Eclipsing Binary Populations across the Northern Galactic Plane from the KISOGP Survey

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Abstract

We present a catalog of eclipsing binaries in the northern Galactic plane from the Kiso Wide-Field Camera Intensive Survey of the Galactic Plane (KISOGP). We visually identified 7055 eclipsing binaries spread across ∼330 deg², including 4197 W Ursae Majoris/EW-type, 1458 β Lyrae/EB-type, and 1400 Algol/EA-type eclipsing binaries. For all systems, I-band light curves were used to obtain accurate system parameters. We derived the distances and extinction values for the EW-type objects from their period–luminosity relation. We also obtained the structure of the thin disk from the distribution of our sample of eclipsing binary systems, combined with those of high-mass star-forming regions and Cepheid tracers. We found that the thin disk is inhomogeneous in number density as a function of Galactic longitude. Using this new set of distance tracers, we constrain the detailed structure of the thin disk. Finally, we report a global parallax zero-point offset of Δπ = −42.1 ± 1.9 (stat.) ± 12.9 (syst.) μas between our carefully calibrated EW-type eclipsing binary positions and those provided by Gaia Early Data Release 3. Implementation of the officially recommended parallax zero-point correction results in a significantly reduced offset. Additionally, we provide a photometric characterization of our EW-type eclipsing binaries that can be applied to further analyses.

Unified Astronomy Thesaurus concepts: Eclipsing binary stars (444); W Ursae Majoris variable stars (1783); Distance indicators (394); Milky Way disk (1050); Catalogs (205)

Supporting material: machine-readable tables

1. Introduction

Eclipsing binary systems (EBSs) exhibit optical variability because of geometric properties rather than intrinsic physical changes. EBSs encompass almost all stages of binary evolution, covering timescales as long as 1–10 Gyr. This explains their large numbers in the Galaxy. EBS analysis offers a good opportunity to obtain precise fundamental physical parameters from their system properties by means of photometric and/or spectroscopic observations—including their periods and distances, as well as accurate parameters for their components, like masses and radii (e.g., Torres et al. 2010). This enables us to study unique aspects of their stellar evolution and stellar activity.

EBSs can be divided into three types based on their light-curve shapes, i.e., Algod (EA) type, β Lyrae (EB) type, and W Ursae Majoris (EW) type. The total luminosity of EA-type EBSs remains almost constant outside the eclipses. EB types exhibit a continuous change in their total brightness outside eclipses, while the depth of the secondary minimum is usually considerably smaller than that of the primary minimum. Meanwhile, EW-type light curves are characterized by a smooth shape with symmetric eclipses, and some evolved systems show sinusoidal-like shapes.

EW-type EBSs can also be used as reliable distance indicators within the Milky Way. Since their two components fill the system’s Roche lobes, their overall visual magnitude is related to the system’s orbital period (based on Roche lobe theory), which leads to a well-defined period–luminosity relation (PLR). Rucinski (1994) derived the first calibration of such a PLR based on 18 systems, which they eventually improved to an accuracy of 12% (Rucinski & Duerbeck 1997). Recently, Chen et al. (2018a) established PLRs in 12 optical to mid-infrared passbands based on Tycho–Gaia astrometric solution (TGAS) parallaxes, reaching an improved accuracy of 8%. PLRs provide us with a means to determine the distances to EW-type EBSs using only photometric light curves. Therefore, as one of the most numerous types of variables in the Milky Way, EW-type EBSs could be used as important Galactic distance tracers (Matsunaga et al. 2018).
Observations of EBSs have a long history. Many ancient cultures observed eclipsing systems (e.g., Jetsu et al. 2013). In modern astronomy, early twentieth-century measurements of both EBSs and other variables were usually reported in papers discussing individual objects. After the 1980s, large surveys commenced, including the MAssive Compact Halo Objects (MACHO) survey (Cook et al. 1995) and the Optical Gravitational Lensing Experiment (OGLE; Graczyk et al. 2011; Pawlak et al. 2013; Pietrukowicz et al. 2013; Pawlak et al. 2016; Soszyński et al. 2016). The number of known EBSs and other types of variable stars has experienced a period of explosive growth. With the development of wide-field cameras, surveys that constantly monitor the entire accessible sky photometrically became commonplace, e.g., the All Sky Automated Survey (ASAS; Pojmanski 1997; Paczyński et al. 2006) and the Robotic Optical Transient Search Experiment (ROTSE; Akerlof et al. 2000), part of the Northern Sky Variability Survey (NSVS; Akerlof et al. 2000; Woźniak et al. 2004; Hoffman et al. 2008, 2009). In the near-infrared (NIR), the VISTA Variables in the Vía Láctea (VVV) Survey offers a less severely reddened window into EBS projected toward the Galactic center (e.g., Minniti et al. 2010; Alonso-García et al. 2015). In addition, some all-sky surveys, such as near-Earth object (NEO) surveys whose primary goal is to detect near-Earth asteroids and comets, are also well suited to discover and characterize variable objects, including EBSs. This way, candidates from the Lincoln Near-Earth Asteroid Research (LINEAR; Palaversa et al. 2013), the Catalina Sky Surveys (CSS; Drake et al. 2014, 2017), the Asteroid Terrestrial-impact Last Alert System (ATLAS; Heinze et al. 2018), the All Sky Automated Survey for Supernovae (ASAS-SN; Kochanek et al. 2017; Jayasinghe et al. 2018), and the Wide-field Infrared Survey Explorer (WISE; Chen et al. 2018b) have been identified.

Although the accumulation of EBSs has multiplied, many previous surveys have avoided targeting the Galactic plane owing to the high extinction there compared with less obscured regions. The few available surveys of the Galactic plane tend to cover only a few degrees in Galactic latitude (e.g., Haas et al. 2012; Hempel et al. 2014). Measurements of EBSs are still lacking in the Galactic disk, particularly in the Galactic anticenter direction. However, understanding the formation and evolution of the Galactic disk, as well as its structure, is a key open issue, since in principle we can investigate our own Galaxy’s structure in much greater detail than that of any other galaxy, thus providing a benchmark for understanding external galaxies.

In this paper, we have collected the light curves of eclipsing binary candidates from the Kiso Wide-Field Camera (KWFC) Intensive Survey of the Galactic Plane (KISOGP), specifically in the northern Galactic plane, and classified 7055 EBSs. In Section 2, we discuss our data reduction procedures, the classification pipeline, and several parameter distributions, e.g., of periods, magnitudes, and eclipse depths. We also discuss the quality of our EBS sample’s light curves. Section 3 focuses on the EW types, outlining our analysis procedure and providing a discussion of their distances and extinction values derived from the PLR, absolute parameters, and the structure of the thin disk mapped by EW-type systems and other tracers (e.g., star-forming regions, Cepheids, etc.). We also discuss the parallax zero-point offset affecting Gaia Early Data Release 3 (eDR3) parallaxes derived from our EW-type analysis. Section 4 concludes the paper.

