

## DISCOVERY OF THE HOST CLUSTER FOR THE FUNDAMENTAL CEPHEID CALIBRATOR ZETA GEMINORUM

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### ABSTRACT

New and existing CORAVEL,  $UBVJHK_s$ ,  $HST$ , HIP/Tycho, ARO, KPNO, and DAO observations imply that the fundamental Cepheid calibrator  $\zeta$  Gem is a cluster member. The following parameters were inferred for  $\zeta$  Gem from cluster membership and are tied to new spectral classifications (DAO) established for 26 nearby stars (e.g., HD53588/B7.5IV, HD54692/B9.5IV):  $E_{B-V} = 0.02 \pm 0.02$ ,  $\log \tau = 7.85 \pm 0.15$ , and  $d = 355 \pm 15$  pc. The mean distance to  $\zeta$  Gem from cluster membership and six recent estimates (e.g., IRSB) is  $d = 363 \pm 9(\sigma_x) \pm 26(\sigma)$  pc. The results presented here support the color-excess and  $HST$  parallax derived for the Cepheid by Benedict et al. Forthcoming precise proper motions (DASCH) and *Chandra/XMM-Newton* observations of the broader field may be employed to identify cluster members, bolster the cluster's existence, and provide stronger constraints on the Cepheid's fundamental parameters.

**Key words:** Hertzsprung–Russell and C–M diagrams – open clusters and associations: general – stars: distances – stars: variables: Cepheids

*Online-only material:* color figures

### 1. INTRODUCTION

An independent distance determination for  $\zeta$  Gem is desirable since *Hubble Space Telescope* ( $HST$ ) and HIP parallaxes for the classical Cepheid exhibit an unsatisfactory spread:  $d = 358\text{--}422$  pc (Perryman & ESA 1997; van Leeuwen et al. 2007; Benedict et al. 2007). Establishing reliable parameters for  $\zeta$  Gem is particularly important given the Carnegie Hubble and SH<sub>0</sub>ES projects (Macri & Riess 2009; Freedman & Madore 2010) are relying on  $HST$  calibrators (Benedict et al. 2007) to break degeneracies hindering the selection of a cosmological model (Riess et al. 2011). The Carnegie Hubble project shall likewise employ Galactic calibrators tied to open clusters (Turner 2010) featuring IRSB corroborated distances (Gieren et al. 2005; Storm et al. 2011). The classical Cepheid  $\zeta$  Gem is the second longest period calibrator possessing a precise  $HST$  parallax (Benedict et al. 2002, 2007), and a solid calibration for such stars is needed since longer-period Cepheids may be less affected by (insidious) photometric contamination (Macri et al. 2006, their Figure 17). Moreover, longer-period Cepheids are detectable in distant galaxies owing to their increased luminosity relative to shorter-period Cepheids (e.g., Gieren et al. 2009, their Figure 1). Sampling remote galaxies in the Hubble flow mitigates uncertainties tied to peculiar velocity corrections and hence  $H_0$  (Freedman et al. 2001, their Figure 1).

In this study, CORAVEL,  $UBVJHK_s$ ,  $HST$ , HIP/Tycho, KPNO, and DAO spectroscopic observations are employed to identify stars potentially associated with  $\zeta$  Gem, thereby permitting its fundamental properties to be deduced from cluster membership ( $\log \tau$ ,  $E_{B-V}$ , and  $W_{VI_c,0}$ ).

### 2. ANALYSIS

HIP/Tycho data were examined for stars surrounding  $\zeta$  Gem which exhibit similar proper motions:  $-10 < \mu_\alpha < -2$  and  $-7 < \mu_\delta < 2$  (Perryman & ESA 1997; van Leeuwen et al. 2007). Stars which display proper motions that deviate significantly from  $\zeta$  Gem were eliminated via the aforementioned limits. However, countless field stars likewise exhibit proper motions marginally offset from zero. The available proper motions could not be employed to substantiate the cluster's existence given their uncertainties (Majaess et al. 2012, see their Figure 3 for  $\delta$  Cep). Stars redder than  $B - V \sim 0.14$  were culled to further mitigate field contamination (e.g., red clump giants).  $UBVJHK_s$  photometry was tabulated for the remaining sample using the compilations of Mermilliod (1991), Perryman & ESA (1997), and Cutri et al. (2003).

