The Value-Added Catalog of ASAS-SN Eclipsing Binaries: Parameters of Thirty Thousand Detached Systems

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ABSTRACT

Detached eclipsing binaries are a fundamental tool for measuring the physical parameters of stars that are effectively evolving in isolation. Starting from more than 40,000 eclipsing binary candidates identified by the All-Sky Automated Survey for Supernovae (ASAS-SN), we use PHOEBE to determine the sum of the fractional radii, the ratio of effective temperatures, the inclinations, and the eccentricities for 35,464 systems. We visually inspect all the light curve models to verify the model fits and examine the TESS light curves, when available, to select systems with evidence for additional physics, such as spots, mass transfer, and hierarchical triples. We examine the distributions of the eclipsing binary model parameters and the orbital parameters. We identify two groups in the sum of the fractional radii and effective temperature ratio parameter space that may distinguish systems approaching the semidetached limit. Combining Gaia EDR3 with extinction estimates from 3-dimensional dust maps, we examine the properties of the systems as a function of their absolute magnitude and evolutionary state. Finally, we present light curves of selected eclipsing binaries that may be of interest for follow-up studies.

Key words: binaries: eclipsing – surveys

1 INTRODUCTION

Detached eclipsing binaries (EBs) can be used to directly measure the stellar parameters of isolated stars. Modeling the light curve of an EB yields the sum of the fractional radii relative to the semimajor axis, \((R_1 + R_2)/a\), the ratio of effective temperatures, the eccentricity, and the orbital inclination (Kallrath & Milone 2009). Physical masses and radii of the components can then be determined by adding radial velocity observations (e.g., Matson et al. 2017; Pourbaix et al. 2004). The resulting stellar parameters can be used to test and validate stellar evolution models (Osterbrock 1953; Hoxie 1970; Andersen 1991; Pietrinferni et al. 2004; Torres et al. 2010; Feiden 2015) and as reddening and distance indicators (e.g., Paczynski 1997; Wyithe & Wilson 2002; Bonanos et al. 2006; Pietrzyński et al. 2009).

Since most massive stars and nearly half of all Solar-type stars are found in binary systems (Raghavan et al. 2010; Sana et al. 2012; Duchêne & Kraus 2013; Moe & Di Stefano 2017), binary evolution cannot be discounted when considering stellar evolution. During star formation, binarity impacts disk fragmentation and circumstellar disk formation (Mathieu 1994; Tokovinin & Moe 2020). Binary evolution on and after the main sequence can, often drastically, alter the evolution of the system. Tidal effects can circularize or synchronize the orbit (Verbunt & Phinney 1995; Hurley et al. 2002) or induce oscillations in eccentric systems (Kumar et al. 1995; Willems & Aerts 2002). Mass transfer and common envelope evolution changes the orbital period, rotational periods, and luminosities of the components (Paczynski 1976; Sana et al. 2012; de Mink et al. 2013) and can also result in single stars through mergers (e.g., Mateo et al. 1990) or when one of the components explodes as a supernova (Hoyle & Fowler 1960). Determining the physical parameters of binary systems at different stages of evolution is therefore crucially relevant in understanding how stellar populations evolve.

The Optical Gravitational Lensing Experiment (OGLE, Graczyk et al. 2011; Pawlak et al. 2013; Pietrukowicz et al. 2013; Soszyński et al. 2016; Bódi & Hajdu 2021), Kepler (Prša et al. 2011; Slawson et al. 2011; Kirk et al. 2016), the Wide-field Infrared Survey Explorer (WISE, Petrosky et al. 2021), and the All-Sky Automated Survey (ASAS, Pojmanski 2002; Paczyński et al. 2006) have all produced extensive catalogs of EBs of varying morphologies and in different evolutionary stages. Selections from these catalogs have been used for more detailed photometric and spectroscopic modeling (e.g., Ratajczak et al. 2021).
Various codes exist to model the light curves of eclipsing binaries. (Wilson & Devinney 1971; Nelson & Davis 1972; Etzel 1981; Prša & Zwitter 2005; Ćokina et al. 2021). Although the physical radii cannot be determined without the inclusion of spectroscopic observations, the fractional radii can be measured from the eclipse widths. The ratio of effective temperatures is determined by the difference in eclipse depths, and the absolute temperatures can be determined with a multi-band light curve (Prša & Zwitter 2005; Torres et al. 2010). Light curve modeling tools have been applied to small selections of systems (e.g., Popper & Etzel 1981) and larger catalogs of EBs (e.g., Devor 2005). Construction of catalogs of models has aided in the study of binary stars of selected spectral types (e.g., Bonanos et al. 2004; Coughlin et al. 2011; Graczyk et al. 2018), to select targets for radial velocity followup (e.g., Matson et al. 2017), and to identify eccentric (Bulut & Demircan 2007; Kjurkchieva et al. 2017; Kim et al. 2018; Zasche et al. 2021) and triple systems (Hajdu et al. 2022; Juryšek et al. 2018).

More than 130,000 eclipsing binaries have been identified in the All-Sky Automated Survey for Supernovae (ASAS-SN, Shappee et al. 2014; Kochanek et al. 2017) V-band data (Jayasinghe et al. 2019, 2021). Here we provide light curve models for the g- and V-band light curves of 35,464 detached EBs. Section §2 describes the ASAS-SN observations and the properties of the detached eclipsing binaries from Jayasinghe et al. (2019) that form the basis of our catalog. Section §2.1 describes the additional filtering applied to the g-band light curves and in Section §2.2 we update the orbital periods. Section §2.3 identifies systems with long-term trends. We use PHysics Of Eclipsing BinariEs (PHOEBE, Prša et al. 2016; Conroy et al. 2020) to model the ASAS-SN light curves in Section §2.4 and visually inspect the solutions in Section §2.5. Section §3 describes the statistics of the detached EB population and examines their empirical period-eccentricity distribution. In Section §3.3 we also explore their properties as a function of absolute magnitude and evolutionary state.

