006; Green et al. 2015; Bovy et al. 2016a,b). Because we do not correct for dust extinction in our samples, they can be directly compared with the Gaia DR2 mock catalog, although dust extinction within 500 pc is not a strong effect (typically $A_V < 0.8$ mag). The Gaia DR2 mock catalog also provides the ages and metallicities of the sampled stars, which is necessary for us to model the eclipsing binary lifetime.

We select stars from the Gaia DR2 mock catalog using the same color and absolute magnitude criteria as our sample, i.e. $0.9 < $BP-RP$ < 1.4$, $|\Delta G| < 1.5$, and parallax $> 2$ mas. The Gaia DR2 mock catalog itself does not simulate the stellar binaries, so for sources that are supposed to be binaries, their luminosities are underestimated by $\leq 0.75$ mag. Our absolute magnitude selection of $|\Delta G| < 1.5$ ensures that such systems are selected in both our eclipsing binary samples from observations and from the mock catalog. We assign weights to the stars in the mock catalog so that their sky distribution is the sample as our observational Gaia EB sample. The tangential velocities are corrected by removing the solar motion and the Galactic differential rotation.

We sample a grid of formation time ($t_0$) and disappearing time ($t_1$) shown in Fig. 7. For each combination of $t_0$ and $t_1$, we feed them into the Gaia DR2 mock catalog, and using the stellar ages recorded in the mock catalog, we compute the preliminary (preliminary because it has not considered the IEBF) eclipsing binary fractions weighted by the sky distribution as a function of tangential velocity. Then the preliminary eclipsing binary fractions are fit to the observed WISE-selected EB sample to determine the best-fit IEBF and the corresponding linear chi-squared costs, presented by the color coding in Fig. 7.

Fig. 7 shows that models with $t_0 = 0$ Gyr and those with $t_1 \geq 12$ Gyr can be rejected. We avoid using fits with 11 Gyr and 13 Gyr because these are the ages of thick-disk stars and halo stars in the mock catalog. We present some rejected examples in the left panel of Fig. 8. The observed drop of eclipsing binary fractions on the low-velocity end leads to rejection of models with $t_0 = 0$ Gyr because such models can naturally only produce monotonically decreasing eclipsing binary fraction with increasing velocity (since the mean stellar ages monotonically increase with increasing velocity). On the other end of the distribution, models with $t_1 \geq 12$ Gyr (i.e. when binaries can only disappear at an age above that of thick disk) make the eclipsing binary fraction too high in the velocity bins $> 100$ km s$^{-1}$, for example the model (b) in the left panel of Fig. 8.

Fig. 7 presents the accepted models where $t_0 \sim 0.6-3$ Gyr and $t_1 =5-10$ Gyr, and the accepted $t_0$ and $t_1$ roughly follow a relation of $t_0 + 0.4t_1 \sim 5$ Gyr. Some examples of the accepted models are shown in the right panel of Fig. 8. They all successfully reproduce the overall trend of eclipsing binary fractions as a function of velocity.

The main uncertainty in these models lies in the Galactic descriptions used, including the star formation history, the adopted age-velocity dispersion relation, kinematics descriptions for different stellar populations (thin disk, thick disk, and halo), etc. These models are currently calibrated by the entirety of data from Galactic surveys. The number of free parameters involved is too large for us to investigate the uncertainty if a different Galactic description is used. Another uncertainty is the step-function-like lifetime model. While it is a reasonable first step, it is likely too simplistic. Because the uncertainties are mostly due to the model assumptions rather than due to measurement uncertainties, we do not pursue a best fit nor the Markov chain Monte Carlo procedure. Even though the modeling uncertainties are still unclear, the observed relation between eclipsing binary fraction and velocity can be successfully reproduced using the state-of-art Galactic descriptions.

6. DISCUSSION
6.1. Different properties between thin-disk, thick-disk and halo stars?

First, we attempt to determine if our results in Fig. 5 can be explained by the different eclipsing binary fractions in the thin-disk, thick-disk, and halo stars, without explicit consideration of stellar ages. Qualitatively, it is difficult because for \( V > 100 \text{ km s}^{-1} \), the sample is dominated by thin-disk stars and therefore a constant eclipsing binary fraction in thin-disk stars cannot explain the trend at \( V < 100 \text{ km s}^{-1} \) in Fig. 5. For \( V > 100 \text{ km s}^{-1} \), the thick-disk and halo stars start to dominate the sample so the decreasing eclipsing binary fraction might be linked to the different eclipsing binary fractions in different stellar populations.

