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Cluster membership for the long-period Cepheid calibrator SV Vul

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ABSTRACT

Classical Cepheids represent the first step of the distance scale ladder. Claims of tension between the locally calculated Hubble constant and the values deduced from *Planck*'s results have sparked new interest in these distance calibrators. Cluster membership provides an independent distance measurement, as well as astrophysical context for studies of their stellar properties. Here, we report the discovery of a young open cluster in the vicinity of SV Vul, one of the most luminous Cepheids known in the Milky Way. *Gaia* DR2 data show that SV Vul is a clear astrometric and photometric member of the new cluster, which we name Alicante 13. Although dispersed, Alicante 13 is moderately well populated, and contains three other luminous stars, one early-A bright giant and two low-luminosity red supergiants. The cluster is about 30 Ma old at a nominal distance of 2.5 kpc. With this age, SV Vul should have a mass around 10 $M_{\odot}$, in good accordance with its luminosity, close to the highest luminosity for Cepheids allowed by recent stellar models.

Key words: stars: evolution – Hertzsprung–Russell and colour–magnitude diagrams – supergiants – stars: variables: Cepheids – open clusters and associations: individual: Alicante 13.

1 INTRODUCTION

Cepheid variables were the earliest standard candles in use and still today constitute the first step in the cosmic distance ladder (Feast 1999, and references therein). With the release of *Gaia* DR2 (Gaia Collaboration et al. 2018) geometrical parallaxes, their role as benchmark distance indicators through the use of Leavitt Law (e.g. Freedman & Madore 2010) is becoming even more paramount. Claims for a statistically significant difference between values of the Hubble constant derived locally and from a combination of cosmic microwave background measurements and the standard cosmological models (e.g. Riess et al. 2018b) call for high-precision distance determinations. In this context, Cepheids in open clusters are doubly valuable. The cluster offers an independent way to measure the distance and provides an astrophysical context for the Cepheid. Thanks to this context, the physical properties and evolutionary stage of the Cepheid can be constrained.

The number of Cepheids believed to belong to clusters or OB associations has increased in recent years (Anderson, Eyer & Mowlavi 2013; Chen, de Grijs & Deng 2015), but not all of them are well studied. The best characterized stars are included in period–luminosity calibrations. Among them, SV Vul, with a 45 d pulsation period, is one of the brightest. It is indeed the star with the longest period in a number of calibrations based on Milky Way Cepheids (e.g. Tammann, Sandage & Reindl 2003; Fouqué et al. 2007). In others (e.g. Storm et al. 2011), it is superseded by the confusingly named 63 d Cepheid S Vul (which is located only 40 arcmin away), whose geometric parallax was recently measured with the *Hubble Space Telescope* (*HST*, Riess et al. 2018a).

By the use of different standard methods, the distance modulus to SV Vul has traditionally been calculated around $\mu = 11.7$ mag ($d = 2.1$ kpc; $\pi = 0.46$; e.g. Fouqué et al. 2007), implying an absolute magnitude approaching $M_V = -6$. Storm et al. (2011) proposed a lower value $\mu = 11.4$, based on the near-infrared (near-IR) surface brightness method. Conversely, Madore, Freedman & Moak (2017) suggest a higher value $\mu = 12.0$ mag ($\pi = 0.40$ mas) by applying a novel method to treat reddening. This latter value is in good agreement with the *Gaia* DR2 parallax $\pi = 0.37 \pm 0.03$ mas, although DR2 values for such a bright ($G = 6.9$) star should be taken with care.

SV Vul has long been assumed a member of the Vul OB1 association, following Turner (1984). The core of Vul OB1 is the very young (star-forming) cluster NGC 6823, which contains a few O-type stars, including the O6.5 V((f)) HD 344784. There are, however, older stars belonging to the association, and SV Vul has been connected to the rather older cluster NGC 6834, which lies about 2 deg North of the Cepheid (Turner 1976). With an estimated

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Table 1. Parameters for the stars observed at high resolution. Spectral type and a measurement of RV are from our spectra, while the other parameters are from *Gaia* DR2.

Star	Spectral type	pm (RA) (mas)	pm (Dec) (mas)	π (mas)	G (mag)	BP–RP (mag)	RV (*Gaia*) (km s^{-1})	RV (km s^{-1})
SV Vul	F8 Iab	− 2.14 ± 0.05	− 5.82 ± 0.05	0.37 ± 0.03	6.87	1.89	+3.2 ± 4.3	− 14.5 ± 0.3
HD 339063	A2 II	− 2.22 ± 0.05	− 5.89 ± 0.05	0.41 ± 0.03	8.51	0.94	–	− 1.5 ± 0.6
HD 339064	K1 Ib	− 2.24 ± 0.05	− 5.72 ± 0.06	0.35 ± 0.03	8.56	2.30	+6.58 ± 0.39	− 3.5 ± 0.1
BD +27°3542	B3 II + K3 Iab	− 2.24 ± 0.05	− 5.92 ± 0.05	0.37 ± 0.03	7.95	1.85	− 0.14 ± 0.25	− 0.5 ± 0.2

age of 80 Ma (Paunzen et al. 2006), NGC 6834 seems too old to be related to SV Vul. In addition, its *Gaia* DR2 parallax π = 0.27 (Cantat-Gaudin et al. 2018) places it too far away to belong to Vul OB1. Moreover membership in an association for isolated stars in this direction is difficult to assess, as three distinct OB associations, Vel OB1, Vel OB2, and Vel OB4, are believed to be projected one of top of the other at different distances (we will come back to this issue in Section 5).

In this work, we demonstrate the presence in this region of a newly recognized open cluster that includes SV Vul as a halo member. The new cluster, which we name Alicante 13,[1] is not apparent to the eye, except as a compact group of three bright stars, namely HD 339063, HD 339064 and BD +27°3542, whose *Gaia* DR2 astrometric parameters (listed in Table 1) are fully compatible with those of SV Vul, i.e. pmRA = −2.14 mas yr^{-1}, pmDec = −5.82 mas yr^{-1}, and $\pi = 0.37$ mas. This group is located about 9 arcmin to the East from SV Vul. In the following sections we identify the cluster as a concentration of early-type stars, determine its astrophysical parameters and characterize its brighter members.