2 MODELING DETACHED ECLIPSING BINARIES

The ASAS-SN V-band observations taken from 2012 to mid 2018 were used to classify more than 420,000 variable stars, including over 70,000 contact binaries (EW, W Uma), 24,000 semi-detached binaries (EB, β-Lyrae), and 40,728 detached binaries (EA, Algol) (Jayasinghe et al. 2018, 2019). We select the detached population for our input catalog. At the end of 2017, ASAS-SN switched to observe in the g-band and expanded with three additional quadruple telescope units. We analyze both the V- and g-band light curves in this work. The ASAS-SN targets in our catalog have median V-band magnitudes ranging from 9.9 to 17.4 mag with a median magnitude of 13.9 mag. The optimal magnitude range for ASAS-SN targets is 11 < V < 17 mag (Jayasinghe et al. 2019). With the combined baseline of the V- and g-band observations, the EBs have a median observation baseline of 6.43 years with an average of 693 epochs.

The three eclipsing binary morphology classes can be distinguished using the coefficients of a Fourier series model of their light curves (Rucinski 1997; Paczyński et al. 2006). Jayasinghe et al. (2019) included these coefficients in the random forest classification of ASAS-SN variable stars, and Figure 1 shows the $a_2$ and $a_4$ coefficients for the three morphology classes with points colored by

![Figure 1](image_url)

**Figure 1.** Fourier coefficients $a_2$ and $a_4$ for the eclipsing binaries from Jayasinghe et al. (2021). The detached eclipsing binaries included in our initial catalog are colored by period. We see that the shorter period binaries are distributed closer to the semi-detached population. Examples of phase folded ASAS-SN $V$-band light curves are shown on the right and as stars on the left.
the orbital period for the detached systems. Unsurprisingly, shorter period systems classified as detached tend to be more similar to the semi-detached population.

2.1 Initial Data Filtering

Some ASAS-SN $g$-band light curves have additional problems from blends, detector edge effects, or saturation. The light curves of these targets can show spurious measurements with large errorbars, resulting in a bimodal magnitude error distribution. Although most of the affected data points can be removed by sigma clipping, we screen these targets before we attempt to model their light curves.

To select targets with bimodal error distributions, we search for stars with broad distributions of magnitude errors. In general, fainter targets and EBs with deep eclipses will also have broad magnitude error distributions, so we visually inspect targets that have large standard deviations in their magnitude error distributions. In total, we flag 132 targets for additional filtering based on the magnitude error distribution. For these targets, we use \texttt{sklearn} (Pedregosa et al. 2011) to fit a two-component Gaussian mixture model to the magnitude error distribution. We then remove observations that have a probability $p > 0.95$ of belonging to the higher error component.

2.2 Orbital Period Calculation

Jayasinghe et al. (2019) determined the orbital periods of the detached EBs with a combination of the Generalized Lomb Scargle (Lomb 1976; Scargle 1982), Multi-Harmonic Analysis of Variance (Schwarzenberg-Czerny 1996), and Box Least Squares (BLS) periodograms (Kovács et al. 2002). In order to correctly phase the data over the much longer time baseline of the $V$- and $g$-band data, these periods need to be updated. We use the \texttt{astrobasis} implementation of the BLS algorithm (Bhatti et al. 2018; Kovács et al. 2002) to search a narrow period window centered on the $V$-band catalog period, $P_{\text{orig}}$, of width $2\Delta P$, where $\Delta P = 0.005P_{\text{orig}}^2$. We chose this narrow window for computational speed and increase the width as $P_{\text{orig}}^2$ since the period errors will be larger for longer period EBs. To prevent returning a period that is a small integer ratio of the input period, we further restrict the search range to $0.95P_{\text{orig}} < P < 1.05P_{\text{orig}}$, which only affects systems with $P_{\text{orig}} > 10$ d.

Before computing the period, we first median normalize the fluxes in each band and use sigma clipping to remove observations fainter than (brighter than) 8.0 (2.0) standard deviations from the median magnitude. The $V$-band and $g$-band data are then combined and the BLS is run with 200 phase bins and eclipse durations ranging from 0.005 to 0.200 in orbital phase units. We select the peak with the highest power as the updated orbital period.

We also use the astropy implementation of the (Kovács et al. 2002) BLS (Astropy Collaboration et al. 2013) to double check the periods. While the two implementations generally return periods matching to within $\sim 10^{-4} - 10^{-5}$ days, we find some cases where the \texttt{astrobasis} KBLS implementation is unable to identify the correct period and we instead use the astropy period. Figure 2 shows the distributions of $P_{\text{new}}$ and $\Delta P$. The EBs span a wide range of periods from 0.35 d to 484.95 d with a median of 2.18 d. There are fewer systems with periods near 1 and 2 days because Jayasinghe et al.
Rotational variability can result in long-period trends in ASAS-SN g-band light curves. We also find that bright g-band targets are more likely to have long-term trends because they are near saturation of the CCDs. For our EA catalog, we use a χ² ratio test to identify g-band light curves with long-term trends as an indication of rotational variability. We compute the χ²₀ of a flat line and the χ²₁ of a linear fit in time for each light curve. EBs with some rotational variability tend to have R_LT = χ²₁/χ²₀ < 1. Figure 3 shows the distribution of the systems in R_LT for the g-band light curves. Many of the EBs with long-term trends are in the bright tail of the magnitude distribution, suggesting that stars approaching saturation also show systematic effects that produce long-term trends in the g-band light curves. We start the PHOEBE modeling with the V-band light curves if R_LT < 0.957, corresponding to the bottom 5% of the distribution (2,037 systems). We also use the boundary of 11.9 mag to separate spotted systems from saturation problems. The 876 EBs in the upper left quadrant defined by these two cuts are flagged as having potential rotational variability in Table 1.