2. Data Reduction and Results

2.1. Sample Selection

The catalog was compiled from observations taken as part of the KISOGP survey (Matsunaga 2017), acquired with the KWFC on the Kiso 105 cm Schmidt telescope at Kiso Observatory, Japan. The KWFC has been designed for wide-field observations, taking advantage of the Kiso Schmidt telescope’s large focal-plane area. It mosaics eight CCD chips with 8k × 8k pixels in total and covers an area of 2° × 2°. Typically, for any object, more than 200 exposures were acquired in the $I$ band to a depth of $I = 9.5–17$ mag with a signal-to-noise ratio (S/N) better than 30. The main goal of the survey is to study the Galactic disk using variable stars as tracers (e.g., Miras; Yao et al. 2017). The KISOGP survey covers the northern Galactic disk, which spans from 60° to 210° in Galactic longitude and from −1° to 1° in Galactic latitude. The region $70° < l < 80°, 1° < b < 3°$ is also covered. (For the relevant maps and pointings, see Figure 1 of Matsunaga 2017.)

For each epoch, a 5 s exposure and three 60 s exposures are taken to optimally cover the full magnitude range. The 5 s exposure is suitable for stars at the bright end ($I = 9$ mag), while the 60 s exposures are better for the faint end, from $I = 11$ mag down to $I = 17$ mag. A reference target list was established by combining all epochs. Candidate variable stars were selected by considering three variability indices, including interquartile ranges, weighted standard deviations, and von Neumann ratios (Sokolovsky et al. 2017). Among ~8 million stars whose time-series data were examined, more than 50,000 objects were selected as candidate variable stars (N. Matsunaga et al. 2021, in preparation). In this paper, 7752 candidate variables are considered for our EBS selection, based on Fourier analysis, with periods determined in Section 2.2 (Chen et al. 2020).

2.2. Eclipsing Binary Selection

To properly identify EBSs, high-quality folded light curves are needed. The basic idea is to determine optimally constrained periods of variability. We adopted the Lomb–Scargle (LS) periodogram (Lomb 1976; Scargle 1982) and String–Length (SL) methods (Lafler & Kinman 1965; Clarke 2002) to obtain optimal periods for all candidates.

The input periods ranged from 0.08 to 10 days in steps of 0.00001 days (for the LS method). The short-period limit for known EW types is 0.16 days (Soszyński et al. 2015). Ultrashort-period EW types, which usually contain highly evolved stars, usually exhibit sinusoidal-like light curves. In this situation, the primary and secondary minima may have similar depths. They are often misidentified as the same feature in phased light curves. This will result in an output harmonic or aliased period of the true period, where $P_{\text{output}}/P_{\text{true}}$ is a ratio of integers, usually 1:2. For this reason, we start at one-half of 0.16 days. Any harmonic period found will be corrected during our subsequent visual determination by multiplying the period to make sure that two eclipses occur within a single period.

To further improve the accuracy of our period determination, the SL method was applied to the output periods from the LS method. We tried 2000 periods within 0.0002 days around the...
output period. This led to an improvement in the fifth decimal place: the majority of our EBSs (64.1%) have periods with errors smaller than $1 \times 10^{-5}$ days. The output periods will be used as input periods for our visual verification.

2.3. Visual Verification

Armed with the periods thus determined, a visual check was done of the photometric parameters and type determination based on phased light curves. EBS candidates were selected based on visual examination of their light-curve morphology. We removed all objects classified as other types of variable stars, such as RR Lyrae, Cepheids, nonperiodic variables, etc. Meanwhile, a visual check of the period (particularly for those objects for which we need to multiply the period to encompass two eclipses within a single period) and a visual determination of the phase of the primary eclipse (which will be shifted to 0 and represents $t_0$), the system’s magnitude outside the eclipse, and the primary and secondary eclipses were done. Subsequently, the objects’ types were determined.

The order in which we examined the candidates was random, and all objects were processed randomly three times. If a system’s type determination was the same and the standard errors of the parameters were less than 0.02 mag or 0.02 in phase, the corresponding type and the mean values of the thrice-determined parameters were adopted. For those objects that failed to pass this round, this procedure was repeated.

Our final catalog contains 7055 carefully visually selected EBSs, composed of 4197 EW-type, 1458 EB-type, and 1400 EA-type systems. Figure 1 shows three randomly selected sample light curves.

Table 1 includes all EBS parameters, including the system ID, effective number of exposures, coordinates, type, period and period error, $t_0$, in units of the modified heliocentric Julian date (HJD $-2,400,000.5$; which sets the primary eclipse at phase zero), the maximum magnitude outside eclipses, the magnitudes of both eclipses within one period in the $I$ band, and the depth ratio of the two eclipses. The objects’ distances, extinction values in the $V$ band for EW-type systems, and the magnitude differences in the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) photometric system will be described in Section 3.1.

2.4. Distribution Map

The parameter distributions for all EBSs are shown in Figure 2. Red points or bars represent EW types, while black and blue symbols correspond to EB and EA types, respectively.

The EBS distribution as a function of Galactic longitude is shown in Figure 2(a). It is inhomogeneous in number density. This inhomogeneity is caused by the presence of groups of stars associated with the Galaxy’s spiral arms, including the Orion spur and the Perseus arm. Since EBS variability is caused by the systems’ geometry, independently of any other criteria associated with object position or selection bias, the EBS distribution is representative of the general distribution of stars in the Galaxy (Rucinski 2006). Extinction also plays an important role in the observed inhomogeneity, since dust obscuration and scattering have a significant effect on stars in the Galactic plane. Only nearby stars can be seen projected toward the most obscured regions. We will return to the inhomogeneous distribution of EBS in Section 3.2.

There are obvious period differences among the three types of EBSs in Figure 2(b). EA type have the longest periods, ranging from 0.3 to 10 days, with a peak at several days. EW types have the shortest periods, i.e., shorter than 1 day; most EW types have periods around 0.3–0.5 days. Both the period range and the peak period of EB types are found in the middle of the three types. Their period distribution also depends on their environment. EBSs in the Galactic plane are thought to be less evolved and have longer periods than those outside the thin disk, since they are usually younger. This is shown in the left panel of Figure 3; see Section 2.5 for a discussion.