The left panel of Fig. 9 presents the fractions of each stellar populations in each tangential velocity bins with the same selection in the H-R diagram as Fig. 1, weighted by the sky distribution of the Gaia eclipsing binary sample. The fractions of each stellar populations are derived from the Gaia Mock DR2 Catalog. The fractions of stellar populations in a tangential velocity bin can also be derived by considering the location distribution in the H-R diagram because thin-disk, thick-disk, and halo stars are located differently in the H-R diagram due to the difference in metallicity (e.g. Fig. 21 and 22 in Gaia Collaboration et al. 2018b). We use this method to obtain the fractions of each stellar populations from the Gaia data, with a similar result to that from the Gaia Mock DR2 Catalog. Fig. 9 shows that >90% of the sample are thin-disk stars for \( \log(V) < 10^{1.7} \text{ km s}^{-1} \), and >60% are thick-disk stars for \( \log(V) > 10^{2.9} \text{ km s}^{-1} \). Halo stars become the dominant population (>50%) when \( \log(V) > 10^{2.3} \text{ km s}^{-1} \), but the fraction of halo stars is reduced to 19% for \( \log(V) > 10^{2.2} \text{ km s}^{-1} \).

The right panel of Fig. 9 shows the best-fit model that considers different eclipsing binary fractions for thin-disk, thick-disk, and halo stars. Because the halo stars only compose 19% of the sample in the highest velocity bin, its eclipsing binary fraction is not well constrained and hence we assume that the thick-disk stars and halo stars have the same eclipsing binary fractions during the fitting. The best-fit eclipsing binary fraction is 0.111 \( \pm 0.003 \% \) for thin-disk stars, and 0.012 \( \pm 0.007 \% \) for thick-disk and halo stars. Therefore, without the consideration of ages, the eclipsing binary fraction of thin-disk stars is \( \sim 10 \) times larger than the one of thick-disk and halo stars.

The best-fit model in the right panel of Fig. 9 is not able to reproduce the rising eclipsing binary fraction at \( \log(V) < 10^{1.5} \text{ km s}^{-1} \). It is expected because thick-disk stars dominate in this velocity range and the model just reflects the eclipsing binary fraction of the thin-disk stars. Therefore, the eclipsing binary fraction of thick-disk stars cannot simply be a constant as a function of age.

The difference in eclipsing binary fractions between thin-disk stars and thick disk stars (and possibly halo stars) can be due to several factors. Because thick-disk and halo stars are older than thin-disk stars, the different eclipsing binary fraction may be the consequence of the eclipsing binary lifetime like Fig. 8. Thick-disk and halo stars are more metal-poor compared to thin-disk stars, and the effect of metallicity is discussed in the next section. Halo stars may be accreted from infalling satellite galaxies instead of forming in the Milky Way, and therefore their formation environment can be different. The different eclipsing binary fractions might also result from the difference in physical properties between populations. For example, at fixed colors, metal-poor stars are smaller in size than metal-rich stars. Because the probability of being an eclipsing system is proportional to \( R/a \), where \( R \) is the size of the star and \( a \) is the semi-major axis of the binary, smaller sizes of thick-disk stars might reduce the eclipsing binary fraction. However, we consider it unlikely. At the color of our sample, thick-disk stars are \( \sim 0.3 \) mag fainter than thin-disk stars.
stars, or a factor of $\sim 0.87$ smaller in the stellar radius. To reduce the eclipsing binary fraction by a factor of 10, thick-disk stars need to have a separation distribution 9 times wider than thin-disk stars. It is unlikely because that would make the period distribution of thick-disk stars $\sim 30$ longer than thin-disk stars.