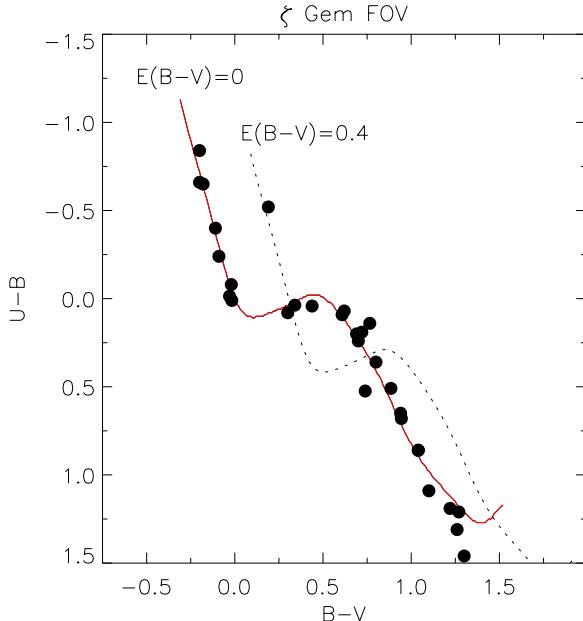
#### 2.1. Reddening and Age

An analysis of all stars near  $\zeta$  Gem featuring  $UBV$  photometry (Mermilliod 1991) confirms that the field is comparatively unreddened (Figure 1). The mean color excess inferred from new DAO spectra (Figure 2) for probable cluster members in Table 1 is  $E(B - V) = 0.019 \pm 0.017$ . The findings support the reddening determined for  $\zeta$  Gem by Benedict et al. (2007).

The cluster age can be constrained by examining the spectral type of members near the turnoff. A distinct sequence of B-stars is visible in the  $BVJH$  color–magnitude diagrams (Figure 3,  $r \leq 2.5$  from  $\zeta$  Gem). The stars HD51102, HD51353, HD53588, and HD55919 aggregate near the turnoff and exhibit B6–B7 spectral classes (Table 1). For example, HD53588 displays  $UBV$  colors and a DAO spectrum conducive to a B7.5 IV (Table 1). The star's radial velocity ( $RV = 10 \pm 3$  km s<sup>-1</sup>) is consistent with that established for  $\zeta$  Gem ( $RV \sim 7$  km s<sup>-1</sup>). However, cluster membership cannot be established solely on the basis of consistent radial velocities since the predicted