For EA types, extremely wide period ranges have been reported in the literature (e.g., Graczyk et al. 2011), reaching up to thousands of days. Our detection approach prevents us from detecting such long-period variables. We are constrained to a longest period of 50.22 days. For EA types with longer periods, it will be harder to fully cover the eclipses to identify their types. However, instead of continuous monitoring, only a few epochs are taken during a given night for each object in our survey, which makes it harder to completely cover their full eclipses. Some EA-type candidates with extremely long periods may only have a few detections during their eclipses. The numbers of detections may be insufficient to characterize such an eclipse, and so such samples would fail to pass our selection criteria. Therefore, our catalog lacks long-period EA-type EBS.

No clear differences in the distribution of the primary depths can be seen, but the distribution of the eclipse-depth ratios varies significantly among the different EBS types (see Figures 2(c)–(d)). A clear plateau can be seen in the histogram of the eclipse-depth ratios of EA-type EBSs between 0.1 and 1. Secondary eclipses may not be visible if the stars are considerably different in size. It is impossible to distinguish EA types with an invisible secondary eclipse from EBSs featuring a double period characterized by similar eclipses solely based on light curves. This may be the reason for the lack of a plateau at the shorter end of the eclipse-depth distribution. Nevertheless, the observed distribution underscores that the EA-type eclipse-depth ratios are randomly distributed, while the ratio of EW types is close to unity, as expected.

The histogram of the magnitudes outside eclipses, the scatter in magnitude during the eclipses, and a color–color diagram exhibiting a roughly linear relation for all types of EBS are

Figure 1. Examples of EA-, EB-, and EW-type EBSs (left to right).
### Table 1
Eclipsing Binaries Catalog

| ID          | Exposure | Type | Period (days) | $\text{err}_{p}$ ($10^{-7}$ days) | $t_0$ (days) | $I_{\text{max}}$ (mag) | $I_{\text{pri}}$ (mag) | $I_{\text{sec}}$ (mag) | Ratio | Distance (kpc) | $A_V$ (mag) | $\Delta m_{2MASS}$ (mag) |
|-------------|----------|------|---------------|-------------------------------|-------------|----------------------|----------------------|----------------------|-------|----------------|------------|------------------------|
| KISOJ000009.94+612905.2 | 264 | EA   | 1.4418015     | 67                            | 56167.64799 | 13.660               | 14.039               | 13.833               | 0.456 | ...            | ...        | ...                    |
| KISOJ000010.73+621848.8  | 189 | EW   | 0.3890992     | 38                            | 56167.69297 | 15.414               | 15.562               | 15.538               | 0.838 | 2.387          | 0.860      | 0.021                  |
| KISOJ000017.82+625339.6  | 184 | EB   | 0.5820739     | 23                            | 56167.31869 | 15.552               | 15.960               | 15.754               | 0.495 | ...            | ...        | ...                    |
| KISOJ000026.19+632139.0  | 43  | EW   | 0.3180290     | 393                           | 56175.60476 | 16.333               | 16.856               | 16.804               | 0.901 | 2.298          | 1.469      | 0.422                  |
| KISOJ000039.63+622214.1  | 174 | EW   | 0.8599520     | 1                             | 56167.59347 | 16.137               | 16.458               | 16.390               | 0.788 | 1.646          | 1.778      | 0.253                  |
| KISOJ000048.17+614603.1  | 178 | EW   | 0.3024611     | 1                             | 56167.77640 | 16.016               | 16.732               | 16.637               | 0.867 | 1.352          | 2.612      | 0.705                  |
| KISOJ000053.24+613059.8  | 256 | EW   | 0.2860911     | 1                             | 56167.60270 | 16.093               | 16.441               | 16.378               | 0.819 | 1.747          | 1.497      | 0.041                  |
| KISOJ000056.84+625228.4  | 267 | EW   | 0.5717867     | 12                            | 56176.37203 | 14.228               | 14.445               | 14.440               | 0.977 | 1.986          | 1.657      | 0.158                  |
| KISOJ000111.08+625139.7  | 113 | EB   | 1.0133044     | 1                             | 56167.36126 | 16.160               | 16.758               | 16.492               | 0.555 | ...            | ...        | ...                    |
| KISOJ000112.76+623859.7  | 296 | EA   | 1.3701021     | 99                            | 56167.30771 | 14.589               | 14.835               | 14.819               | 0.935 | ...            | ...        | ...                    |
| KISOJ000123.66+613746.8  | 230 | EW   | 0.3871284     | 8                             | 56167.49329 | 15.738               | 16.049               | 16.004               | 0.855 | 3.088          | 0.401      | 0.153                  |
| KISOJ000132.54+615234.2  | 78  | EW   | 0.3664444     | 36                            | 56251.31592 | 16.772               | 17.107               | 17.092               | 0.955 | 3.148          | 1.900      | 0.177                  |
| KISOJ000135.90+624456.3  | 171 | EB   | 0.7391682     | 1                             | 56167.17345 | 16.514               | 16.946               | 16.700               | 0.431 | ...            | ...        | ...                    |
| KISOJ000138.55+615348.4  | 186 | EA   | 0.7856778     | 147                           | 56167.74912 | 12.237               | 12.485               | 12.405               | 0.677 | ...            | ...        | ...                    |
| KISOJ000145.92+614214.0  | 265 | EA   | 0.3330188     | 2                             | 56167.67988 | 12.087               | 12.746               | 12.382               | 0.448 | ...            | ...        | ...                    |
| KISOJ000208.16+630633.5  | 311 | EW   | 0.3092946     | 1                             | 56167.58121 | 12.957               | 13.164               | 13.141               | 0.889 | 0.577          | 0.639      | 0.080                  |
| KISOJ000210.22+611924.2  | 175 | EW   | 0.4997257     | 21                            | 56167.51962 | 16.190               | 16.413               | 16.371               | 0.812 | 3.863          | 1.878      | 0.013                  |
| KISOJ000233.43+614514.3  | 167 | EW   | 0.3152875     | 1                             | 56167.71510 | 16.774               | 17.297               | 17.199               | 0.813 | 3.119          | 1.019      | 0.060                  |
| KISOJ000240.13+622844.5  | 285 | EW   | 0.4282596     | 3                             | 56167.75852 | 14.515               | 14.622               | 14.618               | 0.963 | 1.645          | 1.237      | 0.094                  |
| KISOJ000250.76+624850.0  | 169 | EW   | 0.2579880     | 407                           | 56175.50704 | 15.813               | 16.165               | 16.162               | 0.991 | 1.330          | 1.441      | 0.060                  |

(This table is available in its entirety in machine-readable form.)
shown in Figures 2(e)–(g). The lack of faint EBSs with shallow eclipses is caused by selection effects. Faint systems with shallow eclipses, whose magnitude errors during every single epoch are comparable to the eclipse depth, would not pass our selection procedure.