2 CLUSTER DEFINITION

To identify the cluster, we used the Virtual Observatory tool CLUSTERIX 2.0 (Balaguer-Núñez et al. 2020) working on *Gaia* DR2 data. CLUSTERIX is an interactive web-based application that calculates the grouping probability of a list of objects by using proper motions and the non-parametric method proposed by Cabrera-Cano & Alfaro (1990) and described in Galadi-Enriquez, Jordi & Trullols (1998). In its current version, CLUSTERIX works only in the proper motion plane, ignoring all other information. For ease of computation, we restricted ourselves to DR2 objects with $G \leq 16$ and errors in proper motion below 3 mas yr^{-1}. We selected a circle of radius 30 arcmin around the position of HD 339063 and run the tool assuming a cluster radius of 3.6 arcmin (this simply informs the tool of where it should find a significant number of objects belonging to a distinct population). CLUSTERIX identifies over 6300 sources brighter than $G = 16$ and passing its quality criteria. CLUSTERIX then assigns each object a probability of belonging to a distinct population rather than the field population, using an empirical determination of the frequency functions in the vector point diagram (Sanders 1971). After this, we plotted the parallax versus probability plane, and found a clear overdensity of objects with high probability and similar values of parallax.

The population thus identified is strongly concentrated in the proper motion plane and contains the four stars mentioned above. After removal of a handful of outliers, we calculated the weighted means for the astrometric parameters of the population, which turn out to be pmRA = −2.08 ± 0.21 mas yr^{-1}, pmDec = −5.92 ± 0.15 mas yr^{-1}, and $\pi = 0.37 \pm 0.06$ mas, where the errors quoted are the standard deviations for the whole population selected. The median values of these parameters are pmRA = −2.08 mas yr^{-1}, pmDec = −5.87 mas yr^{-1}, and π = 0.38 mas. Their modes are pmRA = −2.09 mas yr^{-1}, pmDec = −5.87 mas yr^{-1}, and π = 0.37 mas. Coincidence of mean, median, and mode indicates that the central values are well defined and a more sophisticated analysis is not needed. An iterative process of 2σ outlier clipping leads to essentially identical median values, confirming that the results of CLUSTERIX are statistically solid. In Fig. 1, we plot the spatial distribution of the objects finally selected (around 200 sources). Although the population is spread over the whole field, there is a very strong concentration towards the position of the three bright stars mentioned above.

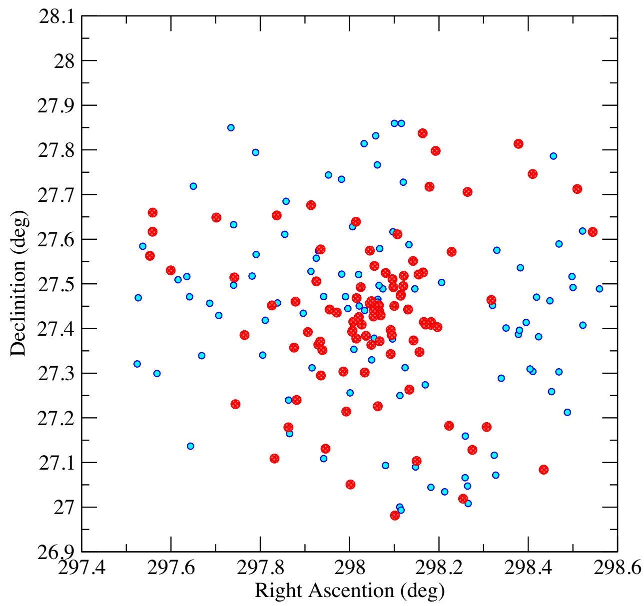

Figure 1. Spatial distribution of the population selected by CLUSTERIX. Small blue circles are objects whose three astrometric parameters lie within 2σ of the average values. Larger red circles are objects whose parameters are less than one σ away from these central values.

To quantify this, we used the Automated Stellar Cluster Analysis (ASTECA) code (Perren, Vázquez & Piatti 2015). We run ASTECA on the selection shown in Fig. 1, i.e. stars whose three astrometric parameters fall within 2σ of the average values for the population. A King profile does not provide a good fit, as the central distribution is very asymmetric, but a strong overdensity is detected, with about 40 stars above the background value within ∼5 arcmin of the central position given. This is however, an underestimate of the cluster contrast, since we are only utilizing stars with the same astrometric parameters and thus the 'background' sources should

[1]Information about other clusters in the series can be found at https://astro.ua.es/alicanteclusters/, where all relevant references are given.