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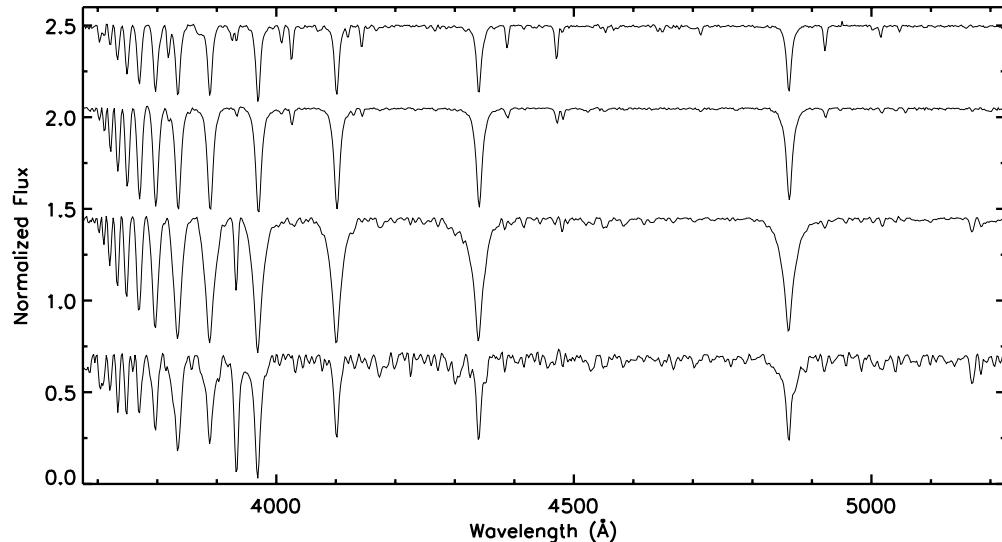
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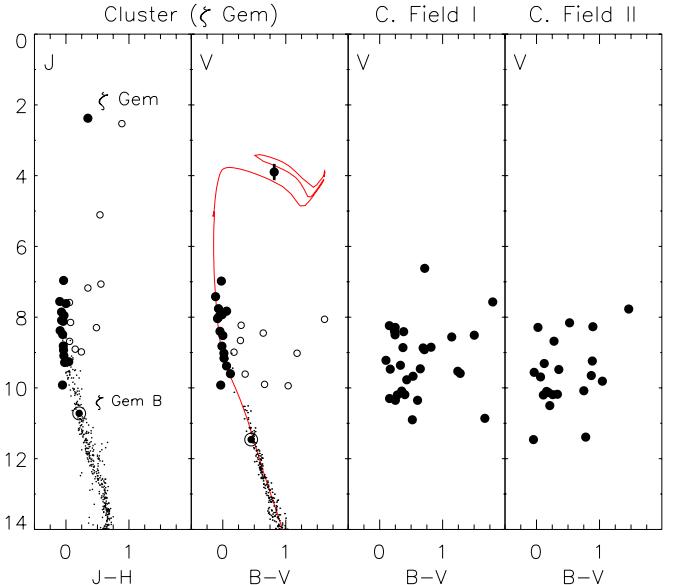
**Figure 1.** Color–color diagram for all stars  $r \leq 4^\circ$  from  $\zeta$  Gem which possess  $UBV$  photometry (Mermilliod 1991). The field is comparatively unreddened. The intrinsic  $UBV$  relation and reddening law for the region were adopted from Turner (1976, 1989). Most objects featured in the diagram are unassociated with  $\zeta$  Gem.

(A color version of this figure is available in the online journal.)

radial-velocity–distance gradient along  $\ell \sim 197^\circ$  is shallow. Membership for the two earliest type of stars examined is less certain (HD50767, HD51354; Table 1). A spectroscopic parallax for HD50767 implies that the star is well behind the cluster. The spectroscopic and HIP parallaxes for HD50767 disagree. The intrinsic colors for HD51354 ( $(B-V)_0:(U-B)_0 = -0.18:-0.65$ ) and the DAO spectrum indicate that the star is a B3 Vnne (H $\beta$  emission). A mean of the HIP parallaxes established for HD51354 (Table 1) is consistent with that established for  $\zeta$  Gem ( $\pi = 2.78 \pm 0.18$  mas; Benedict et al. 2007). The Perryman & ESA (1997) parallax for HD51354 is  $\pi = 2.57 \pm 0.81$  mas, whereas the revised HIP parallax is  $\pi = 3.75 \pm 0.47$  mas (van Leeuwen et al. 2007). Spectroscopic parallaxes for emission stars (i.e., HD51354) are unreliable.



**Figure 2.** Subset of the new DAO spectra obtained for objects in the field of the classical Cepheid  $\zeta$  Gem. From top to bottom the spectra correspond to HD50767, HD53588, HD52474,  $\zeta$  Gem B.



**Figure 3.** Left to right: JHBV color–magnitude diagrams for HIP/Tycho stars within  $r \leq 2.5$  of  $\zeta$  Gem featuring  $-10 < \mu_\alpha < -2$  and  $-7 < \mu_\delta < 2$ . An early-type cluster sequence is absent from the comparison fields (panels 3 and 4, HIP/Tycho), which encompass  $r \leq 4^\circ$ . Small dots denote calibration stars from Majaess et al. (2011a), which were employed to tie the cluster distance to a geometrically anchored scale (van Leeuwen 2009; Majaess et al. 2011a). Open circles are likely field stars. Panel 2, a Padova  $\log \tau = 7.85$  isochrone was applied. The stars  $\zeta$  Gem and  $\zeta$  Gem B are the brightest cluster member (amplitude variation indicated) and circled dot accordingly.

