

The spectral energy distributions of very long-period Cepheids in the Milky Way, the Magellanic Clouds, M31, and M33

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ABSTRACT

The spectral energy distributions (SEDs) of 20 Milky Way (MW), 9 Large Magellanic Cloud (LMC), 7 Small Magellanic Cloud (SMC), 12 M31, and 7 M33 (classical) Cepheids with periods longer than 50 days were constructed using photometric data from the literature and fitted with model atmospheres with the aim of identifying objects with an infrared excess. The SEDs were fitted with stellar photosphere models to derive the best-fitting luminosity and effective temperature; a dust component was added when required. The distance and reddening values were taken from the literature. WISE and IRC images were inspected to verify whether potential excess emission was related to the central objects. Only one star with a significant infrared (IR) excess was found in the LMC and none in the SMC, M31, and M33, contrary to earlier work on the MW suggesting that IR excess may be more prominent in MW Cepheids than in the Magellanic Clouds. One additional object in the MW was found to have an IR excess, but it is unclear whether it is a classical Cepheid or a type-II Cepheid. The stars were plotted in a Hertzsprung–Russell diagram (HRD) and compared to evolutionary tracks for CCs and to theoretical instability strips. For the large majority of stars, the position in the HRD is consistent with the instability strip. For stars in the MW uncertainties in the distance and reddening can significantly change their position in the HRD.

Key words. stars: distances – stars: fundamental parameters – stars: variables: Cepheids

1. Introduction

Classical Cepheids (CCs) are important standard candles because they are bright and provide a link between the distance scale in the nearby universe and that further out via those galaxies that contain both Cepheids and SNIa (see [Riess et al. 2022](#) and [Murakami et al. 2023](#) for a determination of the Hubble constant to 1.0 km s⁻¹ precision or better). Typically, the period-luminosity (PL) relations of CCs that are at the core of the distance determinations are derived in particular photometric filters (V, I, K) or combinations of filters that are designed to be reddening independent, called the Wesenheit functions ([Madore 1982](#)), for example using combinations of (V, I) or (J, K), or the combination used by the SHOES team (F555W, F814W, and F160W HST filters; see [Riess et al. 2022](#)).

On the other hand, the bolometric magnitude or luminosity is a fundamental quantity of stars as it is the output of stellar evolution models and the input to CC pulsation models. This is the continuation of a series of papers that construct and analyse the spectral energy distributions (SEDs) of CCs. In [Groenewegen \(2020a\)](#) (hereafter G20) the SEDs of 477 Galactic CCs were constructed and fitted with model atmospheres (and a dust component when required). For an adopted distance (from *Gaia* DR2 at that time), reddening these fits resulted in a best-fitting bolometric luminosity (L) and the photometrically derived effective temperature (T_{eff}). This allowed the derivation of period-radius (PR) and period-luminosity (PL) relations, the construction of the Hertzsprung–Russell diagram (HRD), and a comparison to theoretical instability strips (ISs). This sample was further studied in [Groenewegen \(2020b\)](#), where the relation was investigated between the bolometric absolute magnitude and the flux-weighted gravity (FWG); this is

known as the flux-weighted gravity-luminosity relation (FWGLR).

In [Groenewegen & Lub \(2023\)](#) 77 Small Magellanic Cloud (SMC) and 142 Large Magellanic Cloud (LMC) CCs were studied along similar lines. The advantage of using the Magellanic Clouds (MCs) is that accurate and independently derived mean distances are available based on the analysis of samples of eclipsing binaries ([Pietrzyński et al. 2019](#); [Graczyk et al. 2020](#)).