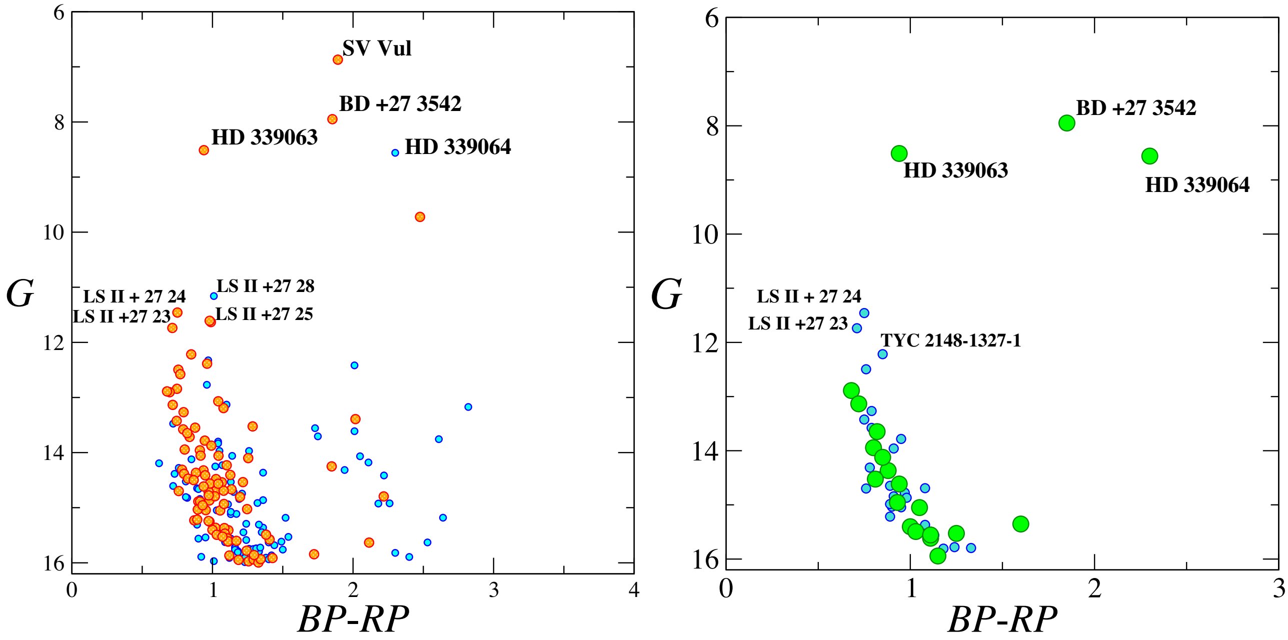

Figure 2. *Gaia* CMD for the sample selected using astrometric data. Left-hand panel: the large (red) circles have astrometric paramenters within one σ of the average values for the population selected by CLUSTERIX. The small blue circles represent stars within 2σ of the same values. Right-hand panel: only stars within 6 arcmin of HD 339063 are shown. The large green circles are stars within 3 arcmin. In both diagrams, the brightest stars are labelled with their catalogue names.

be mostly the dispersed population of the cluster halo. In the left-hand panel of Fig. 2, we plot the *Gaia* photometry for these stars. We can see that around 20 stars (i.e. ∼10 per cent of the objects) occupy positions in the *Gaia* colour-magnitude diagramme (CMD) suggesting that they are interlopers. All the other stars seem to belong to a single population. The spread in ($BP-RP$) is very likely due to differential reddening. For instance, all the bright stars ($G \approx 11-12$) around ($BP-RP$) ≈ 1.0 lie to the East of the cluster, mostly at large distances (>15 arcmin). All the objects located at the top of the main stellar sequence are catalogued early-type stars. They include LS II +27°23, 24, 25 and 28, TYC 2148-1327-1, and the emission-line star Hen 3-1788.

The cluster is small and disperses into the surrounding association. Of the ∼180 likely members of the association shown in the left-hand panel of Fig. 2, there are 47 stars within 6 arcmin of HD 339064 and 90 stars within 12 arcmin. The right-hand panel of Fig. 2 shows the population within 6 arcmin. Differential reddening is reduced to a minimum and the sequence is now much better defined. Only one of the faintest stars is located at some distance from the photometric sequence.

3 OBSERVATIONS AND ANALYSIS

High-resolution spectra of the three bright stars and SV Vul itself were taken with the FIbre-fed Echelle Spectrograph (FIES) attached to the 2.56 m Nordic Optical Telescope (NOT; La Palma, Spain) in service mode during the night of 2019 June 4. FIES is a cross-dispersed high-resolution echelle spectrograph, mounted in a heavily insulated building separated from and adjacent to the NOT dome, with a maximum resolving power $R = 67\,000$. The entire spectral range 370 – 830 nm is covered without gaps in a single, fixed setting. Extended coverage up to 900 nm is available with minor inter-order wavelength gaps. In the present study, we used the low-resolution mode with $R = 25\,000$. The spectra were homogeneously reduced using the FIEStool[2] software in advanced mode. Using a complete set of bias, flat, and ThAr arc frames, the FIEStool pipeline provides wavelength calibrated, blaze-corrected, order-merged spectra.

Classification spectroscopy of blue stars in the area was obtained in service mode during the night of 2019 June 10, with the Alhambra Faint Object Spectrograph and Camera (ALFOSC) attached to the NOT. We used the grism number 18 combined with a 1 arcsec slit to obtain intermediate-resolution spectroscopy. Grism number 18 covers the 3450 – 5350 Å range with a nominal dispersion of 0.9 Å pixel^{-1}. The resolving power for this configuration is $R \sim 1000$. These data were reduced following standard procedures with reduction software inside the *Starlink* suite (Currie et al. 2014).

Spectral classification of the early-type stars has been carried out by comparison to a grid of standards (Negueruela et al. 2019) degraded to the same resolution and application of classical criteria. Spectral classification of late-type supergiants has been carried out by following the procedure specified in Dorda et al. (2018) on their spectra degraded to classification resolution.

Radial velocities (RVs) were calculated for stars with high-resolution spectra by using ISPEC[3] (Blanco-Cuaresma et al. 2014; Blanco-Cuaresma 2019). As a first step, telluric features were removed to improve the RV determination. Then, we cross-match correlated each of our spectra against a high-resolution line-list mask of the Sun (provided by ISPEC) covering our whole spectral range, and we obtained the corresponding mean velocities by fitting a second-order polynomial near the peak to the velocity profile. The errors were automatically calculated by ISPEC following the

[2]http://www.not.iac.es/instruments/fies/fiestool/FIEStool.html
[3]A free integrated spectroscopic software powered by PYTHON, available at https://www.blancocuaresma.com/s/iSpec

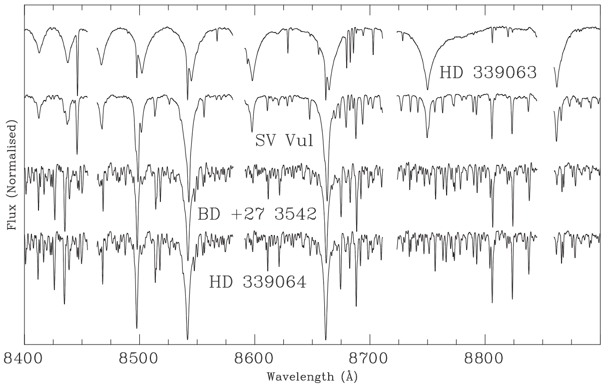

Figure 3. Spectral sequence of luminous stars around the region covered by the *Gaia* RVS. The small gaps are due to the lack of order overlap in FIES for the extreme red.

