ECLIPSING BINARY STARS AS BENCHMARKS FOR TRIGONOMETRIC PARALLAXES IN THE GAIA ERA

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ABSTRACT

We present fits to the broadband photometric spectral energy distributions (SEDs) of 158 eclipsing binaries (EBs) in the Tycho-2 catalog. These EBs were selected because they have highly precise stellar radii, effective temperatures, and in many cases metallicities previously determined in the literature, and thus have bolometric luminosities that are typically good to \( \lesssim 10\% \). In most cases the available broadband photometry spans a wavelength range 0.4–10 \( \mu \)m, and in many cases spans 0.15–22 \( \mu \)m. The resulting SED fits, which have only extinction as a free parameter, provide a virtually model-independent measure of the bolometric flux at Earth. The SED fits are satisfactory for 156 of the EBs, for which we achieve typical precisions of 1–2%.

Combined with the accurately known bolometric luminosity, the result for each EB is a predicted parallax that is typically precise to \( \lesssim 5\% \). These predicted parallaxes—with typical uncertainties of 200 as—are 4–5 times more precise than those determined by Hipparcos for 99 of the EBs in our sample, with which we find excellent agreement. There is no evidence among this sample for significant systematic errors in the Hipparcos parallaxes of the sort that notoriously afflicted the Pleiades measurement. The EBs are distributed over the entire sky, span more than 10 mag in brightness, reach distances of more than 5 kpc, and in many cases our predicted parallaxes should also be more precise than those expected from the Gaia first data release. The EBs studied here can thus serve as empirical, independent benchmarks for these upcoming fundamental parallax measurements.

Key words: binaries: eclipsing — catalogs: Gaia — observational — parallaxes: stars: distances

Supporting material: figure set, machine-readable tables

1. INTRODUCTION

There is arguably no astronomical measurement more fundamental than distance from trigonometric parallax. Such parallax measurements are foundational to the cosmic distance scale generally and to stellar astrophysics specifically, including our basic understanding of stellar evolution, stellar populations, and Galactic structure. Thus, the parallaxes provided by the Hipparcos mission (Perryman et al. 1997; van Leeuwen 2007) have had important, unrivaled impact across many areas of study for the past 20 years.

Yet the Hipparcos parallaxes were not without problems, perhaps the most significant of which was the aberrant distance to the Pleiades which the Hipparcos parallax placed at 120.2 ± 1.9 pc (van Leeuwen 2009) as compared to the broadly accepted distance of \( \approx 135 \) pc from a variety of methods (e.g., Munari et al. 2004; Zwahlen et al. 2004; Soderblom et al. 2005; Groenewegen et al. 2007; Melis et al. 2014; Mädler et al. 2016, and others cited therein). Several of these recent determinations are formally highly precise (\( \sigma = 1.2–1.7 \) pc). The discrepancy in the Hipparcos distance for the Pleiades was identified almost immediately (e.g., Pinsonneault et al. 1998; Soderblom et al. 1998), thanks to the unusual combination of proximity and cluster richness afforded by the Pleiades. In general, however, heretofore there have been very few fundamental benchmarks against which to test the Hipparcos parallaxes across the sky, across various stellar environments, and across stellar parameter space. One notable example is the use of spatially resolved double-lined spectroscopic binaries, which can yield highly accurate and precise orbital parallaxes (see, e.g., Tomkin 2005).

Eclipsing binary (EB) stars have long served as fundamental benchmarks for stellar astrophysics. Through analysis of the light curve and radial velocities, EBs yield direct measurement of the component stellar masses and radii, and temperatures, with accuracies of \( \sim 1\% \) for the best cases. As a result, the bolometric luminosity (\( L_{\text{bol}} \)) of an EB can be determined to very high precision and—importantly—without need of a distance measurement because it depends only on the measured radii and effective temperatures.

EBs with such accurately determined \( L_{\text{bol}} \) can therefore serve as empirical, independent benchmarks for stellar distances obtained by other methods such as trigonometric parallax, if the bolometric flux at Earth (\( F_{\text{bol}} \)) can also be measured empirically and with sufficient precision. For example, in the recent analysis of newly discovered Pleiades EBs in the K2 (successor to Kepler) mission data, David et al. (2016) used the available broadband photometry from GALEX ultraviolet (UV) bands through WISE mid-infrared (mid-IR) bands to determine an empirical distance of \( 132 \pm 5 \) pc to the Pleiades EB HCG 76, consistent with the consensus distance and again showing the Hipparcos distance to be biased. Impressively, this new empirical EB-based distance has a precision of better than 4%, significantly more precise than the 12% discrepancy in the Hipparcos distance, making it useful as a meaningful benchmark.

Variants of this idea have been used to determine distances to EBs in the near field (relying on bolometric corrections) and even in external galaxies such as M31, the Large Magellanic Cloud (LMC) or the Small Magellanic Cloud (SMC) (e.g., Ribas et al. 2005; Pietrzyński et al. 2009; Graff et al. 2014), sometimes based on application of surface brightness relations. These latter EB studies and others like them have been...
extremely important in establishing the lower rungs of the cosmological distance ladder, serving as calibrators for other methods reaching larger distances.

The upcoming \textit{Gaia} mission holds great promise for many areas of stellar and Galactic astrophysics through the provision of fundamental trigonometric parallax measurements for \( \sim 10^5 \) stars. At the same time, there now exists a large sample of benchmark-grade EBs with accurate radii and temperatures, and in many cases metallicities, which provide accurate and distance-independent \( L_{bol} \). In addition, there now exist all-sky, broadband photometric measurements for stars spanning a very broad range of wavelengths, from the \textit{GALEX} far-UV at \( \sim 0.1 \mu m \) to the \textit{WISE} mid-IR at \( \sim 22 \mu m \). These measurements permit construction of spectral energy distributions (SEDs) that effectively sample the majority of the flux for all but the hottest stars. Consequently the bolometric fluxes, and in turn the distances to the EBs, can in principle be determined in a largely empirical manner that preserves the accuracy of the fundamental EB parameters.

