ANALYSIS OF DETACHED ECLIPSING BINARIES NEAR THE TURNOFF OF THE OPEN CLUSTER NGC 7142

ERIC L. SANDQUIST1, MATTHEW SHETRONE2, ANDREW W. SERIO1,3, AND JEROME OROSZ1

1 San Diego State University, Department of Astronomy, San Diego, CA 92182, USA; esandquist@mail.sdsu.edu, aserio@gemini.edu, jorosz@mail.sdsu.edu
2 University of Texas, McDonald Observatory, HC75 Box 1337-L Fort Davis, TX 79734, USA; shetrone@astro.as.utexas.edu

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ABSTRACT

We analyze extensive BVRcIc photometry and radial velocity measurements for three double-lined deeply eclipsing binary stars in the field of the old open cluster NGC 7142. The short period (\(P = 1.9096825\) days) detached binary V375 Cep is a high probability cluster member, and has a total eclipse of the secondary star. The characteristics of the primary star (\(M = 1.288 \pm 0.017 M_\odot\)) at the cluster turnoff indicate an age of 3.6 Gyr (with a random uncertainty of 0.25 Gyr), consistent with earlier analysis of the color–magnitude diagram. The secondary star (\(M = 0.871 \pm 0.008 M_\odot\)) is not expected to have evolved significantly, but its radius is more than 10% larger than predicted by models. Because this binary system has a known age, it is useful for testing the idea that radius inflation can occur in short period binaries for stars with significant convective envelopes due to the inhibition of energy transport by magnetic fields. The brighter star in the binary also produces a precision estimate of the distance modulus, independent of reddening estimates: \((m - M)_V = 12.86 \pm 0.07\). The other two eclipsing binaries are not cluster members, although one of the systems (V2) could only be conclusively ruled out as a present or former member once the stellar characteristics were determined. That binary is within 0.5 of edge-on, is in a fairly long-period eccentric binary, and contains two almost indistinguishable stars. The other binary (V1) has a small but nonzero eccentricity (\(e = 0.038\)) in spite of having an orbital period under 5 days.

Key words: binaries: eclipsing – binaries: spectroscopic – open clusters and associations: individual (NGC 7142) – stars: distances – stars: evolution

Online-only material: supplemental data (FITS) files

1. INTRODUCTION

Of all the methods of determining the ages of stars (other than the Sun), the method that requires the least theoretical intervention involves the measurement of the mass and radius of evolved main sequence stars in detached eclipsing binaries (DEBs). For a group of stars born at the same time, the most massive (and therefore, the hottest and most luminous) stars consume their hydrogen fuel the quickest and begin to change rapidly in size, temperature, and luminosity. The brightest and hottest main sequence stars remaining thereby indicate the age of the group. Unfortunately, observational and theoretical limitations preclude the measurement of really accurate ages from brightness and color alone—uncertainties in distance and reddening estimates: \((m - M)_V = 12.86 \pm 0.07\). The other two eclipsing binaries are not cluster members, although one of the systems (V2) could only be conclusively ruled out as a present or former member once the stellar characteristics were determined. That binary is within 0.5 of edge-on, is in a fairly long-period eccentric binary, and contains two almost indistinguishable stars. The other binary (V1) has a small but nonzero eccentricity (\(e = 0.038\)) in spite of having an orbital period under 5 days.

Separately, evolved field DEBs such as AI Phe and TZ For (with well-determined \(M, R, T_{\text{eff}},\) and \([\text{Fe/H}];\) Andersen 1991) and photometry of star clusters (with well-determined distance and \([\text{Fe/H}];\) VandenBerg et al. 2006) have been used to constrain stellar models (e.g., VandenBerg et al. 2006). Ideally though, the most restrictive constraints will come from DEBs in star clusters. In that case, a well-measured DEB can pinpoint the masses of stars at critical spots in a cluster’s color–magnitude diagram (CMD), while the rest of the single cluster members can be used to collectively probe the physics governing the stars. If we are lucky enough to find multiple DEBs in a cluster, the observations would more tightly constrain the wiggle room available to the theoretical models. A critical aspect of this is to find DEBs in clusters that have evolved off of the main sequence (in other words, changed significantly in radius from their main sequence values) because they break degeneracies involving uncertainties in distance, reddening, color–\(T_{\text{eff}}\) transformations, and chemical composition (e.g., Southworth et al. 2004).

However, only a handful of DEBs with evolved stars in clusters have been identified, much less studied in detail. Our previous work on NGC 7142 (Sandquist et al. 2011) presented variable star discoveries identified in the process of characterizing a previously known (Crinklaw & Talbert 1991) eclipsing binary (V375 Cep) at the cluster turnoff. This paper presents the analysis of the most promising eclipsing binaries from that study.

2. OBSERVATIONAL MATERIAL

The photometry of the binary stars was presented in Sandquist et al. (2011). Briefly, the images were obtained at the Mount Laguna Observatory (MLO) 1m telescope using a 2048 \(\times\) 2048 pixel CCD with a field of view about 13.5 on a side. The photometry was originally undertaken for the purpose of characterizing V375 Cep, but after a second eclipsing binary was identified at the turnoff, photometric observations were used to determine the ephemeris and observe eclipses. Since the Sandquist et al. paper, we obtained additional observations of the eclipses of V2. These new observations are listed in Table 1.

We derived light curves from differential photometry using our updated version of the image subtraction package ISIS.
Table 1

Additional Photometry at Mount Laguna Observatory

| Date          | Filters | mJD Start | N   |
|---------------|---------|-----------|-----|
| 2011 Aug 9    | BR      | 5783.656  | 38.22 |
| 2011 Aug 28   | VR      | 5802.629  | 25.71 |
| 2011 Oct 14   | VR      | 5849.816  | 27.3  |
| 2011 Nov 30   | R       | 5896.566  | 21   |

Note. a mJD = HJD − 2450000.

Table 2

Radial Velocity Measurements

| UT Date   | mJD^a | \(v_A\) (km s\(^{-1}\)) | \(\sigma_A\) | \(v_B\) (km s\(^{-1}\)) | \(\sigma_B\) |
|-----------|------|---------------------|-------------|---------------------|-------------|
| V1        |      |                     |             |                     |             |
| 20100625  | 5372.91397 | 55.9 | 0.7 | −94.2 | 1.0 |
| 20100728  | 5405.81053 | 66.7 | 0.8 | −102.6 | 1.3 |
| 20100731  | 5408.82025 | −83.3 | 1.0 | 52.0 | 1.0 |
| V2        |      |                     |             |                     |             |
| 20091015  | 5119.59672 | −70.0 | 2.2 | −13.6 | 2.5 |
| 20091022  | 5126.60325 | −3.2 | 1.2 | −83.3 | 1.8 |
| 20091125  | 5160.59589 | 4.1 | 1.8 | −90.9 | 2.2 |
| 20100916  | 5455.65953 | 29.1 | 1.5 | −114.5 | 2.2 |
| 20100916  | 5455.77462 | 37.8 | 1.9 | −122.3 | 2.3 |
| 20101007  | 5476.64403 | −46.4 | 1.4 | −33.3 | 4.1 |
| 20101009  | 5478.65485 | −66.0 | 0.9 | −20.0 | 1.3 |
| 20101010  | 5479.64021 | −71.8 | 0.9 | −14.0 | 1.1 |
| 20101011  | 5480.61719 | −76.1 | 1.3 | −8.9 | 1.5 |
| 20101019  | 5488.61755 | 27.2 | 1.1 | −112.7 | 1.4 |
| 20110103  | 5503.58119 | 53.1 | 1.1 | −139.0 | 1.8 |
| 20110105^b | 5505.57139 | −72.9 | 0.9 |             |             |
| 20110707  | 5749.89305 | −80.2 | 0.9 | −4.6 | 1.2 |
| 20110710  | 5752.86970 | 17.1 | 0.8 | −101.8 | 1.1 |
| 20110809  | 5782.78284 | −61.0 | 1.1 | −24.0 | 1.4 |
| 20110823  | 5796.75684 | −80.3 | 1.8 | −4.8 | 2.1 |
| 20110827  | 5800.73788 | 56.8 | 1.5 | −143.3 | 1.9 |
| 20110908  | 5812.73498 | −79.7 | 1.1 | −7.1 | 1.5 |
| 20110925  | 5829.65263 | −63.7 | 1.5 | −22.6 | 2.1 |
| 20110927  | 5831.63652 | 52.4 | 2.1 | −138.4 | 2.7 |

