A Turnoff Detached Binary Star V568 Lyr in the *Kepler* Field of the Oldest Open Cluster (NGC 6791) in the Galaxy

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ABSTRACT

We present the *Kepler* photometric light-variation analysis of the late-type double-lined binary system V568 Lyr that is in the field of the high metallicity old open cluster NGC 6791. The radial velocity and the high-quality short-cadence light curve of the system are analysed simultaneously. The masses, radii and luminosities of the component stars are $M_1 = 1.0886 \pm 0.0031 \, M_\odot$, $M_2 = 0.8292 \pm 0.0026 \, M_\odot$, $R_1 = 1.4203 \pm 0.0058 \, R_\odot$, $R_2 = 0.7997 \pm 0.0015 \, R_\odot$, $L_1 = 1.85 \pm 0.15 \, L_\odot$, $L_2 = 0.292 \pm 0.018 \, L_\odot$ and their separation is $a = 31.060 \pm 0.002 \, R_\odot$. The distance to NGC 6791 is determined to be $4.260 \pm 0.290 \, kpc$ by analysis of this binary system. We fit the components of this well-detached binary system with evolution models made with the Cambridge STARS and EV(TWIN) codes to test low-mass binary star evolution. We find a good fit with a metallicity of $Z = 0.04$ and an age of $7.704 \, Gyr$. The standard tidal dissipation, included in EV(TWIN) is insufficient to arrive at the observed circular orbit unless it formed rather circular to begin with.

Key words: binaries: close – binaries: eclipsing – stars: fundamental parameters – stars: individual: V568 Lyr – stars: low-mass – open clusters and associations: individual: NGC 6791

1 INTRODUCTION

Accurate photometric and spectroscopic observations of binary systems provide well-determined parameters of the components. These parameters, in turn, allow us to test stellar evolution models. Light variations of a large number of variable stars have been obtained by successful observations of the *Kepler* space telescope. The open stellar cluster NGC 6791 is one of the four open clusters that fall in the observed field of the *Kepler* project (Koch et al. 2010). It is the oldest open clusters in the Galaxy and contains many close and wide binary systems. However, only a few of them fall within *Kepler*’s view. Studies of binary systems that are members of a cluster allow us to estimate both the age of the host cluster and its distance.

Galactic clusters provide information about the evolution of the host galaxy. In this regard, old open clusters are crucial and NGC 6791, Be 17, M67, NGC 188, etc. (Phelps 1997; Bedin et al. 2008a; Melbom et al. 2009; Yakut et al. 2009; Basu et al. 2011; Brogaard et al. 2011) are important old open clusters. Binary systems that are members of clusters with different chemical composition are good targets to test how stellar evolution varies with composition, when we can determine their physical parameters and construct appropriate evolutionary models. The system V568 Lyr resides at the main-sequence turn-off in the colour–magnitude diagram (CMD) of the cluster and this turn-off point gives us information on the age of the cluster. Hence, the study of this particular system gives substantial information on both the stars and the cluster in which they reside. This is a crucial system, particularly given its detached configuration and accurate radial velocity curve and photometry.

Boesgaard, Jensen, & Deliyannis (2009) analysed the chemical composition of the stars at the turn-off of NGC 6791 with Keck + HIRES spectra and estimated the metallicity to be more than twice that of the Sun. Recently, Boesgaard, Lum, & Deliyannis (2014) repeated the study and similarly estimated [Fe/H] = 0.30 ± 0.02. Previous studies on the metallicity of the cluster give the [Fe/H] ratio as $0.30 \pm 0.40$ (Peterson & Green 1998;...
Brogaard et al. (2011, 2012) used binary system properties of V568 Lyr to estimate the age of the cluster to be 8.3 ± 0.3 Gyr consistent with other estimates of 8 – 10 Gyr (Brogaard et al. 2012; Boesgaard, Lum, & Deliyannis 2014). There have been a number of photometric studies of NGC 6791 and some of its stars. Montgomery et al. (1994) observed the cluster with the $UBV$ filters of the 0.9 m KPNO telescope. Stetson, Bruntt, & Grundahl (2003) obtained detailed $BVR$ observations with the 2.5 m Nordic Optical Telescope and obtained data for colour–magnitude and colour–colour diagrams. Platais et al. (2011) present comprehensive cluster membership and $g' r'$ photometry of the cluster. Using Kepler photometry, Corsaro et al. (2012) studied solar-like oscillations of red giants of the cluster. Photometric studies of some of the variable stars in NGC 6791 have also been made by Brogaard et al. (2011), Kaluzny & Rucinski (1993) and de Marchi et al. (2007).