In this paper, we use available broadband photometry to construct empirical SEDs and to calculate \( F_{bol} \) for 158 EBs in the Tycho-2 catalog whose fundamental physical properties have previously been established with accuracies better than 3\% (e.g., Torres et al. 2010). The wavelength coverage of the SEDs for most of the EBs in our sample is sufficiently large that the resulting \( F_{bol} \) are typically precise to 3\%, leading to predicted parallaxes that are in most cases precise to better than 5\%. For 99 of the EBs in our study sample, previous \textit{Hipparcos} parallaxes are available for direct comparison to the parallaxes predicted from the EBs.

In Section 2, we present our study sample, the data that we use from the literature, and our SED fitting procedures. The main results of the work, including empirical \( F_{bol} \) and predicted parallaxes for the full sample, and a comparison to \textit{Hipparcos} parallaxes where available, are presented in Section 3. In Section 4 we briefly discuss the upcoming applicability of this work to \textit{Gaia}, which is expected to include all of these EBs as early as its first public data release. We summarize our conclusions in Section 5.

\section{DATA AND METHODS}

\textbf{2.1. Benchmark EB Study Sample}

For this work we have focused on detached EBs with well determined radii and effective temperatures, to allow the derivation of bolometric luminosities of the highest precision. We set a threshold of 3\% for the uncertainties in the absolute radii, although a handful of our objects were allowed to exceed this limit slightly, as described below. More than half of the sample was drawn directly from the compilation by Torres et al. (2010), featuring binaries that have been carefully vetted with special attention paid to the number and quality of the observations, the consistency of the light curve and radial-velocity curve solutions and other details of the analysis, external checks, and efforts to assess and control systematic errors. Additional systems were gathered from the more recent (or sometimes earlier) literature including Stassun et al. (2014) and the DEBCAT list\(^4\) maintained by Southworth (2015), though some have not necessarily received the same level of vetting beyond the requirement of 3\% or better formal uncertainties in the radii. While we have attempted to capture the most relevant systems for our study, our search was not intended to be exhaustive so we make no claims of completeness. All EBs were required to have entries in the Tycho-2 catalog (Hög et al. 2000), and many are contained also in the \textit{Hipparcos} catalog.

Spectral types in our sample span a very wide range from late O to mid M. Most are main-sequence stars, but a few are giants. The challenges involved in analyzing the spectroscopic and photometric observations of these binaries vary greatly depending on the nature of the system, and in some cases unrecognized systematic errors or other problems may not be fully reflected in the formal errors we have adopted. It is also important to note that the temperature estimates are much less fundamental in nature than the radius estimates. This is largely because temperatures often rely on external calibrations, and have been derived in many different ways by different authors. While a light curve typically contains very precise information about the ratio between the primary and secondary temperatures, the value for the primary that sets the absolute scale for the system must generally be determined independently. This is sometimes done from an analysis of disentangled spectra, from color indices, or even simply from its spectral classification. The radii, on the other hand, are always based purely on geometry and dynamics. It is not surprising, therefore, that the temperature uncertainties in our sample can be as large as 10\% in some cases.

Small departures from spherical star shapes for most of the binaries in our sample, or even moderate departures for the closest ones, along with associated limb-darkening, reflection, tidal/rotational, and other effects, are assumed to have been adequately accounted for in the light-curve modeling, as suggested by the typically good agreement these systems show when compared against stellar evolution models in the original publications. In particular, the stellar sizes we have adopted are the volumetric radii, as published.

The complete list of 158 EBs for this study is given in Table 1, sorted by Tycho number. We have made an effort to collect available estimates of the interstellar reddening for these systems, as well as spectroscopic or photometric measures of the metallicity, both of which can serve to constrain the SED fits described later. A number of the binary components have been found to be metallic-line A or F stars and are so noted in the table, with estimates of the iron abundances given when available. Four of our EBs belong to open clusters for which the \textit{Hipparcos} mission has provided highly precise average parallaxes based on individual measurements for half a dozen or more members (van Leeuwen 2009). They are V906 Sco (in NGC 6475), GV Car (NGC 3532), V392 Car (NGC 2516), and TX Cnc (Praesepe). The first also has an individual \textit{Hipparcos} parallax. GV Car and TX Cnc have somewhat poorer radius and/or temperature determinations than the rest (and are only preliminary in the first case), but they were included to enable a check on the \textit{Hipparcos} cluster distances. TX Cnc is an over-contact (W UMa) system rather than a detached one, though this should not affect its usefulness for distance determinations (see, e.g., Wilson et al. 2010).

\textbf{2.2. Broadband Photometric Data from the Literature}

The 158 EBs that comprise our study sample are, by virtue of having previously determined EB solutions and being in the Tycho-2 catalog, relatively bright and well studied. Therefore,
in most cases the EBs appear in many published photometric catalogs. In order to systematize and simplify our procedures, we opted to assemble for each EB the available broadband photometry from only the following large, all-sky catalogs (listed here in approximate order by wavelength coverage) via the VizieR\(^\text{\textregistered}\) query service:

1. **GALEX** All-sky Imaging Survey (AIS): FUV and NUV at
   \(\approx 0.15\) \(\mu\)m and \(\approx 0.22\) \(\mu\)m, respectively.
2. Catalog of Homogeneous Means in the **UBV** System for bright stars from Mermilliod (2006): Johnson UBV bands
   \(\approx 0.35–0.55\) \(\mu\)m.
3. **Tycho-2**: Tycho B (\(B_T\)) and Tycho V (\(V_T\)) bands
   \(\approx 0.42\) \(\mu\)m and \(\approx 0.54\) \(\mu\)m, respectively.
4. Strömgren Photometric Catalog by Paunzen (2015): Strömgren \(uvby\) bands \(\approx 0.34–0.55\) \(\mu\)m.
5. **AAVSO** Photometric All-Sky Survey (APASS) DR6
   (obtained from the UCAC-4 catalog): Johnson BV and
   SDSS gri bands \(\approx 0.45–0.75\) \(\mu\)m.
6. Two-Micron All-Sky Survey (2MASS): JHK\(_S\) bands
   \(\approx 1.2–2.2\) \(\mu\)m.
7. **WISE**: WISE1-4 bands \(\approx 3.5–22\) \(\mu\)m.