V375 Cep

| UT Date   | mJD  | \(v_A\) (km s\(^{-1}\)) | \(\sigma_A\) | \(v_B\) (km s\(^{-1}\)) | \(\sigma_B\) |
|-----------|------|---------------------|-------------|---------------------|-------------|
| 20080905  | 4714.73837 | 18.1 | 2.6 | −158.4 | 3.0 |
| 20080926  | 4735.67830 | 27.6 | 1.0 | −163.4 | 2.6 |
| 20080929  | 4738.68081 | −101.4 | 1.1 | 24.3 | 1.8 |
| 20080930  | 4739.66833 | −5.3 | 0.8 | −112.5 | 2.1 |
| 20081017  | 4756.63643 | 33.4 | 5.0 | −178.8 | 3.3 |
| 20081018  | 4757.57776 | −135.5 | 0.7 | 76.1 | 1.4 |
| 20081031  | 4770.58112 | −103.3 | 0.8 | 34.4 | 5.0 |
| 20081104  | 4774.56837 | −134.3 | 1.3 | 77.8 | 1.9 |
| 20081106  | 4776.58653 | −139.0 | 1.0 | 79.7 | 2.0 |
| 20081118  | 4788.56133 | −38.8 | 1.2 | −73.3 | 8.0 |
| 20081200  | 4790.55131 | −16.2 | 0.9 | −97.3 | 2.6 |
| 20081212  | 4792.55191 | 6.2 | 1.2 | −132.8 | 3.3 |
| 20090909  | 5448.68348 | −133.8 | 2.6 | 74.4 | 4.2 |
| 20090913  | 5452.71345 | −134.5 | 0.9 | 78.2 | 3.0 |
| 20090915  | 5454.72577 | −121.4 | 2.3 | 54.4 | 4.5 |
| 20101003  | 5472.67656 | 41.4 | 1.8 | −180.0 | 3.4 |
| 20101005  | 5474.65060 | 38.3 | 1.8 | −178.5 | 3.8 |
| 20101024  | 5493.58271 | 37.5 | 2.4 | −177.4 | 3.9 |
| 20110105  | 5505.58498 | −33.2 | 3.6 | −61.3 | 10.0 |
| 20110926  | 5530.63860 | −138.2 | 0.9 | 80.6 | 2.3 |

Notes.
a mJD = HJD − 245000.
b Observation during eclipse.

Rotational velocities were determined from clean spectra for both components. This involved creating a first attempt at a clean spectrum by shifting all of the spectra to the rest frame for one of the components and then combining the spectra using a median with a fairly aggressive sigma clip to remove the spectral features of the other component. With preliminary A and B component spectra, we could divide them back into the original spectra (shifted to the correct velocity) and then
repeat the process on these residual spectra files to generate a second set of cleaned A and B component spectra. The cleaned component spectra were then cross-correlated against the solar spectrum, and the width of the cross-correlation peak measured. We then generated synthetic spectra with different rotational velocities and cross-correlated them against the same solar template spectrum. Finally, we estimated the rotational velocity by interpolating in the grid of results for cross-correlation peak widths.

3.2. Abundance Analysis

Abundance analysis for binaries is a fairly specialized and complicated endeavor. To accomplish this, we computed synthetic spectra using the 2010 version of MOOG (Sneden 1973) with a line list based largely on the Kurucz line list⁵ but with some lines adjusted to fit a solar spectrum (Hinkle et al. 2000). MOOG is able to account for continuum light contributed by a companion star in the binary. To minimize the number of free parameters, we used surface gravities and flux ratios from the binary analysis (because the uncertainties on these parameters are far smaller than could be obtained with any spectroscopic analysis) while we let the effective temperature and metallicity of the model atmospheres vary.

We calculated synthetic spectra on a grid of effective temperatures and metallicities with steps of 250 K and 0.07 dex, respectively. We then divided the observed spectrum into the synthetic spectrum, and in several small wavelength regions calculated the residuals about a fitted constant value, where the constant was allowed to change from region to region to compensate for errors in setting the continuum. The regions we chose were: 4866–4995 Å, 4995–5220 Å, 5220–5390 Å, 5300–5330 Å, and 5390–5620 Å. The 5300–5330 Å region is given extra weight by being used twice because it contains a mix of strong lines that increase and decrease with changes in temperature, making it particularly sensitive to $T_{\text{eff}}$. We interpolated the results between grid points to determine the best parameters for each region. The results from the regions were then averaged together to give a final effective temperature and metallicity, along with an estimate of the random uncertainties. For V2 we derived $T_A = 6238 \pm 52$ K and $[\text{Fe/H}]_A = -0.03 \pm 0.06$, while $T_B = 6276 \pm 63$ K and $[\text{Fe/H}]_B = -0.12 \pm 0.02$. Because these two stars are found to have identical characteristics within the uncertainties in the later analysis of the binary, it is unlikely that the inputs to the spectral modeling (log g and/or the flux ratios) are responsible for the difference in the metallicities derived. It is more likely that systematic errors dominate the internal uncertainties. For V375 Cep we derive $T_A = 6230 \pm 50$ and $[\text{Fe/H}]_A = +0.09 \pm 0.02$ (where the quoted uncertainties are errors for the mean), while the B component was too weak to yield useful results. If we consider systematic uncertainties due to inputs for the spectroscopic analysis (such as oscillator strengths and microturbulence), the uncertainties are larger. We estimate that the overall uncertainties are 100 K for $T_A$ and 0.05 dex for $[\text{Fe/H}]_A$. The abundance derived by Jacobson et al. (2008) for NGC 7142 giants is $+0.14 \pm 0.01$. Our metallicity for V375 Cep is thus within 2σ of the Jacobson et al. value.

⁵ http://kurucz.harvard.edu/LINELISTS/GFHYPERTALL.
while our metallicity for the V2 system suggests that it may be a non-member.

3.3. Cluster Membership

Membership determinations for a poorly-studied cluster like NGC 7142 can be fairly difficult. To date, proper motions have only been published for a few stars in the cluster field (e.g., Baumgardt et al. 2000). In addition, there have only been a relatively small number of high precision radial velocity measurements. Jacobson et al. (2007) identified 6 cluster stars out of a sample of 17 and found an average radial velocity of \(-48.6 \pm 1.1\) km s\(^{-1}\), while Jacobson et al. (2008) found \(-50.3 \pm 0.3\) km s\(^{-1}\) from higher resolution spectra of 4 of the same candidate members. Sandquist et al. (2011) observed three red clump star candidates, and found that one had a velocity consistent with these averages, but two had velocities of \(-43.9\) and \(-44.0\) km s\(^{-1}\). Looking more carefully at the photometry for these stars, the two stars with the higher velocities are fainter than other candidates in the Two Micron All Sky Survey (2MASS) \(K_s\) band by more than 0.2 mag, but bluer in the \((J-K_s)\) color. This could indicate that these are foreground giant stars.