V568 Lyr is a relatively long-period system so a full and accurate light curve of the system could not be obtained. Kaluzny & Rucinski (1993) and Rucinski, Kaluzny, & Hilditch (1996) determined its orbital period. Later Grundahl et al. (2008) and Brogaard et al. (2011) performed light and radial velocity analyses of ground-based data and determined masses of $1.0868 \pm 0.0039 M_\odot$ and $0.8276 \pm 0.0022 M_\odot$, radii of $1.397 \pm 0.013 R_\odot$ and $0.7813 \pm 0.0053 R_\odot$ for the primary and secondary components.

The field of NGC 6791 is rich in binary systems, most of which are members of the cluster. The systems V519 Lyr, V522 Lyr and V564 Lyr are interacting close binary systems. There is no published spectroscopic study of these systems. V568 Lyr is, on the other hand, a well-detached system and has excellent radial velocity curves (Grundahl et al. 2008; Brogaard et al. 2011). This, together with the new Kepler light curve, makes it important to determine accurate physical parameters of its components and so provide better distance and age estimates. Here, owing to their high sensitivity and quality, we use public Kepler observations supplemented with the radial velocity and abundance measurements of Grundahl et al. (2008) and Brogaard et al. (2011).

In the next section, we discuss the public Kepler data and the light curve and radial velocity data of V568 Lyr are solved simultaneously. In the third section, the parameters of the system and the distance to the cluster are determined. In the fourth section, non-conservative binary evolutionary models are constructed with $E(W_{TWIN})$ and then these are compared with those of earlier studies.

### 2 ANALYSIS OF THE KEPLER DATA AND LIGHT CURVE MODELLING

The Kepler space telescope has observed nearly 150000 stars with different properties, such as planetary components, pulsating stars, etc. The accuracy of the Kepler telescope is very high. Part of the NGC 6791 field is in the Kepler field. The binary system V568 Lyr is shown on the CMD of NGC 6791 in Fig. 1. Because it lies right at the main-sequence turn-off, its analysis is very important for the cluster as a whole. V568 Lyr was observed during quarters Q1 – Q17 with long cadence (exposure time of about 30 min) and one quarter (Q10) in short cadence (1 min). The observed parameters are summarized in Table 1. For the light-curve analysis, we selected the short-cadence Q10 public data that cover 30.11 d continuously. This covers more than twice the orbital period. The short cadence Kepler observations of V568 Lyr are shown in Fig. 2. The duration of the primary and secondary minima are almost same and are about 7.8 h. The secondary minima show a transit, and its duration is about 2.8 h. These properties of the light curve allow us to determine rather accurate relative radii of the components.

As well as the Kepler light curve, accurate radial ve-

| Table 1. Basic properties of V568 Lyr (KIC 2437452). Magnitudes, temperature and $E(B-V)$ are from Montgomery et al. (1994) and Brogaard et al. (2011) and other parameters from the Kepler Input Catalogue (KIC) and SIMBAD. |
|---------------------------------|---------------------------------|
| Kepler ID | 2437452 |
| 2MASS ID | 19205427+3745347 |
| $\alpha_{2000}$ | 19:20:54.28 |
| $\delta_{2000}$ | 37:45:34.7 |
| 2MASS $J$ | 15.513 mag |
| 2MASS $H$ | 15.057 mag |
| 2MASS $K_s$ | 15.076 mag |
| $K_{p,1}(Kepler)$ | 16.981 mag |
| $V_{12}$ | 17.54 mag |
| $T_{eff}$/K | 5645 |
| $E(B-V)$ | 0.16 |
| Spectral type | G5V + K3V |