(A color version of this figure is available in the online journal.)

A  $\log \tau = 7.85 \pm 0.15$  Padova isochrone<sup>7</sup> provides the best match to the data (Figure 3). The age agrees with that predicted for stars aggregating near the turnoff and the age inferred for  $\zeta$  Gem from its pulsation period (Turner 1996; Bono et al. 2005).

## 2.2. Lower-mass Cluster Members

Turner & Fernie (1978) noted that  $\zeta$  Gem B (J2000 07:04:12.73 +20:34:21.3) may be associated with  $\zeta$  Gem. The

<sup>7</sup> <http://pleiadi.pd.astro.it/>

**Table 1**  
Stars Near  $\zeta$  Gem

ID	V	B - V	U - B	J	H	$K_s$	SpT <sup>a</sup>	$\pi$ (P97) <sup>b</sup>	$\pi$ (V07) <sup>b</sup>
$\zeta$ Gem <sup>c</sup>	3.90	0.82	...	2.38	2.03	2.14	...	$2.79 \pm 0.81$	$2.37 \pm 0.30$
HD 49381	6.80	0.01	...	6.66	6.70	6.65	A0III	$3.87 \pm 0.96$	$3.12 \pm 0.47$
HD 50634	6.98	-0.02	...	6.96	7.00	6.96	B9.5II	$2.41 \pm 0.98$	$3.91 \pm 0.60$
HD 51354	7.12	-0.18	-0.65	7.20	7.18	7.05	B3Vnne	$2.57 \pm 0.81$	$3.75 \pm 0.47$
HD 53588	7.20	-0.11	-0.40	7.33	7.44	7.44	B7.5IV	$4.67 \pm 0.87$	$3.96 \pm 0.56$
HD 51102	7.42	-0.12	...	7.56	7.66	7.70	B6V	$0.36 \pm 1.00$	$1.59 \pm 0.52$
HD 55919	7.43	-0.09	...	7.60	7.68	7.72	B7IV-V	$3.98 \pm 0.79$	$3.86 \pm 0.60$
HD 52372	7.58	0.03	...	7.42	7.45	7.43	A1III	$1.94 \pm 0.93$	$2.17 \pm 0.86$
HD 50767	7.70	-0.20	-0.84	8.09	8.20	8.25	B2V	$2.15 \pm 1.01$	$2.52 \pm 0.74$
HD 51353	7.76	-0.07	...	7.86	7.93	7.92	B7V	$2.00 \pm 0.94$	$3.22 \pm 0.64$
HD 52474	7.83	0.06	...	7.62	7.62	7.59	A2V	$3.07 \pm 1.02$	$2.79 \pm 0.66$
HD 52422	7.93	-0.01	...	7.95	7.98	7.97	B9IV	$2.03 \pm 1.10$	$3.65 \pm 0.86$
HD 52371	8.00	-0.07	...	8.12	8.16	8.23	B7V:	$1.43 \pm 0.97$	$1.13 \pm 0.83$
HD 50509	8.04	-0.08	...	8.09	8.16	8.16	B8V	$-1.28 \pm 1.06$	$0.88 \pm 0.72$
HD 57070	8.14	-0.04	...	8.19	8.25	8.24	B9IV	$1.07 \pm 1.05$	$1.26 \pm 0.66$
HD 54404	8.40	-0.05	...	8.38	8.47	8.45	B9IV	$3.12 \pm 1.05$	$1.49 \pm 0.86$
HD 54692	8.52	0.00	...	8.49	8.54	8.53	B9.5IV	$3.29 \pm 1.12$	$2.26 \pm 0.84$
HD 50107	8.84	-0.01	...	8.83	8.80	8.78	...	...	...
HD 53230	8.84	0.09	...	8.59	8.54	8.51	...	$1.92 \pm 1.24$	$2.56 \pm 1.02$
HD 53288	8.84	-0.02	-0.08	8.81	8.85	8.84	B9.5V	$2.29 \pm 1.05$	$1.53 \pm 0.83$
HD 50164	8.94	-0.07	...	8.91	8.96	8.92	B9Vnn	$3.82 \pm 1.33$	$3.34 \pm 1.19$
HD 49824	8.97	0.10	...	8.70	8.66	8.67	...	$0.33 \pm 1.25$	$-0.74 \pm 0.89$
HD 263791	8.98	-0.05	...	8.99	9.12	9.06	B9V	$0.38 \pm 1.36$	$0.17 \pm 1.24$
HD 51187	9.02	0.02	...	8.93	8.97	8.92	A0V	...	...
HD 53473	9.16	0.02	...	9.09	9.13	9.07	A0V	$0.92 \pm 1.18$	$0.30 \pm 0.99$
HD 51971	9.38	0.06	...	9.28	9.30	9.22	A1V	...	...
TYC 1352-582-1	9.60	0.12	...	9.26	9.22	9.15	...	...	...
BD+18°1470	9.92	-0.03	...	9.92	9.97	9.98	B9.5VpCr-Eu	...	...
$\zeta$ Gem B <sup>d</sup>	11.47	0.42:	...	10.72	10.51	10.46	F4V	...	...
07:03:23.1 +20:37:59.5	11.71	0.38:	...	11.06	10.87	10.85	...	...	...
07:04:12.7 +20:30:19.7	11.83	0.57:	...	10.79	10.49	10.44	F6V	...	...
07:03:38.7 +20:40:59.0	12.00	0.59:	...	10.95	10.68	10.61	...	...	...
07:03:52.6 +20:35:16.3	12.34	0.54:	...	11.37	11.11	11.06	F7V	...	...
07:04:28.6 +20:34:47.3	12.37	0.53:	...	11.46	11.24	11.17	...	...	...
07:04:40.4 +20:35:13.1	12.45	0.46:	...	11.66	11.51	11.47	...	...	...