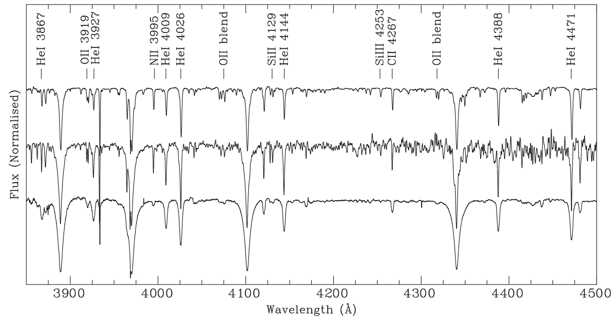

Figure 4. The blue component of BD +27°3542 (middle) compared to stars of similar spectral types. Contamination by the K-type brighter companion is evident beyond 4 200 Å. The top spectrum is 3 Gem (HD 42087; B3 Ib). The bottom spectrum is HD 21483 (B3 III).

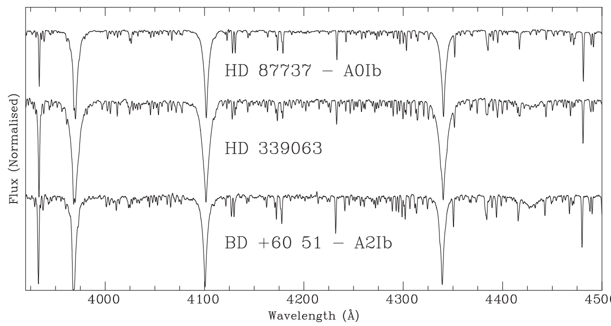

Figure 5. Classification spectrum of HD 339063, with two comparison stars. HD 87737 is a primary MK standard, while BD +60°51 was characterized by Verdugo, Talavera & Gómez de Castro (1999).

procedures described in Zucker (2003). The RVs measured are shown in Table 1, where they are compared to the DR2 values (note that HD 339063, being a blue star, has no DR2 RV).

4 RESULTS

4.1 Stellar content

There are four luminous stars that appear as astrometric and photometric members of the cluster. Their derived parameters are listed in Table 1. The brightest among them is the well-studied Cepheid SV Vul, located in the cluster halo. Spectra of the four stars in the *Gaia* Radial Velocity Spectrometer (RVS) spectral region are shown in Fig. 3. SV Vul appears as an F8 Iab supergiant. Its spectral type is known to vary between F7 and K0 (Code 1947). Its RV oscillates periodically between $\approx +20$ and ≈ -25 km s^{-1} with a systemic velocity[4] ≈ -1 km s^{-1} (Bersier et al. 1994). The high dispersion of the *Gaia* RV measurements testifies to this variability. Our measurement is typical of the velocity seen at early spectral types.

The position of BD +27°3542 in the *Gaia* CMD suggests a yellow star, similarly to SV Vul. However, its spectrum shows it to be a composite, containing a very luminous red star and a B-type object. The red star, for which we derive a K3 Iab spectral type, completely dominates the red spectrum (see Fig. 3). The blue star can be seen up to ∼5000 Å, and dominates the spectrum bluewards of ∼4500 Å. We display this region in Fig. 4, together with comparison spectra. The lines of the blue component are very narrow, indicating a very low projected rotational velocity. The wings of the Balmer lines can be used to estimate its luminosity, which turns out higher than that of the B3 III standard HD 21483. We estimate a spectral type B3 II–III, with some uncertainty due to the strong contamination by the red star. Given that *Gaia* does not separate the two stars, they are very likely to form a physical binary. Against this, our RV measurement is not significantly different from the *Gaia* value, which is the median of observations taken between 2014 and 2016, i.e. more than three years before our observation. On the other hand, a chance projection is highly unlikely, especially if we consider that the blue component is the second most luminous blue star in the cluster.

[4]The systemic velocity cannot be determined with high accuracy because the oscillation period is not stable (e.g. Bersier et al. 1994).

As can be seen in Fig. 2, HD 339063 is a blue star. Its spectrum in the *Gaia* RVS spectral region is shown in Fig. 3, while its classification spectrum is presented in Fig. 5, together with comparison spectra. The strong metallic spectrum and lack of He I lines imply an A spectral type. Its lines are somewhat broader than those of the Ib stars displayed as comparison, suggesting a lower luminosity. The main temperature diagnostic, the ratio of Ca II K to Hϵ, suggests that HD 339063 is not much later than A2. Comparison to BD +60°51 shows a slightly stronger and more complex metallic spectrum, except for those lines that are sensitive to luminosity, such as Fe II 4233 Å, the Fe II and Ti II blend at 4172 – 8 Å, and the Si II doublet at 4128 – 30 Å. In view of this, we classify HD 339063 as A3 II. Our RV measurement, -1.5 ± 0.6 km s^{-1}, is fully compatible with the systemic velocity of SV Vul and BD +27°3542.

Finally, HD 339064 is a slightly less luminous red star, for which we estimate a spectral type K1 Ib. Our RV measurement, -3.5 ± 0.1 km s^{-1}, is very different from the *Gaia* value and much more in line with the velocities of the other members. We do not find evidence for a second stellar component, while the dispersion of the *Gaia* DR2 RVs does not suggest high variability. The reasons for this discrepancy are thus unclear.

We also obtained classification spectra of the brightest stars of the main sequence in the photometric CMD. These spectra are displayed in Fig. 6 and their main parameters are listed in Table 2. The two brightest members are the catalogued early-type objects LS II +27°23 and 24. Their spectra are very similar, and we classify both as B2.5 V. A slightly fainter member is TYC 2148-1327-1, catalogued as an emission-line star (HBHA 2703-20). It has features typical of a Be star, with double-peaked emission in Hβ, a shell-

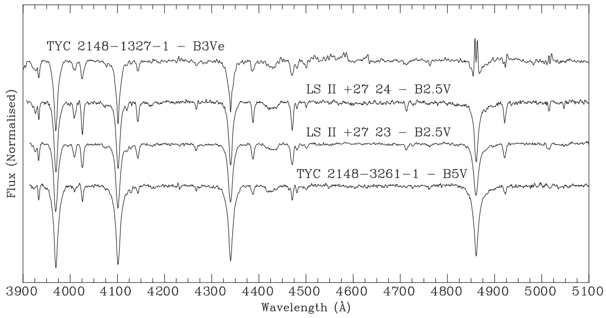

Figure 6. Classification spectra of stars selected as upper main-sequence cluster members.

like profile in Hγ and several moderate-strength Fe II emission lines. This Be nature explains its peculiar position in the CMD, somewhat to the red of the sequence. We classify it as B3 Ve. Finally, TYC 2148-3261-1 has a similar brightness. We classify it as B5 V. However, all lines are broad and very shallow. This, together with the very poor *Gaia* DR2 fit (see formal errors in Table 2) strongly suggests that it is a binary.