2.5. Possible Contamination by Other Variables

We selected our EBS sample using the same method as that proposed by Chen et al. (2020). Contamination of our sample by nonbinary objects is less than 1%, based on careful visual examination. Since different types of variables exhibit different kinds of light curves, it is easy to distinguish EA- and EB-type EBSs from other types of variables, even without access to any color information. RRc Lyrae and EW-type EBSs have similar periods and amplitudes. An RRc Lyrae light curve with a nearly symmetric luminosity decrease may be misclassified as an EW-type EBS characterized by two similar-depth eclipses at double the RR Lyrae’s period. As such, RRc Lyrae are the main possible contaminant. Here we evaluate the likely level of this type of contamination.

This degeneracy can be lifted by considering the light-curve skewness and color. EW-type objects are associated with a significantly larger skewness than RRc Lyrae. The latter exhibit more sinusoidal-like light curves, while EW-type variables remain brighter for longer during their out-of-eclipse phase. EW-type objects are also significantly redder. These properties will be helpful in aiding our efforts to prevent contamination of
Figure 3. Assessment of the possible contamination caused by RRc Lyrae. Left: EW-type color–period distribution. Green: our EW-type sample objects; black and red: RRc Lyrae and EW-type systems, respectively, from Palaversa et al. (2013). Right: skewness distribution of our sample.

our EW-type sample by RRc Lyrae (see, e.g., Palaversa et al. 2013).

Figure 3 presents the color–period and skewness distributions of the EBs discussed in this paper. In the left panel, we show the dereddened 2MASS $J - K_s$ colors as green points (the extinction values were taken from Section 3.1), as well as the LINEAR RRc Lyrae and EW types (black and red points, respectively). Since all LINEAR objects are located at high Galactic latitude ($b > 29^\circ$), their extinction values are negligible in $J - K_s$. Among our LINEAR objects, RRc Lyrae are generally bluer than EW-type EBs. Our EW-type sample objects are scattered from the top to the right section of the color–period plane, where we see little contamination by RRc Lyrae; they match the LINEAR EW types well. The skewness distribution is shown in the right panel. The adopted boundaries of the skewness, based on the LINEAR sample, are $-0.1$ to $1.6$ for EB/EW types and $-0.4$ to $0.35$ for RRc Lyrae. Our sample’s distribution matches that of the LINEAR sample quite well.

Although it is hard to exclude all RRc Lyrae solely based on our current photometric data, contamination effects appear negligible according to these color and skewness tests.

3. Discussion of Our EW-type Sample Objects

3.1. Extinction and Distance

Lucy (1968a, 1968b) proposed convective common-envelope evolution as the key underlying EW-type theory. The modern model (Stepien 2006a; Yildiz & Doğan 2013) suggests that EW types form through both angular momentum loss and nuclear evolution. EW-type binaries usually form a common envelope, and they can thus be regarded as a single structure. In the color–magnitude diagram, they appear as objects close to the main sequence (MS), although one or both components may be more advanced in their evolution (Stepien 2006a, 2006b, 2009, 2011). Among stars in the Galactic disk, EW-type objects are usually found in old open clusters. Meanwhile, as one of the most numerous types of variables in the Galactic field, they can potentially be used to determine the Galactic disk’s structure above and below the Galactic plane and to trace any age gradient across the plane (Chen et al. 2018a). However, studies of the distribution of EW-type systems in the Galactic plane are limited. With our sample, we can now partially fill in the blanks.

Since the publication of Eggen (1967), a number of attempts have been made to use EW-type period–luminosity–color relations as potential distance indicators. Rucinski made several attempts to derive PLRs from nearby EW types (Rucinski 1994), EW types with Hipparcos parallaxes (Rucinski & Duerbeck 1997), ASAS catalogs (Rucinski 2006), and TGAS parallaxes (Mateo & Rucinski 2017). To unify the PLRs obtained from different bands, optical to mid-infrared PLRs from Chen et al. (2018a), based on 183 nearby EW-type systems with TGAS parallaxes, were adopted.

Note that our sample objects are located in the Galactic disk, where the extinction is high and varies significantly. Although the KISOOP survey can efficiently reduce the impact of extinction in the $I$ band compared with that in $V$ band, extinction is expected to still have a sizable effect on the resulting photometry.

To derive accurate distances, we considered distance moduli ($\mu_0$) and extinction values ($A_\lambda$ as a function of passband, $\lambda$) as variable parameters, i.e.,

$$m_\lambda - a_\lambda \times \log P - b_\lambda = (A_\lambda/A_V) \times A_V + \mu_0.$$  \hspace{1cm} (1)

For a given passband $\lambda$, we take the PLR coefficients $a_\lambda$ and $b_\lambda$ from the maximum-magnitude coefficients of the PLRs of Chen et al. (2018a); the extinction law, $A_\lambda/A_V$, from Wang & Chen (2019); and the period, $\log P$, from Table 1 in Section 2.3. For the apparent magnitude, $m_\lambda$, we adopt the maximum $I$-band magnitudes from Table 1, combined with $JHK_s$-band data from 2MASS. However, 2MASS only provides single-epoch photometry, as well as a time stamp for the observation. Since observed color changes are very small during eclipses, the light-curve shape barely changes among the different bands (Chen et al. 2016). This makes it possible to convert the single-epoch magnitudes to the corresponding maximum magnitudes obtained from the full $I$-band light curves. The differences between the $I$-band magnitudes in the observational phase and the maximum $I$-band magnitudes are listed in Table 1. These photometric properties also allow us to convert the 2MASS single-epoch photometry to the maximum $JHK_s$-band magnitudes.

Armed with known or newly determined parameters pertaining to the $IJK_s$ bands, it is now possible to fit the ($\mu_0$, $A_V$) combination for each system; for an example, see
Figure 4. A similar method has been adopted by other authors (e.g., Madore et al. 2017).

In this example, the slope corresponds to the V-band extinction, $A_V$, and the intercept is the best-fitting distance modulus, $\mu_0$. Since the PLR was fitted only to EW-type objects, our results are based on 3996 objects, having first excluded systems without 2MASS observations. The best-fitting distances and extinction values are listed in Table 1. For some sources affected by low extinction, negative slopes implying negative extinction may result for numerical reasons; in those cases we set the extinction to zero.

