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The Valuable Long-period Cluster Cepheid KQ Scorpii and other Calibration Candidates

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Abstract

The classical Cepheid KQ Sco is a valuable anchor for the distance scale because of its long pulsation period ($28\overset{d}{.}7$) and evidence implying membership in the open cluster UBC 1558. Analyses tied to Gaia DR3 astrometry, photometry, spectroscopy, radial velocities, and 2MASS-VVV photometry indicate a common distance of 2.15 ± 0.15 kpc (L21 DR3 corrections applied). Additional cluster Cepheid candidates requiring follow-up are identified, and it is suggested that a team of international researchers could maintain a cluster Cepheid database to guide the broader community to cases where consensus exists.

Unified Astronomy Thesaurus concepts: Star clusters (1567); Cepheid variable stars (218)

1. Introduction

There is resurgent interest in cluster Cepheids since they provide a means of (in)validating concerns regarding Planck ΛCDM H_0 and Gaia parallaxes (e.g., Reyes & Anderson 2023; Wang et al. 2024),[8] and constrain the distance scale (e.g., Hao et al. 2022; Lin et al. 2022). The Cepheid KQ Sco ($28\overset{d}{.}7$) is of particular interest granted remote extragalactic Cepheids are similarly bright long-period pulsators (e.g., Riess et al. 2016; Freedman & Madore 2023).

Turner (1979) suggested KQ Sco (ℓ, $b \simeq 340.3885$, $-0\overset{\circ}{.}7448$) may be associated with early-type stars in the broader field. Gaia observations subsequently fostered the discovery of an open cluster 6′ from KQ Sco (UBC 1558, Castro-Ginard et al. 2022). Lin et al. (2022) did not associate KQ Sco with UBC 1558, likely owing to a parallax disparity between the cluster (Castro-Ginard et al. 2022) and Cepheid. Castro-Ginard et al. (2022) determined that UBC 1558 is $\simeq$3 kpc distant (CMD result), whereas the DR3 parallax for KQ Sco formally implies 2.3 kpc. Indeed, a revised distance for UBC 1558 presented here renders it proximate to the Cepheid.

In this study, DR3 spectroscopy, astrometry, photometry, and radial velocities are inspected in tandem with 2MASS-VVV photometry to clarify the connection between KQ Sco and UBC 1558 (Figure 1). Lastly, a list of reputed cluster Cepheids is provided which would likewise benefit from further examination on a case-by-case basis.

2. Analysis

Figure 1 highlights stars with proper motions (μ_α, μ_δ) within 0.2 mas yr^{-1} of KQ Sco (Gaia Collaboration et al. 2023). An overdensity is readily discernible which represents UBC 1558, and KQ Sco is within the confines of the cluster (Figure 1). UBC 1558 is not densely populated, and may not remain bound as the average cluster dissolution timescale is surpassed (10 Myr, Bonatto & Bica 2011). The Gaia DR3 astrometric solutions for the cluster and KQ Sco are summarized in Table 1. The parallaxes agree to within the uncertainties. A Wesenheit function (Leavitt Law) was employed to independently assess the distance to KQ Sco. The compilation of Ngeow (2012) presents a Cepheid Wesenheit distance of $\simeq$2.2 kpc, and the relation of Majaess et al. (2013a) corroborates the result. Those distances are nearer, thereby hinting at a correction to the DR3 results (e.g., Lindegren et al. 2021; Owens et al. 2022). Applying the Lindegren et al. (2021) prescription bridges the gap, and suggests a mean systematic correction of $\Delta\pi \simeq 0.03$ mas. For example, KQ Sco shifts from 0.43 to 0.47 mas, which is a $\simeq$10% distance offset (pc).

[8] Other viewpoints include Owens et al. (2022) and Freedman & Madore (2023).

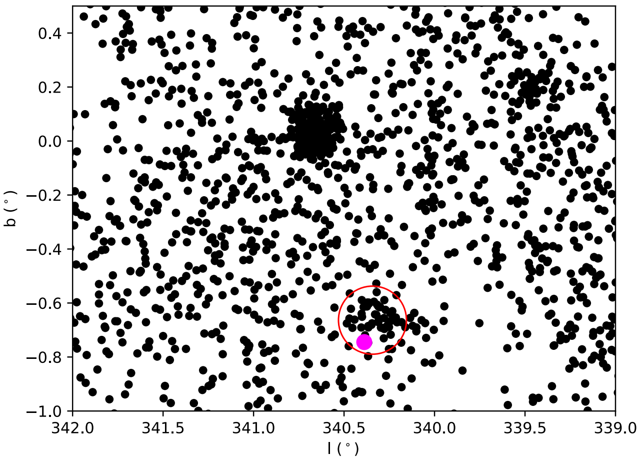

Figure 1. Stars featuring DR3 proper motions similar to the classical Cepheid KQ Sco (magenta). The open cluster UBC 1558 (Castro-Ginard et al. 2022) is encompassed by a red circle.