We found \(B_T\), \(V_T\), JHK\(_S\), and WISE1-3 photometry—spanning a wavelength range \(\approx 0.4–10\) \(\mu\)m—for nearly all of the EBs in our study sample. Most of the EBs also have WISE4 photometry, and many of the EBs also have Strömgren and/or GALEX photometry, thus extending the wavelength coverage to \(\approx 0.15–22\) \(\mu\)m. We adopted the reported measurement uncertainties unless they were less than 0.01 mag, in which case we assumed an uncertainty of 0.01 mag. In addition, to account for an artifact in the Kurucz atmospheres at 10 \(\mu\)m, we artificially inflated the WISE\(_3\) uncertainty to 0.1 mag unless the reported uncertainty was already larger than 0.1 mag.

Although the likelihood is small, it is always possible that some of these brightness measurements were obtained during an eclipse, in which case they would underestimate the total flux of the system. However, most of the catalogs listed above report averages of multi-epoch observations, from as many as 100 or more individual measurements taken over three years in the case of Tycho-2, so they are less likely to be affected. Single-epoch measurements such as those in the 2MASS catalog, on the other hand, are more susceptible to this problem. We found eleven systems in which the 2MASS measurements were clearly obtained in eclipse, and in those cases we applied adjustments by referring back to the original optical light curves at the exact phase of the observation, with small corrections from the optical to the near-infrared for binaries with unequal component temperatures, or corrections for third light if significant. The adjustments in JHK\(_S\) range from about 0.25 to 0.68 mag. The assembled SEDs are presented in Appendix A.

2.3. **SED Fitting**

The observed SEDs were fitted with standard stellar atmosphere models. For the EBs in our sample with \(T_{\text{eff}} > 4000\) K (all but two EBs), we adopted the atmospheres of Kurucz (2013), whereas for the two EBs with \(T_{\text{eff}} < 4000\) K
Table 2

| System      | Tycho ID  | V         | CH2      | Fbol     | Av       | Distance   | Parallax   |
|-------------|-----------|-----------|----------|----------|----------|------------|------------|
| UV Psc      | 0026-0577-1 | 9.01     | 2.72     | 7.748e-09 ± (3.4e-10/3.2e-10) | 0.01 ± (0.00/0.01) | 80.2 ± (3.6/3.5) | 12.47 ± (0.57/0.53) |
| XY Cet      | 0051-0832-1 | 8.75     | 1.60     | 9.072e-09 ± (3.3e-10/3.2e-10) | 0.11 ± (0.07/0.05) | 76.5 ± (10.2/10.7) | 3.62 ± (0.14/0.13) |
| V1130 Tau   | 0066-1108-1 | 6.66     | 1.34     | 6.202e-08 ± (1.4e-09/1.7e-09) | 0.03 ± (0.00/0.02) | 69.7 ± (1.9/1.7) | 14.35 ± (0.36/0.37) |
| EW Ori      | 0104-1206-1 | 9.78     | 0.71     | 2.945e-09 ± (6.3e-11/6.1e-11) | 0.02 ± (0.02/0.00) | 169.6 ± (6.3/6.1) | 5.90 ± (0.22/0.21) |
| V578 Mon    | 0154-2528-1 | 8.55     | 0.65     | 4.922e-07 ± (1.3e-08/1.1e-08) | 1.37 ± (0.02/0.02) | 1327.2 ± (71.9/70.9) | 0.75 ± (0.04/0.04) |
| Al Hya      | 0196-0626-1 | 9.35     | 7.02     | 4.826e-09 ± (3.1e-10/2.9e-10) | 0.21 ± (0.03/0.00) | 548.4 ± (20.5/19.6) | 1.82 ± (0.07/0.07) |
| FM Leo      | 0263-0727-1 | 8.45     | 3.49     | 1.175e-08 ± (5.3e-10/5.0e-10) | 0.11 ± (0.02/0.00) | 1372 ± (11.7/11.1) | 7.29 ± (0.64/0.57) |
| AQ Ser      | 0340-0588-1 | 10.65    | 1.89     | 1.576e-09 ± (3.6e-11/3.2e-11) | 0.12 ± (0.00/0.01) | 583.2 ± (20.0/20.0) | 1.71 ± (0.06/0.06) |
| V335 Ser    | 0353-0301-1 | 7.49     | 1.99     | 3.495e-08 ± (7.5e-10/1.2e-09) | 0.23 ± (0.00/0.03) | 188.2 ± (7.9/6.8) | 5.31 ± (0.20/0.21) |
| U Oph       | 0400-1862-1 | 5.90     | 1.15     | 7.968e-07 ± (1.4e-08/3.1e-08) | 0.73 ± (0.00/0.04) | 229.7 ± (9.1/6.9) | 4.35 ± (0.14/0.17) |

Note.
* Systems flagged with an asterisk have $T_{\text{eff}} > 15,000$ K and a large fraction of their flux extrapolated from a blackbody distribution on the blue side. Those marked with an “X” are considered to have poor SED fits.

(CU Cnc and YY Gem) we adopted the NextGen atmospheres of Hauschildt et al. (1999). The model atmosphere grids are parametrized by $T_{\text{eff}}$, log g, and [Fe/H], in steps of approximately 100 K, 0.5 dex, and 0.1 dex, respectively.

As summarized in Table 1, for each star in each EB we have $T_{\text{eff}}$ and radius (with the masses listed in the original publications, the radius also gives log g), and in many cases [Fe/H] as well (we assume [Fe/H] = +0.2 for the Am-type stars, solar metallicity otherwise). We interpolated in the model grid to obtain the appropriate model atmosphere for each star in units of emergent flux, and then summed the two model atmospheres scaled by the stars’ surface areas to produce the total SED model for the EB. To redden the SED model, we adopted the interstellar extinction law of Cardelli et al. (1989). We then fitted the summed atmosphere model to the flux measurements to minimize $\chi^2$ by varying just two fit parameters: extinction ($A_V$) and overall normalization. (The adopted stellar radii and $T_{\text{eff}}$ also have associated uncertainties, of course; these are handled in a later step via the propagation of errors through $L_{\text{bol}}$; see Section 3.2.) Where an $A_V$ estimate was available from the literature, we adopted it as an initial guess but allowed the fit to vary $A_V$ by as much as $3\sigma$ or 20%, whichever was larger. Where no prior $A_V$ estimate was available, the $A_V$ fit was unconstrained except that we limited the maximum value to that from the Schlegel et al. (1998) dust maps for the given line of sight.

