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THE PULSATION MODE AND DISTANCE OF THE CEPHEID FF AQUILAE

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ABSTRACT

The determination of pulsation mode and distance for field Cepheids is a complicated problem best resolved by a luminosity estimate. For illustration a technique based on spectroscopic luminosity discrimination is applied to the 4.47 day s-Cepheid FF Aql. Line ratios in high dispersion spectra of the variable yield values of $\langle M_V \rangle = -3.40 \pm 0.02$ s.e. (± 0.04 s.d.), average effective temperature $T_{\rm eff} = 6195 \pm 24$ K, and intrinsic color $(\langle B \rangle - \langle V \rangle)_0 = +0.506 \pm 0.007$, corresponding to a reddening of $E_{B-V} = 0.25 \pm 0.01$, or $E_{B-V}(\mathrm{B0}) = 0.26 \pm 0.01$. The skewed light curve, intrinsic color, and luminosity of FF Aql are consistent with fundamental mode pulsation for a small-amplitude classical Cepheid on the blue side of the instability strip, not a sinusoidal pulsator. A distance of 413 ± 14 pc is estimated from the Cepheid's angular diameter in conjunction with a mean radius of $\langle R \rangle = 39.0 \pm 0.7\ R_\odot$ inferred from its luminosity and effective temperature. The dust extinction toward FF Aql is described by a ratio of total-to-selective extinction of $R_V = A_V/E(B-V) = 3.16 \pm 0.34$ according to the star's apparent distance modulus.

Key words: dust, extinction – stars: fundamental parameters – stars: individual (FF Aql) – stars: variables: Cepheids

Online-only material: color figure

1. INTRODUCTION

A defining characteristic of most Cepheid variables is an asymmetric light curve with a rapid rise to maximum light followed by a slower decline to minimum 0.6–0.7 cycles later. For pulsation periods of 5–22 days, there is a superposed period-dependent secondary bump, the Hertzsprung progression (see Turner 2012b), that has enabled astronomers to establish diagnostics for the light curves of short-period Cepheids ($P < 10$ days) from low-order Fourier series fits (Simon & Lee 1981). Fundamental mode and overtone pulsators follow distinct trends in their Fourier parameters as a function of pulsation period that in principle allow identification of pulsation mode (e.g., Antonello & Poretti 1986; Andreasen 1988; Mantegazza & Poretti 1992; Poretti & Pardo 1997).

A complication arises from a small subset of Cepheids with periods $P < 7$ days that have small light amplitudes and light curves that are almost perfectly symmetric, making them very close matches to sine waves. Many such s-Cepheids appear to be overtone pulsators according to diagnostics that include first- and second-order Fourier terms (Mantegazza & Poretti 1992), yet the meaning of such parameters is unclear when the light curve is a close match to a sine wave for which second-order Fourier terms are undefined (see Turner 2012b). Is the Fourier fit providing a match to the Cepheid's true light variations or is it biased by random scatter in the observations? Such considerations are important given that s-Cepheids constitute a portion of the Cepheid demographic in all galaxies. Whether they are fundamental mode or overtone pulsators affects the luminosity expected for them from their periods of pulsation, and hence the inferred distance to a galaxy derived from the total Cepheid sample according to the Leavitt law.

A full characterization of individual Cepheids includes luminosity, which itself can separate fundamental mode pulsators from overtone Cepheids since the latter are typically ~0.5 mag more luminous than fundamental mode pulsators of identical pulsation period. Luminosity estimates require either an accurate knowledge of distance and extinction for individual Cepheids or a precise determination of their spectroscopic absolute magnitudes. Cluster Cepheids are useful for the former, provided their reddening is well established. It was noted by Turner & Majaess (2006), for example, that the possible association of the s-Cepheids EU Tau, EV Sct, DX Gem, SZ Tau, BY Cas, V1334 Cyg, α UMi, BD Cas, QZ Nor, and V1726 Cyg with the clusters Alessi 90, NGC 6664, Alessi J0652.6 + 1439, NGC 1647, NGC 663, Dolidze 45, Harrington 1, King 13, NGC 6067, and Platais 1, respectively, imply a mix of pulsation modes for the pulsators: fundamental mode pulsation for EU Tau, DX Gem, BY Cas, α UMi, and V1726 Cyg, and overtone pulsation for EV Sct, SZ Tau, V1334 Cyg, QZ Nor, and BD Cas.