Latham et al. (2002) claim that there is no significant difference in the period distribution of spectroscopic binaries between disk stars and halo stars. Out of 156 objects with robust orbital solutions in their sample, the shortest period is 1.93 day, and only 7 (4.5%) have objects with robust orbital solutions in their sample, indicating differences between disk stars and halo stars. Out of 156 difference in the period distribution of spectroscopic binaries between disk stars and halo stars. Out of 156 difference in the period distribution of spectroscopic binaries between disk stars and halo stars. Out of 156 difference in the period distribution of spectroscopic binaries between disk stars and halo stars. Out of 156 difference in the period distribution of spectroscopic binaries between disk stars and halo stars. Out of 156 difference in the period distribution of spectroscopic binaries between disk stars and halo stars. Out of 156 difference in the period distribution of spectroscopic binaries between disk stars and halo stars. Out of 156 difference in the period distribution of spectroscopic binaries between disk stars and halo stars.

To summarize, while the declining eclipsing binary fraction at $\log(V_e) > 10^{3.5}\text{km s}^{-1}$ suggests a much smaller eclipsing binary fraction in thick-disk and possibly halo stars, the rising eclipsing binary fraction at $\log(V_e) < 10^{3.5}\text{km s}^{-1}$ is best explained by a delay in formation of eclipsing binaries compared to the formation of their components. We discuss possible causes for the delayed formation time and for the disappearing time in the following sections.

6.2. Metallicity

Recent studies have shown that the close-binary fraction (periods $< 10^4\text{days}$; separation $< 10\text{AU}$) increases with decreasing stellar metallicity (Grether & Lineweaver 2007; Yuan et al. 2015; Badenes et al. 2018; Moe et al. 2019), consistent with formation of close binaries due to disk fragmentation (Tanaka & Omukai 2014). While our eclipsing binary sample has periods much shorter than their close binaries, we investigate if our results can be explained by the metallicity dependence.

Fig. 10 presents the models that take metallicity into account. We adopt the close binary fraction as a function of stellar metallicity from Moe et al. (2019), and determine the normalization during the fitting (because not all close binaries are eclipsing binaries). The red triangles in Fig. 10 show the model that only includes metallicity effect but not age. The resulting binary fraction is inconsistent with the observation in two ways. First, for radial velocity $V_t < 10^{1.5}\text{km s}^{-1}$, the metallicity-only model cannot reproduce the rising binary fraction as steep as the observation. Second, the metallicity-only model does not have the decreasing binary fraction at velocity $V_t > 10^{1.6}\text{km s}^{-1}$. Therefore, taking at face value the metallicity dependence by Moe et al. (2019), our results cannot be explained by metallicity alone.

Fig. 10 also presents a model which includes both metallicity and age (orange squares). The adopted life-time parameters are $t_0 = 1\text{Gyr}$ and $t_1 = 8\text{Gyr}$. The metallicity+age model shows a slight improvement in the velocity bin at $V_t = 100\text{km s}^{-1}$ over the age-only model. Since this velocity bin is dominated by thick-disk stars, the goodness of the fit relies on the model descriptions, and therefore we do not favor the metallicity+age model because of its slight improvement.

We conclude that metallicity dependence is not able to explain the observational trends in eclipsing binary fraction versus kinematics. It is probably due to our sample focusing on the shortest period end, and mechanisms of orbital migration may make this sample more sensitive to the stellar ages. Binaries with longer periods (e.g. spectroscopic binaries) may not experience all the mechanisms of orbital migration, and therefore the effect of age is not prominent.

6.3. The formation of eclipsing binaries

Our results show that short-period eclipsing binaries form with a delay of $\gtrsim 0.6\text{Gyr}$. Because the size of pre-MS stars is much larger than zero-age MS stars, the separation between two stars in a binary must be larger than these eclipsing binaries in the beginning. Therefore, the formation delay is due to the orbital migration that a binary undergoes to lose the orbital angular momentum until the orbital period is $\lesssim 1\text{day}$.

Binaries can lose their orbital angular momentum through the energy dissipation in the pre-MS phase (Bate 1998; Tohline 2002; Moe & Kratter 2018), through the angular momentum exchange with a distant tertiary and tidal effects (Kiseleva et al. 1998; Fabrycky & Tremaine 2007), and magnetic winds (Stepien 1995). These mechanisms dominate different stages of orbital migration over different timescales.