Figure 4 shows examples of the V- and g-band light curves for each quadrant. These four EBs are also marked in the main panel of Figure 3. In some cases, such as ASASSN-V J090558.04–294522.8, long-term variation is also seen in the V-band data, further suggesting its astrophysical nature. On the other hand, ASASSN-V J035913.18+123817.3 (lower left) has a g-band magnitude that decreases in time, but lies in the saturated region (g = 10.7 mag) and there is no such variability seen in the V-band data, suggesting that the g-band trend is due to systematic effects.

### 2.4 Eclipsing Binary Models

We use PHOEBE (Prša & Zwitter 2005; Prša et al. 2016; Conroy et al. 2020) to model the ASAS-SN light curves. PHOEBE has been used extensively for modeling contact binaries (e.g., Kobulnicky et al. 2022), detached systems (e.g., Way et al. 2021), and exotica such as heartbeat systems (e.g., Ou et al. 2021).
We start by constructing a phased, flux normalized light curve and sigma clip points > 5σ from the median light curve. We use the geometry estimator in PHOEBE to estimate the eclipse locations, and expand the limit to 8σ during the eclipses to prevent unwanted clipping of narrow, deep eclipses. During visual inspection (Section 2.5) we check for systems where over-clipping erroneously removes points during eclipses and leads to inaccurate parameter determination. The geometry estimator combines a two Gaussian model with a cosine term to fit for the eccentricity, \( e \), argument of periastron, \( \omega \), and time of superior conjunction, \( t_0 \) (Mowlavi et al. 2017; Conroy et al. 2020).

We do the geometry estimator fits for periods of \( P_{\text{new}}/2 \) and \( 2P_{\text{new}} \) because if the secondary eclipse is very shallow the BLS period can be off by a factor of two. If the ratio of the minimum \( \chi^2 \) of the fits to the second smallest \( \chi^2 \) is less than 0.8, we accept the period corresponding to the minimum to be the period \( P \). Otherwise, we optimize the two best periods and select the fit with the minimum \( \chi^2 \). This additional step is effective at determining the correct period for systems with large eclipse depth ratios where the two-Gaussian model would otherwise return a satisfactory fit at \( 2P_{\text{new}} \).

We also apply the EBAl estimator (Prša et al. 2008) to the median filtered light curve to obtain initial values for the ratio of effective temperatures, \( \text{Teff}_2/\text{Teff}_1 \), the sum of fractional radii, \( R_1/a + R_2/a = \rho_1 + \rho_2 \), and the inclination, \( i \). We use the results from the geometry estimator to define the orbital phase range as \(-0.5\) to \(0.5\) with the primary eclipse at phase zero. We then use the polyfit algorithm (Prša et al. 2008) to transform the light curve into 200 points equally spaced in phase. After running both estimators, we have the initial values of \( e \), \( t_0 \), \( \omega \), \( \text{Teff}_2/\text{Teff}_1 \), \( \rho_1 + \rho_2 \), and \( i \) for a full optimization.

Next we optimize the model of the \( g \)-band light curve (\( V \)-band for systems with long-term trends identified in Section §2.3) with 400 iterations of the Nelder-Mead simplex algorithm (Gao & Han 2012). This is typically sufficient to converge to a minimum for the ASAS-SN light curves. We use the e11c backend (Maxted 2016) with no irradiation. The limb darkening coefficients are from the Castelli-Kurucz model atmosphere tables (Castelli & Kurucz 2003) and span 3500 < \( T_{\text{eff}} \) < 5000 K. Since only the relative temperatures, rather than the absolute temperatures, are constrained by a single-band light curve fit, we solve for the \( \text{Teff}_2/\text{Teff}_1 \) and keep \( T_{\text{eff},1} = 7000 \) K fixed to allow a wide range of values for \( T_{\text{eff},2} \) within the constraints of the Castelli–Kurucz model atmospheres. We then add in the \( V \) or \( g \)-band data and run an additional 200 iterations on the multiband light curve. The optimization with the additional light curve further constrains the model parameters and is especially effective at improving the fits for systems with narrow eclipses.

### 2.5 Visual Inspection

Although this approach is generally effective at producing reliable fits with minimal manual intervention, we visually inspect all 40,728 light curve solutions to identify systems that require additional optimization or have found a local minimum. In addition to evaluating the \( \chi^2 \) of the solution, we consider the alarm statistic defined by Tamuz et al. (2006). The phased model residuals are grouped into \( M \) ‘runs’ over which consecutive residuals in phase have the same sign and

\[
\mathcal{A} = \frac{1}{\chi^2} \sum_{i=1}^{M} \left( \frac{r_{1,i} + r_{1,2} + \ldots + r_{1,k_i}}{\sigma_{1,i} + \sigma_{1,2} + \ldots + \sigma_{1,k_i}} \right)^2 \left( 1 + \frac{4}{\pi} \right)
\]

where \( r_{i,j} \) is the \( j \)th residual in the \( i \)th run with uncertainty \( \sigma_{i,j} \). The alarm statistic is particularly useful for identifying cases where
The table shows the detached eclipsing binary model fit results sorted by orbital period. The time of superior conjunction \( t_0 \), period (P), sum of the fractional radii \( (\rho_1 + \rho_2) \), ratio of effective temperatures \( T_{\text{eff},2}/T_{\text{eff},1} \), eccentricity (e), argument of periastron \( (\omega) \), and inclination (i), are from the PHOEBE models. The Gaia EDR3 color and absolute magnitude are corrected for extinction using \texttt{magext} (Bovy et al. 2016). The reduced chi-squared is given for the optimized solution. The alarm statistics \( \mathcal{A}_V \) and \( \mathcal{A}_G \) (Equation 1) are given for the V- and g-band fits. Systems with long-term trends that are likely due to rotational variability are marked in the ROT column. Finally, we use the MIST isochrones and evolutionary tracks (Choi et al. 2016; Dotter 2016) to classify the systems based on the evolutionary state of the photometric primary (MS=main sequence, SG=subgiant, RG=giant). The full catalog is available as an online table.