The technique of determining Cepheid absolute magnitudes spectroscopically by averaging numerous line ratios relating neutral to ionized species of iron group elements in their spectra has been developed by Kovtyukh and collaborators (Kovtyukh et al. 2008, 2010, 2012a). In practice a single line ratio can specify absolute magnitude M_V to ± 0.26 mag for FG supergiants. Application to all potential luminosity-sensitive line ratios in an observed spectrum can reduce the overall uncertainty in absolute magnitude by $1/n^{\frac{1}{2}}$ according to the number (n) used, provided the uncertainties in each estimate are governed by random errors of measurement. There is no evidence otherwise. The technique yields Cepheid luminosities of greater precision (~1%) than other methods, and is fairly

Table 1
Spectroscopic Results for FF Aquilae

JD(obs)	Phase	$T_{\rm eff}$ (K)	± s.d. (K)	n	± s.e. (K)	M_V	± s.d.	n	± s.e.	$(B-V)_0$
2450672.747	0.562	6002	81	87	9	−3.34	0.15	67	0.02	0.566
2450674.685	0.995	6425	95	72	10	−3.32	0.30	48	0.04	0.437
2450675.687	0.220	6172	77	85	8	−3.46	0.18	70	0.02	0.512
2450677.746	0.680	6083	105	68	10	−3.36	0.18	31	0.03	0.540
2450678.712	0.896	6421	66	63	10	−3.13	0.35	39	0.06	0.438
2450735.595	0.619	6062	43	90	5	−3.41	0.23	67	0.03	0.547
2450736.608	0.846	6328	61	82	7	−3.26	0.22	67	0.03	0.465
2450737.600	0.067	6387	38	61	5	−3.62	0.27	68	0.03	0.448
2450738.592	0.289	6113	49	68	6	−3.54	0.13	67	0.02	0.531
2450739.607	0.516	6008	58	70	7	−3.48	0.17	63	0.02	0.564
2450740.625	0.744	6196	78	68	9	−3.17	0.22	70	0.03	0.505
2451056.690	0.437	6022	71	58	11	−3.46	0.16	55	0.02	0.559
2451095.619	0.145	6285	53	60	7	−3.52	0.26	65	0.03	0.478
2451096.647	0.374	6040	49	68	6	−3.56	0.20	63	0.03	0.554

robust. An application to the s-Cepheids V1334 Cyg, V440 Per, and V636 Cas by Kovtyukh et al. (2012b) confirmed the overtone nature of V1334 Cyg inferred from cluster membership (Turner & Majaess 2006) and implied fundamental mode pulsation for V440 Per and V636 Cas. A subsequent application to α UMi (Turner et al. 2013) confirmed the case for fundamental mode pulsation in the Cepheid, despite a conflict with results implied by the star's *Hipparcos* parallax (van Leeuwen 2013). Of the dozen s-Cepheids studied to date, seven (58%) appear likely to be fundamental mode pulsators while only five (42%) are overtone pulsators. Apparently a sinusoidal light curve is not a characteristic of a specific pulsation mode.

This Letter examines the case of the 4.47 day s-Cepheid FF Aql, which presents its own challenges. It is not associated with an open cluster, according to previous surveys, and conclusions about its pulsation mode differ according to which measured parallax for the star is adopted. The *Hubble Space Telescope* (*HST*) parallax for FF Aql (Benedict et al. 2007) implies fundamental mode pulsation, while its *Hipparcos* parallax (van Leeuwen 2007) matches expectations for overtone pulsation. Alternatively, its rate of period change is consistent with fundamental mode pulsation (Turner 2010), although the match is not ideal. Possible contamination of the star's photometry by nearby and unresolved companions (Evans et al. 1990; Udalski & Evans 1993) is a problem, but is of only minor concern for spectroscopic observations. As demonstrated here, FF Aql is one case where the spectroscopic method of deducing luminosity may be ideally suited to resolving uncertainties about a Cepheid's pulsation mode and evolutionary status.