**Notes.**<sup>a</sup> Stars classified by D. Turner (DAO spectra).<sup>b</sup> Perryman & ESA (1997, P97), van Leeuwen (2007, V07).<sup>c</sup> van Leeuwen et al. (2007) cite  $\pi = 2.71 \pm 0.17$  mas for  $\zeta$  Gem.<sup>d</sup> The star  $\zeta$  Gem B is a spectroscopic binary (Section 2.2). Benedict et al. (2007) classified  $\zeta$  Gem B as an F3.5V.

stars are separated by  $r \sim 1'.4$ . A mean radial velocity was determined for  $\zeta$  Gem B from six CORAVEL measurements obtained at l'Observatoire de Haut-Provence (OHP).<sup>8</sup> The radial velocities acquired from the OHP span  $-16.2$  to  $36.9 \text{ km s}^{-1}$ , yielding a mean of  $9.9 \text{ km s}^{-1}$ .  $\zeta$  Gem B is thus a spectroscopic binary since the uncertainty tied to an individual measurement is  $1.4 \text{ km s}^{-1}$ . The mean radial velocity matches that established for the Cepheid to within the uncertainties. However, as noted in Section 2.1, the shallow radial-velocity-distance gradient along the line of sight requires that cluster membership be secured by independent means. *UBV* photometry by Fernie (1969) indicates that  $\zeta$  Gem B is an F-type star (Turner & Fernie 1978). That is corroborated by the 2MASS colors for the object ( $(J - H):(H - K) = 0.206:0.056$ ), which are indicative of an unreddened F5-F8V (Straižys & Lazauskaitė 2009). A spectrogram of the star was acquired on HJD = 2,444,122.995 from the 2.1 m telescope at Kitt Peak. That spectrogram and a DAO spectrum confirm that  $\zeta$  Gem B is an F4V (Table 1, Figure 2).

<sup>8</sup> M. Mayor kindly obtained CORAVEL observations of  $\zeta$  Gem B for D. Turner.