As an independent means to determine distances, EW-type PLRs have a wide variety of uses, including as probes to map the structure of the Galactic plane and as benchmarks to cross-check other means of distance determination.

3.2. Mapping the Galactic Thin-disk Structure with EW Types

Equipped with distance estimates from our PLR application, it is now feasible to derive the structure of the northern Galactic plane as traced by EW-type EBSs. To minimize selection effects, we excluded KISOGP objects located at $70^\circ < l < 80^\circ$, $1^\circ < b < 3^\circ$ to retain a uniform distribution across $-1^\circ < b < 1^\circ$ of the thin disk.

The spatial and extinction distributions of EW-type tracers derived from application of the PLR are shown in the top panel of Figure 5. Different colors represent different extinction values; all objects affected by $A_V \geq 5$ mag have been assigned the same color. Our sample objects near the Sun are, in general, affected by low extinction, usually less than $A_V = 2$ mag, while objects in more distant regions are significantly more highly obscured. The spatial distributions defined by different tracers, as well as that traced by our EW types, are shown in the bottom panel of Figure 5. Members of high-mass star-forming regions (HMSFRs; Reid et al. 2014), Galactic Cepheids (Genovali et al. 2014) and the 478 EA-type and 454 EB-type objects from Table 1 with accurate Gaia parallaxes ($0 < \sigma_\pi/\pi < 0.1$) are shown as cyan and black triangles, respectively. Members of all groups are dispersed across the northern Galactic thin disk in the same region. Background image credit: modified from the original artist’s conception; NASA/Joint Propulsion Laboratory–California Institute of Technology/R. Hurt (Spitzer Science Center).

Table 1 with accurate Gaia parallaxes ($0 < \sigma_\pi/\pi < 0.1$) are shown as magenta diamonds, red circles, and cyan and black triangles, respectively. EW-type systems with distances obtained from the PLR are also shown in the density map. The density map was constructed using MathWorks’ “scatplot” tool,† while colored data points and contours were plotted using Voronoi cells to determine the relevant densities. Members of all groups are dispersed in the same region across the northern Galactic thin disk.

† https://www.mathworks.com/matlabcentral/fileexchange/8577-scatplot
Figure 6. Detailed distributions of EBSs in different distances along three sight lines. Red, black, and blue bars represent EW-, EB-, and EA-type EBSs, respectively. (a) $l = 70^\circ$. (b) $l = 93^\circ$. (c) $l = 150^\circ$–$210^\circ$. The equivalent numbers in the last panel were calculated from a combination of the relevant number density and the area covered, which is the same as for panels (a) and (b) at the same distance ($N_{\text{equi}} = S_{\text{eq}} \times \frac{\Delta l}{\Delta x}$).

The density distributions of EW-type and other tracers show that the Galactic thin disk appears inhomogeneous. This exercise can potentially help us to reveal substructures such as bubbles and filaments. Meanwhile, the components of EBSs usually form from MS stars, and their differences within each type of EBS are not affected by age (or at most to a limited extent). Different EBS types are generally associated with different ages, in the sense that EA types are younger, EB types are older, and EW types are the oldest tracers. Meanwhile, Cepheids are young stars and HMSFRs are very young. These different tracers can thus also be used as age tracers.

The derived structure of the thin disk varies significantly as a function of direction. In some directions, e.g., toward $l \sim 120^\circ$ and $l \sim 165^\circ$, EW types can be seen out to considerable distances given the slowly increasing extinction trends there. It appears that these directions offer low-extinction windows, reaching and even crossing the Perseus arm. These areas are known as diffuse regions (Wang et al. 2017, their Figure 1). In other directions, the extinction increases quickly and the largest visible distance from the Sun is small. For example, around $l \sim 80^\circ$ a clear lack of objects is caused by high extinction, $A_V > 5$ mag within 1 kpc. A young, dense cloud with high star-forming activity and high extinction is located in that direction (i.e., the Cygnus X region; Rygl et al. 2012). Its location among the accumulation of EBSs may have been caused by second-generation star-forming activity. The double-peak features along the sight lines to $l \sim 70^\circ$ and $93^\circ$ are caused by significant extinction toward $l \sim 80^\circ$, which prevents detections of objects. The Orion spur happens to be located in this dense region (from a distance of $D_{\text{pc}}$ toward $l \sim 70^\circ$ to $2$ kpc toward $l \sim 93^\circ$; for reference, the distance of the equidistant circle in the background image is 5000 lt-yr or about 1.5 kpc). Similarly, rapidly increasing extinction values can also be seen toward $l \sim 145^\circ$. Unlike the line of sight toward $l \sim 80^\circ$, star-forming activity is not found here.

In general, the stellar distribution appears inhomogeneous as a function of direction along the Galactic plane. For example, for distances between 0.5 and 3 kpc, compare the sector between $l \sim 70^\circ$ and $l \sim 93^\circ$ with a second sector between $l = 150^\circ$ and $l = 210^\circ$; see the bottom panel of Figure 5. The regions contained within the dashed rectangles have widths of 300 pc. The corresponding EBS distributions are shown in Figure 6. Figure 2(e) suggests that our sample’s completeness is higher for systems brighter than $I = 16$ mag, an upper limit we therefore adopt for our subsequent analysis.

Figure 6(a) shows that the systems located along this specific sight line ($l \sim 70^\circ$) are distributed inhomogeneously and tend to cluster on scales of several hundred parsecs, irrespective of EBS type. The distribution of EW types exhibits two ridges separated by a valley on a scale of approximately 1 kpc. The EB- and EA-type distributions also show two ridges, within about 2.5 kpc, although the details differ. Within our target sectors, the spatial clustering scale, i.e., the width of the nearby ridges, increases from EW through EB to EA types. Along the same direction, an age gradient can also be discerned.

Moreover, the extinction behavior also suggests that these clustering scales reflect reality.

However, the sight line toward $l \sim 93^\circ$ shows a different pattern, as shown in Figure 6(b). All three types of EBSs exhibit clustered distributions between 1 and 2 kpc, but only EA types show a rise beyond 2.5 kpc. Compared with Figure 6(c), which also offers some evidence of clustering behavior, the peak of the distribution along this sight line is located at greater distances. We suspect that the peaked distributions of our EBSs may be driven by the structure of the thin disk, as traced by EBSs, rather than by sampling incompleteness.

As such, it is clear that the EBS density distribution in the thin disk is not uniform. Future work should address the detailed structure of the Galactic thin disk based on a larger EBS sample.