2. OBSERVATIONS AND DATA REDUCTIONS

The observations used for the present study consist of the McDonald Observatory Sandford echelle spectrograph observations for FF Aql included in the earlier study of s-Cepheids by Luck et al. (2008), further analyzed to establish absolute magnitude estimates M_V for the Cepheid as a function of pulsation phase. Correct phasing of the observations was made using the ephemeris of Berdnikov & Pastukhova (1994), as done by Luck et al. (2008). The Cepheid exhibits a slow evolutionary period increase superposed upon its orbital $O-C$ changes (Berdnikov & Pastukhova 1994; Turner 2010), although a study to separate such effects by Berdnikov et al. (1997) left the matter unresolved. FF Aql is a spectroscopic binary with an orbital period of about 3.92 yr (Abt 1959; Evans et al. 1990; Gorynya et al. 1995), making it difficult to separate $O-C$ changes arising from evolution from scatter introduced by the Cepheid's orbital motion (Berdnikov & Pastukhova 1994).

The results of the luminosity calculations for FF Aql derived from the observed spectra are summarized in Table 1 along with the $T_{\rm eff}$ changes found earlier by Luck et al. (2008). The latter have been converted into equivalent variations in intrinsic $(B-V)_0$ color using the relationship between the two derived by Gray (1992). Uncertainties in the inferred values of $T_{\rm eff}$ and M_V are included in the table, and the results are presented graphically as a function of pulsation phase in Figure 1 along with the Cepheid and its unresolved companion's visual brightness variations from Moffett & Barnes (1980).

3. RESULTS

Initially the observed variations in visual magnitude, absolute magnitude, effective temperature, and intrinsic color were matched to best-fitting sine waves, but that yielded sizable systematic residuals in most cases. Low-order Fourier series of fairly similar morphology for each parameter produced much smaller residuals, and are the fitted relations shown in Figure 1. The inferred mean values are $\langle V\rangle = 5.38 \pm 0.02$, $\langle M_V\rangle = -3.40 \pm 0.02$ s.e. (± 0.04 s.d.), $\langle T_{\rm eff}\rangle = 6195 \pm 24$ K, and mean intrinsic color $\langle (B-V)_0\rangle = 0.506 \pm 0.007$. The observed mean color of FF Aql is $\langle B-V\rangle = 0.755$ (Berdnikov 2007), implying a reddening of $E_{B-V} = 0.25 \pm 0.01$. The corresponding color excess for a B0 star observed through the same amount of extinction is $E_{B-V}({\rm B0}) = 0.26 \pm 0.01$ according to the relationship of Fernie (1963).

The best-fitting curve for absolute magnitude closely resembles the skewed light curves of standard Cepheids, with a rapid rise to maximum followed by a slow decline to minimum. It is less noticeable in photometric observations for the Cepheid (Moffett & Barnes 1980), presumably because of contamination by the star's companions. FF Aql is recognized to have a nearby optical companion 5.8 mag fainter (Udalski & Evans 1993), a close speckle companion perhaps 2 mag–4 mag fainter (McAlister et al. 1987, 1989; Evans et al. 1990), and an unresolved spectroscopic companion estimated to be ∼6 mag fainter (Evans et al. 1990). Although the net effect on the Cepheid's observed brightness variations from aperture photometry is small, the constant presence of light contamination in the observations

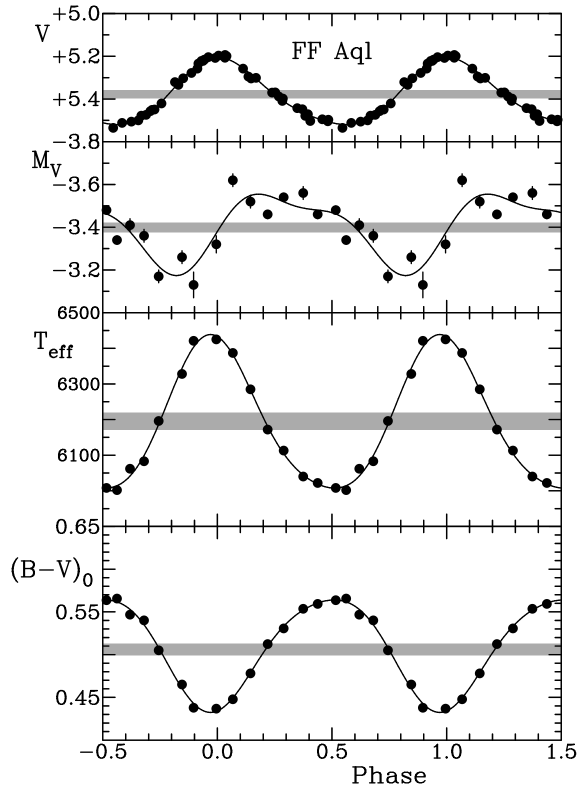

Figure 1. Phased variations in, from top to bottom, visual magnitude (Moffett & Barnes 1980), absolute magnitude M_V, effective temperature $T_{\rm eff}$, and associated intrinsic color variations $(B-V)_0$ for FF Aql, the lower three from the spectra analyzed here, with uncertainties in the data indicated. The gray relations represent the adopted mean values and the superposed curves are best-fitting Fourier series.