Table 1
KQ Sco and UBC 1558 Parameters

	KQ Sco	UBC 1558
$\pi_{\rm DR3}$ (mas)	0.43 ± 0.02	0.41 ± 0.03
$\pi_{\rm DR3-L21}$ (mas)	0.47	0.45
μ_α (mas yr^{-1})	-1.37 ± 0.02	-1.34 ± 0.01
μ_δ (mas yr^{-1})	-2.50 ± 0.02	-2.49 ± 0.01
$\log \tau$	7.48 ± 0.15	7.55 ± 0.10
$d_{\rm W}$ (mas)	0.45	…
d_{J-JH} (mas)	…	$0.46^{+0.06}_{-0.03}$

Note. * Uncertainties for cluster astrometry are the standard error. $\pi_{\rm DR3-L21}$ represents the corrected parallax following Lindegren et al. (2021). $d_{\rm W}$ is the Wesenheit distance, and d_{J-JH} represents an isochrone fit to 2MASS-VVV photometry.

The Cepheid and cluster are in temporal agreement (Table 1). The age for KQ Sco was determined using relations derived by Bono et al. (2005), Turner (2012), and Anderson et al. (2016). The estimated Cepheid age is $\log \tau = 7.48 \pm 0.15$. Castro-Ginard et al. (2022) determined $\log \tau = 7.25$ for UBC 1558, whereas Cavallo et al. (2024) favored $\log \tau \gtrsim 7.9$, and thus a redetermination of the cluster age was pursued below that yields $\log \tau = 7.55 \pm 0.10$. The $B_P G R_P$ differentially dereddened color–magnitude diagram indicates that UBC 1558 is a younger open cluster (Figure 2), and was constructed using preliminary DR3 spectroscopically determined data such as A_G and $E(B_P - R_P)$ (Gaia Collaboration et al. 2023). However, there are caveats linked to that advantageous new data set, and research is ongoing to rectify problems therein (Andrae et al. 2023). For example, Majaess & Turner (2024) noted that certain unobscured clusters do not align with DR3 spectroscopically dereddened observations, and

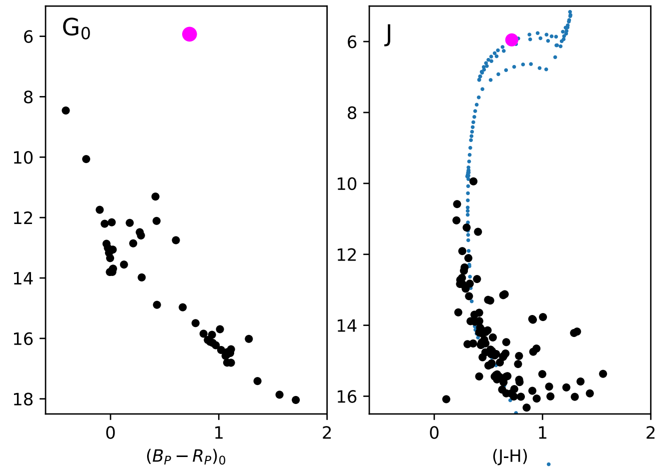

Figure 2. Left, dereddened $G_0/(B - R)_0$ color–magnitude diagram for UBC 1558. The main-sequence and turnoff morphology are conducive to a younger open cluster that could host a longer-period $28^{\rm d}_{.}7$ classical Cepheid. Right, 2MASS-VVV near-infrared JH color–magnitude diagram for UBC 1558. KQ Sco ($\log \tau = 7.48 \pm 0.15$, Cepheid period–age relation) is conveyed by the magenta datum, and the $\log \tau = 7.55$ isochrone is the dotted line.