From the binary modeling discussed later, we find a system velocity \(\gamma = -17.2\) km s\(^{-1}\) for V1, which unambiguously rules out cluster membership. By comparison, the system velocity for V375 Cep was found to be \(\gamma = -49.86 \pm 0.05\) km s\(^{-1}\), in very good agreement with the mean values found by the two high-resolution spectroscopic studies of the cluster. We therefore judge V375 Cep to be a very likely cluster member.

The fit for V2 returns a system velocity \(\gamma = -42.57 \pm 0.02\) km s\(^{-1}\) that falls near the mean cluster value, but about 7–8 km s\(^{-1}\) higher. Although there has not been extensive enough proper motion or radial velocity survey of cluster stars to determine a reliable velocity dispersion for NGC 7142, the dispersion is expected to be \(<1\) km s\(^{-1}\) for bound clusters with typical masses and radii (Piskunov et al. 2008), and most old open clusters do seem to have radial velocity dispersions of that size (NGC 188, Geller et al. 2008; NGC 6819, Hole et al. 2009; Berkeley 32, Randich et al. 2009). Thus, V2 is unlikely to simply be in the wing of the cluster radial velocity distribution. The effects of a tertiary on a long period orbit could potentially produce this difference between the presently measured system velocity and the cluster mean, and we examine that possibility in more detail in the next subsection. A strong gravitational interaction within the cluster could also give a cluster member enough energy to escape.

We can examine other information (such as projected sky position and CMD position) that provides circumstantial evidence. Janes & Hoq (2011) found an “effective” radius of 4′ for the cluster, which roughly corresponds to 1.5 times the \(\sigma\)-width of a Gaussian fitted to the stellar distribution. V375 Cep is projected 2.9′ from the cluster center, nonmember V1 is 3.9′ from center, and V2 is approximately 4.8′ from center. Once again V2 has a lower likelihood of cluster membership, but this could also be related to its large velocity relative to other cluster members.

As can be seen in Figure 4, the system photometry (see Table 3) and decomposed optical photometry of V375 places it firmly within the main sequence band. The colors of V1 are very similar to those of the other eclipsing binaries despite indications that both component masses are lower than the primary masses of the other binaries (see Section 5.1), which is consistent with the smaller reddening of a foreground object.

The system photometry for V2 is brighter and slightly bluer than cluster turnoff stars, but when the photometry is

![Figure 3](image-url)

**Figure 3.** Upper panel: phased radial velocities for V1. Model fits are shown with solid lines, and the cluster mean radial velocity is shown as the flat dashed line. Lower panels: observed minus calculated velocities for the two stars.
Figure 4. Color–magnitude diagrams for NGC 7142 with the system photometry (■ for cluster member V375 Cep, □ for nonmembers) and binary star components identified (+ for members, × for nonmembers). Probable cluster members (identified from spectroscopic radial velocities) are shown with small open circles, and nonmembers are shown with small ×.

decomposed, only the color is slightly discrepant—the stars are at the blue edge of the distribution at the turnoff in the CMD, which could be explained by lower-than-average reddening. They are slightly brighter than the primary star in V375 Cep in optical bands. In the 2MASS bandpasses, they are approximately the same brightness, assuming that the individual stars are about 0.75 mag fainter than the combined photometry of V2 and the primary of V375 Cep is about 0.15 mag fainter than the combined photometry of that binary (roughly consistent with the I-band secondary eclipse depth). If V2 is a member of the cluster having lower reddening than V375 Cep, it is consistent that the primary of V375 Cep is brighter relative to the two stars of V2 in the 2MASS bands.

To summarize, we judge V1 to be nonmember based on its radial velocity. For V375, the argument for cluster membership is much stronger than it is for V2. None of the information we have available unambiguously supports V2 membership. The age determination for V2 more definitively argues against cluster membership, however, and that will be discussed in Section 5.1.2.

3.4. Search for Tertiary Stars

Because there are now numerous examples of known triple systems in open clusters (a partial list includes Mermilliod & Mayor 1989; Mermilliod et al. 1994; Alencar et al. 1997; Sandquist et al. 2003; Liu et al. 2011; Jeffries et al. 2013), it is worth checking whether the influence of tertiary stars can be detected. If a tertiary star is massive or bright enough, it can affect the models of an eclipsing binary enough to produce systematic errors in the measured characteristics of the eclipsing stars. None of the binaries we discuss here had a third set of detectable lines in our spectra, but with a long enough baseline of observations, photometric methods (such as eclipse timing) or spectroscopic methods (such as center-of-mass motion) can reveal tertaries via their effects on the eclipsing binary. Table 4 gives our measurements of the times of eclipse minimum for the binaries. Due to the relatively small number of radial velocity and eclipse minimum observations for V1, the detection of a tertiary star’s effects is unlikely, so we do not discuss it here.

The radial velocity results for V2 are shown in Figure 2, assuming the best fit mass ratio q = 1.001. This binary shows more than a 7 km s$^{-1}$ offset from the cluster mean velocity ($-50.3 \pm 0.3$ km s$^{-1}$ from 4 stars; Jacobson et al. 2008), which could potentially result from the action of a tertiary star. However, the center-of-mass velocities did not vary significantly over three seasons and more than a 700 day interval of observations, and there is no sign of variations in eclipse timing.

The lower panel of Figure 1 shows the measured center-of-mass velocities for V375 Cep, assuming the best fit mass ratio q = 0.676 from the binary models. There does not appear to be evidence of significant motion during the three seasons (covering more than 1100 days) that we observed the system. Our own eclipse observations for V375 Cep cover a period of almost 1800 days. For the finely sampled light curves from our study, we used the method of Kwee & van Woerden (1956) to determine times of minima and the errors, and we show a comparison of those times with a best-fitting linear ephemeris in Figure 5. We include in Table 4 our best estimates of eclipse minima from the published observations of Crinklaw & Talbert (1991) and Seeberger et al. (1991) to improve the accuracy of the ephemeris and test for the possibility of a nonlinear ephemeris over the 27 yr baseline.

The earlier observations were discussed in Sandquist et al. (2011). Most of the observations by Crinklaw & Talbert (1991) agree well with our phased light curve and they had observations in and out of eclipse on the night of one eclipse. Using our
model light curves in $BV$, we fit their data in order to derive an approximate time of minimum. One additional observation in $V$ on a different date also appears to have fallen near an eclipse minimum. Crinklaw & Talbert shifted the photometric zero points of each of their frames to be consistent, so the relative photometry of the single observation should be approximately correct. The interval between this and the nearest primary eclipse is about 14 orbital cycles, but implies a period of about 1.9164 days, which is significantly different than we find in our more recent observations.

Sandquist et al. (2011) concluded that data from Seeberger et al. (1991) was not of sufficient quality to test for nonlinearities in the ephemeris. Seeberger et al. quoted fairly large uncertainties (0.05 mag) on their measurements, and the shape and depth of the observations on one night (HJD 2446650) that appeared to contain a primary eclipse egress were inconsistent with our model light curves. This may be due to their use of photographic plates as the recording medium.

We conclude that there is a possibility of eclipse timing variations for the V375 Cep system, but the fact that it has been well-behaved during the time covered by our own eclipse observations and radial velocity measurements makes the existence of a tertiary less probable.

3.5. Reddening, Stellar Photometry, and Temperature Estimates

In order to use the photometry for temperature estimates for the stars, we need to have a measurement of the reddening. Sandquist et al. (2011) derived a reddening value [$E(B-V) = 0.32\pm0.06$] via a comparison of the red clump stars in NGC 7142 with those of M67. We revisit that estimate here by examining how the difference in median clump magnitudes between the two clusters changed with filter. M67 and NGC 7142 have similar ages and metallicities, and have values in ranges where small differences have minimal effects on the photometry of the red clump (Girardi & Salaris 2001; Grocholski & Sarajedini 2002).