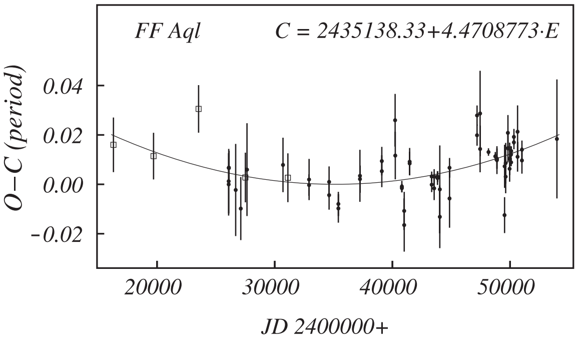

Figure 2. Observed minus predicted times of light maximum $(O-C)$ for FF Aql, in units of fractions of its pulsation period, with associated uncertainties. The long-term trend indicated corresponds to $\log \dot{P} = -1.153$, in units of s yr^{-1}.

and potential color effects arising from the different temperatures of the companions likely smooth out the skewness in the Cepheid's visual light variations (Figure 1, top).

The mean absolute magnitude inferred for FF Aql of $\langle M_V \rangle = -3.40 \pm 0.02$ is consistent with fundamental mode pulsation for a 4.47 day Cepheid. The corresponding Fourier parameters of $\phi_{21} = 5.69 \pm 0.66$, $\phi_{31} = 4.46 \pm 0.94$, $R_{21} = 0.37 \pm 0.20$, and $R_{31} = 0.27 \pm 0.20$ are also generally consistent with fundamental mode pulsation, as noted for LMC and M31 Cepheids (Beaulieu et al. 1995; Vilardell et al. 2007) as well as Galactic Cepheids (Andreasen 1988; Zakrzewski et al. 2000; Storm et al. 2011), but the match is not ideal in ϕ_{21} and ϕ_{31}, presumably because of scatter in the data. In any case, the skewed nature of the absolute magnitude curve for FF Aql in conjunction with its skewed radial velocity variations (Evans et al. 1990) and the similarly skewed variations in $T_{\rm eff}$ and $(B-V)_0$ indicate that it is not a true s-Cepheid, so does not belong in that category.

The $O-C$ variations for FF Aql tabulated by Berdnikov & Pastukhova (1994) and Berdnikov et al. (1997), and updated by additional times of light maximum derived from ASAS observations and Harvard photographic plates (L. N. Berdnikov & D. G. Turner 2013, in preparation), is shown in Figure 2. The slow period increase of $+0.0703 \pm 0.0160$ s yr^{-1} (Berdnikov & Pastukhova 1994; L. N. Berdnikov & D. G. Turner 2013, in preparation) for FF Aql was shown previously to be consistent with the rate expected from stellar evolutionary models for a Cepheid pulsating in the fundamental mode in the third crossing of the instability strip (Turner 2010). The larger reddening found here for the Cepheid confirms that conclusion, since the blue intrinsic color for FF Aql relative to other 4.47 day Cepheids places it solidly on the blue edge of the instability strip (see Turner, Abdel-Sabour Abdel-Latif & Berdnikov 2006; Turner 2010), a region dominated by small-amplitude variables (see papers cited by Turner et al. 2006). The observed rate of period increase ($\log \dot{P} = -1.153$) is also consistent with expectations for a Cepheid on the hot edge of the instability strip, since it is slightly larger than values derived for other third crossing Cepheids (i.e., slow period increases). Cepheids of a given period on the hot edge of the instability strip are more massive and are evolving faster than those near strip center (see discussion by Turner et al. 2006), so their rates of period change are systematically higher. Fundamental mode pulsation for FF Aql is therefore consistent with its derived parameters.