### 3.3. Absolute Parameters

To arrive at homogeneous estimates of the physical parameters of the EW-type EBS in the Galactic plane, we created a model for each system using the 2015 version of the Wilson–Devinney (W–D) code (Wilson & Devinney 1971; Wilson 1979, 1990; Sun et al. 2020). The input parameters of the models were based on the results listed in Table 1. We excluded systems with fewer than 150 photometric epochs given the limited accuracy of the resulting parameters.

For all systems, “Mode 3” (contact mode, usually applied to systems in geometric contact without constraints on the thermal contact configuration) was used to analyze the light curves. The input light curves were based on the parameters listed in
Table 1. The effective temperatures of the primary components were taken from Pecaut & Mamajek (2013), based on their 2MASS \((J-K_s)\) colors and the extinction calculated previously. The distances derived from the PLR were used to render absolute system parameters. The bolometric corrections are from Chen et al. (2017).

EW types can be divided into two groups, split at a photospheric temperature of 6200 K (Marsh et al. 2017). The hotter objects correspond to stars dominated by radiative energy transport, while cooler objects are stars with convective envelopes. We set the gravity-darkening coefficients and the bolometric albedos to \(g = 0.32, A = 0.5\) and \(g = 1.0, A = 1.0\) for stars with temperatures less than and greater than 6200 K, respectively. A bolometric logarithmic limb-darkening law was applied. No spots, third bodies, or time derivatives of the orbital period were considered in our light-curve fitting.

We used an extensive \(q\)-search method to find the best mass ratio, \(q = M_2/M_1\). Mass ratios \(q\) from 0.1 to 10 were tried, in steps of 0.0125 from 0.1 to 1, 0.025 from 1 to 2, 0.125 from 2 to 5, and 0.5 from 5 to 10; see the left panel of Figure 7. The mass ratios are shown on the horizontal axis, while the residuals are shown on the vertical axis. In this example, the minimum residual occurs for a mass ratio \(q = 0.1875\). The best-fitting light curve, compared with the original observations, is shown in the right panel of Figure 7. Outliers rejected during our light-curve solution procedures are marked as orange crosses. The phase shift of the primary eclipse, the orbital period were considered in our light-curve fitting.

The Gaia mission (Gaia Collaboration et al. 2016, 2018, 2020) represents a leap forward for tests of stellar and Galactic astrophysics. In particular, Gaia parallaxes, with precisions of 30 \(\mu\)as or better for sources with \(G \leq 15\) mag, can be used to solve the greatest and most challenging problems in stellar astrophysics. However, there is clear evidence of the presence of systematic errors in Gaia parallaxes. Lindegren et al. (2018) found a general, systematic parallax offset of \(\Delta \pi = 29\) \(\mu\)as from their quasar catalog. The Gaia eDR3 parallax solution is a significant improvement compared with that affecting Gaia Data Release 2 (DR2): a typical 20% parallax improvement has been reported for Gaia eDR3 quasars (Fabricius et al. 2020). However, despite being the best benchmark for Gaia parallaxes, quasars (typically with \(G > 17\) mag) are rather faint, and their color distribution does not match well the stellar color distribution. Clearly, independent
Table 2

| ID            | $T_1$ (K) | $T_2$ (K) | $q$ | $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $R_1$ ($R_\odot$) | $R_2$ ($R_\odot$) | $M_{bol1}$ (mag) | $M_{bol2}$ (mag) | $L_1/(L_1 + L_2)$ | $\Omega_1 = \Omega_2$ | $A$ (deg) | $i$ (deg) |
|---------------|-----------|-----------|-----|-------------------|-------------------|-------------------|-------------------|------------------|------------------|------------------|-------------------|------------|-----------|
| KISOJ000039.63+622214.1 | 8157      | 6551      | 7.5 | 0.156             | 1.167             | 0.494             | 1.156             | 4.78             | 3.894            | 0.23             | 11.821            | 2.005      | 57.044    |
| KISOJ000048.17+614603.1 | 6129      | 7699      | 0.462 | 1.226             | 0.567             | 1.042             | 0.732             | 3.668            | 3.475            | 0.528            | 2.79              | 2.304      | 86.796    |
| KISOJ000053.24+613059.8 | 4607      | 4381      | 4.375 | 0.251             | 1.1               | 0.539             | 1.041             | 5.41             | 4.163            | 0.248            | 8.279             | 2.004      | 63.157    |
| KISOJ000056.84+625228.4 | 7337      | 7698      | 0.3  | 1.94              | 0.582             | 1.929             | 1.1               | 1.567            | 2.567            | 0.731            | 2.463             | 3.946      | 56.189    |
| KISOJ000123.66+613746.8 | 5771      | 5477      | 0.4  | 1.185             | 0.474             | 1.246             | 0.825             | 3.822            | 4.926            | 0.731            | 2.645             | 2.647      | 63.908    |
| KISOJ000208.16+630633.5 | 5285      | 5772      | 0.587 | 0.963             | 0.566             | 0.952             | 0.746             | 4.773            | 4.934            | 0.548            | 3.031             | 2.217      | 54.22     |
| KISOJ000210.22+611924.2 | 5312      | 5588      | 5.0  | 0.354             | 1.768             | 0.894             | 1.817             | 3.662            | 1.991            | 0.167            | 9.015             | 3.405      | 58.017    |
| KISOJ000233.43+614514.3 | 4917      | 4658      | 4.375 | 0.251             | 1.098             | 0.605             | 1.141             | 5.332            | 4.17             | 0.254            | 8.147             | 2.154      | 72.266    |
| KISOJ000250.76+624850.0 | 5126      | 5345      | 4.875 | 0.321             | 0.638             | 0.977             | 6.143             | 4.43             | 1.74             | 8.86             | 1.838             | 68.057    |
| KISOJ000300.42+631913.6 | 6261      | 5215      | 1.95  | 0.577             | 1.125             | 0.806             | 1.093             | 4.013            | 4.062            | 0.493            | 5.137             | 2.455      | 83.705    |
| KISOJ000308.44+622223.9 | 5126      | 5016      | 7.5  | 0.16              | 1.201             | 0.48              | 1.192             | 5.66             | 3.762            | 0.15             | 12.146            | 2.132      | 61.469    |
| KISOJ000329.49+613312.2 | 5632      | 5463      | 1.575 | 1.01              | 1.591             | 1.144             | 1.396             | 2.768            | 2.473            | 0.425            | 4.513             | 3.191      | 75.15     |
| KISOJ000356.37+611452.6 | 6356      | 5651      | 0.237 | 2.032             | 0.483             | 2.089             | 1.168             | 1.355            | 2.785            | 0.825            | 2.216             | 3.837      | 67.856    |
| KISOJ000359.11+615018.1 | 5394      | 5659      | 0.188 | 1.04              | 0.195             | 1.13              | 0.557             | 4.42             | 5.783            | 0.783            | 2.141             | 2.052      | 74.899    |
| KISOJ000401.47+613034.7 | 4962      | 5308      | 0.387 | 1.115             | 0.432             | 1.068             | 0.692             | 4.1              | 4.761            | 0.65             | 2.641             | 2.28       | 81.237    |
| KISOJ000417.46+620836.4 | 6733      | 6526      | 9.5   | 0.151             | 1.438             | 0.549             | 1.471             | 4.978            | 2.938            | 0.129            | 14.35             | 2.52       | 66.477    |
| KISOJ000429.77+608585.6 | 5771      | 5784      | 3.25  | 0.385             | 1.25              | 0.834             | 1.401             | 4.76             | 3.579            | 0.258            | 6.796             | 2.807      | 68.041    |
| KISOJ000441.52+623631.7 | 6829      | 6771      | 1.05  | 1.383             | 1.93              | 2.155             | 2.197             | 1.598            | 1.59             | 0.496            | 3.562             | 5.072      | 78.901    |
| KISOJ000501.27+611509.9 | 4729      | 4840      | 0.125 | 1.822             | 0.228             | 2.158             | 0.939             | 1.854            | 3.63             | 0.835            | 1.958             | 3.634      | 71.187    |
| KISOJ000505.12+630032.3 | 5903      | 5052      | 1.3   | 0.896             | 1.165             | 0.915             | 1.037             | 3.545            | 3.9              | 0.571            | 4.277             | 2.621      | 57.358    |