Our estimated formation time of short-period binaries places strong constraints on the binary evolution theory. Because the pre-MS phase happens on a very short timescale ($\lesssim$ a few Myr), it does not fulfill the delayed formation time of $\sim 1\text{Gyr}$. This means that short-period binaries cannot be produced only by the interaction in the pre-MS phase. The timescale of the Kozai-Lidov effect to produce short-period binaries depends on the initial conditions of the binary, including the initial separations and initial eccentricity of inner binary, ranging from $\sim 0.1\text{Gyr}$ to a few Gyr (Fabrycky & Tremaine 2007; Perets & Fabrycky 2009). Further investigation is necessary to determine whether KCTF can satisfy our constraints in the average sense. Since it is difficult for the Kozai-Lidov mechanism to reduce orbital periods below 1 day, other interactions like magnetic winds may be needed to complete the last step of orbital migration. Magnetic winds can bring detached binaries from periods of 5 days to contact binaries over a few Gyr (Stepien 1995). This timescale seems to agree
Figure 9. Left: fraction of the population (thin-disk, thick-disk, and halo stars) in each tangential velocity bin from the Galactic model. Right: eclipsing binary fraction versus tangential velocity, with a best-fit model (black horizontal bars) that considers different eclipsing binary fractions in each population. Age is not explicitly taken into account in the model. The best fit gives that the eclipsing binary fraction is \( \sim 10 \) times smaller in thick-disk (and probably halo) stars than in thin-disk stars. The population model can reproduce the observational trend on the high velocity end, but not on the low velocity end.

Figure 10. The eclipsing binary fraction versus tangential velocity, with models that take metallicity into account. The age-only model uses \( t_0 = 1 \) Gyr and \( t_1 = 8 \) Gyr. The metallicity-only model (red triangles) cannot reproduce the observed trend.

with our constraint, but our upper limit of \( \sim 3 \) Gyr for the formation time places a strong constraint on the possible parameter space.

Fig. 4 shows that the bluer color selection of BP-RP=0.4-0.9 has an eclipsing binary fraction peaking at a higher tangential velocity than the redder sample, indicating a potential mass dependence. While it requires a more detailed analysis, such mass dependence may be an important clue on the dominant orbital migration process. For example, magnetic winds require the presence of subphotospheric convection zones that are only in low-mass stars (\( \lesssim 1.3 M_\odot \)). Therefore, if magnetic winds are the main cause for the delayed formation time in the color range of BP-RP=0.9-1.4, we may expect a longer delayed formation time for high-mass short-period binaries. The mass dependence of fragmentation during the proto-stellar phase may also play an important role (e.g. Kratter & Matzner 2006).

Our constraint of the formation time \( \gtrsim 0.6 \) Gyr is consistent with observations that no short-period binaries (\( P < 1 \) day) are found in T Tauri stars and young clusters (Mathieu 1994; Melo et al. 2001; Hebb et al. 2010). While short-period eclipsing binaries are easy to detect if they exist, none is found with periods < 1 day in Hyades and Pleiades (Torres 2003; David et al. 2015, 2016), and only one is found in Praesepe (Rucinski 1998; Zhang et al. 2009). Further investigation is required to determine the true eclipsing binary fraction in open clusters for comparison with our results.

6.4. The disappearance of eclipsing binaries

In Sec. 6.1, we show that thick-disk and halo stars dominate the sample for \( \log(V_t) > 10^{3.9} \) km s\(^{-1}\), and a factor of \( \sim 10 \) smaller eclipsing binary fraction in thick-disk and halo stars can explain the observed declining eclipsing binary fraction at the high-velocity end. One possibility is that the eclipsing binary lifetime is shorter than the MS lifetime of these thick-disk and halo stars, making the eclipsing binary fraction in these populations much smaller compared to thin-disk stars. In this scenario, our results suggest that the disappearing time is between 5-10 Gyr, depending on the formation time. Although the disappearing time is not well constrained, we discuss some possible scenarios that limit the lifetime of eclipsing binaries.

Contact binaries may end up as stellar mergers. Tylenda et al. (2011) report a stellar merger of a contact binary V1309 Scorpii, although its progenitor is probably at the beginning of the red giant branch and not a MS considered here. The merging product may eventually become a blue straggler (Robertson & Eggleton 1977). By using binary evolutionary models, Stepien
show that some contact binaries can merge and become blue stragglers within the age of globular clusters (\( \leq 13 \) Gyr), and they suggest that this formation track may constitute a substantial fraction of all blue stragglers in globular clusters.