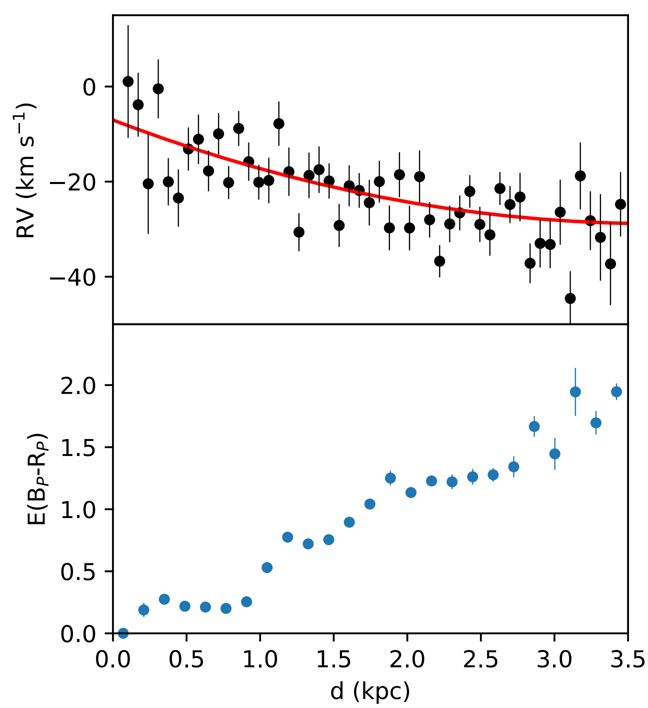

Figure 3. Top, the binned distribution of radial velocities indicates the classical Cepheid KQ Sco (-22.1 ± 1 km s^{-1}) lies near $\simeq$2 kpc. The red line represents a polynomial fit (2nd order). Bottom, UBC 1558 may reside in the interarm region between the Carina (reddening increase near $\simeq$1 kpc) and Centaurus-Norma ($\gtrsim$2.8 kpc) spiral arms, according to the map of Xu et al. (2023). Uncertainties in both panels reflect the standard error.

Table 2
Understudied Cluster Cepheid Candidates Warranting Follow-up

ID	Mode	P (days)	ID	Mode	P (days)
AN Aur	F	10.3	X Pup	F	26.0
AP Cas	F	6.8	V335 Pup	1O	4.9
BB Cen	1O	4.0	V724 Pup	F	5.6
BV Cas	F	5.4	ATO J297.7863 + 25.3136	1O	2.9
CD Cyg	F	17.1	ATO J300.0102 + 29.1869	F	18.4
CM Sct	F	3.9	ZTF J192152.00 + 150346.9	F	8.8
CN Sct	F	10.0	ASAS J075840-3330.2	F	4.4
CS Vel	F	5.9	ASAS J115701-6218.7	F	26.5
CV Mon	F	5.4	ASAS J183904-1049.3	1O	3.1
DP Vel	F	5.5	ASASSN-V J040516.13+555512.9	1O	1.8
EX Vel	F	13.2	ASASSN-V J151832.37-580128.7	F	9.2
FF Car	F	16.3	ASASSN-V J194806.54+260526.1	1O	6.6
FM Car	F	7.6	ASASSN-V J201151.18+342447.2	F	9.8
FZ Car	1O	3.6	ASASSN-V J211659.94+514556.7	F	5.9
GI Cyg	F	5.8	ASASSN-V J213533.70+533049.3	1O	3.2
GQ Vul	F	12.7	NSVS 11232104	F	6.9
IM Car	F	5.3	OGLE GD-CEP-0422	F	4.6
NO Cas	1O	2.6	OGLE GD-CEP-0549	F1O	2.2/1.6
OO Cen	F	12.9	OGLE GD-CEP-0605	1O	3.1
RS Ori	F	7.6	OGLE GD-CEP-0609	F	25.1
SV Cru	F	7.0	OGLE GD-CEP-1544	F	5.5
SV Vul	F	44.9	Gaia DR3 5254518760118884864	1O	3.8
TY Sct	F	11.1	Gaia DR3 5878427527969505024	1O	0.3
X Cru	F	6.2	Gaia DR3 5935070926723295232	F	15.3

Note. IDs, pulsation modes and periods, mainly from the Pietrukowicz et al. (2021) catalog. Candidates can overlap with other published tables, for example, DP Vel is ruled out as a cluster member by Lin et al. (2022), whereas Hao et al. (2022) include it in a Class B subsample, and it is absent from Reyes & Anderson (2023). Hence the impetus for a cluster Cepheid database site.