### Table 1

| ASAS-SN Name | \( t_0 \) | Period (d) | \( \rho_1 + \rho_2 \) | \( T_{\text{eff},2}/T_{\text{eff},1} \) | Ecc | \( \omega \) (deg) | \( \text{Incl} \) (deg) | \( M_G \) (mag) | \( M_{\text{BP}} - M_{\text{RP}} \) (mag) | \( \chi^2 \) | \( \mathcal{A}_V \) | \( \mathcal{A}_G \) | g (mag) | ROT | State |
|--------------|----------|-----------|----------------|-----------------|-----|----------------|----------------|-------------|----------------|----------|-------------|--------|--------|------|------|
| J063849.93-090909.2 | 2333.590999 | 11.94017 | 0.24 | 0.94 | 0.421 | 140.20 | 83.9 | -0.44 | 0.26 | 1.25 | 1.00 | 3.61 | 14.1 | MS |
| J000538.47+360212.4 | 2024.27545 | 9.55828 | 0.15 | 1.00 | 0.013 | 88.29 | 88.2 | 2.01 | 0.61 | 0.90 | 6.46 | 12.8 | 12.6 | MS |
| J184413.44-372828.3 | 2016.34688 | 9.28395 | 0.29 | 0.53 | 0.010 | 78.03 | 83.3 | 1.75 | 0.77 | 1.07 | 3.44 | 1.00 | 13.0 | SG |
| J174224.72+203501.8 | 2037.68761 | 7.35937 | 0.17 | 0.98 | 0.016 | 27.85 | 87.4 | 2.86 | 0.83 | 1.05 | 0.37 | 31.0 | 13.8 | SG |
| J054647.45-692208.9 | 2039.96598 | 5.41394 | 0.56 | 0.95 | 0.031 | 288.90 | 76.8 | -3.38 | -2.25 | 0.75 | -0.08 | -0.06 | 13.8 | SG |
| J224558.20-473207.0 | 2019.96100 | 5.04787 | 0.31 | 0.73 | 0.026 | 259.32 | 85.4 | 3.24 | 1.12 | 2.67 | 2.60 | 0.70 | 14.6 | SG |
| J150133.03-442524.3 | 1464.78415 | 4.65577 | 0.26 | 0.90 | 0.016 | 279.92 | 84.8 | 2.62 | 0.77 | 1.40 | -0.28 | -0.27 | 15.2 | SG |
| J175243.07-285138.2 | 2231.40177 | 3.79646 | 0.29 | 0.93 | 0.046 | 271.47 | 80.9 | 0.92 | -0.01 | 0.39 | 11.9 | 12.0 | MS |
| J180311.94+321113.9 | 2024.20196 | 3.70811 | 0.19 | 0.79 | 0.043 | 89.79 | 84.8 | 3.28 | 0.65 | 0.82 | 0.61 | -0.05 | 12.0 | MS |
| J093238.91-302546.4 | 2063.62600 | 3.39645 | 0.43 | 0.39 | 0.002 | 114.58 | 83.1 | 0.74 | 0.24 | 0.76 | 0.25 | 0.17 | 12.9 | MS |
| J071101.65+301928.8 | 2021.24827 | 2.77476 | 0.30 | 0.99 | 0.003 | 118.64 | 87.3 | 1.82 | 0.47 | 1.38 | 1.62 | 0.40 | 12.3 | MS |
| J090616.35-382316.0 | 2283.50335 | 2.02032 | 0.42 | 0.77 | 0.000 | 280.12 | 79.4 | 2.12 | 0.63 | 0.55 | 0.05 | 0.95 | 12.9 | MS |
| J083938.77-050614.1 | 622.35730 | 1.78501 | 0.38 | 0.96 | 0.058 | 87.92 | 89.1 | 3.40 | 0.90 | 1.31 | 0.33 | -0.14 | 15.3 | SG |
| J065612.80-291300.2 | 1422.41747 | 1.58379 | 0.59 | 0.59 | 0.000 | 98.24 | 72.9 | 1.52 | 0.51 | 2.53 | -0.33 | 0.30 | 13.9 | MS |
| J232812.76-395523.9 | 2015.02062 | 0.76870 | 0.44 | 0.63 | 0.000 | 358.90 | 80.7 | 2.64 | 0.28 | 0.87 | -0.44 | 0.23 | 13.2 | MS |
interpolate over MIST evolutionary tracks for masses 1–6 M⊙ to define this boundary. We set the maximum absolute magnitude limit for the subgiant/giant branch to be at M_G = 4.5 mag.

3 DISTRIBUTION OF ECLIPSING BINARY PARAMETERS

The distribution of the EB model parameters from the PHOEBE models can be used to explore both the intrinsic binary parameter distributions as well as selection effects in our sample. Table 1 gives model parameters for the 35,464 eclipsing binaries remaining after visual inspection. A selection of the light curve solutions are shown in Figure 7 and in Appendix A and Figure 8 shows their parameter distributions. The features of these distributions are combinations of probabilistic, systematic, and physical features.

3.1 Inclination and Argument of Periastron Distribution

The distribution of inclinations is peaked toward edge-on systems, and the lowest inclination systems are almost exclusively found at short periods and high p1 + p2. This is simply due to the eclipse probability scaling as \( \sim (p_1 + p_2)^{-2/3} \). Eccentric systems also tend to be more edge on because it is easier to miss one of the eclipses for inclined systems.