The best-fit model SED with extinction is shown for each EB in Appendix A, and the reduced $\chi^2$ values ($\chi^2_r$) are given in Table 2. The fits were satisfactory in 156 cases, leaving two EBs with very large $\chi^2_r$ flagged in Table 2. We were not able to discern the cause of the very poor fits in these two cases—we rechecked that the stellar radii and $T_{\text{eff}}$ from the original publications appear reliable and that the photometric measurements are not flagged as bad. Thus we simply discarded these two cases for the remainder of our analyses.

The primary quantity of interest for each EB is $F_{\text{bol}}$, which we obtained via direct summation of the fitted SED, without extinction, over all wavelengths. The formal uncertainty in $F_{\text{bol}}$ was determined according to the standard criterion of $\Delta\chi^2 = 2.30$ for the case of two fitted parameters (e.g., Press et al. 1992), where we first renormalized the $\chi^2$ of the fits such that $\chi^2_r = 1$ for the best fit model. Because $\chi^2_r$ is in almost all cases greater than 1 (see Table 2), this $\chi^2$ renormalization is equivalent to inflating the photometric measurement errors by a constant factor and results in a more conservative final uncertainty in $F_{\text{bol}}$ according to the $\Delta\chi^2$ criterion. While not strictly equivalent to $1\sigma$ errors, we consider these uncertainties to be representative of our true errors, and evidence presented in Section 3.4 supports this.

Finally, because the model atmosphere grids do not extend to wavelengths shorter than 0.1 $\mu$m, we found it necessary to augment the model atmospheres at the blue end for hot stars with $T_{\text{eff}} > 15,000$ K, for which the emergent flux at $\lambda < 0.1$ $\mu$m becomes comparable to the typical uncertainty in $F_{\text{bol}}$ of 3%. Therefore, for these hot stars we appended to the model SED a simple blackbody representing the sum of two blackbodies corresponding to the two stars’ temperatures scaled by their surface areas. To account for the non-blackbody nature of the SED at $\lambda > 0.1$ $\mu$m, we adjusted the blackbody portion at $\lambda < 0.1$ $\mu$m by the flux difference of the actual SED relative to a blackbody at $\lambda > 0.1$ $\mu$m.

2.4. How Model-dependent are the Bolometric Fluxes?

For the purposes of the present work, the ultimate aim of the SED fitting is to obtain a measure of $F_{\text{bol}}$ for each EB that is as model-independent as possible. It could be argued that the procedure is dependent on the model atmospheres used, which of course it is to some extent. This model dependence is mitigated, however, by the very large wavelength range covered by the actual flux measurements, which for most of the EBs includes a very large fraction of the emergent stellar flux.

To quantify this, we have calculated the fraction of each EB’s $F_{\text{bol}}$ that is from beyond the span of the flux measurements, which for hot stars is most important at the blue end. For 50% of the EBs this flux fraction is less than 4%, and for only 25% of the EBs is it greater than 25%; for 5% of the EBs, representing the very hottest stars, it is greater than 90%. Given the large span of the flux measurements, in principle one could perform a simple linear interpolation between the measurements and, say, a simple polynomial extrapolation at the ends. The atmosphere model essentially serves as a more intelligent, more physically motivated way of
performing the interpolation (and extrapolation, where needed), grounded in basic stellar astrophysics. Hot EBs, for which the extension of the SED model to the blue represents a relatively large contribution of the total $F_{\text{bol}}$, could be of concern. However, as we show in Section 3, the efficacy of the procedure appears to be independent of $T_{\text{eff}}$.

Other concerns may be that we have had to assume solar metallicity for some of the EBs. We therefore performed a check by varying the adopted [Fe/H] from $-0.5$ to $+0.3$—representing the range of metallicity for the vast majority of Milky Way stars— for several EBs in our sample over the full range of $T_{\text{eff}}$. We find that the effect on the resulting $F_{\text{bol}}$ is negligible for the hot stars and as much as $\approx0.5\%$ for the cool stars, in all cases much smaller than the typical $F_{\text{bol}}$ uncertainty of $3\%$ (Table 2).

Arguably the most important purpose of the fitting procedure is to determine $A_V$, for determining what $F_{\text{bol}}$ would be in the absence of extinction, thus permitting the distance to be calculated simply via

$$d = (L_{\text{bol}}/4\pi F_{\text{bol}})^{1/2}$$  \hspace{1cm} (1)$$

For 67 of the 156 EBs with good SED fits, $A_V$ estimates can be derived from published reddening values previously reported in the literature via $A_V = 3.1 E(B-V)$. The comparison between our fitted $A_V$ and the literature values is shown in Figure 1, where the agreement is very good. Indeed, we expect that the $A_V$ values newly determined here should represent an improvement over the original values in many cases. We have adopted a single ratio of total-to-selective extinction, $R_V = 3.1$ in our fits. $R_V$ values in the literature span the range $\approx2.5$–4 for most Galactic sight lines, and thus in principle fitting for $R_V$ could further improve the SED fits. However, we have opted for simplicity not to introduce a third free parameter to the SED fitting procedure. In any event, if any of the SED fits are poorer than the literature values, their $A_V$ will be in turn smaller than the typical literature uncertainties on $F_{\text{bol}}$.

3. RESULTS

The results of the SED fitting procedure described in Section 2.3 are summarized in Table 2, and the full set of 158 SED fits provided in Figure Set 11 in Appendix A. In this section we discuss several representative SED fits that demonstrate the range of cases, and then present the resulting $F_{\text{bol}}$ for our sample of EBs. Next, we present the predicted parallaxes that result from applying $F_{\text{bol}}$ together with the $L_{\text{bol}}$ values from the literature. Finally, we compare our predicted parallaxes with the subset measured by Hipparcos, and we assess the reliability of the uncertainties in our predicted parallaxes.