We have, however, calculated theoretical corrections for intrinsic differences in clump magnitude from Girardi & Salaris (2001) models in order to make the reddening determination more precise. At constant age, the higher metallicity of NGC 7142 ($\Delta[Fe/H] = 0.14$) is theoretically expected to make the clump magnitude brighter in 2MASS infrared filters (by 0.05 mag in $K_s$), but increasingly fainter at bluer wavelengths, reaching almost 0.13 mag in $B$. At constant metallicity, the larger age of M67 is expected to make the red clump fainter in all filters by approximately 0.03 mag (Girardi & Salaris 2001; Grocholski & Sarajedini 2002).

We made use of our own optical photometry along with 2MASS (Skrutskie et al. 2006) and WISE (Wright et al. 2010) infrared photometry to simultaneously derive the differences in true distance moduli [$\Delta(m-M)_0 = 2.45^{+0.11}_{-0.07}$] and optical depths ($\Delta\tau_1 = 0.278 \pm 0.053$) between the two clusters, assuming an extinction law based on the study by McCall (2004) with Cardelli et al. (1989) used to extend predictions to the WISE filters. $\Delta(m-M)_0$ is primarily determined by observations in the infrared where the extinction is small, while $\Delta\tau_1$ is constrained by the variation in the extinction from filter to filter. The fit is shown in Figure 6. The uncertainties on each measurement are based on uncertainties on the medians of each clump (dominated by the uncertainties for NGC 7142), and the goodness of fit was calculated using a $\chi^2$ algorithm. The uncertainties in $\Delta(m-M)_0$ and $\Delta\tau_1$ were derived from the ranges covered by fits that were within 1 of the minimum value. Using the well-determined distance modulus ($\langle m-M \rangle_0 = 9.60\pm0.03$; Sandquist 2004) and

![Figure 5. Observed time of eclipse vs. prediction of the linear ephemeris for V375 Cep from our photometric observations. Primary eclipses are shown with •, and secondary eclipses are shown with ○.](image-url)
reddening \((E(B-V) = 0.041 \pm 0.004; \text{Taylor 2007})\) for M67, we find \((m - M)_0 = 12.05^{\pm 0.11}\) and \(E(B-V) = 0.29 \pm 0.05\) for NGC 7142. Because there appears to be a significant amount of differential reddening in the cluster, infrared colors should be employed when possible. We discuss below the characteristics of each system that we are able to exploit to produce temperature estimates from the photometry of the binary stars.

The characteristics of the binary systems make it possible to obtain good estimates of the colors of the component stars. Table 3 lists the photometry for the binary systems and their components, and Figure 4 shows their positions in the CMD.

For V2, the two eclipses are deep and very nearly the same in depth, which supports our later results (Section 4.2.1) that the two stars are nearly identical in all of their major characteristics. As a result, the system color is an excellent representation of the star colors. (The components are therefore about 0.75 mag fainter than the combined photometry.) Later results also indicate that the binary is probably not a member of the cluster, and is slightly behind the cluster. To get a temperature estimate, we therefore use the infrared colors of the binary

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Table 3

| Star | B   | V   | R_C | I_C | J   | H   | K_s |
|------|-----|-----|-----|-----|-----|-----|-----|
| V1   |     |     |     |     |     |     |     |
| Combined | 15.695 ± 0.009 & 14.864 ± 0.010 & 13.825 ± 0.010 & 13.096 ± 0.027 & 12.757 ± 0.035 & 12.671 ± 0.029 |
| Primary | 16.29 | 15.46 | 14.43 | 13.70 | 13.37 | 13.28 |
| Secondary | 16.63 | 15.79 | 14.75 | 14.02 | 13.67 | 13.59 |
| V2   |     |     |     |     |     |     |     |
| Combined | 16.107 ± 0.008 & 15.310 ± 0.009 & 14.300 ± 0.009 & 13.661 ± 0.032 & 13.342 ± 0.035 & 13.227 ± 0.037 |
| V375 Cep | Combined | 16.992 ± 0.009 & 16.115 ± 0.010 & 15.035 ± 0.011 & 14.326 ± 0.031 & 13.877 ± 0.040 & 13.814 ± 0.048 |
| Ecl. Depth | 0.092 ± 0.008 & 0.118 ± 0.004 & 0.140 ± 0.001 & 0.154 ± 0.007 |
| Primary | 17.084 ± 0.012 & 16.233 ± 0.011 & 15.189 ± 0.013 |
| Secondary | 19.72 ± 0.09 & 18.58 ± 0.04 & 17.23 ± 0.05 |

Table 4

| Filter | mJD^a |
|--------|-------|
| V1     |       |
| P      | 53639.9256 ± 0.0006 |
| P      | 54657.7878 ± 0.0005 |
| S      | 54678.7786 ± 0.0008 |
| S      | 55355.7864 ± 0.0008 |
| S      | 55833.7955 ± 0.0007 |
| P      | 55390.8320 ± 0.0009 |
| S      | 55411.8168 ± 0.0014 |
| V2     |       |
| P      | 53693.6889 ± 0.0002 |
| P      | 54656.9770 ± 0.0011 |
| P      | 55423.8558 ± 0.0011 |
| P      | 55517.7581 ± 0.0002 |
| P      | 55736.8673 ± 0.0003 |
| S      | 55755.9707 ± 0.0004 |
| P      | 55783.8178 ± 0.0003 |
| S      | 55802.9238 ± 0.0026 |
| S      | 55849.8720 ± 0.0011 |
| V375 Cep |       |
| P      | 46650.4845 ± 0.0005 |
| P      | 47442.81 ± 0.025 |
| P      | 47409.659 ± 0.004 |
| S      | 55394.9749 ± 0.0066 |
| S      | 55396.8816 ± 0.0003 |
| S      | 55598.7923 ± 0.0005 |
| P      | 55739.7467 ± 0.0002 |
| S      | 53600.7011 ± 0.0006 |
| S      | 53637.9396 ± 0.0003 |
| P      | 53639.8496 ± 0.0002 |
| S      | 53640.8054 ± 0.0004 |
| P      | 53641.7594 ± 0.0002 |
| P      | 54630.9733 ± 0.0024 |
| S      | 54633.8450 ± 0.0016 |
| S      | 54634.7949 ± 0.0007 |
| P      | 54655.8013 ± 0.0003 |
| S      | 54656.7542 ± 0.0008 |
| S      | 54657.7114 ± 0.0002 |
| P      | 54675.8491 ± 0.0012 |
| P      | 54676.8071 ± 0.0005 |
| P      | 54677.7630 ± 0.0007 |
| P      | 54678.7170 ± 0.0004 |
| P      | 55121.7629 ± 0.0005 |
| S      | 55146.5934 ± 0.0009 |
| S      | 55372.8853 ± 0.0012 |

Note. ^a mJD = HJD – 2400000.
and assume that the reddening and metallicity of the binary are close to that of NGC 7142. Using these assumptions, we find $T_{\text{eff}} = 6150 \pm 200$ K from the $(J - K_S)$ color using the color–temperature calibration of Casagrande et al. (2010). The temperatures derived from optical colors are consistent with this estimate, but are much more uncertain due to reddening uncertainties.

The main difficulty for V1 is that it appears to be a foreground system, and so the cluster metallicity and reddening do not apply. However, we can derive fairly accurate temperature estimates if we note that the stellar temperatures only differ by a little under 2% according to later models (see Section 4.3), so that the system color will be a fair representation of the colors of the components. (The luminosities of the stars differ, however, so we have used the results of the binary models to determine the fraction of the flux contributed by each star. The estimates of the component magnitudes are given in Table 3, and the results are plotted in Figure 4.) We can minimize the effects of reddening uncertainties by using infrared colors. A reddening approximately equal to the mean cluster reddening gives an upper limit to the average temperature of about 6120 K. Given the slightly super-solar masses of the stars (again, see Section 4.3), the Sun’s temperature provides us with a lower temperature limit. Temperature uncertainty due to the unknown metallicity is likely to be small (a few 10s of K) as long as the stars have near-solar abundances. Based on these arguments we constrain the primary (hotter) star temperature to be between 5850 K and 6250 K.