Figure 1. The CMD of the open cluster NGC 6791. Data are from Stetson, Bruntt, & Grundahl (2003). The large filled circle indicates V568 Lyr, located at the main-sequence turn-off in the cluster CMD.
velocity observations of the system exist in the literature. Grundahl et al. (2008) and Brogaard et al. (2011) solved radial velocities with part of the light curve of V568 Lyr obtained with ground-based telescopes. Here, we use the highly accurate and full light curve obtained by Kepler. The system analysis is made simultaneously with Kepler photometric observations and the radial velocity curves. We expect to obtain more accurate orbital and physical parameters. The Kepler are solved with the PHOEBE code (Prša & Zwitter 2005, based on the Wilson & Devinney (1971) code. Initial parameters for the light–curve analysis are taken from Grundahl et al. (2008) and Brogaard et al. (2011). The gravity-darkening coefficients $g_1$ and $g_2$ are obtained from Lucy (1967). Albedos $A_1$ and $A_2$ are from Rucinski (1969) and the limb-darkening coefficients from Claret & Bloemen (2011). The orbital inclination $i$, mass ratio $q$, temperature of the secondary $T_2$, surface potentials $\Omega_1$ and $\Omega_2$, luminosity $L_1$, phase shift $\phi$, the time of minimum light $T_0$ and the orbital period $P$ are treated as free parameters. Previous observations have suggested a third body in the system so, during the light–curve analysis, the contribution of a third body to the total light parameter $l_3$ is added as a free parameter. With a detailed solution, the orbital, geometric and radiative parameters we obtain are given in Table 2. The results obtained from observations (dots) and from our light–curve model (solid line) are shown in Fig. 3a. To show the accuracy of the solution the residuals and minima are expanded in Figs 3b–d. In Fig. 3e, the radial velocity curves of the components and those calculated with simultaneous solutions are shown.

3 PHYSICAL PARAMETERS OF THE SYSTEM

Light curve analysis of V568 Lyr gives radii, as fractions of the separation, $R_1/a = 0.04568$ and $R_2/a = 0.02572$. These small ratios mean that the components closely preserve their spherical symmetry. Because of the high sensitivity of the Kepler data, the light curve of the system gives us the opportunity to determine much more accurately its inclination and especially the radii of the components relative to previous studies. Third light is detected at the level of 17 per cent. The reddening is computed, from $E(B − V)$ in Table 1, to be $A_V = 0.49$. Radial velocity curves yield the velocity amplitudes of the components as listed in Table 2.

When we leave the eccentricity as a free parameter during the solution it tends to zero. Using the orbital parameters (Table 2) we obtained the physical parameters of V568 Lyr and list them in Table 3. While solving, the temperature of the Sun is taken to be 5772 K and its bolometric magnitude to be 4.755 mag (Pecaut & Mamajek (2013)). The temperatures of the components with the Flower (1996) tables give the bolometric corrections as BC1 = −0.10 mag, and BC2 = −0.44 mag. Using these BC values for $V$ band, we then obtain the absolute magnitudes of the components. These new estimates of the system parameters, with the magnitudes and reddening, reveal the distance of the system to be 4.26 ± 0.29 kpc. The masses we find are consistent with those found by Brogaard et al. (2011). The radius of the primary star, on the other hand, is estimated to be

![Figure 2. Short-cadence Kepler observations of V568 Lyr.](image-url)

Table 2. Photometric and spectroscopic elements of V568Lyr and their formal 1σ errors. See text for details.