3.1. SED Fits and Bolometric Fluxes

Satisfactory SED fits were achieved for 156 of the 158 EBs in our study sample. For context, these 156 EBs are represented in the $T_{\text{eff}}$–radius plane in Figure 2, color coded according to the $\chi^2$ of the SED fit. Six representative SED fits, covering a range of $T_{\text{eff}}$, radius, and $\chi^2$ from Figure 2, are presented in Figure 3: YY Gem, BD $+36:3317$, CW Cep, V380 Cyg, WX Cep, and HD 187669. V380 Cyg, with $\chi^2 = 0.90$, is a good example of the best fits achieved by our procedures. WX Cep, with $\chi^2 = 12.5$, is an example of one of the worst fits that we nonetheless deem acceptable. In this case, the quality of the fit has been affected by the 2MASS data, which appear systematically offset upward relative to the rest of the fit. BD $+36:3317$ is an example of a case in which the original 2MASS measurements have been corrected for having been observed during eclipse (see Section 2), with a very good resulting $\chi^2 = 1.96$. 

![Figure 1](image1.png)

**Figure 1.** Comparison of fitted $A_V$ vs. literature $A_V$ for the EBs possessing such literature measurements.

![Figure 2](image2.png)

**Figure 2.** $T_{\text{eff}}$–radius diagram of the primary stars in the 156 EBs with satisfactory SED fits, color coded by the $\chi^2$ of the fit. Points highlighted with blue halos represent EBs with otherwise satisfactory SED fits that are flagged by Hipparcos as having sub-arcsecond companions that could compromise the $F_{\text{bol}}$.

due to our choice of $R_V$, the resulting increased $\chi^2$ will in turn result in more conservative uncertainties on $F_{\text{bol}}$. 

![Figure 3](image3.png)
For comparison, the two cases of truly unacceptable SED fits with $\chi^2 > 20$ are shown in Figure 4. Both of these are cases for which we adjusted the 2MASS measurements for having been observed in eclipse, but this did not improve the fits sufficiently. It is possible that alternative photometric measurements from among the many catalogs in which these EBs...
appear could salvage these cases. However, for the sake of consistency in methodology and in the data sources used, we have opted in this work to simply discard these two cases.

Eight of the EBs with otherwise satisfactory SED fits were flagged by Hipparcos as possessing sub-arcsecond companions. Such close companions could be contributing flux to the catalog photometric measurements, which typically have spatial resolutions on the order of 1 arcsec. This additional flux in the data would lead to an incorrectly high $F_{\text{bol}}$ and thus an erroneously short inferred distance (i.e., erroneously large predicted parallax). In fact, the quality of the SED fits in these cases is in general quite good. For example, CW Cep in Figure 3 is one such EB; its $\chi^2 = 1.22$ gives no indication of problems. Nonetheless, to be conservative we have opted in the analysis that follows to disregard these eight cases.

A key empirical product of this work is the $F_{\text{bol}}$ for each EB that results from direct summation of the SED. These $F_{\text{bol}}$ values are tabulated in Table 2, and the distribution of their uncertainties presented in Figure 5. The best cases have uncertainties of $\lesssim 1.5\%$. The median uncertainty for the full EB sample is 3.0%, and is better than 5% for 90% of the sample. This means that the uncertainty in the predicted parallaxes for the EBs will in almost all cases be dominated by the uncertainty in the EB $L_{\text{bol}}$, which is typically $\lesssim 10\%$.

3.2. Predicted Parallaxes

With $F_{\text{bol}}$ and $L_{\text{bol}}$ in hand for each EB, we can calculate the predicted distance to each EB according to Equation (1). The uncertainty in $F_{\text{bol}}$ comes directly from our SED fitting procedure (Section 2.3). The uncertainty in $L_{\text{bol}}$ is less straightforward, as it requires propagation of uncertainties in the stellar radii and $T_{\text{eff}}$, which themselves require a proper
The color bar represents the difference of the uncertainties in the original EB analyses. Our procedure for determining handling of correlated uncertainties in the measured quantities from the original EB analyses. Our procedure for determining the uncertainties in \( L_{\text{bol}} \) is explained in Appendix B.

The predicted distances so computed, and the parallaxes derived from them, are tabulated in Table 2. The distribution of their uncertainties is presented in Figure 6. We note that, as explained by Bailer-Jones (2015) and others, estimating a distance from a parallax, or in our case a parallax from a distance, is not trivial when the relative errors are larger than about 20\%, and becomes sensitive to prior assumptions. The EBs in our sample all have relative errors well below 20\%, so a straightforward conversion to parallaxes is sufficient for our purposes.

The implied precision of the predicted EB parallaxes is remarkably good: the uncertainty is \( \sim 30 \mu\text{as} \) in the best cases, and the median for the entire sample is 190 \( \mu\text{as} \). The precision is better than \( \sim 500 \mu\text{as} \) for 90\% of the sample.

### 3.3. Comparison to Hipparcos

As just mentioned the precision of the predicted EB parallaxes is typically 4–5 times better than the formal uncertainties in the Hipparcos trigonometric parallaxes (van Leeuwen 2007). Although the latter are therefore poorer than the EB parallaxes on an individual basis, collectively they do allow for a check on the accuracy of our results, by comparing values for the 86 EBs that were observed by the satellite and that have acceptable SED fits.

Figure 7 presents the direct comparison of our predicted EB parallaxes against the trigonometric parallaxes reported by Perryman et al. (1997) in the original reduction (hereafter referred to as “old Hipparcos”) and as reported in the “new Hipparcos” reduction of van Leeuwen (2007). In both cases the overall agreement is excellent. The EB parallaxes appear to slightly better follow the new Hipparcos parallaxes for the most distant EBs (i.e., the smallest parallaxes) for which the old Hipparcos parallaxes appear systematically smaller than the EB parallaxes. However, this small trend is well within the errors.

Indeed, the old Hipparcos parallaxes on the whole exhibit fewer large residuals relative to the EB parallaxes, and much of this difference occurs among the smallest parallaxes for which the new Hipparcos reported uncertainties are much smaller than in the old Hipparcos reduction.