The result is supported by Benedict et al. (2007), who classified the star as an F3.5V. The spectral and luminosity class for  $\zeta$  Gem B is consistent with that expected for a cluster member at the star's location in the *BVJH* color-magnitude diagrams (Figure 3).

DAO spectra were obtained for two additional stars in close proximity to  $\zeta$  Gem ( $r < 6'$ ). The spectral and luminosity class for 2MASS 07041267+2030196 is consistent with that expected for a cluster member at the star's location in the *BVJH* color-magnitude diagrams (Figure 3, Table 1). The same is true for 2MASS 07035262+2035162. Benedict et al. (2007) inferred an analogous classification for 2MASS 07035262+2035162 (F6V). Four additional stars in close proximity to  $\zeta$  Gem exhibit multiband photometry conducive to late-type (potential) cluster members. New *BV* observations for those stars were acquired from the Abbey Ridge Observatory (ARO; Lane 2008; Majaess et al. 2008). The data were processed via ARAP (Lane 2008) and DAOPHOT (Stetson 1987), and subsequently standardized to photometry obtained from the New Mexico State University 1 m telescope (T. Harrison 2012, private communication; see also Benedict et al. 2007). The following equations were derived

to place the instrumental ARO photometry onto the Johnson system:

$$\begin{aligned}B - V &= (0.99 \pm 0.06) \times (b - v) - (0.57 \pm 0.08) \\V - v &= -0.86 \pm 0.02.\end{aligned}$$

Observations from the AAVSO's Bright Star Monitor (BSM) provided additional data for  $\zeta$  Gem B and 2MASS 07041267+2030196. The BSM is located at the Astrokolkhoz telescope facility near Cloudcroft, New Mexico.

*HST* WFC3 images (HST Proposal 12215, Evans 2009) reveal a star 15'' west of the Cepheid at J2000 07:04:05.5 +20:34:12.0. The object was identified after subtracting (normalized) the image featuring  $\zeta$  Gem from a master, which was constructed (median combine) using Cepheids observed for proposal 12215. The object displays a signal-to-noise-ratio greater than 20 in both WFC3 images. However, N. Evans (2012, private communication) noted that the star's photometry is not conducive to cluster membership.

Later-type stars associated with  $\zeta$  Gem should presumably exhibit X-ray emission (Evans 2011). Additional observations are required to assess the candidates (e.g., *Chandra/XMM-Newton*). The objects are not featured in the *ROSAT* catalogs.

### 2.3. Cluster Distance

A precise cluster distance may be determined since the reddening, age, and chemical composition of the sample are constrained ( $[Fe/H]_{\zeta\text{Gem}} \sim 0$ ; Luck et al. 2011). The magnitude shift required to overlay the intrinsic relation upon the data yields  $d = 355 \pm 15$  pc (Figure 3). The zero point is tied to seven benchmark open clusters ( $d < 250$  pc) that exhibit matching  $JHK_s$  and revised HIP distances (e.g., the Hyades,  $\alpha$  Per, Coma Ber; van Leeuwen 2009; Majaess et al. 2011a). A redetermination of the *HST* parallax for the Hyades supports that scale (McArthur et al. 2011). The scale employed here is anchored to clusters where consensus exists, rather than to the discrepant case (i.e., the Pleiades). A ratio of total to selective extinction  $R_J$  was adopted from Majaess et al. (2011b; see also Bonatto et al. 2004), whereas a value for  $R_V$  was adopted from Turner (1976). Deviations from the canonical reddening law are mitigated since the field is comparatively unreddened (Figure 1, note that  $V_0 = V - E_{B-V} \times R_V$ ).

A mean distance inferred from potential members possessing revised HIP parallaxes is  $d = 366 \pm 57(\sigma_x) \pm 196(\sigma)$  pc. Certain stars were excluded from the derivation since they exhibit uncertainties greater than the parallax cited, deviate significantly from the mean, or feature negative parallaxes (e.g., HD49824,  $\pi = -0.74 \pm 0.89$  mas). Stars with spectral types inconsistent with cluster membership were likewise removed (e.g., HD50767, Section 2.1).