| Parameter                  | Value (1σ Error)       |
|----------------------------|------------------------|
| $T_0$ as JD/d − 2400000    | 5574.71981(46)         |
| $P/d$                      | 14.47672(50)           |
| $i/\circ$                  | 89.05(4)               |
| $\Omega_1$                | 21.71(5)               |
| $\Omega_2$                | 32.87(3)               |
| $q = m_2/m_1$              | 0.7616(1)              |
| $T_1/K$                    | 5645                   |
| $T_2/K$                    | 4734(80)               |
| Luminosity ratios:         |                        |
| $l_1/l_{total}$            | 74.5%                  |
| $l_2/l_{total}$            | 8.5%                   |
| $l_3/l_{total}$            | 17.0%                  |
| Fractional radius of primary ($R_1/a$) | 0.04568(11)           |
| Fractional radius of secondary ($R_2/a$) | 0.02572(10)        |
| $K_1$/km s$^{-1}$          | 46.92(9)               |
| $K_2$/km s$^{-1}$          | 61.60(12)              |
| System velocity $V_\gamma$/km s$^{-1}$ | −46.6(1)              |
| $e$                        | 0.000(0.001)           |
| $a/R_\odot$               | 31.060(2)              |
Table 3. Absolute parameters of V568 Lyr. Standard errors of 1σ in the last digits are given in parentheses.

|                      | Primary       | Secondary     |
|----------------------|---------------|---------------|
| Masses M/M⊙         | 1.0886(31)    | 0.8292(26)    |
| Radii R/R⊙          | 1.4203(58)    | 0.7997(15)    |
| Effective temperatures T_{eff}/K | 5.645(95) | 4.734(80)    |
| Luminosities L/L⊙    | 1.846(15)     | 0.292(18)     |
| Surface gravity log_{10}(g/cm s^{-2}) | 4.170(44) | 4.551(33)    |
| Absolute bolometric magnitude M_B    | 4.09(7) mag  | 6.09(7) mag   |
| Absolute visual magnitude M_V     | 4.19(8) mag  | 6.53(8) mag   |
| Separation between stars a/R⊙     | 31.06(3)     |               |
| Distance d/pc         | 4260(29)      | 7 per cent larger while the secondary star is estimated 4 per cent smaller than in their study. These differences are most probably due to the higher accuracy of Kepler data relative to ground-based observations.

4 MODELLING AND DISCUSSION

We have simultaneously solved the radial velocity and light curve of the detached and relatively long period binary V568 Lyr and determined its orbital and physical parameters (Table 3). The well-detached configuration of V568 Lyr allows us to determine very accurate orbital and physical parameters (Tables 2 and 3). The distance to the cluster is found to be 13.14 ± 0.22 kpc, equivalent to a distance modulus of 13.14 ± 0.22 mag. This is roughly consistent with other distance estimates. Harris & Canterna (1981) found a distance modulus of 14.0 ± 0.2 by analysing a CMD. Anthony-Twarog & Twarog (1985) found 12.6 using isochrones. Carraro et al. (2006) obtained 12.6 – 13.6 again with isochrones. Based on the fit to the white dwarf cooling sequence Bedin et al. (2008b) obtained distance scale as 13.5. Brogaard et al. (2011) determined 13.51 ± 0.06 with binary system parameters. Basu et al. (2011) measured 13.11 ± 0.06 for the red giant stars.

To model this system and compare it with observations allows us to test our understanding of stellar evolution. V568 Lyr, in particular, gives us the opportunity to estimate the age of the cluster. We made with the ev code (Eggleton & Kiseleva-Eggleton 2002) and its much more powerful twin variant (Yakut & Eggleton 2005; Eggleton 2006, 2010), both of which are based on the Cambridge STARS code (Eggleton 1971, 1972, 1973; Pols et al. 1995).

In single-star evolution, the effects of rotation and dynamo activity on mass–loss and the proximity of the companion are often not considered. The ev code admits various non-conservative processes to be applied to the primary component of the binary system. In the newer twin variant, both components are solved simultaneously so that the effect of tidal dissipation on stellar rotation, orbital period and eccentricity and on dynamo activity, and hence on mass–loss, in both components are treated self-consistently. Stellar winds carry off angular momentum by way of magnetic braking and this angular momentum can be extracted from the orbit if tidal dissipation is strong enough. We might imagine that tidal dissipation has played a role in the evolution of
V568 Lyr because its orbit is circular and many systems with $P > 5$ d are markedly eccentric. Tidal dissipation leads to spin–orbit synchronization (or pseudo-synchronization in eccentric orbits) much more quickly than it causes circularization.