4.2 Cluster parameters

The stellar content described in the previous section identifies Alicante 13 as a young open cluster. The brightest stars still close to the main sequence have spectral type B2.5 V. At solar metallicity, this earliest spectral type is typical of clusters in the age range 25–35 Ma. To derive global parameters, we used JHK_S photometry from the 2MASS (Two Micron All Sky Survey) catalogue (Skrutskie et al. 2006). For this, we cross-matched the population selected within 12 arcmin of HD 339063 with the 2MASS point-source catalogue, admitting only objects with well-defined errors in all three bands. Given the high-quality astrometry of both catalogues, we only accepted matches separated by less than 0.3 arcsec. The completeness limit of this catalogue is set at $K_S = 14.2$.

The mean value of the cluster parallax in DR2 data is 0.37 mas, in total agreement with the DR2 value for SV Vul itself (π = 0.37 ± 0.03 mas). However, there are systematic errors affecting all astrometric parameters in DR2 (Luri et al. 2018). In particular, there is a zero-point offset (Lindegren et al. 2018), which seems to depend on colour and perhaps position in the sky (Zinn et al. 2019; Khan et al. 2019). Given this uncertainty, we simply assume a nominal $\pi = 0.40$ mas ($d = 2.5$ kpc), i.e. $DM = 12.0$ mag, in agreement with the values obtained by Madore et al. (2017) for SV Vul. In Fig. 7, we plot the 2MASS CMD for the population selected on the basis of their astrometric parameters together with Padova PARSEC isochrones. A 30 Ma isochrone provides a very good fit to the whole blue sequence and the position of the two red supergiants (note that only the red component of BD +27°3542 contributes in these bands), with an extinction $A_V = 1.67$ mag, again fully consistent with the value derived by Madore et al. (2017) for SV Vul. In particular, the location of HD 339063 on this diagram is a strong constraint on the fit. Older clusters at shorter distances fail to give a good fit for the upper main sequence. As an example, we show a 35 Ma isochrone with $DM = 11.5$ mag (the other end of the range suggested for SV Vul in the literature) and the same extinction. A small decrease or increase of the reddening does not improve the fit, ruling out the older age.

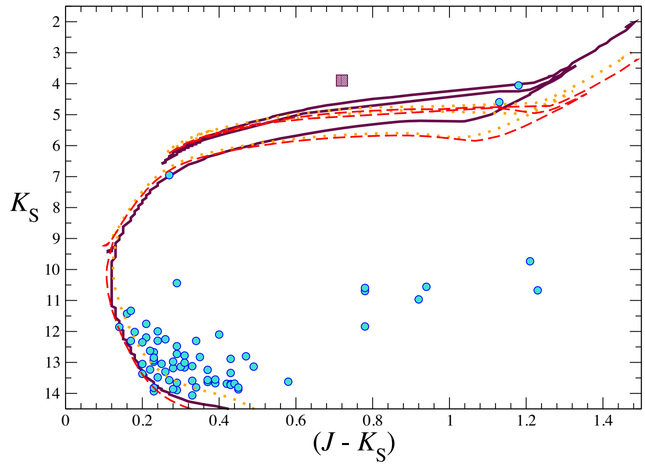

Figure 7. IR CMD for the population of Alicante 13, built with 2MASS data. As with the *Gaia* photometry, there is a small number of astrometric members that do not fit the sequence at $(J - K_S) \geq 0.7$. The thick continuous (maroon) line is a 30 Ma isochrone with $DM = 12.0$ mag and $A_V = 1.67$ mag. The dotted (orange) line is a 35 Ma isochrone with $DM = 11.5$ mag and the same extinction. The dashed (red) line is a 25 Ma isochrone with $DM = 12.2$ mag. The large square is SV Vul (as it is saturated in 2MASS, we have taken its average magnitudes from Fouqué et al. 2007). The blue stars lying immediately to the right of the main sequence can be considered candidate Be stars.

A younger cluster with the same extinction can provide a good fit to the blue sequence for a slightly higher distance. However, it fails to fit the red supergiants, as the gap in magnitude between the blue and red supergiants increases with age. As an example, in Fig. 7 we also show a 25 Ma isochrone with $DM = 12.2$ mag.

Despite the excellent fit to the 2MASS CMD, the *Gaia* photometry cannot be fit with the same parameters. In particular, Padova PARSEC isochrones using the passbands of Maíz Apellániz & Weiler (2018) can only fit the sequence with $A_V \approx 2.0$ mag, a much higher value than implied by the 2MASS data. Given this higher extinction, isochrones give a good fit to the main sequence for a shorter $DM = 11.7$ mag. As shown in Fig. 8, this shorter distance requires a slightly older cluster (35 Ma) to fit the location of the supergiants. The reason for this discrepancy between the

Table 2. Observed parameters for blue stars with classification spectra. The four stars in the top panel have astrometric parameters compatible with membership. The star in the bottom panel is not an astrometric likely member.