In the case of V375 Cep, we can see a period of totality in the secondary eclipse, so that the light from the secondary star can be precisely disentangled from that of the primary. The errors on the secondary star photometry in this case are calculated from

$$
\sigma^2(m_2) = \sigma^2(m_{12}) + \frac{\sigma^2(\Delta m_2)}{(10^{\Delta m_2/2.5}) - 1)^2}
$$

where $m_2$ is the secondary magnitude, $m_{12}$ is the binary magnitude, and $\Delta m_2$ is the secondary eclipse depth. For shallow eclipse depths, the factor in the denominator of the second term amplifies the uncertainty considerably.

We do not have measurements of the secondary eclipse depths in infrared filters for V375 Cep, so we resort to optical/near-infrared colors. These imply $T_A = 6080 \pm 170$ K for the primary star, again using the Casagrande et al. (2010) calibration. For comparison, we obtained a temperature 6230 $\pm$ 100 K, $[M/H] = 0.09 \pm 0.05$, and $[\alpha/Fe] = 0.0 \pm 0.15$ from our spectroscopic analysis in Section 3.2. There is greater uncertainty for the secondary star resulting from the uncertainties in the photometric deconvolution, but the most certain determination using the $(V - I)$ color puts its temperature at about 5050 $\pm$ 180 K.

4. ANALYSIS OF THE DETACHED ECLIPSING BINARIES

To model the radial velocities and photometry from MLO, we used the Eclipsing Light Curve code (hereafter ELC; Orosz & Hauschildt 2000). ELC is a versatile code, and we briefly describe the most relevant features here. ELC is capable of fitting for a number of different binary star parameters depending on the situation, and the quality of the model fit was judged by an overall $\chi^2$. The minimum value can be sought using a genetic or Markov chain Monte Carlo algorithm. After an initial optimization run, the error bars on the data were scaled to return a reduced $\chi^2 = 1$ for each type of measurement. The reason for this is that the magnitudes of the estimated measurement uncertainties affect the uncertainties in the derived parameters through the $\chi^2$ values. So to maximize the reliability of the parameter uncertainty estimates, we use observational uncertainties that are reflective of scatter around a best fit model. The quoted parameter uncertainties are based on the range of values that produce a total $\chi^2$ within 1 of the minimum value (Avni 1976).

For light curve models, we made use of ELC’s ability to describe center-to-limb intensity variations using either analytic limb darkening laws or model atmospheres. When using analytic limb darkening, we chose a quadratic law with two coefficients for each star, where the coefficients are expected to be dependent on surface temperature, gravity, and composition. Because of the possibility that systematic errors might be introduced through the use of incorrect limb darkening coefficients, we selected one coefficient ($x$) for each star from ATLAS atmospheres (Clarét 2000) and fit for the other coefficient ($y$). The effects of systematic errors in one coefficient can be mitigated by such a fit because the coefficients tend to be correlated (Southworth et al. 2007). Alternatively, we used PHOENIX model atmospheres (Hauschildt et al. 1997) to describe the variation of emitted intensity with emergent angle, which removes the need to assume limb-darkening coefficients. However, systematic errors could still be introduced to our binary models if the $T_{\text{eff}}$ values we used are incorrect or if there systematics in the atmosphere models.

4.1. V375 Cep

The light curves (with primary and secondary eclipses of different depths, as seen in Figures 7 and 8) and radial velocities for V375 both implied from the start that the mass ratio for this system was likely to be significantly different from 1. This led us to believe that the system’s light was dominated by one of the stars, and that star therefore resided close to the cluster turnoff. The decomposed photometry shown in Figure 4 confirms this, and makes the primary star an excellent candidate for constraining the cluster age if it is a member.

Another notable feature of the light curves for this system is the small amount of out-of-eclipse light variation. This can be seen especially in the $R_C$ light curve, which generally had the images with the highest signal-to-noise ratio and also had the best coverage of out-of-eclipse phases. In spite of the rather short orbital period, effects due to the distortion of the stellar surfaces by the other star are barely discernable. Most of the scatter in other filter bands comes from observations made during poor weather conditions. However, there is a hint that stellar activity might be producing some night-to-night variations in $B$. More observations would be needed to confirm this.

4.1.1. Radial Velocity Modeling

Because this binary appears to be circularized and there is little or no out-of-eclipse light variation, the light curves do not effectively constrain the mass ratio of the stars. Therefore we modeled the radial velocities separately from the light curves. In the radial velocity models, we fit for the velocity semi-amplitude of the primary star $K_A$, the mass ratio $q = M_B/M_A$, and the system velocity $\gamma$ as parameters. We did an experiment where we allowed the system velocities to differ for the two stars (to allow for differences in gravitational redshift or convective blueshift resulting from their differing evolutionary states), but found a difference of only 0.1 km s$^{-1}$. This negligibly affected the derived masses.
Table 5
Characteristics of the Eclipsing Binaries

| Parameter | V375 Cep | V2 | V1 |
|-----------|---------|----|----|
|           | Limb Darkening | Atmospheres | Limb Darkening | Atmospheres | Limb Darkening | Atmospheres |
| $\gamma$ (km s$^{-1}$) | $-49.86 \pm 0.05$ | | $-42.64 \pm 0.02$ | $-42.66$ | $-17.16^{+0.03}_{-0.09}$ |
| $q$ | $0.676 \pm 0.004$ | | $1.0001 \pm 0.0033$ | $0.9992$ | $0.951 \pm 0.004$ |
| $K_A$ (km s$^{-1}$) | $89.13 \pm 0.24$ | | $69.92 \pm 0.20$ | $69.91$ | $80.81 \pm 0.30$ |
| $v_{\text{rot}}(A)$ (km s$^{-1}$) | $42^{+2}_{-0.1}$ (set) | | $20^{+1}_{-0.3}$ (set) | | |
| $v_{\text{rot}}(B)$ (km s$^{-1}$) | $16^{+2}_{-0.3}$ (set) | | $10^{+1}_{-0.3}$ (set) | | |
| $t_0 = 2450000$ | $3599.74650$ | $3599.74651$ | $5502.85043$ | $5502.8507$ |
| $\sigma(n_0)$ | $\pm 0.00007$ | $\pm 0.00008$ | | | $\pm 0.00008$ |
| $t_0 = 2450000$ | $3599.74650$ | $3599.74651$ | $5502.85043$ | $5502.8507$ |
| $P$ (days) | $1.90968257$ | $1.90968252$ | $15.6505950$ | $15.6505954$ | $4.6690576$ |
| $\sigma(P)$ (days) | $\pm 0.00000016$ | $\pm 0.00000018$ | $\pm 0.0000016$ | $\pm 0.0000007$ |
| $i$ (°) | $85.34^{+0.02}_{-0.05}$ | $85.39^{+0.03}_{-0.02}$ | | | |
| $e$ | $0$ (set) | | $52.165 \pm 0.00002$ | $52.158$ | $0.0379^{+0.0031}_{-0.0004}$ |
| $a (\) /a$ | $90$ (set) | | $326.692 \pm 0.003$ | $326.696$ | $285.0^{+0.1}_{-0.2}$ |
| $R_A/a$ | $0.1937 \pm 0.0003$ | $0.1958 \pm 0.0004$ | $0.04381 \pm 0.00011$ | $0.04350$ | $0.0877 \pm 0.0009$ |
| $R_A/R_B$ | $1.8098 \pm 0.0018$ | $1.840 \pm 0.002$ | $1.0022 \pm 0.0030$ | $0.9847$ | $1.140^{+0.010}_{-0.021}$ |
| $R_B/a$ | $0.10704 \pm 0.00020$ | $0.1064^{+0.0014}_{-0.0003}$ | $0.04372 \pm 0.00012$ | $0.04417$ | $0.0769 \pm 0.0007$ |
| $(R_A + R_B)/a$ | $0.3008 \pm 0.0005$ | $0.3023 \pm 0.0006$ | $0.08753 \pm 0.00012$ | $0.08767$ | $0.1647 \pm 0.0003$ |
| $T_B/T_A$ | $0.8268 \pm 0.0008$ | $0.8122 \pm 0.0012$ | $0.9969 \pm 0.0005$ | $0.9944$ | $0.983 \pm 0.002$ |
| $M_A (M_\odot)$ | $1.288 \pm 0.017$ | $1.288 \pm 0.17$ | $1.377 \pm 0.009$ | $1.379$ | $1.147 \pm 0.012$ |
| $M_B (M_\odot)$ | $0.871 \pm 0.008$ | $0.871 \pm 0.008$ | $1.377 \pm 0.009$ | $1.378$ | $1.090 \pm 0.013$ |
| $R_A (R_\odot)$ | $1.623 \pm 0.006$ | $1.642 \pm 0.007$ | $1.616 \pm 0.005$ | $1.605$ | $1.338 \pm 0.008$ |
| $R_B (R_\odot)$ | $0.897 \pm 0.003$ | $0.893 \pm 0.004$ | $1.613 \pm 0.005$ | $1.630$ | $1.190 \pm 0.008$ |
| log $g_A$ (cgs) | $4.129 \pm 0.003$ | $4.120 \pm 0.003$ | $4.160 \pm 0.003$ | $4.166$ | $4.244 \pm 0.007$ |
| log $g_B$ (cgs) | $4.473 \pm 0.002$ | $4.478 \pm 0.002$ | $4.462 \pm 0.003$ | $4.452$ | $4.324 \pm 0.007$ |