Interestingly, in the latter study, only one case was found where there was evidence of an infrared excess, namely the longest period object in the LMC. This is in contrast to Galactic CCs where near-IR (NIR) and mid-IR (MIR) excess is known to exist, revealed for example via direct interferometric observations in the optical or NIR (e.g. [Kervella et al. 2006](#); [Mérand et al. 2006](#); [Gallenne et al. 2012](#); [Nardetto et al. 2016](#); [Hocdé et al. 2025b](#)), modelling with the SPIPS code (e.g. [Breitfelder et al. 2016](#); [Trahin 2019](#); [Trahin et al. 2021](#), and [Gallenne et al. 2017](#) for the LMC) and was also found in modelling of the SEDs of Galactic CCs ([Gallenne et al. 2013](#); G20).

This raises the question of whether this apparent difference in the presence of IR excess could be related to metallicity. To investigate this further, a complete sample of long-period Cepheids (periods longer than 50 days; see below) is studied in this paper, in the MW, the MCs, and M31 and M33. This study is connected to the class of ultra long-period (ULP) Cepheids, a term introduced by [Bird et al. \(2009\)](#) as fundamental mode (FU) Cepheids with periods longer than 80 days (see reviews by [Musella et al. 2021](#) and [Musella 2022](#) specifically on ULPs).

The paper is structured as follows. In Section 2, the sample of Cepheids is introduced, while Section 3 introduces the photometry that is used, the distances used, and how the modelling of the SED was done. Section 4 discusses several results,

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Table 1. Adopted distances.

Region	Distance model (kpc)	References
M33	840 ± 11 + geometric correction ($i = 57^\circ$, PA= 22.5°)	Breival et al. (2023), Kourkchi et al. (2020)
M31	761 ± 11 + geometric correction ($i = 70^\circ$, PA= 43°)	Li et al. (2021), Dalcanton et al. (2012)
SMC	62.44 ± 0.94	Graczyk et al. (2020)
LMC	49.59 ± 0.55 + geometric correction ($i = 25^\circ$, PA = 132°)	Pietrzyński et al. (2019), Riess et al. (2019)
BUL	8.28 ± 0.03	GRAVITY Collaboration (2022, 2021)
MW	See text	–

in particular the location of the objects in the HRD, the presence of infrared excess, the PR and PL relations, and models with alternative distances or reddenings. A brief discussion and summary concludes the paper in Sect. 5.

2. Sample

For this paper a sample of 55 Cepheids was studied. In particular the sample is compiled from the following:

- Galactic Cepheids from Pietrukowicz et al. (2021)¹ which contains 3666 CCs. The longest period listed there is S Vul with a period of 68.65 d, clearly shorter than the classical limit of 80 days for ULPs. An (arbitrary) lower limit of 50 days is used, which results in nine objects.
- SMC and LMC CCs from the OGLE-IV catalogue (Soszyński et al. 2019), resulting in six and eight objects, respectively, with periods longer than 50 days.
- From the *Gaia* DR3 `vari_cepheid` table all CCs with a period longer than 50 days and type DCEP were selected, for a total of 53 objects (Ripepi et al. 2023; Gaia Collaboration 2023, 2016).

All of the sources from Pietrukowicz et al. (2021) are in the `vari_cepheid` table, except OGLE-GD-CEP-1505. It is listed there, but classified as a Type-II Cepheid (T2C) of the RV Tau class. It was kept in the sample as our analysis may shed light on its nature. All of the sources from Soszyński et al. (2019) are in the `vari_cepheid` table, except OGLE-LMC-CEP-4689. This is the well-known variable HV 2827, listed in the *Gaia* main catalogue, but not in the *Gaia* Cepheid and `vari_summary` tables. The source is kept. Thirty-one sources from the `vari_cepheid` table are not in the samples from Pietrukowicz et al. (2021) and Soszyński et al. (2019).

The 55 sources were matched with the SIMBAD database to obtain additional names and identifiers. Twelve objects are likely members of M31 and seven are likely members of M33. The remaining 20 appear to be in the Milky Way. Five of them are in the direction of the Galactic Bulge and four of these have been classified as T2C by the OGLE team.