Star	Spectral type	pm (RA) (mas)	pm (Dec) (mas)	π (mas)	G (mag)	$BP-RP$ (mag)
LS II +27°23	B2.5 V	−2.18 ± 0.05	−5.81 ± 0.05	0.42 ± 0.03	11.74	0.71
LS II +27°24	B2.5 V	−2.02 ± 0.05	−5.91 ± 0.05	0.32 ± 0.03	11.46	0.75
TYC 2148-1327-1	B3 Ve	−2.07 ± 0.04	−5.86 ± 0.05	0.40 ± 0.03	12.22	0.85
TYC 2148-3261-1	B5 V	−2.10 ± 0.25	−6.01 ± 0.31	0.47 ± 0.16	12.13	0.82
LS II +27°19	B2.5 III	−2.75 ± 0.05	−5.77 ± 0.05	0.27 ± 0.03	11.21	0.88

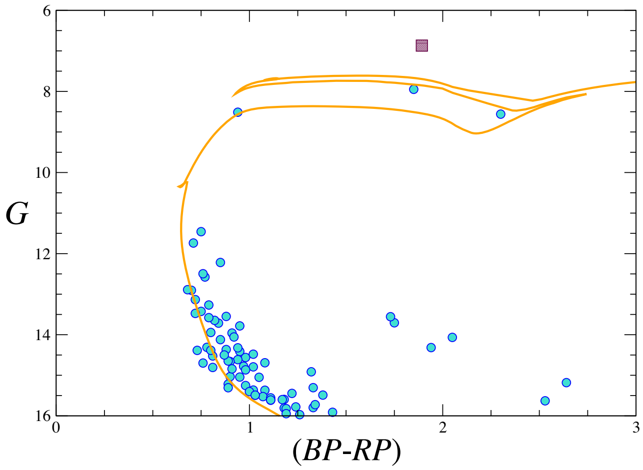

Figure 8. Best-fitting isochrone for the population of Alicante 13, by using *Gaia* photometry. The thick continuous (orange) line is a 35 Ma isochrone with $DM = 11.7$ mag and $A_V = 2.0$ mag. The large square is SV Vul. Different transformations have been used for bright and faint stars, as indicated by Maíz Apellániz & Weiler (2018).

extinction derived from optical and IR photometry is unclear, but it points towards non-standard extinction law. Turner (1980) derives $E(B - V) = 0.65$ and 0.69 for LS II +27°23 and 24, respectively, in agreement with the reddening estimated from the *Gaia* photometry, implying that there are no systematics affecting the optical photometry. Any anomaly in the extinction law, however, will have a smaller impact on the near-IR magnitudes and colours, and thus we favour the age derived from the fit in the 2MASS CMD.

5 DISCUSSION

We have identified a previously unknown cluster in the region of Vul OB1, which we name Alicante 13. The long-period classical Cepheid SV Vul is a halo member, located about 9 arcmin West from the centre. About half of the classical Cepheids confirmed as cluster members lie in their respective haloes (Anderson et al. 2013). At a distance of 2.5 kpc, 9 arcmin correspond to 6.5 pc, comparable to the distances of V Cen, EV Sct or QZ Nor to their respective clusters, and much shorter than the distance from V379 Cas to the centre of NGC 129, of which it is an obvious astrometric member (cf. Anderson et al. 2013, and *Gaia* DR2 data).

The 2MASS CMD is best fit by a 30 Ma isochrone, which agrees well with the spectral type of the brightest main-sequence members. According to the isochrone, the mass of the cluster supergiants should be ~9.2 $M_\odot$. SV Vul is clearly brighter than the location of the blue loop in the isochrone (about 0.6 mag in K_S and 0.9 mag in *G*). This is not unusual (cf. the position of V340 Nor with respect to the best-fitting isochrone for NGC 6067 in Alonso-Santiago et al. 2017) and could be due to moderately high initial rotation. As an example, Anderson et al. (2014) state that a 9 $M_\odot$ star with high initial rotation will reach the blue loop ~5 Ma later than a star with zero initial rotation, and so will considerably outlive stars of the same mass with slow rotation. Using isochrones by Georgy et al. (2013), we find that an $M_* = 10$ $M_\odot$ star with 'standard' initial rotation will traverse the blue loop after ≈28 Ma, reaching a luminosity of $\log L/L_\odot = 4.3$. For SV Vul, the *P*/*L* relation of Anderson et al. (2013) gives $M_V = -5.8$, while that of Madore et al. (2017) gives $M_V = -5.7$. Assuming a *BC* not very different from zero for an 'average' spectral type around G0 Iab, this means $\log L/L_\odot \approx 4.2$. On the other hand, a star of $M_* = 9.2$ $M_\odot$ with low initial rotation will be leaving the loop (i.e. becoming a red supergiant) after 30 Ma, at a $\log L/L_\odot = 3.9$. Therefore, the time-scales and luminosities agree very well with the fit to the rest of the cluster obtained with a PARSEC isochrone. Interestingly, according to Anderson et al. (2014), fast rotators with masses higher than 10 $M_\odot$ do not experience blue loops. Therefore, SV Vul would be very close to the highest mass for which a fast rotator may appear as a Cepheid variable.[5]

Membership in a cluster allows a good estimation of the mass of SV Vul. In the past, it had been considered a field member of the Vul OB1 association, but this region of the sky is very complex; three different OB associations are believed to be projected one on top of the other, Vul OB4 at ~1 kpc, Vul OB1 at ~2 kpc and Vul OB2 at ~4 kpc (Turner 1980). Fig. 9 shows the relative positions of relevant objects in this area. The star-forming cluster NGC 6823, generally identified as the core of Vul OB1 lies about 4 deg South of SV Vul and has *Gaia* DR2 astrometric values pmRA = −1.7 mas yr^{-1}, pmDec = −5.3 mas yr^{-1}, and $\pi = 0.45$ mas (Cantat-Gaudin et al. 2018). The few stars visible in the vicinity of the nearby H II region NGC 6820 have compatible values. The nearby cluster NGC 6830, which is much older (~100 Ma), has pmRA = −3.2 mas yr^{-1}, pmDec = −5.8 mas yr^{-1}, and $\pi = 0.42$ mas. More to the North, Roslund 2 has pmRA = −1.7 mas yr^{-1}, pmDec = −5.1 mas yr^{-1}, and $\pi = 0.46$ mas, fully compatible with the values for NGC 6823. Roslund 2 is also a very young cluster, although somewhat older than NGC 6823, as it contains the blue supergiant HD 186745 (B8 Ia).