We show this directly in Figure 8, where we observe that while the overall distribution of parallax residuals is similar for both the old and new Hipparcos parallaxes, there are more outliers larger than 2\( \sigma \) with the new Hipparcos parallaxes (12 in the new, 4 in the old). In addition, for the nearest EB in our sample (CU Cnc), the old Hipparcos parallax agrees with the EB parallax within 1\( \sigma \), whereas the difference is nearly 2\( \sigma \) for the new Hipparcos parallax. These outliers are identified by name in Figure 8 so that the SED fits may be readily compared (Figure 11).

We have checked for any indications of potential problems that might be common to the outliers. We checked the EBs that were reported in the original EB publications to possess tertiary companions (although any “third light” in these cases should already be accounted for in the EB solutions from which the radii and \( T_{\text{eff}} \) were derived); we checked the EBs containing metallic A (Am) stars whose metallicities are less well determined and/or anomalous (although metallicity in general has a negligible effect on the derived \( F_{\text{bol}} \), see Section 2.4); we checked the EBs flagged by Hipparcos as “Variability-Induced Movers” (although this should have been accounted for in the Hipparcos reduction); we checked the EBs with the largest \( A_V \) values (although our SED-derived \( A_V \) values agree very well with the published values, see Figure 1); finally, we checked the EBs with large amounts of flux in the SED fits that are beyond the span of the photometric measurements (this is represented in Figure 8). The outliers have none of these factors in common.

It is notable that the predicted EB parallaxes compare so favorably even when the \( F_{\text{bol}} \) determination involves a large contribution from beyond the span of the photometric measurements, considering that this contribution to \( F_{\text{bol}} \) is as large as \( \sim 90\% \) in the most extreme cases. Though this
may seem surprising, it is simply a consequence of the fact that the SED fit is very stringently constrained by the stellar properties—which are in turn very accurately determined from the published EB solutions—and of the fact that the available photometry spans a sufficiently large range of wavelengths to stringently constrain $A_V$, the only remaining free parameter. It is an extrapolation only in the sense that the model extends beyond the data, not in the sense that there is no knowledge of the nature of the SED beyond the data.

It is also notable that the predicted EB parallaxes retain their high precision regardless of distance. This is a consequence of the fact that the accuracy of the stellar properties arising from the EB solutions does not depend on the EB distance, as long as the light curves and radial velocities used in the EB analysis are of sufficient quality. Indeed, even the EB-based distance to the LMC at $\sim 50$ kpc has a demonstrated precision of $\sim 2\%$ (Pietrzyński et al. 2013).

### 3.4. Reliability of the EB Parallax Uncertainties

The comparison of the predicted EB parallaxes to the available Hipparcos parallaxes suggests that our estimated EB parallax precisions are reliable. With only a few exceptions, the residuals relative to the Hipparcos parallaxes are distributed as expected, especially when compared to the old Hipparcos parallaxes. The two large outliers seen in Figure 8 (top) may represent nothing more than the few $>2\sigma$ deviations expected from a normal sample of $\sim 100$.

The larger number of $>2\sigma$ outliers relative to the new Hipparcos parallaxes (Figure 8, bottom), however, suggests that our EB parallax uncertainties may be underestimated in some cases. Another way of checking our EB parallaxes and uncertainties is to use the distances to those EBs in our sample that reside in star clusters for which accurate distances have been determined. There are four such EBs in our sample, from the new Hipparcos parallaxes (we exclude the Pleiades for reasons discussed in Section 1), and these are highlighted in Figure 8 (bottom). In all four cases, the agreement between our predicted EB parallax and the Hipparcos cluster parallax is within $2\sigma$. At the same time, the distribution of the four residuals is strictly speaking slightly broader than for a normal distribution; two of the four EBs agree to within $1\sigma$, whereas a normal distribution would expect three of the four to agree with $1\sigma$.

It is difficult to say more than this on the basis of only four measurements. Certainly, there is not compelling evidence that the uncertainties in our predicted EB parallaxes are not reliable. However, more conservatively, these four measurements could also be interpreted as suggesting that our EB parallax uncertainties are underestimated by $\sim 50\%$. This is depicted in Figure 9, where now the four EBs with cluster parallaxes are more normally distributed, although the large number of systems that deviate by more than $2\sigma$ remains large, suggesting that perhaps it is some of the new Hipparcos parallax uncertainties that are underestimated. In any event, these comparisons allow us to conclude that the EB parallaxes are very precise, with typical errors in the range of 200–300 $\mu$as.

We can also assess the accuracy of the EB parallaxes. We have measured this by computing the mean and median parallax difference compared to Hipparcos. For the old Hipparcos reduction, we obtain mean and median differences of $-60$ $\mu$as and $+60$ $\mu$as (in the sense of Hipparcos–EB), respectively. For the new Hipparcos reduction, we obtain mean and median differences of $-40$ $\mu$as and $-55$ $\mu$as, respectively. For both the old and new Hipparcos reductions, these differences are $\lesssim 1/3$ of our typical random errors. This is important, as it not only confirms that our EB parallaxes are highly accurate as well as very precise, but also that our
estimated uncertainties are realistic and reflect any systematics inherent to the method.

4. DISCUSSION: APPLICABILITY TO GAIA

The Gaia mission is poised to revolutionize many areas of astrophysics by mapping the entire sky and delivering high-precision astrometry, photometry, and spectroscopy for up to a billion stars. Most notably, it will provide trigonometric parallaxes that in some cases will be as precise as a few μas, yielding useful distances to individual objects halfway across the Galaxy. While the final results from the nominal five-year mission are not expected until after 2020, interim data releases will already provide extremely valuable information beginning with the first (DR1) slated for late 2016.

In addition to accurate positions and mean magnitudes for stars over at least 90% of the sky, and additional information for sources at the ecliptic poles, DR1 will contain parallaxes for up to 2.5 million stars based on the Tycho-Gaia Astrometric Solution (TGAS; Michalik et al. 2015). This full-sky solution takes advantage of the Tycho-2 astrometry (Høg et al. 2000) gathered 20 years ago during the Hipparcos mission, and combines it with the first six months of Gaia data to solve for the positions, proper motions, and parallaxes of the majority of the Tycho-2 stars. The precision expected for these parallaxes is comparable to or better than that of Hipparcos for most stars, with typical nominal errors below a milli-arc second, and somewhat poorer precision up to about 3 mas along the ecliptic. The data set should be almost complete down to V ≈ 11.5, or about 3–4 mag deeper than Hipparcos.