Basic information of the 55 stars are compiled in Table A.1. All LMC objects except LMC-Dachs2-24, and all SMC objects except SMC-Dachs3-5 and SMC-CEP-1977 were studied by Groenewegen & Lub (2023), while S Vul and GY Sge were studied in G20. However, the analysis of the SEDs was repeated here independently. It should be noted that there are known CCs in other galaxies with periods longer than 50 days (see e.g. Musella 2022), but they are not included in the *Gaia* `vari_cepheid` table.

¹ Version dated September 17, 2022 <https://www.astrouw.edu.pl/ogle/ogle4/OCVS/allGalCep.listID>

As for some sources there is a possible confusion about whether they are CCs or T2C of the RV Tau type, Cols. 8 and 9 give the predicted luminosity for the two classes based on the LMC PL relations of Groenewegen & Lub (2023) and Groenewegen & Jurkovic (2017), respectively. Typically, these luminosities differ by a factor of 20–30 for periods in the range 50–200 days, implying changes in distance by a factor of 5 to ‘convert’ a T2C into a CC, or vice versa, purely based on consistency with a PL relation.

3. Photometry, distance, masses, and modelling

3.1. Photometry

The SEDs were constructed using photometry retrieved mostly, but not exclusively, via the VizieR web-interface². Table B.1 lists the filters and references to the photometry that were considered. An additional reason for not considering known CCs with periods longer than 50 days in more distant galaxies is that there are less (and less accurate) MIR data available, which are needed to detect an IR excess, and the problem of contamination or blending as a given beam size or aperture corresponds to a larger physical size (as indeed turns out to be the case for some objects, see Sect. 4.3). The data contain single-epoch observations (typically from GALEX and Akari) but whenever possible values at mean light were taken or multiple data points were averaged.

3.2. Distance and geometric correction

For the LMC, M31, and M33, mean distances from the literature were adopted and a geometric correction was applied to correct for the fact that the sources are to first order located in an inclined disc, following Grocholski et al. (2007). The depth effect in the SMC is considerable (e.g. Ripepi et al. 2017), and all SMC sources were adopted to be at the mean distance. For the Galactic Bulge region³ the distance from the GRAVITY experiment was adopted (GRAVITY Collaboration 2022). For the remainder of the MW sources the geometric distance from Bailer-Jones et al. (2021) was adopted. Details and references are listed in Table 1. The distances to the individual sources are given in Table A.2.

The 3D reddening maps of Lallement et al. (2022) and Vergely et al. (2022) were used⁴ to obtain the A_V in a given direction as well as the distance to which this reddening refers. For the sources in M31 and M33 a value of $A_V = 0.17$ was adopted which is the average value from the 3D reddening map at the largest available distance in the direction of those

² <http://vizier.u-strasbg.fr/viz-bin/VizieR>

³ Defined as the region with $266 < RA < 270^\circ$ and $-33 < \delta < -28^\circ$ and comprising the four sources with BLG-T2CEP in their names and the source marked GDR404357.

⁴ <https://explore-platform.eu>

galaxies. For the MCs the reddening map of Skowron et al. (2021) was used and the $E(V - I)$ value in the map closest to the source is taken. The visual extinction was then taken as $A_V = 3.1 \cdot E(V - I)/1.318$, following Skowron et al. (2021). The reddenings to the individual sources are given in Table A.2.

3.3. Modelling

The SEDs are fitted with the code More of DUSTY (MoD, Groenewegen 2012)⁵, which uses a slightly updated and modified version of the DUSTY dust radiative transfer (RT) code (Ivezić et al. 1999) as a subroutine within a minimisation code. The dust optical depth is initially set to zero. In that case the inputs to the model are the distance, reddening, and a model atmosphere. The cases where an infrared (IR) excess may be present are discussed in Sect. 4.3.

