THE CLUSTER AGES EXPERIMENT (CASE). III. ANALYSIS OF THE ECCENTRIC ECLIPSING BINARY V32 IN THE GLOBULAR CLUSTER NGC 6397

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ABSTRACT

We present spectroscopic and photometric observations of the eclipsing binary V32 located in the central field of the globular cluster NGC 6397. The variable is a single-line spectroscopic binary with an orbital period of 9.8783 days and a large eccentricity of $e = 0.32$. Its systemic velocity ($v = 20.7 \text{ km s}^{-1}$) and metallicity ([Fe/H] $\sim -1.9$) are both consistent with cluster membership. The primary component of the binary is located at the top of the main-sequence turnoff on the cluster color–magnitude diagram. Only a shallow primary eclipse is observed in the light curve. Based on stellar models for an age of 12 Gyr and the mass function derived from the radial velocity curve, we estimate the masses to be $M_p = 0.79 M_\odot$ and $M_e = 0.23 M_\odot$. The light curve of V32 can be reproduced by adopting $R_p = 1.569 R_\odot$ and $R_e = 0.236 R_\odot$ for the radii and $i = 85.44^\circ$ for the system inclination. The system geometry precludes observations of the secondary eclipse. The large eccentricity of the orbit is puzzling given that for metal-poor, halo binaries the transition from circular to eccentric orbit occurs at an orbital period of about 20 days. We suppose that the orbit of V32 was modified relatively recently by dynamical interaction with other cluster star(s). An alternative explanation of the observed eccentricity calls for the presence of a third body in the system.

Key words: binaries: spectroscopic – stars: individual (V32-NGC 6397)
Online-only material: machine-readable and VO tables

1. INTRODUCTION

Little is known about the properties of main-sequence binary stars in globular clusters. These systems offer the potential for measurements of cluster age and distance independent of cluster main-sequence fitting (see, for example, Paczyński 1997; Thompson et al. 2001), and as test beds for theories of the stellar evolution of Population-II stars.

The eclipsing binary V32-N6397 (hereafter V32) was discovered by Kaluzny et al. (2006) during a survey for variable stars in the central field of the globular cluster NGC 6397. They observed only one shallow eclipse event with a depth of about 30 mmag. With $V_{\text{max}} = 16.13$ the variable is located at the very top of the cluster main sequence, and is a candidate member of NGC 6397. In this paper, we report results of follow-up photometric and spectroscopic observations of V32. Section 2 describes new photometry and a measurement of the spectroscopic orbit of V32. A self-consistent model of the system is presented in Section 3. Finally, Section 4 briefly discusses the implications of the large measured eccentricity of the orbit of V32.

2. SPECTROSCOPIC AND PHOTOMETRIC OBSERVATIONS

Spectroscopic observations of V32 stars were carried out with the MIKE echelle spectrograph (Bernstein et al. 2003) on the Magellan II (Clay) telescope at Las Campanas Observatory. The data were collected during several observing runs between 2005 May and 2007 August. For this analysis, we use data obtained with the blue channel of MIKE covering the wavelength range 3350–5000 Å at a resolving power of $\lambda/\Delta\lambda \approx 38,000$. All of the observations were obtained with a $0.7 \times 5.0$ arcsec slit and with $2 \times 2$ pixel binning. At 4380 Å, the resolution was $\sim 2.7$ pixels with a scale of 0.043 Å pixel$^{-1}$. The spectra were first processed using a pipeline developed by Dan Kelson following the formalism of Kelson (2003) and then analyzed further using standard tasks in the IRAF/Echelle package. Each of the final individual spectra typically consisted of two 30 s exposures interlaced with an exposure of a thorium–argon lamp. We obtained 16 spectra of V32.

Velocities were measured with the IRAF FXCOR package. For the template we used a single MIKE spectrum of the metal-poor subgiant HD 193901 ([Fe/H] $= -1.22$; Tomkin et al. 1992) with an adopted radial velocity of $-172 \text{ km s}^{-1}$. The velocity measurements were made over the wavelength range 4000–5000 Å with the Balmer lines masked out of the template and object spectra. There was no evidence for a second velocity peak in any of the object spectra and we conclude that the variable is a single-line spectroscopic binary. The observations are presented in Table 1 which lists the heliocentric Julian Date (HJD) at mid-exposure, the velocities of the primary and errors. All of these velocities as returned by the FXCOR routine.