The initial estimates of the velocity uncertainties for the two stars were scaled separately to return reduced $\chi^2$ values of 1. After scaling, the typical uncertainties were 0.5–2 km s$^{-1}$ for the primary and 2–4 km s$^{-1}$ for the secondary. Once the light curves were modeled, the orbital inclination $i$ was used in a final modeling run to derive the stellar masses. The results are given in Table 5.

4.1.2. Light Curve Modeling

In our fits of the light curves, we separately ran models using a quadratic limb darkening law and using PHOENIX model atmospheres. When using model atmospheres, the limb darkening is fully described, and so we fitted for six parameters: orbital period $P$, time of primary eclipse $t_0$, inclination $i$, ratio of the primary radius to average orbital separation $R_A/a$, ratio of radii $R_A/R_B$, and temperature ratio $T_B/T_A$. In the models using a limb darkening law, we fit for one coefficient of the limb darkening law for each star in each filter, thereby adding eight additional parameters. In both cases, the results of the radial velocity fits (specifically, $K_A$ and $q$) and the spectroscopic temperature of the primary star $T_A$ were input as constrained values along with their uncertainties. This means their values were allowed to vary, but models incur a $\chi^2$ penalty as the value deviates more and more from the constraint.

Although the out-of-eclipse light curve variations are small and indicate that there is little tidal distortion of the stellar surfaces, we find that if we assume that the two stars are spherical our radius measurements end up systematically higher by about 1%. This appears to be because the small out-of-eclipse variations are taken to be part of the eclipses in the fits. When we allow for nonsphericity though, we find good consistency between our model atmosphere and limb-darkening law fits.
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Figure 8. BVRI phased light curves for the detached eclipsing binary V375 Cep near its eclipses. Model fits (employing analytic limb darkening laws) are shown.

In a short period binary such as V375 Cep, stellar activity can produce variations in the light levels. For this reason, we opted to shift nights with eclipse observations to a common zero point (as determined by out-of-eclipse observations on the same night) in order to remove possible spot modulation. These shifts were never more than 0.025 mag, and were most frequently less than 0.015 mag. We did not do the same for nights when the system was observed completely out of eclipse so that we did not remove the signature of non-spherical stars. We will come back to the issue of whether more stellar activity should be present in Section 5.1.1.

4.2. V2

The light curves of V2 show two very deep (0.7–0.8 mag) eclipses per cycle (see Figure 9), and two components are very clearly seen in spectra of the system. The separation of the eclipses in phase ($\Delta \phi = 0.2206$) and the much longer duration of the shallower eclipse conclusively show that the system has a substantial eccentricity.

4.2.1. Combined Radial Velocity and Light Curve Modeling

For eccentric binaries, both the radial velocities and the light curves contain information on the orbits of the two stars, so it is more important to model the two datasets simultaneously. As we did with V375 Cep, we scaled the errors for each dataset (photometry by filters, radial velocities for each component) separately to produce a reduced $\chi^2$ value near 1.

For a combined run with model atmospheres, we fitted the binary with a set of 12 parameters: orbital period $P$, time of periastron $t_0$, velocity semi-amplitude of the primary star $K_A$, mass ratio $q$, system velocity $\gamma$, eccentricity $e$, argument of periastron $\omega$, inclination $i$, ratio of the stellar radii to average orbital separation $R_A/a$ and $R_B/a$, primary star temperature $T_A$, and temperature ratio $T_B/T_A$. When using a quadratic limb darkening law, we forced the fitted limb darkening coefficients to be the same for both stars due to the indications that the star temperatures, masses, and radii were nearly identical. Generally when limb darkening coefficients are fitted, they are not tied to the stellar temperatures. In our case, when we allowed the coefficients to vary independently, the fits converged on values that were significantly different for the two stars. The most likely reason is that systematic trends in the eclipse light curves were presenting $\chi^2$ incentives for the coefficients to differ.

We trimmed the light curve data down to observations in and near eclipse (see Figure 10) because of the lack of significant variation at other phases. As expected for a fairly long period binary, there is no sign of variation associated with nonsphericity of the stars. We did make zero point adjustments to the photometry (as we did for V375 Cep), but in all cases the shifts were less than 0.011 mag.

The main result of the analysis is that the two stars have very similar characteristics. In particular, the mass ratio $q$ is consistent with 1 to within the 1$\sigma$ uncertainty. As a result, we cannot definitively state which star is the more massive one, and so for the purposes of this paper, we will define the primary star to be the one eclipsed during the deeper eclipse. According to the binary star modeling, the primary star is slightly larger and hotter at about 2$\sigma$ and 4$\sigma$ levels of significance, respectively. However, the radius and temperature ratios only differ from 1 by less than a percent. These results are supported observationally.
by the very long eclipse ingresses and egresses with no sign of totality (in spite of an inclination found to be within 0.5 of 90°), and by the very similar depths of the eclipses.

4.3. V1

The combined photometry of this system puts it in the blue straggler portion of the cluster CMD, and when the components are decomposed, they fall at the blue end of the distribution of likely cluster stars at the turnoff. However, our radial velocities clearly identify it as a nonmember. Although we have only three radial velocity observations, we conducted trial model runs to get preliminary estimates of the star characteristics. As can be seen in Figure 11, the light curves show relatively shallow eclipses (≈0.08 and 0.12 mag), and the secondary eclipse is found at phase $\phi = 0.492$, indicating a slight eccentricity. Binaries with periods shorter than 5 days are typically found to be circularized even in young populations (Meibom & Mathieu 2005), so it is worth trying to establish how large the eccentricity is.