The MARCS model atmospheres are used as input (Gustafsson et al. 2008) for $\log g = 1.5$ and for adopting canonical metallicities of -0.50 and -0.75 dex for the LMC and SMC stars, and $+0.00$ for M31, M33, the Bulge, and the MW sources⁶. The model grid was available at 250 K intervals for the effective temperature range of interest, and adjacent model atmospheres were used to interpolate models at 125 K intervals, which more closely reflects the accuracy in T_{eff} that can be achieved. For every model atmosphere (that is, T_{eff}) a best-fitting luminosity (with its [internal] error bar, based on the covariance matrix) is derived with the corresponding reduced χ^2 (χ_r^2) of the fit. The model with the lowest χ_r^2 then gives the best-fitting effective temperature. Considering models within a certain range above this minimum χ_r^2 then gives the estimated error in the effective temperature and luminosity. For the luminosity this error is added in quadrature to the internal error in luminosity.

In the model fitting procedure photometric outliers were excluded in the following way. The photometric error bar for each data point was added in quadrature to $1.4826 \cdot \text{median absolute deviation (MAD)}$ of the residuals in the fit to give the equivalent of 1σ in a Gaussian distribution. If the absolute difference between the model and observations was larger than 4σ , the point was flagged and plotted with an error bar of 3.0 mag so that it was still identified, but had no influence on the fitting. The model grid over temperatures was run again, and the clipping procedure repeated. Then the run over effective temperatures was repeated a last time. The best-fitting effective temperature and luminosity with error bars are listed in Table A.2.

4. Results

4.1. General

Figure 1 shows some best fits without considering dust. This illustrates the quality of the modelling with the residual (model minus observations) in the bottom part of each panel⁷.

4.2. Hertzsprung–Russell diagram

Figure 2 shows the HRD together with sets of evolutionary tracks and the ISs of CCs in two panels. Objects from the sample are plotted as filled squares (SMC), open squares (LMC), open triangles (M31), filled triangles (M33), filled circles (Galactic Bulge),

⁵ <http://homepage.oma.be/marting/codes.html>

⁶ Metallicity gradients in M31 and M33 are not considered (see e.g. Li et al. 2025).

⁷ The complete set of SEDs is available at <https://doi.org/10.5281/zenodo.15422721>