hence currently, $T_{\rm eff}-(B_P-R_P)_0$ inhomogeneities in the preliminary DR3 spectroscopic data inhibit a reliable isochrone fit in dereddened space. Consequently, DR3 astrometrically cleaned near-infrared 2MASS-VVV observations were analyzed (Cutri et al. 2003; Minniti et al. 2011; Saito et al. 2012), and the VVV data were standardized to 2MASS using common stars in the field. Furthermore, reddening and extinction law variations and their uncertainties are smaller in the infrared (Majaess et al. 2016). Salasnich et al. (2000) scaled-solar isochrones were applied to the 2MASS-VVV photometry for UBC 1558 (see also Bonatto et al. 2004). The isochrone was shifted using a mean reddening inferred from a suite of B-stars confirmed by DR3 spectroscopy. The intrinsic near-infrared colors of Straižys & Lazauskaitė (2009) were utilized, and yielded a cluster reddening of $E(J-H)=0.39\pm0.03$. The ensuing cluster parameters are $d=2.1\pm0.2$ kpc and $\log\tau=7.55\pm0.10$ (Figure 2). *JH* data for KQ Sco were drawn from the Breuval et al. (2021) compilation (Welch et al. 1984; Laney & Stobie 1992).

The radial velocity trend along the sightline was investigated by inspecting existing and new velocities for KQ Sco (Coulson & Caldwell 1985; Anderson et al. 2024), and DR3 measurements. The two cited studies relay a velocity for KQ Sco of -22.1 ± 1 and -23.777 ± 0.052 km s^{-1}, accordingly. Figure 3 (top panel) conveys stars within 30′ of KQ Sco featuring DR3 radial velocities, and adhering to canonical culling criteria (e.g., RUWE < 2). The mean trend over the baseline shown (2nd order polynomial) indicates the Cepheid is $\simeq$2 kpc away. The originally cited $\simeq$3 kpc distance for UBC 1558 instead points to $\simeq-29$ km s^{-1}.

Figure 3 (bottom panel) relays the trend of distance with reddening along the KQ Sco sightline. Step-functions can be indicative of interstellar clouds or traversal across a spiral arm. A comparatively nearby cloud is responsible for the initial color-excess near 0.2 kpc, and thereafter the Carina arm is traversed at this longitude ($\ell\simeq340°$, $d\simeq1$ kpc). A subsequent slightly positive linear trend is apparent from $\simeq$2 to 2.8 kpc, whereafter the Centaurus[9]-Norma spiral arm emerges according to the Xu et al. (2023) map. UBC 1558 may inhabit the interarm region between the Carina and Centaurus-Norma spiral arms, yet note that Galactic structure is contested.

9 Majaess et al. (2009) and Xu et al. (2023) advocate that a perfect spiral pattern does not characterize the Milky Way, and there is evidence of branching (e.g., Centaurus).

3. Conclusions

KQ Sco exhibits parameters which are consistent with UBC 1558, and the Cepheid is a probable member (Figure 1, Table 1). The distance to UBC 1558 was revised nearer by $\simeq -0.8$ kpc. An unweighted mean and standard deviation associated with all distance methods yield $d = 2.15 \pm 0.15$ kpc (excluding uncorrected DR3 parallaxes). A separate investigation is desirable to examine whether bound or dissolving clusters encompassing UBC 1558 (Figure 1) are associated (e.g., Ruprecht 121). For example, the denser open cluster NGC 6216 may be in relative vicinity to UBC 1558, yet the former may be potentially older and therefore unrelated.

Going forward, numerous understudied potential Cepheids may be cluster members (Table 2). The targets were identified by cross-referencing the Pietrukowicz et al. (2021) Cepheid catalog with DR3. A subsample were discussed previously (e.g., Negueruela et al. 2020; Zhou & Chen 2021; Lin et al. 2022), and all candidates may benefit from individual follow-up, which presents pertinent insights as conveyed here.

More broadly, owing to the importance attributed to cluster Cepheids in diverse endeavors (e.g., ascertaining whether the Planck ΛCDM H_0 requires adjustment): a database site could be constructed to provide *suggested* guidance for the broader community whereupon (I), an updated list of cluster Cepheids unanimously agreed upon by a panel of international researchers is presented, and (II), reputed cluster Cepheids lacking consensus are highlighted which may require additional funding to secure data and undertake a comprehensive analysis. For example, QZ Nor (Eggen 1983; Majaess et al. 2013b) is featured in the Gold sample of Reyes & Anderson (2023; see also Breuval et al. 2020), but absent from Medina et al. (2021) and Hao et al. (2022). Conversely, GQ Vul is classified within the Class A sample of Hao et al. (2022), and is absent from Reyes & Anderson (2023), and a 0.47 membership probability was assigned by Medina et al. (2021, their Table 1). Turner et al. (2008) suggest CG Cas is a member of Berkeley 58, whereas Wang et al. (2024) indicate it is a member of NGC 7790. Therein lies the motivation for researchers to maintain a cluster Cepheid site.

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