The measured radial velocities of the primary were fitted with a nonlinear least-squares solution of the eccentric orbit using code written by G. Torres. The derived orbital elements are listed in the second column of Table 2. The quantity $T_1$ is the moment of periastron passage and the remaining...
By fitting five parameters we obtained a \( P \) value which exactly predicts the moment of superior conjunction. The shortest orbital period which gives a symmetric primary eclipse is \( P = 9.8779 \) days. For this period, we obtained \( T_1 = 2453899.8289 \). The solution with \( P = 9.8779 \) days and \( T_1 = 2453899.8289 \) correctly predicts the moment of superior conjunction. By fitting five parameters we obtained \( \gamma = 20.71 \pm 0.18 \) and \( K_r = 24.00 \pm 0.25 \). The instrumental setup and reduction methods were the same as those described in Kaluzny et al. (2006). These observations were mostly hampered by poor weather but on one of the nights we obtained some useful data covering the phases immediately preceding the predicted ingress into primary eclipse. These observations helped to constrain the spectroscopic solution as described above. The \( V \)-band light curve based on all available observations of V32 is shown in Figure 2 for the region of the light curve near the observed eclipse. It is phased with the spectroscopic ephemeris listed in the third column of Table 2. The continuous line shows the synthetic light curve corresponding to the model presented in the next section. The full \( V \)-band observation data set is given in Table 3. The \( V/B-V \) color–magnitude diagram for NGC 6397 based on the du Pont photometric observations is presented in Figure 3.

### 3. PROPERTIES OF V32

A direct determination of the absolute parameters of the components of V32 is hampered by the lack of velocity observations of the secondary. In the following analysis, we assume that the variable is a member of the globular cluster NGC 6397. This conclusion is based on four arguments. First, the systemic velocity of V32 (\( \gamma = 20.65 \pm 0.19 \) km s\(^{-1}\)) agrees with the mean velocity of the cluster determined by Meylan.
& Mayor (1991), \( V_{\text{rad}} = 18.1 \pm 0.1 \, \text{km s}^{-1} \) with a central velocity dispersion of 4.5 km s\(^{-1}\). Second, on the \( V/B - V \) diagram shown in Figure 3 the binary is located at the top of the cluster turnoff, the primary is apparently just beginning to evolve onto the cluster subgiant branch (SGB). Third, the variable is located on the sky only 51 arcsec from the projected center of NGC 6397. The cluster itself has a half-light radius to evolve onto the cluster subgiant branch (SGB). Assuming for the moment an orbital inclination of \( i = 90 \) deg, we use the measured mass function to derive a secondary mass of \( M_s = 0.232 \pm 0.003 M_\odot \). The Dotter et al. (2007) models then suggest a secondary radius of \( R_s = 0.236 R_\odot \).

We fit the light curve of V32 using the PHOEBE code (Prša & Zwitter 2005) which is based on the models of Wilson & Devinney (1971) and Wilson (1979). Two free parameters were fit: the inclination \( i \) and the radius of the primary. The remaining parameters were fixed as follows: the orbital elements were adopted from the third column of Table 2. The effective temperature of the primary was set at \( T_\text{p} = 6490 \, \text{K} \) based on an unreddened \( (B-V)_p = 0.368 \) and the empirical calibration of Worthey & Lee (2006). Following Gratton et al. (2003) we adopted \( (B-V) = 0.183 \). The temperature of the secondary was set at \( T_s = 3874 \, \text{K} \) using the Dotter et al. (2007) models. The solution converged to \( i = 84.96 \) deg and \( R_s = 1.53 R_\odot \). We then made one more iteration of the above procedure starting with \( i = 84.96 \) deg, \( M_s = 0.233 M_\odot \), and \( R_s = 0.237 R_\odot \). The solution converged to \( i = 85.03 \) deg and \( R_s = 1.53 R_\odot \). The calculated luminosity ratio in the \( V \)-band is \( L_p/L_s = 664 \). In the middle of the primary eclipse, the entire disk of the secondary is projected against the disk of the primary—the eclipse is a transit. The secondary (occultation) eclipse is not observable. The estimated radius of the primary is consistent with its location above the main-sequence turnoff on the color–magnitude diagram of the cluster. For a mass of 0.790\( M_\odot \) and an age of 12 Gyr the models of Dotter et al. (2007) predict a radius of \( r = 1.40 R_\odot \). For the same age, the radius reaches \( r = 1.54 R_\odot \) for a mass of 0.793\( M_\odot \). Given the approximate nature of our analysis, we consider the derived solution to be self-consistent.

Clearly, the limited data make a direct and accurate determination of the absolute parameters for components of V32 impossible. The light curve lacks a secondary eclipse and the photometric coverage of the primary eclipse is not complete. However, the deduced parameters of V32 reproduce its observed radial velocity and light curves well, and are self-consistent with evolutionary models of low-mass stars.

### 4. DISCUSSION

The properties of V32 are consistent with membership in the globular cluster NGC 6397. The system is composed of two main-sequence stars with an age of about 12 Gyr. The orbit shows a large eccentricity with \( e = 0.32 \). Such an eccentricity is unexpected since tidal forces should circularize the orbit of the binary on a short timescale. The theoretical and observational aspects of the circularization of binary orbits for solar mass binaries are discussed in some detail in Meibom & Mathieu (2005). They estimate, based on the results of Latham et al. (2002), that halo binaries with periods shorter than 15.6\( \pm 3.3 \) days should have circular orbits. For the old open clusters NGC 188 (age \( \approx 7 \) Gyr) and M67 (age \( \approx 4 \) Gyr) circularization has occurred for periods shorter than 14.5 days and 12.1 days, respectively.