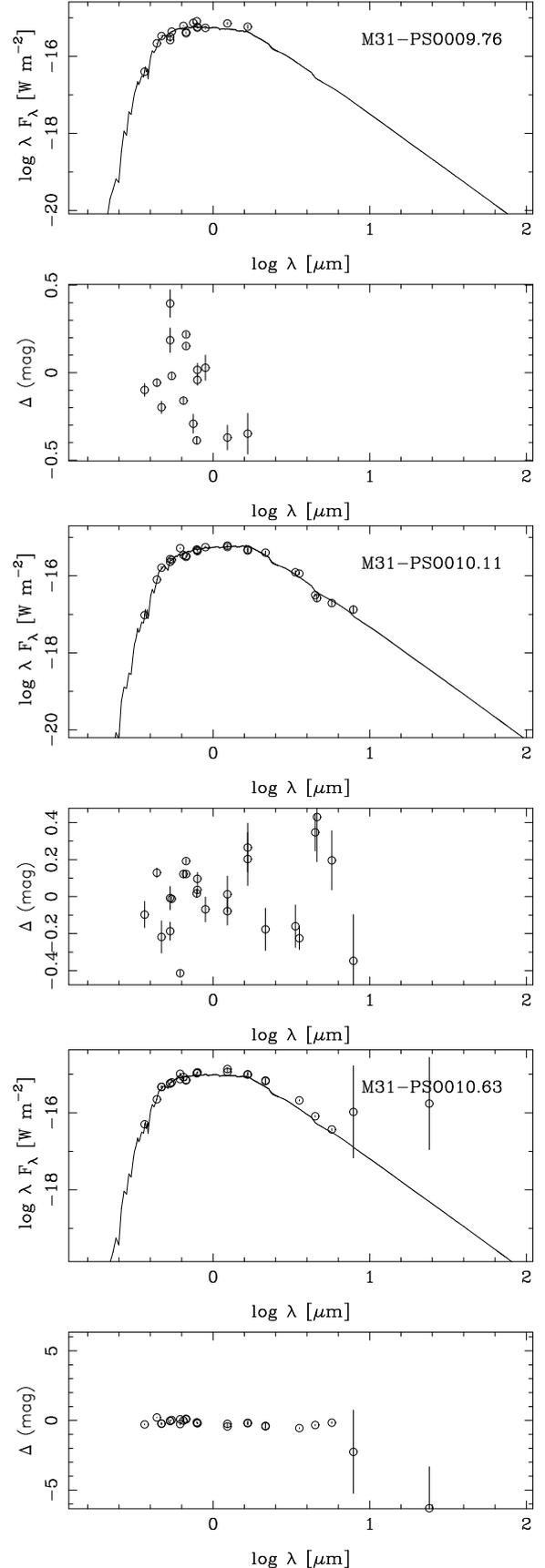


Fig. 1. Examples of best-fitting models assuming no dust. The upper panels show the observations (with error bars) and the model. The lower panel shows the residuals. Outliers that have been clipped are plotted with an (arbitrary) error bar of 3.0 mag.