Even if it is preliminary, this large collection of parallaxes featuring 20 times more stars than Hipparcos will have numerous scientific applications. In particular, it will significantly improve the stellar characterization of targets of exoplanet searches, including transit surveys, many of which observe relatively bright stars that are contained in the Tycho-2 catalog. This, in turn, should have an immediate impact on the precision and accuracy of the derived planetary properties.

NASA’s Transiting Exoplanet Survey Satellite mission (Ricker et al. 2015) will benefit enormously as well, as Gaia DR1 will supply parallaxes for a large fraction of the bright nearby stars being considered for observation, enabling a better selection of the optimal targets in preparation for launch at the end of 2017. While the external accuracy of the Gaia DR1 parallaxes is expected to be very good, and perhaps similar to that of Hipparcos according to simulations by Michalik et al. (2015), independent checks are highly desirable as a means to validate the new astrometric results. The set of predicted EB parallaxes derived in this work, obtained in a completely different way, offers an excellent opportunity for this test given that our typical 200 μas precision is at least as good as, and often better than, that expected of Gaia DR1. We note also that our parallax errors do not tend to increase as stars get fainter or more distant. Our faintest system, CoRoT 102918586 (V = 12.4), has a predicted parallax with an uncertainty of 30 μas; our most distant system, V467 Vel, is more than 5 kpc away and has a correspondingly well-determined parallax under 0.2 mas also with an uncertainty of only 20–30 μas. Furthermore, as shown in Figure 10, our stars are distributed over the entire sky, and span more than a 10 mag range in brightness (V = 1.9–12.4) potentially allowing the discovery of magnitude-dependent parallax discrepancies, should they be present.

5. SUMMARY AND CONCLUSIONS

EBs with well-measured physical properties allow the determination of distances that are essentially model-independent, and can be both highly accurate and highly precise. They are therefore ideal as benchmarks for validating other methods of establishing distances, and can often be used out to many kiloparsecs without loss of precision. They have been employed to great advantage even in external galaxies such as the LMC, the SMC, and others.

In this paper we have assembled an all-sky list of 158 EBs contained in the Tycho-2 catalog with high-quality
determinations of the component radii and effective temperatures from the literature, and combined this information with constrained SED fits using existing photometric measurements over a wide range of wavelengths. The distances calculated from the accurate absolute stellar luminosities and bolometric fluxes lead to predicted parallaxes having typical precisions of 200 μas (5% relative errors), which are 4–5 times better than the trigonometric parallaxes from Hipparcos. We find excellent overall agreement between our results and those from Hipparcos. To the extent that our EB parallaxes represent a test of the Hipparcos parallaxes, we find no obvious systematic deviations of the sort that appear to have affected the Pleiades, at least for this particular sample. In any case, the good agreement between our EB parallaxes and the Hipparcos parallaxes supports the accuracy of our measurements, and other tests suggest that our precision estimates are also realistic.

The quality of our predicted parallaxes also compares very favorably with that expected for the Gaia parallaxes from the TGAS (Michalik et al. 2015), soon to be delivered as part of the mission’s first Data Release. Our results will therefore serve as an important external check on the spacecraft’s astrometric performance early on in the mission. While subsequent Gaia releases will feature steadily increasing parallax precision for larger numbers of stars as the time base lengthens, we anticipate that predicted parallaxes from EBs will continue to provide a valuable reference that is completely independent of astrometry and whose precision does not degrade with increasing distance or diminishing brightness.

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APPENDIX A
SED MEASUREMENTS AND FITS FOR THE EB STUDY SAMPLE

In Figure Set 11 we present the observed and fitted SEDs of the 158 EBs in our study sample (Table 1).

APPENDIX B
THE UNCERTAINTIES IN THE TOTAL BOLOMETRIC LUMINOSITY

The uncertainty in the total bolometric luminosity \( L_{\text{bol}} \) of each of our EBs, which factors into the final error in the distances and parallaxes, depends on the radius and temperature uncertainties of both components. A naive approach to error propagation would consider the published primary and secondary temperature errors to be independent, and the radius errors to also be independent, whereas in reality they are not. For example, light curve analyses typically yield highly precise temperature ratios from the relative depth of the eclipses such that the secondary temperature essentially scales with the primary temperature (a positive correlation), and most of the uncertainty in the secondary value is inherited from the primary. The primary temperature and its error are usually determined from external information (e.g., spectroscopically) and held fixed in the photometric analysis. Similarly, light curves can often determine the radius sum very precisely from the total duration of the eclipses, whereas the radius ratio is less well constrained, as are the individual radii if solved for separately. This results in the primary and secondary radius errors being highly anti-correlated.

Given these correlations, propagating the temperature errors for the primary and secondary as if they were independent will cause the uncertainty in \( L_{\text{bol}} \) to be underestimated, and doing the same with the radius errors will tend to give an \( L_{\text{bol}} \) error that is too high, partially offsetting the temperature bias. However, as temperature errors dominate due to the fourth power dependence in the Stefan–Boltzmann law, and because they are typically larger (fractionally) compared to the radius errors, the net result will be an underestimate of the total luminosity error.