Very little is known about globular cluster binaries with orbital periods longer than a few days. Several surveys for spectroscopic binaries among cluster giants were conducted in the

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**Table 3**

| HIP  | \( V \)     | \( \sigma_V \) |
|------|-------------|---------------|
| (−245000) | 16.128 | 0.008 |
| 2765.8121 | 16.128 | 0.008 |
| 2765.8209 | 16.134 | 0.008 |
| 2765.8277 | 16.128 | 0.008 |
| 2765.8371 | 16.126 | 0.008 |
| 2765.8677 | 16.125 | 0.008 |
| 2765.8894 | 16.129 | 0.008 |
| 2765.8966 | 16.122 | 0.008 |
| 2765.9061 | 16.129 | 0.008 |
| 2765.9128 | 16.127 | 0.008 |
| 2765.9294 | 16.131 | 0.008 |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

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**Figure 3.** Position of V32 in the \( V/B - V \) diagram for NGC 6397.
1980s and 1990s. They led to the detection of some candidates but generally spectroscopic orbits of these stars remain undetermined (Yan & Cohen 1996, see also references therein). Four eclipsing binaries with periods $4 < P < 10$ days were detected in the central part of 47 Tuc in the Hubble Space Telescope (HST)/WFPC2 survey by Albrow et al. (2001) using photometric observations. All of these have presumed circular orbits although observations do not cover the full orbital cycle for two of the systems with the longest periods. Extensive ground base surveys of 47 Tuc (Weldrake et al. 2004) and $\omega$ Cen (Kaluzny et al. 2004; Weldrake et al. 2007) led to the detection of two eclipsing binaries with orbital periods exceeding 10 days. Follow-up observations conducted by our group show that 47 Tuc-V69 and $\omega$ Cen-V406 have eccentric orbits with $P = 29$ days and $P = 71$ days, respectively (I. B. Thompson et al. 2008, in preparation).

All of the other cluster-eclipsing binaries reported so far have orbital periods less than 10 days and show circular orbits. The eccentric orbit of V32 can possibly be due to a relatively recent dynamical interaction of the binary with other cluster stars(s). NGC 6397 has a "collapsed" core (Djorgovski & King 1986) containing a population of about 20 X-ray sources including nine candidate cataclysmic variables, a millisecond pulsar, and seven young binaries with orbital periods exceeding 10 days. Follow-up observations conducted by our group show that 47 Tuc-V69 and $\omega$ Cen-V406 have eccentric orbits with $P = 29$ days and $P = 71$ days, respectively (I. B. Thompson et al. 2008, in preparation).

As an alternative explanation of the eccentric orbit of V32 we consider the possibility that the system is in fact a hierarchical triple. The third component located on the outer orbit is capable of generating eccentricity in the inner binary. Extensive reviews of the evolution of the orbits of binary stars have been presented by Eggleton (2006) and Mazeh (2008). Numerical simulations of stellar clusters predict dynamical formation of triple stars, especially in the presence of primordial binaries (McMillan et al. 1990; Heggie & Aarseth 1992). Examples of known triple stars in globular clusters include the pulsar PSR B1620-26 in M4 (Thorsett et al. 1993) and possibly the ultracompact X-ray binary 4U 1820-303 (Zdziarski et al. 2007). The hypothesis that V32 is a triple can be tested by spectroscopic observations aimed at the detection of variability of the systemic velocity of the putative inner binary. We see no systemic velocity residuals from the orbit given in Table 3 over the 2.2 year duration of our velocity observations.

Finally, we comment on the possibility that the eccentric orbit of V32 is related to its rather low mass ratio $q = M_2 / M_1 \approx 0.30$. According to Mathieu & Mazeh (1988), the timescale of circularization of a binary is related to $q$ by the relation $\tau_{\text{circ}} \propto q^{-3/2}(1 + q^{-1})^{1/3}$. This corresponds to an increase of $\tau_{\text{circ}}$ of a factor of 1.6 as the mass ratio ranges from $q = 1$ to $q = 0.3$. For low values of $q$, the contribution of the secondary to the circularization process becomes negligible (Mazeh 2008). At the same time $\tau_{\text{circ}}$ is a strong function of the orbital period $P$, with $\tau_{\text{circ}} \propto P^{10/3}$ (Zahn 1977). The net result is that the circularization period will lengthen as the mass ratio decreases from $q = 1$ and $q = 0.3$, especially for long-period systems. It is appropriate to note at this point that the sample of halo stars presented by Latham et al. (2002) consists entirely of single-line binaries and hence objects with mass ratios noticeably lower than unity. More globular cluster binaries with periods of the order of 10 days have to be detected and analyzed before V32 can be called a truly unusual system. The CASE group is in the process of collecting data which can shed more light on the relation between the eccentricity and orbital period for binaries in globular clusters.

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