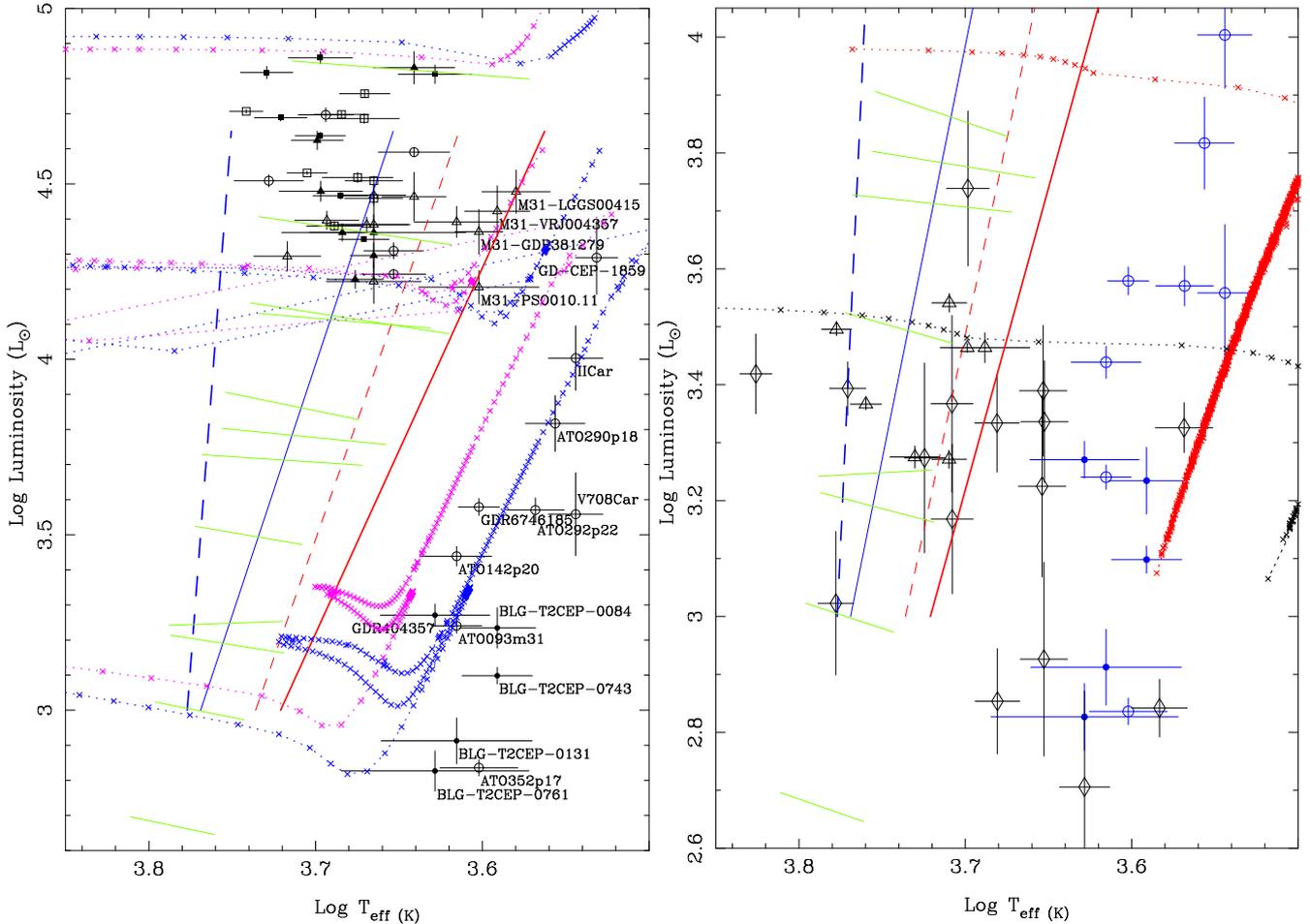


Fig. 2. Hertzsprung–Russell diagram. The left panel presents an overview while the right panel focusses on the T2Cs. The symbols are follows: filled squares (SMC), open squares (LMC), open triangles (M31), filled triangles (M33), filled circles (Galactic Bulge), and open circles (MW). Stars located outside the bulk of objects are identified. The blue and red lines indicate the blue and red edge of the IS of CCs. The results from De Somma et al. (2021) are plotted for $Z = 0.03$ (thick solid lines) and $Z = 0.004$ models (thinner dashed lines), for their type A mass–luminosity relation. The green lines indicate evolutionary models from Anderson et al. (2016) (see text for details). The blue and pink crosses indicate MIST evolutionary tracks for $v/v_{\text{crit}} = 0.4$ for 5.0, 10, and 17 M_{\odot} (and $[\text{Fe}/\text{H}] = 0.0$ dex) and 4.8, 9, and 15 M_{\odot} (and $[\text{Fe}/\text{H}] = -0.50$ dex), respectively, plotted at 10^4 year intervals (Dotter 2016; Choi et al. 2016; Paxton et al. 2015, 2013, 2011). The first crossing of the IS is also visible, except for the highest mass tracks. In the right panel the objects in the sample are plotted in blue, without names and the MIST evolutionary tracks are not shown. Instead, the black and red crosses indicate the evolutionary tracks of the 1.0 and 2.5 M_{\odot} solar metallicity stars, respectively, including the post-AGB phase, plotted at 10^3 year intervals (from Vassiliadis & Wood 1994). For comparison, the black triangles and spades indicate T2C with periods longer than 50 days in the MCs (from Groenewegen & Jurkovic 2017) and the MW (from Bódi & Kiss 2019), respectively. GD-CEP-1505 is located outside both plots at $\log T_{\text{eff}} \sim 3.48$ and $\log L \sim 2.18$.

and open circles (MW). Stars located outside the bulk of objects are plotted with error bars and some are labelled as well. The red and blue edges of the IS of CCs are plotted for $Z = 0.015$ and 0.004 (De Somma et al. 2021). The near horizontal green lines indicate the evolutionary tracks of CCs for $Z = 0.014$ and average initial rotation rate $\omega_{\text{ini}} = 0.5$ from Anderson et al. (2016). Increasing in luminosity are tracks for initial mass (the number of the crossing through the IS): 4 (1), 5 (1), 5 (2), 5 (3), 7 (1), 7 (2), 7 (3), 9 (1), 9 (2), 9 (3), 12 (1), and 15 M_{\odot} (1). The blue and pink crosses in the left panel indicate the MIST evolutionary tracks for 5.0, 10, and 17 M_{\odot} (for $[\text{Fe}/\text{H}] = 0.0$ dex) and 4.8, 9, and 15 M_{\odot} (for $[\text{Fe}/\text{H}] = -0.50$ dex), respectively, plotted at 10^4 year intervals (Dotter 2016; Choi et al. 2016; Paxton et al. 2015, 2013, 2011). The 4.8 and 5.0 M_{\odot} tracks are the lowest mass ones with blue loops that reach the IS of CCs.