Our sample of BP-RP=0.9-1.4 has a MS lifetime longer than 14 Gyr. If the declining eclipsing binary at \( \log(V_t) > 10^{3.9} \) km s\(^{-1}\) is due to the stellar mergers of contact binaries, our results imply that the majority of short-period MS binaries are destroyed before the age of the thick disk (\( \sim 11 \) Gyr) and before the end of their own MS lifetime. This scenario can be tested by searching for high-velocity merging products, for example field blue stragglers.

A few other possibilities may reduce the binary fraction in old stars. One possibility is that their lower metallicity makes the orbital migration more inefficient, for example by suppressing the formation of triples, but this interpretation is disfavored by Moe et al. (2019) where they show that the triple star fraction increases with decreasing metallicity. Alternatively, these old stars were originally in binaries with more massive stars, which have evolved into compact objects (white dwarfs, neutron stars, or black holes) and therefore only the originally less-massive stars are visible now. It is not impossible because O- and B- binaries with periods < 20 days seem to favor modest mass ratios (\( q \sim 0.5; \) Moe & Di Stefano 2017). If some of the high-velocity stars in our sample indeed have invisible companions with periods < 20 days, the radial velocity variation is on orders of \( \sim 10 \) km s\(^{-1}\), which is detectable by Gaia’s radial velocity measurements.

### 6.5. Interpretation of the formation time and disappearing time

Our results are consistent with the age estimate of contact binaries in literature. Kinematic studies show that the age of contact binaries is of several Gyr (Guinan & Bradstreet 1988; Bilir et al. 2005). Yildiz (2014) estimate the age of \( \sim 4.5 \) Gyr for W UMa binaries based on the stellar model (Yildiz & Dogan 2013) and kinematics. These estimates are consistent with our formation time and disappearing time. Furthermore, the preference of kinematics of eclipsing binaries may result in a dependence on galactic latitude of eclipsing binary fraction seen in the literature (e.g. Prsa et al. 2011; Slawson et al. 2011; Kirk et al. 2016).

One distinction between this work and the literature is that we constrain the formation time and the disappearing time, not just the average age of eclipsing binaries. We emphasize that the formation time and disappearing time of short-period binaries are constrained in an average sense because of the use of the simple lifetime model. Our results do not imply that all eclipsing binaries form and disappear at the same time. In fact, it is very likely that the formation time itself is a wide distribution because the orbital migration processes, especially the Kozai-Lidov mechanism, is sensitive to the initial conditions (e.g. Perets & Fabrycky 2009).

Because the formation time and disappearing time are derived in an average sense, their difference (\( t_1 - t_0 \)) may not directly reflect the lifetime of the contact phase. Such timescale of the contact phase is rather uncertain, with some estimates ranging from 0.1 Gyr (van’t Veer 1979; Eggen & Iben 1989) to \( \sim 10 \) Gyr (Mochnacki 1981). If the contact phase is short (< 1 Gyr), then \( t_1 - t_0 \) is mainly related to the distribution of the formation time. If the contact phase can last for \( > 1 \) few Gyr, \( t_1 - t_0 \) may be able to constrain the timescale of the contact phase.

### 7. CONCLUSIONS

In this paper, we investigate the kinematics of short-period (< 1 day) main-sequence eclipsing binaries. We construct two samples of eclipsing binaries: one from the time series analysis of WISE light curves, and the other from the photometric variations in Gaia DR2. These two eclipsing binary samples are complementary to each other: WISE eclipsing binary sample has nearly no contamination, while Gaia eclipsing binary sample has a more homogeneous sky distribution and is not affected by the limitations of period-finding algorithms. We carefully investigate the potential effects from different selection criteria, and require a volume-limited sample instead of magnitude-limited since binaries are brighter than singles. With the kinematics from Gaia DR2, we present the following findings:

1. Our primary result is that the eclipsing binary fraction peaks at tangential velocity \( V_t = 10^{1.3-1.6} \) km s\(^{-1}\) and decreases towards both low and high velocity ends (Fig. 5).