As we move further to the North, we find the small star-forming cluster Dolidze 53 (pmRA = −1.5 mas yr^{-1}, pmDec = −4.6 mas yr^{-1}, and $\pi = 0.48$ mas), and a number of early-type stars associated with the H II region Sh2-S88B, such as HD 338926 (pmRA = -2.05 ± 0.06 mas yr^{-1}, pmDec = -3.37 ± 0.06 mas yr^{-1}, and $\pi = 0.45 \pm 0.04$ mas) or HD 338916 (pmRA = -3.68 ± 0.06 mas yr^{-1}, pmDec = -3.39 ± 0.05 mas yr^{-1}, and $\pi = 0.49 \pm 0.04$ mas), whose parallaxes are fully compatible with those of the association, but presenting very different proper motions. Based on their RVs, both Sh2-S88B and Sh2-89 are considered members of Vul OB1, conforming a large star-forming complex (e.g. Turner 1986). The parallax to Alicante 13 ($\pi = 0.37$ mas) is not sufficiently far away from the value for this complex to completely rule out an association (especially given the possibility of important systematics affecting sources that are more than 4 deg away), but the cluster is considerably older. Two nearby clusters have very similar astrometric parameters in the catalogue of Cantat-Gaudin et al. (2018), Czernik 41 (pmRA = −2.9 mas yr^{-1}, pmDec = −6.2 mas yr^{-1}, and $\pi = 0.37$ mas) and Gulliver 34 (pmRA = −2.9 mas yr^{-1}, pmDec = −5.8 mas yr^{-1}, and $\pi = 0.35$ mas). Both are dispersed, little-studied clusters, without reliable estimates of their ages.

The parameters for NGC 6834 (pmRA = −2.5 mas yr^{-1}, pmDec = −5.1 mas yr^{-1}, and $\pi = 0.27$ mas), on the other hand, cannot be reconciled with those of the the Vul OB1 complex, against previous suggestions. It seems to be rather more distant. The *Gaia* parameters for S Vul, assumed in the past to be a member of Vul OB2

[5]We can also speculate that SV Vul is brighter than the other supergiants because it is a mass gainer in a binary interaction, which resulted in a higher mass than those of other members. However, it is unlikely that mass gain would have resulted in a slow rotator, while the difference in magnitude does not allow for a very large mass difference. Therefore the hypothesis of a somewhat more massive fast rotator seems to fit better.

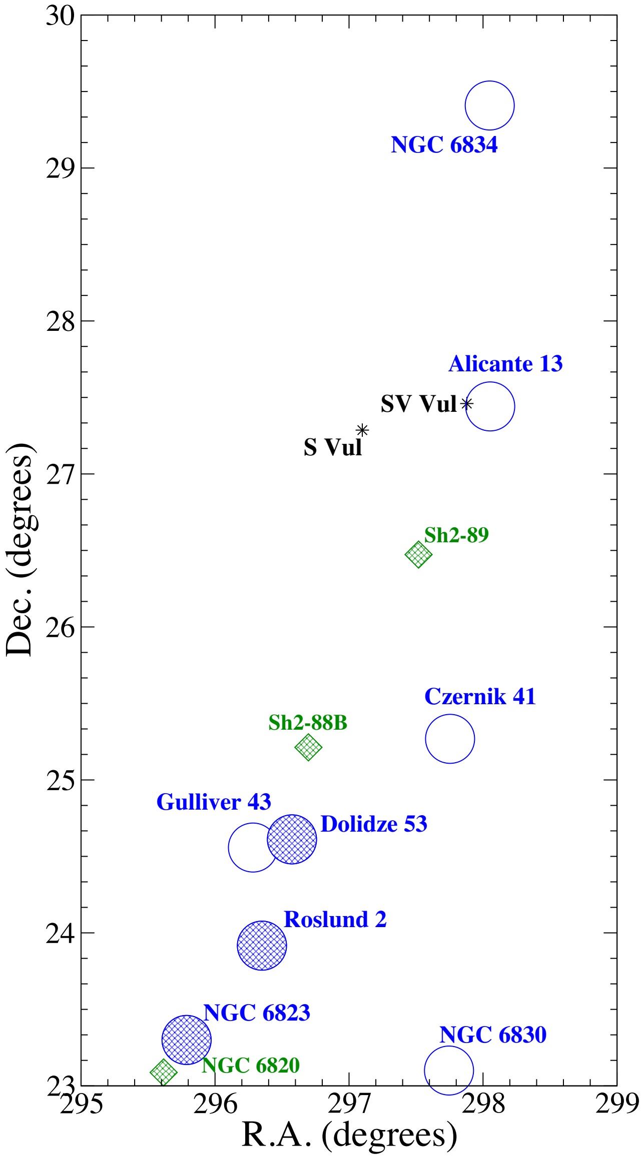

Figure 9. Relative position in the sky for objects that could be related to Vul OB1. Circles indicate open clusters, while diamonds mark H II regions. All filled symbols indicate objects associated with star-forming nebulosities and thus younger than a few Ma.

(Turner 1980), are pmRA $= -3.40 \pm 0.06$ mas yr^{-1}, pmDec $= -5.92 \pm 0.06$ mas yr^{-1}, and $\pi = 0.31 \pm 0.04$ mas (in agreement with the *HST* parallax $\pi = 0.32 \pm 0.04$ mas; Riess et al. 2018a). In view of this, it would seem that the classical view of two separate associations, Vul OB1 and Vul OB2, projected over the same region, but with clearly distinct distances of ∼2 and ∼4 kpc (Turner 1980) has to be abandoned.[6] The emerging picture is much more complex, with objects projected over a wide range of distances. As an example, within the central region of Alicante 13, we find the catalogued OB star LS II +27°19, with DR2 parameters pmRA $= -2.75 \pm 0.05$ mas yr^{-1}, pmDec $= -5.77 \pm 0.05$ mas yr^{-1}, and $\pi = 0.27 \pm 0.03$ mas. As can be seen in Fig. 10 and Table 2, this is a giant star of the same spectral type as those at the top of the cluster

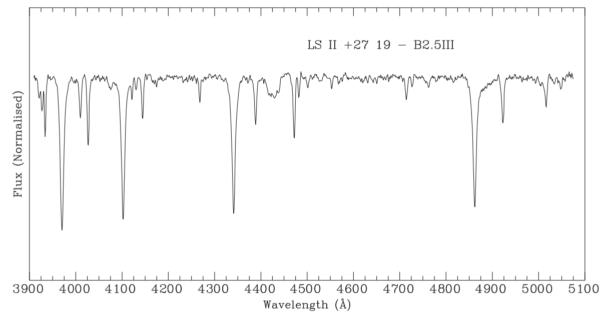

Figure 10. Classification spectrum of a background star in the field of Alicante 13.

sequence. Its parallax is inconsistent with that of the cluster at $> 2\sigma$ and it is only very slightly brighter than the main-sequence stars, indicating a longer distance modulus. Its reddening, however, is only very slightly higher. Using the *UBV* photometry from Turner (1980) and our spectral type, we calculate a $DM = 12.8$ ($d = 3.6$ kpc), in good agreement with its parallax.[7] All this suggests that, beyond the obscuring clouds associated to Vul OB1, at about 2 kpc, the reddening increases very little in this direction until at least close to 4 kpc, resulting in the projection of large numbers of stars at different distances on to what seems to be a single association.