The right panel focusses on the T2C, and the black and red crosses respectively indicate the evolutionary tracks of 1.0 and 2.5 M_{\odot} solar metallicity stars, including the post-AGB phase,

plotted at 10^3 year intervals (from Vassiliadis & Wood 1994). In addition, triangles and diamonds indicate T2C with periods longer than 50 days in the MCs (from Groenewegen & Jurkovic 2017) and the MW (from Bódi & Kiss 2019), respectively.

In the left panel there is a clear separation between objects whose location is consistent with the IS of CCs, and those that are clearly cooler, and in almost all cases, are significantly less luminous. Most of them have been classified as T2C in the literature. It is noted that 4 of the 12 CCs in M31 are close to the red edge of the IS for $Z = 0.03$. Based on the MIST and Anderson et al. (2016) evolutionary models the CCs have masses in the ~ 10 –15 M_{\odot} range.

The right panel, which focusses on the T2C region shows that the location of the stars in the sample is different from the known MCs and MW T2Cs with periods longer than 50 days from Groenewegen & Jurkovic (2017) and Bódi & Kiss (2019). The selection was very different in the sense that the latter studies started from samples of T2C, while the stars in this sample

Table 2. Results of the fitting of dust models.

Identifier	T_{eff} (K)	Luminosity (L_{\odot})	χ_r^2	T_d (K)	τ_v	BIC	BIC	BIC
M31-PSO010.63	4625	33 948 \pm 1425	36.1	343 \pm 47	0.793 \pm 0.096	725	712	78 137
M31-GDR369249	4375	24 688 \pm 1516	41.3	609 \pm 148	0.495 \pm 0.154	738	781	2529
M31-VRJ004357	4000	28 105 \pm 2006	27.0	557 \pm 226	0.626 \pm 0.244	453	430	964
M31-PSO011.09	5500	23 672 \pm 1377	55.7	471 \pm 60	0.760 \pm 0.127	1296	1349	29 370
M31-VRJ004434	5000	37 394 \pm 1545	83.1	330 \pm 45	1.037 \pm 0.100	2188	2414	232 000
M33-013312	5125	29 199 \pm 5011	201.8	446 \pm 197	1.161 \pm 0.412	3556	3805	6002
LMC-CEP-0619	4875	47 329 \pm 1315	54.8	925 \pm 111	0.082 \pm 0.015	1730	1750	29 766
II Car	3600	9312 \pm 592	164.3	1858 \pm 502	0.527 \pm 0.218	3014	4077	5276

Notes. Column 1. The identifier used in this paper. Column 2. (Photometric) effective temperature with error bar from the SED fitting. Column 3. Luminosity with internal error bar from the SED fitting (for the fixed distance). Column 4. Reduced chi-squared of the fit. Column 5. Dust temperature at the inner radius. Column 6. Dust optical depth in the V band. The errors in T_d and τ_v are scaled to $\chi_r^2 = 1$. Column 7. BIC of this model. Column 8. BIC of the model without dust and removing outliers (the model in Table A.2). Column 9. BIC of a model without dust and including all data points.

were initially believed to be largely CCs. Six objects have luminosities that lie above or close to the post-AGB track for a 1 M_{\odot} track, but seven do not. These objects are most probably post-RGB objects (see Kamath et al. 2016), although they are not dusty. Among the potential T2Cs only II Car shows some evidence of the presence of dust (see Sect. 4.3), all the others are well fit by a stellar atmosphere and do not show the characteristic disc or shell IR signature in their SEDs.