In a relatively short period binary like V1, it is not surprising to find some evidence of spot activity. During most nights of observation, there were few deviations in the light curve that could be identified with spot activity. However, on the night of one secondary eclipse (HJD 2455383.8), we found that the out-of-eclipse level was fainter than was typical in $R$ observations, and there was a difference in the pre- and post-eclipse levels as well. To correct for this to first order, we applied a zero point shift to observations from that night to bring the average out-of-eclipse level for that night into agreement with others.

We then followed a procedure similar to that of binary V2, modeling the radial velocities and photometry simultaneously. We used the same binary model parameters with the exception of substituting time of conjunction (primary eclipse) $t_c$ for time of periastron $t_0$. $t_c$ is more directly constrained by observations in our combined dataset for V1. The model fit indicates that the binary orbit has a very small but significant eccentricity (the radial velocities are nearly consistent with a circular orbit), and the long axes of the orbits are almost in the plane of the sky.

5. DISCUSSION

5.1. Mass, Radius, and Age

The masses and radii for the six stars are plotted in Figure 12. Comparing the results of limb darkening law and model atmosphere runs in Table 5, there are relatively small (≈1%) but significant differences in radius. In the discussion below, we use the results from limb darkening law runs for their greater ability to fit eclipse ingresses and egresses. However, it should be remembered that we have not identified the root cause of the differences.

5.1.1. V375 Cep

When the components of the two stars in V375 Cep are compared with isochrones in the $M$–$R$ plane, we are immediately confronted with several issues. The most striking one involves the radius of the lower mass secondary star in the V375 Cep system. A star of mass $0.87 M_\odot$ should have not have evolved significantly during the lifetime of a cluster like NGC 7142, but
we find that the star is more than 10% larger than expected from models. This kind of behavior has been seen before: Clausen et al. (2009) discuss well-studied eclipsing binaries in the field containing stars with masses of 0.80–1.10 $M_\odot$, finding that stars in binaries with short periods (0.6–2.8 days) tend to have larger radii and lower temperatures than predicted. Indicators such as spot-induced photometric variations and X-ray emission support the idea that stellar activity is related to the radius discrepancies (Torres et al. 2006). Stellar activity is thought to produce magnetic flux tubes that can inhibit the flow of the convective gas blobs that transport energy to the surface, forcing the star to grow in size to compensate for the lost transport capability. Stellar models have been produced that can reproduce such anomalously large radii via an ad hoc decrease in the mixing length parameter (Chabrier et al. 2007), or recently via a self-consistent (although one-dimensional) treatment of the magnetic field (Feiden & Chaboyer 2012).

Because the primary star has a larger mass, its convective envelope is predicted to be about an order of magnitude smaller in mass than that of the secondary star. As such, magnetic activity should play a less important role in influencing the energy transport in the outer layers of the star, and the radius should be closer to predictions for the cluster age (although it may still be inflated to a smaller degree). The decomposed photometry of the primary star places it toward the blue edge of the main sequence band for NGC 7142 (see Figure 13), supporting the idea that its temperature has not been affected significantly.

FL Lyr (Popper et al. 1986), V1061 Cyg (Torres et al. 2006), and EF Aqr (Vos et al. 2012) are three other short-period binaries ($P = 2.1782, 2.3467,$ and $2.8536$ days, respectively) containing inflated secondary stars and primary star masses ($1.218 \pm 0.016 M_\odot, 1.282 \pm 0.015 M_\odot,$ and $1.244 \pm 0.008 M_\odot$, respectively) similar to that of V375 Cep ($1.288 \pm 0.017 M_\odot$). In the cases of V1061 Cyg and FL Lyr, the primary star radius can be matched with standard models for reasonable ages of 2.4 and 3.4 Gyr. It should be understood that this is not conclusive evidence that the primary stars are free of influences that modify the radius. A modest increase in radius could be camouflaged as a larger age in both cases. For EF Aqr (which has the largest orbital period of the three systems), the primary star shows some signs of being affected. However, the secondary stars can be definitely tagged as unusual because their radii are significantly larger than could possibly be expected for reasonable ages at their lower masses.

V375 Cep is a potentially more interesting test case than those field binaries because the cluster age can be constrained independently using the CMD, and its orbital period is even shorter. Taking the mass and radius of the primary star at face...
value, an age of about 3.3–3.6 Gyr is indicated, depending on the model. This is consistent with results from isochrone fitting in the CMD (Sandquist et al. 2011). We also measured the rotational velocities of the two stars from broadening of the spectral lines. Because the binary has a short period and has circularized, the stars should have synchronized their spins with the orbit, and the measured rotational velocities are indeed consistent with synchronous rotation for the measured stellar radii. In order to check the possibility that magnetic activity is responsible for the unusually large radius of the secondary, we looked at several indicators. We see very little evidence of spot-induced light curve variations unless the variations occur preferentially in the $B$ bandpass. We looked for signs of X-ray emission in archival data from space-based missions. Although the cluster was observed by XMM-Newton (PI: Verbunt), no source was detected at the position of V375 Cep during a pointing of more than 10600 s. So we do not have corroborating evidence that magnetic activity is responsible for the unusual characteristics of the secondary. A search for emission in the core of the Ca~II lines is probably one of the more promising ways remaining for proving the presence of such activity.

Unfortunately, the primary star in V375 Cep is so far the only “normal” star that can be used to derive the age of NGC 7142 using the eclipsing binary technique. Other groups (Clausen et al. 2009; Torres et al. 2006) have attempted to derive age constraints from inflated stars like V375 Cep B using models with reduced convective mixing length, but this is beyond the scope of this study. Ideally a full analysis for this cluster would make use of three or more stars so that composition questions could be addressed. Helium, for example, is one of the more substantial unknowns affecting an age analysis, and its abundance for stars of super-solar metallicity is still somewhat uncertain. However, the helium abundance can be inferred from the shape of the mass-radius isochrones if the observational data is sufficiently precise (Brogaard et al. 2011, 2012). Brogaard et al. discussed the old, very metal-rich cluster NGC 6791, which has a helium abundance significantly above the solar value. NGC 7142 stars have metal content a little less than halfway between the Sun and NGC 6791. Until we have additional cluster stars for analysis, we will implicitly be using helium enrichment laws assumed by the different model isochrones, meaning that the helium abundance will be super-solar. This enrichment will have an effect on the age determination if the assumed value is significantly in error.

Figures 13 and 14 show a CMD of the cluster with isochrones pinned to the position of V375 Cep A at the mass measured here. Generally speaking, isochrones of the age implied by the binary star analysis are consistent with cluster photometry as well. The details differ between isochrone sets due to differences in physics. NGC 7142 is in a range of ages where the physics of the convective core (including core overshooting and CNO cycle reaction rates) is important.

The photometry of V375 Cep B is consistent with that of a cluster main sequence star, although the position predicted for a star of its mass from isochrones is only marginally consistent with the photometry. Indications from field binaries (Stassun et al. 2012) are that chromospheric activity tends to increase the stellar radius and decrease effective temperature in a way that leaves the luminosity unchanged. In short period binaries such as V1061 Cyg (Torres et al. 2006), activity induced by forced synchronous rotation also appears to drive similar changes that keep the luminosity approximately constant.

Because of its position in the CMD, the determination of the mass of V375 Cep A is essentially a direct measurement of the turnoff mass for the cluster. Single stars appear to reach slightly bluer colors just before starting their subgiant branch evolution toward the red giant branch, but V375 Cep A is quite close to bluest point on the main sequence, which is the traditional definition of the turnoff. Subsequent evolution is comparatively rapid, and this places a strong upper limit on the age of the cluster. Isochrones with ages of 4 Gyr or above would require a
star of V375 Cep A’s mass to have evolved significantly to the blue (and then red). We can therefore rule out the much greater age (6.9 ± 0.9 Gyr) determined by Janes & Hoq (2011) in their study of the cluster CMD.