(This table is available in its entirety in machine-readable form.)
assessment of Gaia parallaxes is important to fully characterize any lingering systematic errors. Since EW-type EBSs are among the most numerous variables in the Milky Way that have independently determined distance measurements in the solar neighborhood, here we will use our EW-type distances to check for zero-point offsets in the Gaia eDR3 parallaxes.

Of the 3996 EW-type EBSs with distances from the PLR, 3920 have parallaxes available in Gaia eDR3. Figure 8 (a) shows a direct comparison of the EBS parallaxes derived from the PLR versus Gaia eDR3 parallaxes. The cyan dashed one-to-one line is meant to clearly show the extent of the offset in distances. The deviation between the samples hints at a clear offset in parallaxes, in the sense that the PLR parallaxes are larger on average than their Gaia counterparts. After excluding objects with large errors and negative parallaxes ($\sigma_\pi/\pi > 0.2$ and $\pi < 0$), marked as red points in Figure 8(a), 2334 EW-type EBSs were left. Figure 8(b) presents the distribution of parallax differences, $\pi_{\text{Gaia}} - \pi_{\text{PLR}}$. The distribution appears to be a roughly symmetric, normally distributed offset in the negative direction. The mean offset is $\Delta \pi = -42.1 \pm 1.9$ μas, where the error is the standard error on the mean for all sample objects. In other words, the Gaia parallaxes are systematically smaller.

The Gaia team has released a model allowing us to adjust this zero-point offset, which was based on an analysis of

![Figure 8. Comparison of predicted EBS parallaxes derived from the PLR vs. Gaia eDR3 parallaxes. (a) Direct comparison for all EW types. Red points have uncertainties exceeding 20% or negative parallaxes. The cyan dashed line is the one-to-one locus. (b) Distribution of the parallax offsets affecting Gaia eDR3, $\Delta \pi (\text{Gaia}_{\text{eDR3}} - \text{PLR}) = -42.1 \pm 1.9$ μas. (c) Parallax offsets of corrected Gaia eDR3 parallaxes (Lindgren et al. 2020), $\Delta \pi (\text{Gaia}_{\text{eDR3}} - \text{PLR}) = -10.6 \pm 2.9$ μas. (d) Equivalent distribution of Gaia DR2 parallaxes, $\Delta \pi (\text{Gaia}_{\text{DR2}} - \text{PLR}) = -52.2 \pm 3.6$ μas. The red curves in panels (b), (c), and (d) represent the best-fitting Gaussian distributions.](image)
quasars, binary stars, and stars in the Large Magellanic Cloud (Lindegren et al. 2020). We also compared the parallaxes implied by our EW-type distances with the corrected Gaia parallaxes (see Figure 8(c)) and found an offset of $\Delta \pi = -10.9 \pm 2.9$ μas. This suggests that the parallax zero-point correction provided by the Gaia team significantly reduces but may not fully eliminate the prevailing bias in the Gaia eDR3 parallaxes.

Quantification of the parallax systematics in Gaia DR2 was based on careful analysis of a series of tracer objects, yielding the following: Cepheids, $\Delta \pi = -46 \pm 13$ μas (Riess et al. 2018); nearby bright EBSs, $\Delta \pi = -82 \pm 33$ μas (Stassun & Torres 2018); stars with astereosismically determined radial, $\Delta \pi = -52.8 \pm 2.4$ (statistical) $\pm 8.6$ μas (systematic) (Zinn et al. 2019); and Bayesian distances for a radial velocity sample, $\Delta \pi = -54 \pm 6.0$ μas (Schönrich et al. 2019)). For comparison, we similarly used our EBS sample as a parallax tracer and found $\Delta \pi = -52.2 \pm 3.6$ μas. This offset is similar to those of other authors’ concurrent, independent analyses based on different benchmark samples (e.g., Zinn et al. 2019; Schönrich et al. 2019). Our result should have similar systematic uncertainties to those determined by Zinn et al. (2019) and Schönrich et al. (2019), since the maximum parallax difference among these three tracer populations is less than 2 μas.

We will now estimate the likely systematic error range pertaining to our PLR-based EW-type distances. Five fundamental issues affect the level of the systematic uncertainties: (i) the offset in the PLR, (ii) its internal spread, (iii) uncertainties in the photometric zero-points, (iv) errors in our extinction evaluation, and (v) third-component effects.

The PLR was obtained from 183 objects within 330 pc with an average parallax of 5.46 mas. Considering a 30 μas systematic uncertainty (Gaia Collaboration et al. 2016), the systematic error contributed by the offset is about 0.5%. The systematic error associated with the internal spread in the PLR is of order $0.21/\sqrt{183} \approx 0.016$ mag. Here 0.21 mag is the mean spread in the $IHK_s$-band PLRs. As regards the photometric zero-points, the $I$-band systematic error is most important, given that the $JHK_s$-band PLR and KISO GP EW data both came from 2MASS; our $I$-band photometric data for all EBS PLRs were based on the USNO-B catalog. We correlated our $I$-band data for all sample EBSs with those published in the USNO-B catalog. We found that the KISO GP $I$-band magnitudes are systematically 0.009 mag brighter than the corresponding USNO-B $I$-band magnitudes for the 6894 targets in common.