4. THE DISTANCE TO FF AQL

A variety of methods enable one to establish the distance to FF Aql. As noted in Section 1, there is a discrepancy between the results obtained from trigonometric parallaxes. The distance to FF Aql implied by the star's *HST* parallax (Benedict et al. 2007) is 356 ± 23 pc, whereas its *Hipparcos* parallax (van Leeuwen 2007) yields a distance of 474 ± 74 pc, results that are discordant within the cited uncertainties. The difference accounts for previous questions about the pulsation mode of FF Aql (see Turner 2010). The infrared surface brightness (IRSB) technique yields a distance of 370 ± 10 pc (Storm et al. 2011), a higher precision result consistent with the *HST* parallax.

The mean luminosity for FF Aql derived here can be used to establish the distance to the Cepheid independently. A first step is to derive the mean radius of FF Aql from its luminosity and effective temperature relative to solar parameters (see Turner & Burke 2002). That yields a mean radius of $\langle R \rangle = 39.0 \pm 0.7\ R_{\odot}$, a value larger than that obtained by Gallenne et al. (2012) using the interferometric Baade–Wesselink method, yet in better agreement with the period–radius relations they used for comparison as well as with the period–radius relations of Turner & Burke (2002), Turner et al. (2010), and Molinaro et al. (2011). The limb-darkened angular diameter of $\theta_{\rm LD} = 0.878 \pm 0.013$ mas found for FF Aql by Gallenne et al. (2012) from near-infrared interferometry then combines with the star's estimated mean radius to yield a distance of 413 ± 14 pc to FF Aql, a value lying roughly midway between the two estimates from the star's trigonometric parallax and larger than the value obtained by the IRSB method.

A weighted mean of the four semi-independent estimates yields a distance of 388 ± 8 pc, while an unweighted average is 398 ± 50 (s.d.) pc, but that assumes no sources of systematic

Table 2
Photometric Properties of FF Aquilae

Parameter	FF Aql	Uncertainty
$\langle M_V \rangle$	−3.40	±0.02
$(B-V)_0$	+0.506	±0.007
$T_{\rm eff}$ (K)	6195	±24
E_{B-V}	0.25	±0.01
R_{21}	0.37	±0.20
R_{31}	0.27	±0.20
ϕ_{21}	5.69	±0.66
ϕ_{31}	4.46	±0.94
$\dot{P}$ (s yr^{-1})	+0.0703	±0.0160
$\langle R \rangle / R_\odot$	39.0	±0.7
d (pc)	413	±14
R_V	3.16	±0.34

error in each, which may not be valid. The origin of the discrepancy in the spectroscopic distance relative to the values associated with the *HST* and *Hipparcos* parallaxes is uncertain, although the presence along the line of sight to FF Aql of a moderately bright companion with a changing optical separation relative to the Cepheid (McAlister et al. 1987, 1989) may introduce bias into parallax estimates tied to measurements of the star's photocenter. The photometric contamination of the companions to FF Aql on its brightness and colors may also account for the discrepancy relative to the IRSB technique.

It is possible to go further to determine a value for the ratio of total-to-selective absorption $R_V = A_V/E(B-V)$ that applies to dust along the line of sight to FF Aql. That requires an estimate of the apparent distance modulus for the Cepheid, which is somewhat difficult given uncertainties about the amount of light contamination inherent to the optical photometry. The optical and spectroscopic companions are faint enough (Evans et al. 1990) to affect the total light of the system by only 0.01 mag, but contamination by the interferometric companion may be responsible for 0.04 mag–0.22 mag of the total visual light from FF Aql (see Evans et al. 1990). Adoption of a simple mean of the latter values leads to an apparent distance modulus of $V - M_V = 8.91 \pm 0.07$, which yields an estimated value of $R_V = 3.16 \pm 0.34$ for the extinction properties of the dust toward the Cepheid.

The region of Aquila is not well studied in terms of extinction along the line of sight. Open clusters lying within ∼10° of FF Aql yield a mean value of $R_V = 3.18 \pm 0.18$ from variable-extinction studies (Turner 1976), while a value of $R_V = 3.0$ was adopted by Forbes (1984) in his study of the distribution of OB stars in this direction. The value of R_V obtained here from the spectroscopic luminosity and effective temperature of FF Aql is therefore consistent with previous studies of the dust extinction in Aquila. Note that adoption of the *HST* parallax for FF Aql would yield a value of $R_V \simeq 4$ for the extinction, while adoption of the *Hipparcos* parallax would yield a value of $R_V \simeq 2$, albeit with an uncertainty that permits agreement with the present result. The more typical value ($R_V \simeq 3$) following from the present results appears to provide further substantiation for the robust nature of the spectroscopic luminosity technique.