The distribution of the argument of periastron \( \omega \) has two peaks at 90° and 270°. For circular orbits where the phase separation of the eclipses is 0.5, the geometry estimator sets the argument of periastron to \( \omega = 90° \). While this parameter sometimes deviates from this initial value during optimization, usually flipping by 180°, it is poorly constrained unless the binary is significantly eccentric.

3.2 Eccentricity Distribution

Figure 9 shows the distribution of EB periods and eccentricities along with the SB9 catalog of spectroscopic orbits (Pourbaix et al. 2004) and the Zasche et al. (2021) catalog of eccentric eclipsing binaries for comparison. The extremely high eccentricity (e = 0.79) system identified in Way et al. (2021) is also labeled. We find that 83.0% of systems have eccentricities consistent with circular orbits (e < 0.05). The spread in eccentricity expands with increasing periods until \( \sim 10 \) d, after which few e > 0 systems are observed. The increasing absence of short period eccentric systems is due to tidal circularization (Verbunt & Phinney 1995).

Figure 9 shows the upper eccentricity envelope of

\[
e < E - A \exp\left(-\left(\frac{PB}{C}\right)^2\right)
\]

with \( E = 0.98, A = 3.25, B = 6.3, \) and \( C = 0.23 \) found by Mazeh (2008) for the SB9 catalog. Our parameters are generally consistent with this envelope, but some lie beyond this empirical model. We also show (very) hard upper limits for the eccentricities of binary twins of different spectral types using the eccentricity \( e = (1 - 2R_e/a) \) where the stars would be in contact at pericenter where \( a \) is the semi-major axis and values of \( M_e \) and \( R_e \) are taken from Pecaut & Mamajek (2013). Systems that fall above the Mazeh (2008) envelope are still consistent with the range of acceptable eccentricities for main sequence binaries of spectral type AOV.

In general, we expect to find fewer high eccentricity systems in eclipsing systems than in spectroscopic binaries because at a fixed period, the probability of detecting a second eclipse decreases with increasing eccentricity. When only the first eclipse is detected the system will tend to be modeled either as a system with \( T_{\text{eff,2}}/T_{\text{eff,1}} \sim 1 \) at half of the true period or with \( T_{\text{eff,2}}/T_{\text{eff,1}} \ll 1 \) at the correct period.
In total, we find 2,643 systems with $e > 0.1$, 560 systems with $e > 0.25$, and 66 systems with $e > 0.5$. Figure A3 shows examples of light curves with high eccentricity and Figure A4 shows examples of short period systems with non-zero eccentricities.

### 3.3 Period Distribution

Out of the 35,464 detached eclipsing binaries in our catalog after visual inspection, 35,307 are in Gaia EDR3 and 27,254 meet the quality cuts described in Section 2.6. Figure 10 shows the Gaia EDR3 extinction-corrected color magnitude diagram with systems colored by log($P$). A large fraction of long period systems are found for higher mass main sequence stars and evolved stars partly because shorter period systems increasingly cannot exist around these stars and because the detection probability for long period systems is smaller for lower mass, smaller radius stars.

The CMD suggests that there is a large population of subgiant primaries in the EB catalog. Using the MIST isochrone divisions of the CMD as described in Section 2.6, we identify 22,392 main sequence primaries, 4,213 subgiant primaries, and 649 giant primaries (Table 1). The full orbital period distribution contains contributions from short period systems with low mass primaries, early-type stars in longer period binaries, and giants in the longest-period systems. To better understand the period distribution, we divided the CMD into 13 absolute magnitude bins each containing ~2750 stars with parallax_over_error > 10 and $A_V < 2.0$ mag, and use MIST isochrones to separate the main sequence stars from the subgiants and giants as described in Section §2.6. Figure 11 shows the orbital period distribution for each magnitude bin.

The bottom panel of Figure 11 shows the eclipse probability for twin main sequence binaries of mass $M$ and radius $R$,

$$P = 2R \left( \frac{2GM}{4\pi^2} \right)^{-1/3} P^{-2/3}.$$  

(3)
To determine $M$ and $R$ for each $M_G$ bin, we use a grid of Solar-metallicity evolutionary tracks from MIST and integrate over the main sequence lifetime to get the average $M_G$ and $R$. We then interpolate the relations between $M_G$–$M$ and $M_G$–$R$ to solve for the typical stellar parameters of the $M_G$ bin. As before, we double the Gaia $G$-band flux to consider equal mass binaries.

The vertical lines in Figure 11 show the period, corresponding to the Roche radius where $f$ is the Roche-lobe filling factor and

$$E(q) = \frac{0.49 q^{-2/3}}{0.6 q^{-2/3} + \ln(1 + q^{-1/3})},$$

is the Eggleton (1983) approximation for the scaling with mass ratio $q$. We compute these periods for binaries of equal mass, taking $M$ and $R$ from MIST evolutionary tracks, as before. When moving to fainter magnitude bins, the distribution of orbital periods moves to shorter periods, reflecting the lower detection probability for low-mass stars in long-period orbits and the minimum period required.
for a detached system at the high mass end. As expected, systems with subgiant/giant primaries are found at larger orbital periods than main sequence primaries of similar absolute magnitude $M_G$.

### 3.4 Effective Temperatures and Fractional Radii

There are three features in the $T_{\text{eff},2}/T_{\text{eff},1}$ and $\rho_1 + \rho_2$ distributions. The linear feature at $T_{\text{eff},2}/T_{\text{eff},1} = 0.5$ is a modeling artifact from systems with no detectable secondary eclipse. The rest of the systems form two distinct groups. One group is concentrated at roughly equal temperatures and smaller fractional radii, while the second group has larger temperature differences and larger fractional radii. The second group has shorter periods, which is not surprising given the larger temperature differences.