2. Since thick-disk and halo stars dominate at high velocity (\( V_t > 100 \) km s\(^{-1}\)), our results imply that the eclipsing binary fraction is at least \( \sim 10 \) times smaller in thick-disk and halo stars compared to thin-disk stars (Fig. 9).

3. The relation between eclipsing binary fraction and kinematics is best explained by the lifetime of eclipsing binaries (Fig. 7 and 8). By using Galactic models, we constrain the formation time (\( t_0 \)) of eclipsing binaries to be between 0.6 and 3 Gyr and the disappearing time (\( t_1 \)) to be between 5 and 10 Gyr, where \( t_0 \) and \( t_1 \) are related through \( t_0 + 0.4t_1 \sim 5 \) Gyr. The lower eclipsing binary fraction in thick-disk and halo stars may be a consequence of the finite lifetime of eclipsing binaries.
4. The delayed formation time of $0.6 - 3$ Gyr means that short-period binaries cannot form directly from pre-MS interaction. This timescale is more consistent with the Kozai-Lidov mechanism with tidal interaction and magnetic winds, but the upper limit of $\sim 3$ Gyr provides a strict constraint for the theory.

5. The disappearance of eclipsing binaries may be due to their mergers within the MS lifetime. This scenario may be tested by studying the kinematics of the merging products, if they can be identified in survey data.