It is not easy to determine the initial state of a binary system if the evolution is not conservative. We can reasonably assume that the initial masses were larger than now but it is not clear, without some trial and error, by how much they were larger. Further, it is entirely likely that there is some non-linearity in the behaviour so that a straightforward convergence procedure that assumes near-linearity may not in fact converge or at least converge badly.

The metallicity of NGC 6791 has been estimated to be about two and a half times solar (Grundahl et al. 2008), rather surprisingly because the cluster is also estimated by them to be nearly twice the age of the Sun. However, the metallicity of the Sun has itself been subject to recent downward revision (Asplund, Grevesse, & Sauval 2005) although there is probably still some uncertainty because the new value seems to spoil the apparent agreement of earlier models of the Sun with helioseismology (Bahcall, Serenelli, & Basu 2005). We have used the tabular data of the OPAL data base (Rogers, Swenson, & Iglesias 1996) for $Z = 0.04$, corresponding to nearly three times the value that Asplund, Grevesse, & Sauval (2005) obtained for the Sun, and to about 2.5 times the solar metallicity as estimated by more recently by Caffau et al. (2011). However we adopt this value mainly because it leads to much better agreement between the observational and theoretical luminosities, radii and masses of the components, as illustrated in Fig. 4. The zero-age helium abundance was taken to be $Y = 0.32$, and the mixing-length ratio to be 2.0. Aspects of the code have been described in detail by Eggleton (2006) and papers referred to therein. The only (slight) novelty is that convective core overshooting has been calibrated fairly carefully in a study by Eggleton & Griffin (2015) of 53 binaries almost all of which are evolved to giant or supergiant dimensions, where the issue of convective overshooting is much more challenged than by near-main-sequence stars including the present subject. The new model of overshooting in fact makes very little difference in the present case.

After some experimentation, we evolved a pair of stars with initial masses 1.0994 and 0.8603 $M_{\odot}$, spin periods of 2 d each, an eccentricity of 0.3 and an orbital period of 15.79 days. We expect the orbital period to decrease if the orbit circularizes, but it is also influenced by magnetic braking and by mass loss. In addition, it will also increase as the orbit acquires angular momentum from the spins of the stars by tidal friction. The particular model of the non-conservative processes in the code (Eggleton & Kiseleva-Eggleton (2002), but see below) led the system to evolve, after 7.733 Gyr to the primary that is reasonably close to the observed value, and the blue asterisk is the coeval point on the secondary’s (very short) track, i.e. a point on the same isochrone as the primary. However, in order to produce a nearly circular orbit we had to increase the model tidal friction by a factor of 100, and even then the eccentricity, starting from a hypothetical 0.3, was only reduced by a factor of 6, which might just be compatible with the observations. We believe that the inadequacy of tidal friction is likely to be a problem for any other model, because 14.5 d is a rather long period for two near-main-sequence stars to have circularized their orbit, even in quite an old cluster (Eggleton 2006).

The fact that the two masses decreased by as much as 1 per cent and 3 per cent in the course of 8 Gyr is perhaps noteworthy. Single stars similar to either component would lose less mass but that is because they would have spun down to much slower rotation rates by magnetic braking in the absence of tidal friction. The same non-conservative model as used above, when applied to the Sun, gives the observed solar-wind strength and Alfvé radius, by design, at age 4.57 Gyr. This model predicts a loss of 1.4 per cent of the initial mass but almost all of this takes place in the first Gyr when the Sun is rotating in about 14 d or less. The lower-mass component of our binary loses mass faster, partly because its deeper convective layer is assumed to make it more active and partly because old K dwarfs are normally rotating even more slowly than the Sun. This one is rotating substantially faster if it is synchronized, which it surely must be.
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