5. SUMMARY

A study of phase-dependent spectroscopic variations in absolute visual magnitude M_V and effective temperature $T_{\rm eff}$ for the 4.47 day Cepheid FF Aql reveals a skewed nature for its uncontaminated light curve (Figure 1) that implies it is not a sinusoidal s-Cepheid. That is supported by Fourier parameters inferred from the Cepheid's absolute magnitude variations (Table 2), which differ from similar values derived from optical photometry (Storm et al. 2011), presumably because of contamination by the Cepheid's three close companions. Although Storm et al. (2011) assumed that FF Aql is a s-Cepheid, the present results contradict such a conclusion.

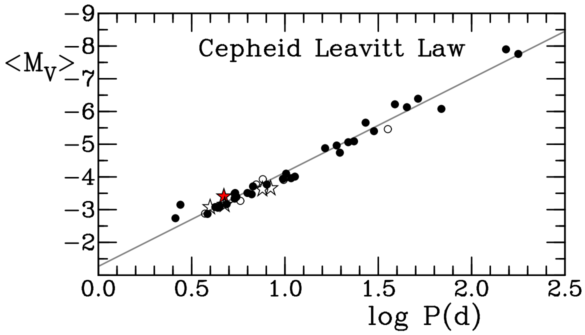

Figure 3. Dependence of absolute visual magnitude on pulsation period for cluster Cepheids and Cepheid-like objects (filled circles), *HST* Cepheids (open circles), and spectroscopic parallax Cepheids (stars). FF Aql is denoted by the red filled star, and the gray relation is a least-squares fit for cluster Cepheids.

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

Observed variations in effective temperature have been linked to phased variations in intrinsic color $(B-V)_0$ to derive a reddening of $E_{B-V} = 0.25 \pm 0.01$ ($E_{B-V}({\rm B0}) = 0.26 \pm 0.01$) for FF Aql (Table 2). An identical reddening was found by Turner et al. (1987) from *JHK* photometry, but lies on the high end of values (0.191–0.250) cited by Turner (2010), which include an estimate of 0.224 by Kovtyukh et al. (2008) from the same spectra. It is larger than the reddening of 0.196 cited by Storm et al. (2011). Contamination of optical photometry by the Cepheid's companions may be responsible for the differences.

This study yields a mean radius and effective temperature for FF Aql (Table 2) that have been combined with the star's mean angular diameter (Gallenne et al. 2012) to derive a distance of 413 ± 14 pc, a value lying within the range of estimates from the star's *HST* (Benedict et al. 2007) and *Hipparcos* (van Leeuwen 2007) parallaxes, as well as its IRSB method distance (Storm et al. 2011), but falling outside the uncertainty estimates for all but the *Hipparcos* result. The resulting extinction along the line of sight to the Cepheid derived by spectrophotometric means appears to be relatively normal ($R_V = 3.16 \pm 0.34$). The dust toward $l = 49\overset{\circ}{.}21$ and $b = +6\overset{\circ}{.}36$ therefore appears to share similar properties to most other sight lines in the Galaxy.

The spectroscopic luminosity for FF Aql derived here is compared in Figure 3 with other best estimates of luminosity for Galactic Cepheids and Cepheid-like objects established by spectroscopic means (Kovtyukh et al. 2012b; Turner et al. 2013), open cluster membership (Turner et al. 2009, 2010, 2012a, 2012b; Turner 2010; Majaess et al. 2011, 2012a, 2012b), including new unpublished results for S Vul, and *HST* parallaxes (Benedict et al. 2007). The result for FF Aql in the last source was excluded in favor of the present spectroscopic estimate, and the *HST* luminosity for ℓ Car cited by Turner (2010) was adjusted to account for an anomalous extinction law in Carina described by $R_V = A_V/E(B-V) \simeq 4$ rather than $R_V \simeq 3$ (Turner 2012a; Carraro et al. 2013). The periods of recognized overtone pulsators were also adjusted to their equivalent fundamental mode values. The location of FF Aql relative to fundamental mode pulsation for other calibrating

Cepheids in the P–L plane of Figure 3 coincides closely with expectations and confirms the previous mode identification. FF Aql is slightly overluminous (smaller M_V) relative to other calibrating Cepheids of comparable period (4.4 days) because it lies toward the hot edge of the instability strip.

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