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REFERENCES

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, Physical Review X, 6, 041015
—. 2017, PhRvL, 119, 161101
Arenou, F., Luri, X., Babusiaux, C., et al. 2018, A&A, 616, A17
Badenes, C., Mazzola, C., Thompson, T. A., et al. 2018, ApJ, 854, 147
Bate, M. R. 1998, ApJ, 508, L95
—. 2009, MNRAS, 392, 590
—. 2011, MNRAS, 417, 2036
—. 2012, MNRAS, 419, 3115
Bate, M. R., Bonnell, I. A., & Bromm, V. 2002, MNRAS, 332, L65
Belokurov, V., Erkal, D., Deason, A. J., et al. 2017, MNRAS, 466, stw3357
Bilir, S., Karata, Y., Demircan, O., & Eker, Z. 2005, MNRAS, 357, 497
Borkovits, T., Hajdu, T., Sztakovics, J., et al. 2016, MNRAS, 455, 4136
Bovy, J. 2017, MNRAS, 468, L63
Bovy, J., Rix, H.-W., Green, G. M., Schlafly, E. F., & Finkbeiner, D. P. 2016a, ApJ, 818, 130
Bovy, J., Rix, H.-W., Schlafly, E. F., et al. 2016b, ApJ, 823, 30
Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127
Chen, X., Wang, S., Deng, L., de Grijs, R., & Yang, M. 2018, ApJS, 237, 28
Cheng, S., Cummings, J. D., & Ménard, B. 2019, arXiv:1905.12710
Cowperthwaite, P. S., Berger, E., Villar, V. A., et al. 2017, ApJ, 848, L17
Cutri, R. M., Wright, E. L., Conrow, T., et al. 2011, Technical reports, Explanatory Supplement to the WISE Preliminary Data Release Products
David, T. J., Stauffer, J., Hillenbrand, L. A., et al. 2015, ApJ, 814, 62
David, T. J., Conroy, K. E., Hillenbrand, L. A., et al. 2016, AJ, 151, 112
Dehnen, W., & Binney, J. 1998, MNRAS, 298, 387
Drake, A. J., Graham, M. J., Djorgovski, S. G., et al. 2014, ApJS, 213, 9
Drimmel, R., Cabrera-Lavers, A., & Lopez-Corredoira, M. 2003, A&A, 409, 205
Duchêne, G., & Kraus, A. 2013, ARA&A, 51, 269
Eggen, O. J., & Iben, I. J. 1989, AJ, 97, 431
Eggleton, P. P. 1983, ApJ, 268, 368
Eggleton, P. P., & Kiseleva-Eggleton, L. 2001, ApJ, 562, 1012
El-Badry, K., Ting, Y.-S., Rix, H.-W., et al. 2018, MNRAS, 476, 528
Evans, D. W., Riello, M., De Angeli, F., et al. 2018, A&A, 616, A4
Fabrycky, D., & Tremaine, S. 2007, ApJ, 669, 1298
Fong, W., & Berger, E. 2013, ApJ, 776, 18
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018a, A&A, 616, A1
Gaia Collaboration, Babusiaux, C., van Leeuwen, F., et al. 2018b, A&A, 616, A10
Gaia Collaboration, G., Eyer, L., Rimoldini, L., et al. 2018c, eprint arXiv:1804.09382
Graham, M. J., Drake, A. J., Djorgovski, S. G., et al. 2013, MNRAS, 434, 3423
Green, G. M., Schlafly, E. F., Finkbeiner, D. P., et al. 2015, ApJ, 810, 25
Grether, D., & Lineweaver, C. H. 2007, ApJ, 669, 1220
Guinan, E. F., & Bradstreet, D. H. 1988, in Formation and Evolution of Low Mass Stars. NATO ASI Series (Series C: Mathematical and Physical Sciences), ed. A. Dupree & M. Lago, Vol. 241 (Springer, Dordrecht), 345
Hammer, J. H., & Schlaufman, K. C. 2019, arXiv:1908.06998
Harrington, R. S. 1968, AJ, 73, 190
Hebb, L., Stempels, H. C., Aigrain, S., et al. 2010, A&A, 522, A37
Hoffman, D. L., Cutri, R. M., Masci, F. J., et al. 2012, AJ, 143, 118
Holmberg, J., Nordströrm, B., & Andersen, J. 2009, A&A, 501, 941
Hwang, H.-C., Shen, Y., Zakamska, N., & Liu, X. 2019, arXiv:1906.02292
Iben, I. J., & Tutukov, A. V. 1984, ApJS, 54, 335
Katz, D., Sartoretti, P., Cropper, M., et al. 2019, A&A, 622, A205
Kirk, B., Conroy, K., Prˇ sa, A., et al. 2016, Appl. Phys., 151, 68
Kiseleva, L. G., Eggleton, P. P., & Mikkola, S. 1998, MNRAS, 300, 292
Kozai, Y. 1962, AJ, 67, 591
Kratter, K. M., & Matzner, C. D. 2006, MNRAS, 373, 1563
Larson, R. B. 1969, MNRAS, 145, 271
Latham, D. W., Stefanik, R. P., Torres, G., et al. 2002, AJ, 124, 1144
Lidov, M. 1962, Planetetary and Space Science, 9, 719
Lindegren, L., Hernandez, J., Bombrun, A., et al. 2018, A&A, 616, A2
Mainzer, A., Bauer, J., Cutri, R. M., et al. 2014, ApJ, 792, 30
Marrese, P. M., Marinoni, S., Fabrizio, M., & Altavilla, G. 2019, 621, A144
Marshall, D. J., Robin, A. C., Reyle, C., Schultheis, M., & Picaud, S. 2006, A&A, 453, 635
Mathieu, R. D. 1994, ARA&A, 32, 465
Melo, C. H. F., Covino, E., Alcalá, J. M., & Torres, G. 2001, A&A, 378, 898
Mochanacki, S. W. 1981, ApJ, 245, 650
Moe, M., & Di Stefano, R. 2017, ApJS, 230, 15
Moe, M., & Kratter, K. M. 2018, ApJ, 854, 44
Moe, M., Kratter, K. M., & Badenes, C. 2019, ApJ, 875, 61
Naoz, S. 2016, ARA&A, 54, 441
Naoz, S., Farr, W. M., Lithwick, Y., Rasio, F. A., & Teyssandier, J. 2013a, MNRAS, 431, 2155
Naoz, S., Kocsis, B., Loeb, A., & Yunes, N. 2013b, ApJ, 773, 187
Nordström, B., Mayor, M., Andersen, J., et al. 2004, A&A, 418, 989
Paczynski, B., Szczygiel, D., Pilecki, B., & Pojmanski, G. 2006, MNRAS, 368, 1311
Perets, H. B., & Fabrycky, D. C. 2009, ApJ, 697, 1048
Pribulla, T., & Rucinski, S. M. 2006, AJ, 131, 2986
Prša, A., Batalha, N., Slawson, R. W., et al. 2011, AJ, 141, 83
Reid, M. J., Menten, K. M., Zheng, X. W., et al. 2009, ApJ, 700, 137
Riello, M., De Angeli, F., Evans, D. W., et al. 2018, A&A, 616, A3
Robertson, J. A., & Eggleton, P. P. 1977, MNRAS, 179, 359
Robinson, A. C., Reynlé, C., Derrière, S., & Picaud, S. 2003, A&A, 409, 523
Rucinski, S. M. 1998, Appl. Phys., 116, 2998
Rucinski, S. M., Pribulla, T., & van Kerkwijk, M. H. 2007, AJ, 134, 2353
Rybizki, J., Demleitner, M., Fouesneau, M., et al. 2018, PASP, 130, 074101
Schönrich, R., Binney, J., & Dehnen, W. 2010, MNRAS, 403, 1829
Schwarzenberg-Czerny, A. 1996, ApJ, 460, L107
Sharma, S., Bland-Hawthorn, J., Johnston, K. V., & Binney, J. 2011, ApJ, 730, 3
Sharma, S., Bland-Hawthorn, J., Binney, J., et al. 2014, ApJ, 793, 51
Shibata, M., & Taniguchi, K. 2006, PhRvD, 73, 064027
Sloan, R. W., Prša, A., Welsh, W. F., et al. 2011, AJ, 142, 160
Smartt, S. J., Chen, T.-W., Jerkstrand, A., et al. 2017, Nature, 551, 75
Stepien, K. 1995, MNRAS, 274, 1019
Stepien, K., & Kiraga, M. 2015, A&A, 577, A117
Tanaka, K. E. I., & Omukai, K. 2014, MNRAS, 439, 1884
Tohline, J. E. 2002, ARA&A, 40, 349
Tokovinin, A., Thomas, S., Sterzik, M., & Udry, S. 2006, A&A, 450, 681
Tokovinin, A. A. 1997, Astronomy Letters, 23, 727
Torres, G. 2003, Information Bulletin on Variable Stars, 5402, 1
Tylenda, R., Hajduk, M., Kamiński, T., et al. 2011, A&A, 528, A114
VanderPlas, J. T. 2018, ApJS, 236, 16
van’t Veer, F. 1979, A&A, 80, 287
Warner, B. 1995, Cataclysmic variable stars (Cambridge Astrophysics Series. Cambridge Univ. Press, Cambridge, New York)
Webbink, R. F. 1984, ApJ, 277, 355
Whelan, J., & Iben, I. 1973, ApJ, 186, 1007
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A., et al. 2010, AJ, 140, 1868
Yildiz, M. 2014, MNRAS, 437, 185
Yildiz, M., & Dogan, T. 2013, MNRAS, 430, 2029
Yuan, H., Liu, X., Xiang, M., et al. 2015, ApJ, 799, 135
Zhang, X. B., Dong, L., & Lu, P. 2009, AJ, 130, 680