Figure 13 shows an expanded view of this distribution with the systems that fall in the linear feature at $T_{\text{eff},2}/T_{\text{eff},1} = 0.5$ removed.

$$T_{\text{eff},2}/T_{\text{eff},1} = 0.4(\rho_1 + \rho_2) + 0.55$$

(6)

roughly separates the two populations and we label systems that fall above and below the line as Groups I and II, respectively. The light curves in Group I are "classical" detached binaries, while the Group II light curves resemble semidetached systems with more curved out-of-eclipse shapes. Examples of Group II light curves are shown in Figure A7.

Figure 10 shows the EBs on a Gaia CMD colored by $T_{\text{eff},2}/T_{\text{eff},1}$. Systems with lower $T_{\text{eff},2}/T_{\text{eff},1}$ are preferentially found on the upper main sequence and below the isochrones corresponding to the equal mass binaries. This is seen more clearly in Figure 12 where we show the distribution of $T_{\text{eff},2}/T_{\text{eff},1}$ in different $M_G$ bins after removing systems with $T_{\text{eff},2}/T_{\text{eff},1} > 0.5$. The broad Gaussian feature corresponding to the low $T_{\text{eff},2}/T_{\text{eff},1}$ Group II systems decreases moving down the CMD, more rapidly for the evolved stars than the main sequence stars, and disappears entirely by $M_G \sim 3.5$ mag. Lower main sequence stars span a broad range of luminosities but a limited range of temperatures, so lower main sequence stars with the temperature ratios of Group II will have large differences in luminosity and size, making it difficult to detect eclipses. And, at the very bottom of the MS, it is simply not possible to have a companion with half the temperature of the primary.

We can investigate the likely properties of the stars by taking pairs of stars from MIST isochrones with primary masses of $M_1 = 0.5M_\odot$ to $8.0M_\odot$ and secondary masses $M_2 = 0.5M_\odot$ to $M_1$ and keeping all pairings that match the extinction-corrected Gaia $M_G$ magnitude and $G_\text{BP} - G_\text{RP}$ color of the binary to 0.1 and 0.01 mag, respectively. From each of these pairings we find the one that minimizes

$$\chi^2 = (T_{\text{eff},2}/T_{\text{eff},1} - (T_{\text{eff},2}/T_{\text{eff},1})_{\text{model}})^2 + (\rho_1 + \rho_2 - (\rho_1 + \rho_2)_{\text{model}})^2.$$  

(7)

Figure 14 shows the results for the 5 Group II systems shown in Figure A7. Each seems to pair an upper main sequence star with a low-mass dwarf.

Finally, Figure 15 shows the distribution of periods, inclinations, and eccentricities for Group I and II systems. Very few of the Group II systems are eccentric, so they must be sufficiently compact to be tidally circularized. More curiously, we find a dearth of edge-on Group II systems. With finite errors on the inclination estimate, we expect the distribution to drop as the inclination approaches edge-on, as seen for the Group I systems. However, the Group II distribution is already falling by $75^\circ$. The lack of high-inclination Group II systems could be due to the competing effects of inclination and $T_{\text{eff},1}$ in determining the eclipse depth. In standard detached eclipsing binaries it is the ratio of the temperatures, not the absolute temperatures.
that dictates the eclipse depth. However, the ellipsoidal variations observed in Group II light curves are dependent on the temperature-dependent limb-darkening parameters. As a result of fixing the primary effective temperature in Section 2.4, the inclination distribution may be artificially skewed to lower inclinations. In addition, it is also possible that the high-inclination semi-detached systems were classified as semidetached rather than detached in Jayasinghe et al. (2019) and thus were not included in our catalog.

Although the individual fractional radii are poorly constrained for most systems except for total eclipses and eccentric orbits, and we only give the sum of the fractional radii for the PHOEBE model solutions in Table 1, we show the fractional radii for each component in Figure 16. As expected, the distribution is skewed to the left.
boundary because we examined only detached systems. We find that there are two populations along the boundary, near $\rho_1 \sim 0.15$ and $\rho_1 \sim 0.25$. A similar distribution was observed by Devor (2005, Fig. 10), who suggested that the clustering is due to the systems in the lower $\rho_1$ cluster having their periods erroneously doubled. While it is unlikely that so many systems had inaccurate periods after visual inspection, we inspected ~500 TESS light curves for targets in the smaller $\rho_1$ cluster and confirm that all the periods were correct. We find that the smaller $\rho_1$ cluster consists of Group I systems from the left peak of the $\rho_1 + \rho_2$ distribution (Figure 13). The 4,481 systems in the highlighted upper cluster in Figure 16 are evenly divided between Group I and Group II systems.

Figure 11. Distribution of orbital periods for different absolute magnitude bins ordered from brightest to faintest magnitude bin from left to right then top to bottom. The solid blue histograms show the main sequence primaries selected using the MIST isochrones and the gray histograms show the subgiant/red giant systems. The absolute magnitude $M_G$ range, number of main sequence primaries, $N_{MG}$, number of subgiant+red giant primaries, $N_{SG} + N_{RG}$, and main sequence mass $M$ are included for each magnitude bin. The dashed vertical lines show the periods where equal mass binaries have a ratio $f = R/R_{Roche}$ between the stellar and Roche radii. Finally, the purple line in the faintest magnitude bin shows the $P^{-2/3}$ eclipse probability for main sequence stars (Equation 3).
3.5 High Energy Emission

High energy emission produced from chromospheric or coronal activity is closely related to stellar rotation and magnetic fields (Walter & Bowyer 1981; Dobson & Radick 1989; Pizzolato et al. 2003). Eclipsing binaries with high energy emission can be used to model spot activity in greater detail than for single stars (e.g., Lanza et al. 1998) and to study the connection between orbital period modulations and magnetic fields (Applegate 1992). Strong stellar winds can also lead to X-ray emission through wind accretion (e.g., Linder et al. 2009). By combining the ASAS catalog of eclipsing binaries (Pojmanski & Maciejewski 2005) with the ROSAT All-Sky Survey (Voges et al. 1999), Szczepicki et al. (2008) and Kiraga (2012) identified 836 and 347 systems, respectively, with evidence of coronal or chromospheric activity.