With the current *Gaia* DR2, this hypothesis cannot be tested. As long as systematic errors as high as 0.1 mas are possible (Luri et al. 2018), differentiating between 2 and 4 kpc is not straightforward. Despite this, it is worth noting that the *Gaia* parallaxes for the two Cepheids (SV Vul and S Vul), which are complicated *Gaia* targets, are fully consistent with previous estimates (including the *HST* parallax for S Vul). At the same time, stars in their neighbourhoods that were classified as members of Vul OB2 by Turner (1980) have parallaxes ranging from $\pi = 0.42 \pm 0.03$ (LS II +27°23) to 0.15 ± 0.04 (HD 332848), which strongly suggests that they are not all at the same distance. Further *Gaia* releases will clarify this issue.

Whatever the case, it is clear that SV Vul is not directly linked to the star-forming clusters in Vul OB1, but to a rather older population. Its membership in Alicante 13 shows that one of the most luminous Cepheid variables in the Milky Way has a mass of only ≈10 $M_{\odot}$. Indeed, there is no strong reason to believe that the even more luminous S Vul belongs to a younger population. This is in agreement with the models presented by Anderson et al. (2014), where the highest mass for a star with typical rotation (their 'average' rotation rate of $\omega = 0.5$) to experience a blue loop is slightly higher than 10 $M_{\odot}$. Models with zero rotation allow Cepheids as massive as 11.5 $M_{\odot}$. Such null rotation is in fact unphysical, but stars with low rotational velocities do indeed exist, and they could become Cepheids for masses of at least 11 $M_{\odot}$, although with a luminosity comparable to that of the most luminous 'rotating' Cepheids ($\log L/L_{\odot} \approx 4.3$), considered by Anderson et al. (2014) the upper limit in luminosity for Cepheids.

Among Cepheids in clusters, the only strong evidence for a mass higher than ≈10 $M_{\odot}$ is given by the 23 d Cepheid in vdBH 222 (Clark et al. 2015). At the distance implied by the Cepheid properties (≈6 kpc), the cluster has an age ≈20 Ma (Marco et al. 2014) and thus the properties of this Cepheid, which has a luminosity similar to that of SV Vul can be explained by a $\gtrsim 11$ $M_{\odot}$ star with low

[6]Note that, with the current *Gaia* DR2 data, the parallaxes for SV Vul and S Vul are consistent within their errors.

[7]Noting that we assume a standard reddening law, which, in view of the discrepancy between fits to the optical and IR photometry, does not seem to hold.

rotation. For example, using isochrones by Georgy et al. (2013), we find that an $M_* = 11.2$ M$_\odot$ star with low rotation ($\omega = 0.1$) will be in the blue loop at an age of ≈20.3 Ma, with $\log L/L_\odot \approx 4.3$. Again, we find very good agreement, even if we have to consider that all tracks by Georgy et al. (2013) between 9 and 12 M$_\odot$ are interpolated, and not directly calculated. Although further study of vdBH 222 is needed for a better characterization, all observations of Milky Way Cepheids in clusters seem to agree to a very good degree with the models of Anderson et al. (2014). Further *Gaia* data releases will undoubtedly provide us with a larger number of high-luminosity Cepheids with accurate distances.

Meanwhile, the very accurate proper motions provided by DR2 are already allowing us to discover new clusters with very low background contrast, such as Alicante 13, which would be completely inconspicuous except for the fortunate presence of three (super)giants within one arcminute. With an accurate distance to the cluster, successive *Gaia* releases may turn SV Vul into a key landmark for the local distance scale and the study of the evolutionary status of long-period Cepheids.

6 CONCLUSIONS

We find that the 45 d classical Cepheid SV Vul is a certain astrometric halo member of a new young open cluster, Alicante 13. The star is slightly brighter than predicted by the best-fitting isochrones, suggesting that it started its life as a fast rotator. With the best-fitting age, stars close to the main sequence have ≈9 M$_\odot$ and SV Vul has a mass of ≈10 M$_\odot$, in agreement with the highest mass compatible with a fast rotator entering the blue loop (Anderson et al. 2014). Isochrone fit to the cluster CMD favours a distance of 2.5 kpc, in good agreement with its *Gaia* parallax and the distance proposed by Madore et al. (2017). There is, however, a discrepancy between the amount of extinction needed to fit the optical and the IR photometry, suggestive of a moderately non-standard reddening law. The connection of Alicante 13 to the Vul OB1 association, dominated by NGC 6823, is unclear. In fact, only clusters with current star formation seem to be certain members of the association. With upcoming *Gaia* releases providing a definitive distance, SV Vul will become an anchoring point in the study of long-period classical Cepheids.

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NOTE ADDED IN PROOF

After submission of this paper, Castro-Ginard et al. (2020) presented the results of a systematic search for clusters, conducted by applying a machine learning methodology to *Gaia* DR2 data. Among their 245 class A candidate clusters, they find Alicante 13, under the name UBC 130, with centre at RA: 19:52:12.17, Dec: +27:26:42.9. Their estimated parameters are $\pi = 0.39 \pm 0.03$ mas, pmRA=-2.11 ± 0.08 mas yr^{-1}, and pmDec = -5.85 ± 0.08 mas yr^{-1}, fully consistent with the values derived in this paper. According to their criteria, TYC 2148-893-1 is an outlying cluster member. If so, it must be a third red supergiant. Its *Gaia* DR2 RV 0.86 ± 0.24 km s^{-1} is compatible with those of other members. However, both its *Gaia* and 2MASS magnitudes, $K_S = 5.44$, $(J - K_S) = 1.21$, place it below the cluster isochrone. Spectroscopic data will be needed to assess its membership.

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