As we discussed in a study of eclipsing binaries in the somewhat younger cluster NGC 6819 (Sandquist et al. 2013), the Dartmouth isochrones (Dotter et al. 2008) are to be preferred among current publicly available isochrones because they include the most up-to-date inputs for physics that affects the evolution of turnoff-mass stars. Since that paper, the PARSEC models (Bressan et al. 2012) have been revised, and contain similar input physics. One important difference between the Dartmouth and PARSEC models and most others is the inclusion of an improved nuclear reaction rate for the CNO cycle reaction $^{14}$N($p, \gamma$)$^{15}$O. In addition, stellar model calculations typically include a varying amount of convective core overshooting for stars with masses around that of V375 Cep A. The amount (expressed in units of the pressure scale height $H_P$) is typically ramped up from zero at a lower mass limit (1.1 $M_{\odot}$ for the Dartmouth models) to a maximum value at a high mass limit (0.2 $H_P$ at 1.3 $M_{\odot}$). Both physics effects have minimal effects on the CMD except near the cluster turnoff and subgiant branch, where the details of central hydrogen exhaustion in the stars significantly influence the shape of the isochrones. With the possibility of nailing down the isochrones at the position of one or more binary stars, we therefore have leverage to test the physics of the stellar cores. This test would be stronger in NGC 7142 if the effects of differential reddening and field star contamination could be reduced. Until then, the indications are that different isochrone sets can reproduce the cluster turnoff in a qualitative sense.

Before leaving the discussion of this binary star, we use the stars to calculate a distance modulus for the cluster. From the measured radius and effective temperature, we can calculate the bolometric luminosity. For the temperature, we have used the spectroscopic estimate in order to avoid uncertainties associated with the cluster reddening. After applying a theoretical bolometric correction (VandenBerg & Clem 2003), we derive $M_V$ and the distance modulus. The primary star provides the best estimate $[m - M]_V = 12.86 \pm 0.07$ because its photometry and its effective temperature are better constrained, but the measurement from the secondary star is completely consistent $[m - M]_V = 12.86 \pm 0.15$ if the star’s temperature is derived from the effective temperature of the primary and the temperature ratio from the light curve fits using the analytic limb darkening law. These measurements are in nice agreement with our previous determination using the CMD (12.96 ± 0.24; Sandquist et al. 2011), but are of higher precision and effectively independent of any need for reddening estimates.

5.1.2. V2

In the case of the V2 system, we find that the masses and radii (as well as their temperatures) agree to within 1%, and the masses are consistent with being equal to within the 1σ uncertainties. Both stars appear to have evolved significantly and equally in radius, and these facts imply that the characteristics of these stars were set early on in their evolution, and have remained unchanged. Nearly equal mass binaries are commonly found in the field and in cluster environments (see Reggiani & Meyer 2011 and references therein) in agreement with hydrodynamical simulations of fragmentation (e.g., Bate 2009) during the star formation process. It is difficult to imagine a process (such as stable mass transfer) that could have forced the masses of the stars to become equal after birth without circularizing the orbits. Even if one could, the differences in the prior rates of evolution for the stars (in other words, how much of the central hydrogen had been processed to helium) would produce differences in radius. The equality of the stars along with their eccentric orbits imply that they have evolved undisturbed since their formation.

If V2 was a current or former member of NGC 7142 and had the same chemical composition, we should expect the stars to fall on the same isochrone as the primary star in V375 Cep. The characteristics of the stars of V2 differ from the isochrone that falls on the same isochrone as the primary star in V375 Cep. The uncertainties in their orbit imply that they have evolved undisturbed since their formation.

Figure 14. ($V, V - I_C$) color–magnitude diagrams for NGC 7142 compared with isochrones (ages 3.3, 3.5, and 3.7 Gyr) fitted to the mass and photometry of V375 Cep A, with symbols as in Figure 13.
be about 1.5 Gyr younger. This is the most convincing evidence that the stars in V2 are not cluster members—the mass and radius pairs imply age and/or chemical composition that is significantly different than the cluster. A calculation of the distance modulus for this binary star using the photometric temperature estimate returns \((m - M)_V = 12.55 \pm 0.09\), which is significantly smaller than found for the cluster member V375 Cep.

5.1.3. V1

The binary star V1 has essentially zero probability of cluster membership based on its system velocity and the signs that its reddening is lower than the other binaries. Because the stars are part of a relatively short period binary, we checked to see whether there were signs of radius inflation, as there is for V375 Cep B (see the earlier discussion). Although the metallicity of the binary has not yet been determined, the two stars have positions in the \(M-R\) diagram that are consistent with being on the same isochrone. Both stars are likely to still have convective envelopes but with smaller mass than the Sun’s, and the period of the binary is larger than found for other systems with seemingly inflated stars. V636 Cen (Clausen et al. 2009) is an interesting comparison, having a slightly shorter period (4.28 days) than V1, but having a secondary star of lower mass (0.87 \(M_\odot\)) with a more massive convective envelope. Based on a simple interpretation of the stellar activity hypothesis, the two stars should be expected to show small or no radius inflation.

The small eccentricity \((e = 0.038)\) that is detected is also of some interest. The circularization timescale for the binary is around a Gyr according to the formulation in Zahn (1977) for stars with convective envelopes—less than, but of similar magnitude to, the age of the binary. It is therefore plausible that the circularization process has not been completed for this binary. If this binary does not have a third orbiting object that is maintaining the eccentricity, we could be seeing the final stages of circularization as brought on by the evolutionary expansion of the stars. Their expansion, even over the last Gyr, has significantly decreased the circularization timescale by about a factor of two.

Because the metallicity of the binary is not known, it is not possible to derive a precise age, but the indication is that the binary is slightly older (~1 Gyr) than NGC 7142. To put this differently, any isochrone that connects the two stars in V1 does not pass through the error ellipse for the primary star in V375 Cep. This provides more evidence that the system is not a member of NGC 7142, if any was needed.

6. CONCLUSIONS

We have studied three DEB stars that were discovered near the turnoff of the open cluster NGC 7142 in the CMD. From multiple lines of evidence, we conclude that the V375 Cep system is the only one of the three that is a cluster member. The measured mass and radius of the primary star of V375 Cep support an age of 3.3–3.6 Gyr for the cluster. We are also able to compute a distance modulus for the cluster \([(m - M)_V = 12.86 \pm 0.07]\) that is mostly independent of estimates of the cluster reddening.

V375 Cep is a short period binary, however, and this appears to be responsible for the abnormally large radius of the secondary star. Because the binary has total eclipses of the secondary star, we can accurately disentangle the photometry of the two stars. Because the binary is a member of the cluster, we can use the photometry for other cluster stars to judge whether the components of V375 Cep have experienced a color/temperature shift. The primary star is found toward the blue end of the cluster main sequence band, so its surface does not appear to have been affected by the interactions with its companion. The secondary star shows clear evidence that its radius has been inflated, and there is some marginal evidence that it is slightly redder in the \((V - I_c)\) color than predicted by models. Higher precision observations of the secondary eclipse will be needed to prove this point more definitively.

In order to further test the connection between magnetic activity and the inflated radius of the secondary, additional targeted observations are called for. Our spectroscopy has provided rotational velocities for the stars that are consistent with synchronous rotation, supporting the possibility of rotationally-induced activity, but there are not yet strong tests of magnetic activity in the system. X-ray emission might reveal activity in the system, although the archived XMM-Newton integration did not reveal V375 Cep to be a significant X-ray source. Because V375 Cep is more distant than commonly studied field binaries, deeper observations would be challenging. A search for emission in the cores of the Ca II H and K lines (Clausen et al. 2009) would seem to be the best next test.

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