We follow a similar procedure and match our catalog of detached eclipsing binaries to the HEASARC Master X-ray cata-
We use this model to roughly divide the systems into Group I (high $T_{\text{eff}, 2}/T_{\text{eff}, 1}$) and Group II (low $T_{\text{eff}, 2}/T_{\text{eff}, 1}$) using the red line defined in Equation 6.

4 CONCLUSIONS

We present a catalog of detached eclipsing binary parameters for 35,464 ASAS-SN eclipsing binaries. After refining the ASAS-SN $V$-band period from Jayasinghe et al. (2019) with the $g$-band data, we use PHOEBE to model the ASAS-SN data to determine the sum of fractional radii, ratio of effective temperatures, inclination, and eccentricity. We visually inspect all 40,728 light curve solutions, and select 35,464 solutions for our final catalog. As a part of visual inspection, we use the TESS light curves from the SPOC (Caldwell et al. 2020) and QLP pipelines (Huang et al. 2020a,b; Kunimoto et al. 2021) to validate the orbital period results. We identify a range of physically interesting features in the parameter distributions:

- The eccentricity distribution expands with increasing period, and we identify 66 systems with $e > 0.5$. High eccentricity systems are, in general, less detectable as eclipsing binaries than as spectroscopic binaries due to selection effects at longer periods.

1 https://heasarc.gsfc.nasa.gov/W3Browse/all/xray.html
Table 2. X-ray detections of detached EBs from Table 1. The X-ray luminosity is calculated using the observed flux and Gaia EDR3 parallax. The column density $N_\text{H}$ is calculated using the median extinction and dust-to-gas ratio from Dai & Kochanek (2009). For targets detected by multiple observatories, we include the observation corresponding to the greatest exposure time. The full table is available online.

| ASAS-SN Name                              | $P$ (d) | Observatory | Distance (pc) | $L_X$ (erg/s) | $N_\text{H}$ (cm$^{-2}$) | Separation (") | Reference                  |
|-------------------------------------------|--------|-------------|---------------|--------------|-------------------------|----------------|---------------------------|
| J000225.41+701848.3                       | 0.52   | XMM-NEWTON  | 690.0         | $3.0 \times 10^{30}$ | $2.7 \times 10^{21}$ | 2.22           | Webb et al. (2020)        |
| J001856.11-795455.6                       | 0.90   | XMM-NEWTON  | 324.0         | $7.5 \times 10^{30}$ | $3.1 \times 10^{20}$ | 1.46           | Webb et al. (2020)        |
| J002148.55+205512.2                       | 1.14   | SWIFT       | 2309.0        | $4.1 \times 10^{31}$ | $4.6 \times 10^{20}$ | 0.71           | Dai et al. (2015)         |
| J002415.10+603501.1                       | 0.55   | ROSAT       | 147.0         | $7.1 \times 10^{30}$ |               | 7.16           | Boller et al. (2016)      |
| J002717.28-233642.5                       | 1.53   | SWIFT       | 572.0         | $4.6 \times 10^{30}$ |               | 2.05           | Evans et al. (2020)       |
| J003328.72+423331.1                       | 0.78   | XMM-NEWTON  | 651.0         | $4.7 \times 10^{30}$ | $2.9 \times 10^{20}$ | 0.26           | Traulsen et al. (2020)    |
| J003338.67+392024.0                       | 3.33   | XMM-NEWTON  | 676.0         | $1.5 \times 10^{30}$ | $2.3 \times 10^{20}$ | 1.05           | Traulsen et al. (2020)    |
| J003827.07+410330.2                       | 6.28   | XMM-NEWTON  | 1532.0        | $7.7 \times 10^{30}$ | $4.0 \times 10^{20}$ | 1.01           | Traulsen et al. (2020)    |
| J003905.81+791911.4                       | 1.23   | ROSAT       | 150.0         | $2.5 \times 10^{31}$ |               | 6.31           | Boller et al. (2016)      |
| J004138.67+403215.7                       | 2.22   | XMM-NEWTON  | 1203.0        | $3.7 \times 10^{30}$ | $3.5 \times 10^{20}$ | 1.72           | Traulsen et al. (2020)    |
| J004409.05-731418.6                       | 6.05   | XMM-NEWTON  | 13135.0       | $4.2 \times 10^{32}$ | $2.5 \times 10^{21}$ | 9.41           | Traulsen et al. (2020)    |
| J004549.34-013020.6                       | 1.96   | SWIFT       | 2099.0        | $7.1 \times 10^{31}$ | $2.9 \times 10^{20}$ | 2.26           | Evans et al. (2020)       |
| J004515.37+412523.6                       | 1.57   | XMM-NEWTON  | 2187.0        | $1.2 \times 10^{31}$ | $6.3 \times 10^{20}$ | 0.45           | Traulsen et al. (2020)    |
| J004923.13+320036.5                       | 1.59   | CHANDRA     | 1218.0        | $1.7 \times 10^{30}$ | $5.2 \times 10^{20}$ | 0.11           | Evans et al. (2010)       |
| J005146.51-715953.5                       | 0.87   | XMM-NEWTON  |               |              |              | 0.61           | Traulsen et al. (2020)    |

Figure 14. We combine the extinction-corrected Gaia magnitudes, the fit light curve parameters, and MIST evolutionary tracks to estimate the properties of the components of example Group II binary systems. Each binary system is represented by a pair of points, one for each component, connected by a line of the same color. The black line shows a single-star isochrone. The light curves for these systems are shown in Figure A7.