A more sensible approach would be to recast the published uncertainties in the secondary temperature \( T_{\text{eff,2}} \) in terms of the errors in the primary value and in the temperature ratio \( t \equiv T_{\text{eff,2}}/T_{\text{eff,1}} \), which are usually uncorrelated, and the radius uncertainties in terms of those of their sum \( r \equiv R_1 + R_2 \) and their ratio \( k \equiv R_2/R_1 \), which are also uncorrelated, and to then propagate these new uncertainties independently to infer the error in \( L_{\text{bol}} \). This should lead to more realistic errors for \( L_{\text{bol}} \). However, in practice it is not possible to recover the uncertainties in \( t \), \( r \), and \( k \) accurately without access to the details of each light curve analysis, which are not always published, and the issue is further complicated by the sometimes subjective assignment of radius and/or temperature uncertainties in some of the original publications. For this work we have nevertheless attempted to estimate \( \sigma_t \), \( \sigma_r \), and \( \sigma_k \) in a statistical sense to match the ensemble of reported errors for the

![Figure 11. AD Boo is shown as example of the figure set. Each panel in the Figure Set is labeled at top by the Tycho-2 ID and name of the EB, and shows the observed fluxes (in units of erg cm\(^{-2}\) s\(^{-1}\)) vs. wavelength (in μm) as red error bars, where the vertical error bar represents the uncertainty in the measurement and the horizontal “error” bar represents the effective width of the passband. Also in each figure is the fitted SED model including extinction (light gray curve), on which is shown the model passband fluxes as blue dots.](image-url)

The corresponding un-extincted SED model is also shown (dark black curve); the reported \( F_{\text{bol}} \) is the sum over all wavelengths of this un-extincted model (see the text).

(The complete figure set (158 images) is available.)
individual temperatures and radii as closely as possible. We proceed as follows.

Beginning with the radii, the individual component values may be expressed in terms of their sum and ratio as

\[ R_1 = \left( \frac{1}{1+k} \right) r_1, \quad R_2 = \left( \frac{k}{1+k} \right) r_2 \]

(see Torres et al. 2000) in which the correlation between \( r \) and \( k \) is generally weak. Standard error propagation then gives

\[
\sigma_{R_1} = \frac{1}{1+k} \left[ \left( \frac{r}{1+k} \right)^2 \sigma_1^2 + \sigma_k^2 \right]^{1/2},
\]

\[
\sigma_{R_2} = \frac{1}{1+k} \left[ \left( \frac{r}{1+k} \right)^2 \sigma_2^2 + k^2 \sigma_k^2 \right]^{1/2},
\]

from which it can be seen that if the secondary is a smaller star, its uncertainty should in principle also be smaller. As mentioned above, many systems with smaller secondaries have reported \( \sigma_{R_2} \) values that are in fact larger than \( \sigma_{R_1} \), which prevents one from solving Equation (3) directly for \( \sigma_r \) and \( \sigma_k \). Since the expectation is that the radius sum should be better determined than the radius ratio, we introduce this condition by defining

\[ f_R = \frac{\sigma_r}{\sigma_k/k} \]

We may express in terms of their sum and ratio as

\[ f_T = \frac{\sigma_f}{\sigma_{fT}/T_{\text{eff}}}. \]

We apply a similar reasoning to the temperatures, assuming the uncertainties in the primary temperature and in the temperature ratio are largely independent. In that case, since \( T_{\text{eff},2} = T_{\text{eff},1} \), the uncertainty \( \sigma_T \) in \( T_{\text{eff},2} \) is expressed as

\[
\sigma_T^2 = T_{\text{eff},1}^2 \sigma_1^2 + f_T^{-2} \sigma_2^2,
\]

and as before we may define

\[ f_T = \frac{\sigma_T}{\sigma_{fT}/T_{\text{eff},1}} \]

with the expectation that the fractional error in the temperature ratio will typically be smaller than that of the primary temperature. Solving for \( \sigma_r \) and inserting it in Equation (6) leads to the required estimate of the uncertainty in the temperature ratio,

\[ \sigma_T = \sigma_2 T_{\text{eff},1}^{-1} (1 + f_T^{-2})^{-1/2}. \]

Because of the ways in which individual temperature errors have sometimes been assigned to our EBs, it is not always possible to use the above formalism to infer a value of \( \sigma_r \) or \( f_T \) for each system directly from the published uncertainties \( \sigma_1 \) and \( \sigma_2 \). This is similar to the difficulty mentioned earlier for the radii. We have therefore chosen to adopt a single value of \( f_R \) and \( f_T \) for the entire sample, and to use the ensemble of published measurement errors for all 156 systems to tell us what the optimal values should be, such that when inserted into the expressions for \( \sigma_r \), \( \sigma_k \), and \( \sigma_T \) for each EB we obtain the closest match to the published individual radius and temperature errors using Equations (3) and (6). Denoting the individual radius and temperature errors predicted by our prescription for given values of \( f_R \) and \( f_T \) as \( \sigma_{R_{\text{eff}}} \), \( \sigma_{R_{\text{eff}}} \), \( \sigma_{T_{\text{eff}}} \), and \( \sigma_{T_{\text{eff}}} \), we construct a figure of merit \( \eta \) for \( R \) and \( T_{\text{eff}} \) as follows:

\[
\eta(f_R) = \sum \left( 1 - \frac{\sigma_{R_{\text{eff}}}}{\sigma_{R_1}} \right)^2 + \sum \left( 1 - \frac{\sigma_{R_{\text{eff}}}}{\sigma_{R_1}} \right)^2,
\]

\[
\eta(f_T) = \sum \left( 1 - \frac{\sigma_{T_{\text{eff}}}}{\sigma_{T_{\text{eff}}}} \right)^2.
\]

Both statistics have a single absolute minimum yielding best-fit values \( f_R = 0.56 \) and \( f_T = 0.46 \) (see Figure 12). These factors are both smaller than unity, supporting our assumption that the radius sum is usually better determined than the radius ratio, and that the temperature ratio is typically more precise than the fractional error in the primary temperature. The fact that the \( f \) factors are not much smaller, as one might expect for canonical light curve solutions, is a reflection of the inhomogeneous nature of the published errors.

We used the above prescription to estimate the uncertainty in \( L_{\text{bol}} \) for each system by propagating the errors in \( r \) and \( k \) through a Monte Carlo procedure as if they were independent, and similarly with \( T_{\text{eff}} \) and \( t \). Compared to the more simplistic approach in which the individual temperature errors and individual radius errors are considered to be uncorrelated, our approach results in typical luminosity uncertainties up to 50% larger, which we expect to be more realistic.

Figure 12. Illustration of how we estimated the scale factors \( f_R \) and \( f_T \) that provide the best overall fit to the ensemble of published errors in the radii and temperatures for the 156 EBs in our sample. The best-fit values that minimize the respective figures of merit \( \eta \) are indicated.