Since we make use of the $IHK_s$ bands, here we consider an average extinction corresponding to 0.225A$_V$. We also adopt a 10% uncertainty in the extinction determination, which reflects uncertainties owing to the choice of extinction law. For a mean observed extinction of $A_V = 1.94$ mag, these choices lead to an uncertainty of $1.94 \text{ mag} \times 0.225 \times 10\% = 0.0437$ mag. Next, if a third component can be discerned, a study of 75 nearby EW-type EBSs (D’Angelo et al. 2006) has shown that this will affect the systematic uncertainty at the median distance of our sample by about 0.3%. As neither our KISO GP sample objects nor those contributing to the PLR explicitly excluded third-body effects, the bias caused by third- or higher-order multiplicity should not differ much between both sets of EBSs. We estimate that the associated systematic uncertainty is less than 0.3%. As such, the systematic uncertainty range affecting our results is

$$\sigma = 581\mu$$

as

$$\lambda = \{(0.005)^2 + (0.016 \times \ln(10))/5)^2 + (0.009 \times \ln(10)/5)^2 + (0.0437 \times \ln(10)/5)^2 + (0.003)^2\}^{1/2}$$

μas.

The offset we found based on our catalog of 2334 EW-type EBSs is well within the prevailing uncertainties and also fully consistent with a systematic error below 100 μas as reported by the Gaia team. Our EW-type EBSs in the Galactic plane result in a larger offset than that derived from quasars ($-17\mu$as), but the offset can be reduced significantly by application of the official parallax zero-point correction. The Gaia team found that the parallax zero-point depends on a target’s magnitude, color, and position, and hence the small difference we found between EBSs and quasars is not surprising. The difference may come from the details of the distribution of the parallax zero-point, since quasars are fainter and bluer than our EBSs, which are all located in the Galactic plane. In addition, for faint sources outside the Galactic disk parallax calibrations are estimated directly from the quasar sample. However, the parallax bias for objects in the Milky Way is derived indirectly, based on binary stars and stars in the Large Magellanic Cloud.

Stassun & Torres (2021) found a mean parallax offset of $-37 \pm 20$ μas, which decreased to $-15 \pm 18$ μas following the official corrections based on 76 EBSs. Their result matches our result well, which is particularly encouraging since our result is affected by small statistical errors and based on a large sample. Our EBS sample can be used as useful tracers for further work on the zero-point offset of Gaia parallaxes. In addition, our result is based on EW-type EBSs in the Galactic plane, which most other studies try to avoid. It can therefore serve as a useful reference for other studies that need to deal with the Gaia zero-point offset in the Galactic plane and complement studies of the zero-point distribution across the sky.

In conclusion, we found a Gaia eDR3 zero-point offset of $\Delta \pi = -42.1 \pm 1.9$ (stat.) $\pm 12.9$ (syst.) μas, based on 2334 EW-type EBSs covering a wide range of magnitudes and extinction values in the northern Galactic plane. The official parallax zero-point correction can significantly reduce the bias in eDR3 parallaxes to $-10.9 \pm 2.9$ (stat.) $\pm 12.9$ (syst.) μas for our sample.

### 3.5. Extinction Compared with 3D Extinction Map

Green et al. (2019) presented a 3D dust reddening map of the northern sky derived from Gaia parallaxes and stellar photometry from Pan-STARRS 1 and 2MASS. Green et al.’s 3D extinction map happens to overlap with the KISO GP survey’s spatial coverage. In Figure 9, we compare the extinction derived from our PLR analysis with that from the 3D extinction map.

As shown in Figure 9, a linear correlation is clearly discernible. The extinction values from both studies fit well within the relevant scatter envelopes. This scatter may originate from various sources. First, both the error in the extinction from our PLR analysis and that in the 3D extinction map cannot be ignored. Second, the error in distance used as input into the 3D extinction map may exacerbate the intrinsic errors in the
extinction from the 3D map. Finally, the distances and spatial resolutions pertaining to the 3D map are coarse, with distance modulus steps of 0.5 mag and angular resolutions of several arcminutes. These steps lead to nonnegligible errors when comparing the extinction values for single objects, particularly for our sample in the Galactic plane, where the extinction is usually high. In any case, given the prevailing uncertainties, both methods are mutually consistent.

4. Conclusion

We have presented a new catalog of EBSs in the northern Galactic plane based on the KISOGP survey. We visually identified 7055 EBSs spread across \( \sim 330 \) deg\(^2\), including 4197 EW-type, 1458 EB-type, and 1400 EA-type EBSs. For all sample objects, we used their I-band light curves to determine accurate parameters, including their periods (accurate to better than the fifth decimal place), a reference \( t_0 \), the depths of the two eclipses, etc.

We also examined the spatial distribution of our sample objects. We found an inhomogeneous density distribution of EBSs in the thin disk at different Galactic longitudes. In addition, we found a random distribution of the ratios of the eclipse depths for EA types and a concentration tending to unity for EW-type EBSs. Moreover, we checked that the distributions of their periods vary among different EB types, increasing from EW to EB and EA type. We also obtained the distribution of the eclipse depths, the I-band magnitudes, etc. Finally, we tested the level of contamination of our sample by other types of variables, which we found to be negligible.

We derived the distances and extinction values pertaining to the EW types in our sample using their PLRs, reaching distances in excess of 6 kpc and V-band extinction values exceeding \( A_V = 9 \) mag. We combined our EBS sample with HMSFRs and Cepheids to trace the structure of the thin disk. Stars of the same type (including but not limited to EBSs) tend to cluster on spatial scales of several hundred parsecs. Using different tracers, we revealed some structural properties of the thin disk.

As an independent distance measurement, our EBS distance analysis offers a complementary measurement of the global parallax offset affecting Gaia eDR3. We found \( \Delta \pi = -42.1 \pm 1.9 \) (stat.) \( \pm 12.9 \) (syst.) as based on a careful analysis of 2334 EW-type EBSs. Our newly derived offset is consistent with the results from the Gaia team. We also found that the official parallax zero-point correction can significantly reduce the bias affecting the eDR3 parallaxes. Finally, we performed a photometric analysis of all EW-type light curves using the W–D method to derive individual system parameters, and we cross-checked our extinction values with Green et al.'s 3D extinction map.

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Figure 9. Extinction comparison \((A_V, \text{ mag})\) between the values derived from the PLR and those from Green et al. (2019).