Three HIP parallaxes exist for  $\zeta$  Gem:  $\pi = 2.79 \pm 0.81 : 2.37 \pm 0.30 : 2.71 \pm 0.17$  mas (Perryman & ESA 1997; van Leeuwen 2007; van Leeuwen et al. 2007). The results inferred from cluster membership and *HST* observations for  $\zeta$  Gem ( $\pi = 2.78 \pm 0.18$  mas; Benedict et al. 2007) support the van Leeuwen et al. (2007) HIP determination. Distances to  $\zeta$  Gem are also available from the infrared surface brightness technique ( $d = 386 \pm 9$  pc; Storm et al. 2011) and the Palomar Testbed Interferometer (PTI;  $d = 336 \pm 44$  pc; Lane et al. 2000, and references therein). A straight mean of the six (+2 cluster based) estimates to  $\zeta$  Gem yields  $d = 363 \pm 9(\sigma_x) \pm 26(\sigma)$  pc. A weighted mean of  $d = 368$  pc was obtained by assigning  $w = 1$  for the HIP and PTI estimates, and  $w = 2$  for the rest.

### 3. CONCLUSION AND FUTURE RESEARCH

The evidence indicates that the 10<sup>d</sup> classical Cepheid calibrator  $\zeta$  Gem belongs to a newly identified cluster (Figure 3). Potential members were identified on the basis of new and existing CORAVEL, *UBVJHK<sub>s</sub>*, *HST*, HIP/Tycho, KPNO, and DAO ( $n = 26$ ) spectroscopic observations. The analysis indicates that the field is comparatively unreddened (Figure 1), and that  $\zeta$  Gem exhibits  $E(B - V) = 0.019 \pm 0.017$  (Section 2.1). The age and distance were inferred from spectroscopic and multiband *UBVJHK<sub>s</sub>* analyses of the cluster stars, yielding  $\log \tau = 7.85 \pm 0.15$  and  $d = 355 \pm 15$  pc (Figure 3). The results support the parameters derived for  $\zeta$  Gem by Benedict et al. (2007). However, the breadth of the standard deviation tied to several recent estimates for  $\zeta$  Gem is unsatisfactory (Section 2.3,  $d = 363 \pm 9(\sigma_x) \pm 26(\sigma)$ ), and continued research is required. CORAVEL, KPNO, and DAO observations indicate that  $\zeta$  Gem B is an F-type spectroscopic binary. DAO spectra were likewise obtained for two other low-mass members in close proximity to  $\zeta$  Gem. Additional observations are required to highlight bona fide members on the candidate list (Table 1). Those stars are potential members pending further evidence. Membership identification may be facilitated by obtaining precise proper motions for fainter stars near  $\zeta$  Gem from photographic plates stored at the CfA (Grindlay 2007; DASCH).<sup>9</sup> The plates offer multi-epoch coverage spanning a  $\sim 100$  year baseline, and uncertainties are further mitigated owing to sizable statistics ( $\sim (5-10) \times 10^2$  plates per object). Searching for X-ray emission from lower-mass stars near  $\zeta$  Gem is likewise a viable pursuit for corroborating membership (Evans 2011; Evans et al. 2011). However, the star Polaris B is of a similar spectral type as  $\zeta$  Gem B (Turner 1977) and does not exhibit X-ray emission (Evans et al. 2010).

At least two classical Cepheids featuring *HST* parallaxes are cluster members ( $\delta$  Cep and  $\zeta$  Gem; de Zeeuw et al. 1999; Majaess et al. 2012). Cluster membership provides a means to secure independent fundamental parameters ( $\log \tau$ ,  $E_{B-V}$ ,  $W_{V,I_c,0}$ ,  $\log L_*/L_\odot$ , and  $M_V$ ). The results shall complement a suite of diverse efforts unified by a common objective to reduce uncertainties associated with  $H_0$  in order to constrain cosmological models (Feast 2008; Shappee & Stanek 2011; Gerke et al. 2011; Ngeow 2011, 2012; Steer & Madore 2011).

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<sup>9</sup> Digital Access to a Sky Century @ Harvard (DASCH), <http://hea-www.harvard.edu/DASCH/>

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