APPENDIX

A. GAIA QUERY

Here is the query for Gaia DR2 used in this paper:

SELECT gaia.*,
       allwise.w1mpro, allwise.w2mpro, allwise.w3mpro, allwise.w4mpro,
       allwise.cc_flags, allwise.var_flag
FROM gaiadr2.gaia_source AS gaia
LEFT JOIN gaiadr2.allwise_best_neighbour AS allwisexmatch
ON gaia.source_id = allwisexmatch.source_id
LEFT JOIN gaiadr1.allwise_original_valid AS allwise
ON allwise.allwise_oid = allwisexmatch.allwise_oid
WHERE
    gaia.parallax_over_error > 10 AND
    gaia.phot_g_mean_flux_over_error>50 AND
    gaia.phot_rp_mean_flux_over_error>20 AND
    gaia.phot_bp_mean_flux_over_error>20 AND
    gaia.phot_bp_rp_excess_factor < 1.3*0.06*power(gaia.phot_bp_mean_mag-gaia.phot_rp_mean_mag,2)
AND
    gaia.phot_bp_rp_excess_factor > 1.0*0.015*power(gaia.phot_bp_mean_mag-gaia.phot_rp_mean_mag,2)
AND
gaia.visibility.periods_used > 8 AND
gaia.parallax >= 2.