- The period distribution varies with absolute magnitude, reflecting the physical limits and detectability of stars of different radii in detached systems. We use the Gaia CMD to identify systems with subgiant and giant components.
- The $T_{\text{eff,2}}/T_{\text{eff,1}}$ and $\rho_1 + \rho_2$ populations are both bimodal. The low $T_{\text{eff,2}}/T_{\text{eff,1}}$ Group II component is associated with larger $\rho_1 + \rho_2$. The Group II systems tend to be more luminous and have light curves that begin to look more like semidetached binaries while the Group

Figure 15. Distributions of log $P$, inclination, and eccentricity for EBs in Group I (black histograms), Group II (colored histograms). We find that Group II EBs are typically at shorter periods, lower inclinations, and are in more circular orbits.
Fractional radii for each component of the eclipsing binary where $\rho_1$ is defined to be the larger component. The dashed lines indicate the detached limit where $\rho_1 = \rho_2$ (left) and the contact limit where $\rho_1 + \rho_2 = 1$ (right). The solid black lines show contours of the distribution, and we find two populations near the detached limit, centered $\rho_1 \sim 0.15$ and $\rho_1 \sim 0.25$ (highlighted contours).

I systems are clearly detached systems. The Group II systems also show a deficit of edge on inclinations, which could be explained if the high inclination Group II systems were classified as semidetached or be a systematic effect from the fixed primary temperature.

- While the individual fractional radii are not well constrained, there are two clear peaks in the distribution of the systems in the $\rho_1$-$\rho_2$ plane. This was noticed by Devor (2005) who suggested it was due to period confusion. Our visual inspection of the TESS light curves shows that this is not the case.

Finally, we match the catalog of detached EBs with X-ray catalogs to identify 795 systems with evidence of chromospheric or coronal activity that may be of interest for followup. We also identify 782 systems with more physically complicated TESS light curves that will be the focus of a subsequent paper. The binaries included in this catalog span a wide range of stellar parameter space for periods ranging from a less than a day to more than 100 days. Interesting subsets of the binaries include short period eccentric systems and systems with subgiant and giant primaries that can easily be identified for detailed study.

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DATA AVAILABILITY

The ASAS-SN photometric data underlying this article are available in the ASAS-SN eclipsing binaries database (https://asas-sn.osu.edu/binaries) and the ASAS-SN Photometry Database (https://asas-sn.osu.edu/photometry). The data underlying this article are available in the article and in its online supplementary material.
APPENDIX A: SELECTED LIGHT CURVE FITS

All light curve fits from in Table 1 will be included in the ASAS-SN Variable Stars Database. Here we show subsets of light curves that may be of particular interest for followup. Figure A1 shows some of the shortest period EBs in the catalog. Although some of these could be classified as semi-detached, we only removed obvious contact systems during visual inspection. Figure A2 shows the longest period EBs. Figure A3 shows systems with high eccentricity, and Figure A4 shows short period systems with non-zero eccentricity. Figure A5 shows systems with deep primary eclipses and Figure A6 shows binaries with low luminosity $G$-band magnitudes. The light curves for these targets in Figures A1 to A6 are shown on a Gaia CMD in Figure A10.

In Section 3.4 we identified two groups in the $\rho_1 + \rho_2$ and $T_{\text{eff,2}}/T_{\text{eff,1}}$ parameter space. Figure A7 shows examples for Group II systems that resemble semidetached binary light curves.

During visual inspection we removed 3,161 systems classified as EAs in Jayasinghe et al. (2021) from the catalog. Figure A8 shows examples of the types of systems removed as well as their classification probabilities, $P_{\text{class}}$, from Jayasinghe et al. (2019).

Finally, during visual inspection we identified 782 systems as potentially having spots, evidence of mass transfer, or potential third bodies. Many of these systems were identified through visual inspection of the TESS light curves. Figure A9 shows the ASAS-SN $g$-band and TESS $T$-band light curves four examples of systems with more complex light curves.

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Figure A1. Examples of the shortest period binaries and their models. The phase range of $-0.25$ to $+0.75$ is used to clearly show both eclipses.
Figure A2. Same as Figure A1, but for some of the longest period variables.

Figure A3. Same as Figure A1, but for high eccentricity systems.
Figure A4. Same as Figure A1 but for EBs with short periods and high eccentricities.

Figure A5. Same as Figure A1 but for EBs with deep primary eclipses.
Figure A6. Same as Figure A1 but for low-luminosity EBs. The absolute Gaia $G$-band magnitude corrected for extinction is given in the upper right of each panel.

Figure A7. Same as Figure A1 but for Group II EBs identified in Section 3.4.
Figure A8. Examples of targets rejected during visual inspection. From top to bottom, the light curves show an RR Lyrae, a contact binary, a non-variable target, a EB with a near 3 day period and poor phase sampling, and a faint target. The period, classification probability $P_{\text{class}}$, and median $g$-band magnitude are labeled in each panel.
Figure A9. Examples of targets with extra physics identified during visual inspection. We show the ASAS-SN $g$-band and TESS $T$-band light curves from the QLP pipeline (Huang et al. 2020a,b; Kunimoto et al. 2021). Panel (a) may be an eclipsing cataclysmic variable (e.g., Feline et al. 2004). The system in panel (b) is a quadruple system (V0849 Aur) with a near 3:2 period ratio (Cagaš & Pejcha 2012). The system in panel (c) shows rapid changes in shape likely due to spot modulation. Finally, the system in panel (d) shows evidence of additional pulsations, but the ATLAS REFCAT 2 catalog (Tonry et al. 2018) suggests there are multiple nearby sources, so this could be an example of a blend.
Figure A10. PHOEBE model fits for the systems shown in Figures figs. A1 to A6 and A9 on a Gaia CMD colored by log $P$. For the extra physics targets from Figure A9, the median filtered TESS light curve is shown instead of the PHOEBE fit.