4.3. Infrared excess

The default assumption in the modelling was that there is no IR excess and the SEDs can be modelled by a stellar atmosphere. However, NIR and MIR excess are known to exist in Galactic CCs, for example direct interferometric observations in the optical or NIR and other methods (see references quoted in the Introduction), and one possibility to explain the IR excess is through dust emission. For T2Cs dust emission is a very plausible explanation as the long period T2C are associated with the RV Tau variability class that are generally believed to be in the post-AGB evolutionary phase (e.g. Manick et al. 2018).

In a next step, models were run with the dust optical depth (τ_d , at 0.5 μm) and dust temperature at the inner radius (T_d) as additional fit parameters. The dust shell was assumed to be spherically symmetric. Models with different initial guesses were run (T_d starting from 250, 400, 600, 800, 1000, and 1500 K; τ_d starting from 0.1, 0.3, 0.6, and 1). The Bayesian information criterion (BIC; Schwarz 1978) was used as a first check to determine whether a model with dust fitted the SED better than a model atmosphere. However, some flexibility in a strict application was needed as some seemingly better models converged to T_d values higher than the effective temperature, or had an error bar on T_d of the same order as T_d . In addition, the initial set of models was run for an effective temperature that resulted from the models without dust. A model with dust will increase the flux in the infrared due to emission but it will also absorb radiation in the optical, and therefore the best-fitting effective temperature will likely become higher. It should be pointed out that for a few objects (M31-PSO009.76, shown in Fig. 1, M33-013331, M33-V00021, and M33-013405) there is no photometry available beyond the NIR. As the contrast between the emission by dust and the stellar photosphere increases with wavelength this is not ideal to detect any excess emission; the absence of proof for infrared excess is not the proof of absence.

Based on these considerations, additional models were run for 9 stars out of the 55 in the sample, where the effective temperature was allowed to vary as well. For one star the results were not deemed conclusive (M33-013305) and the best-fitting models including dust for eight stars are listed in Table 2, one star each in the MW, LMC, and M33, and five in M31. Figure 3 compares the best-fitting models with and without dust for two objects, while the six others are shown in Fig. C.1. Table 2 includes the BIC of models under three model assumptions; the SEDs fitted including a dust component, a model without dust and where photometric outliers were removed (the model in Table A.2), and a model without dust and including all data points. The last model clearly represents the worst fit. In six cases the BIC of the model including dust is lower than the model without the outliers. Comparing the reduced χ^2 (Col. 4 in Table 2 to Col. 6 in Table A.2) this is only the case for two objects.

To further investigate the nature of the IR excess and to check the possibility that the IR excess is not associated with the CCs but related to diffuse background, the emission images from the ALLWISE survey⁸ and the Spitzer Enhanced Imaging Products (SEIP)⁹ were inspected. Figure C.2 and Figure C.3 show images in the WISE W1 and W3, and IRAC 1 and 4 filters, respectively, around selected CCs. The two objects in the top rows are different examples of stars without IR excess that are located in empty fields. The other panels show the eight stars with an IR excess in the SEDs from Table 2. Except for II Car and LMC-CEP-0619, the emission of the stars at the longest WISE3 and IRAC4 wavelengths (when detected) seems not be clearly associated with the central star, but appears to be diffuse emission or possibly partly blended. In the cases of M31-PSO010.63, M31-GDR369249, M31-VRJ004357, M31-PSO011.09, M31-VRJ004434, and M33-013312 the correct model is the standard model without dust and not considering the photometric outliers because these are very likely not associated with the objects.

4.4. Alternative models for the MW

For objects in the Bulge and MW, uncertainties in the adopted distance and reddening are important limitations in deriving accurate luminosities and photometric effective temperatures

⁸ <https://irsa.ipac.caltech.edu/applications/wise/>

⁹ <https://irsa.ipac.caltech.edu/data/SPITZER/Enhanced/SEIP/>

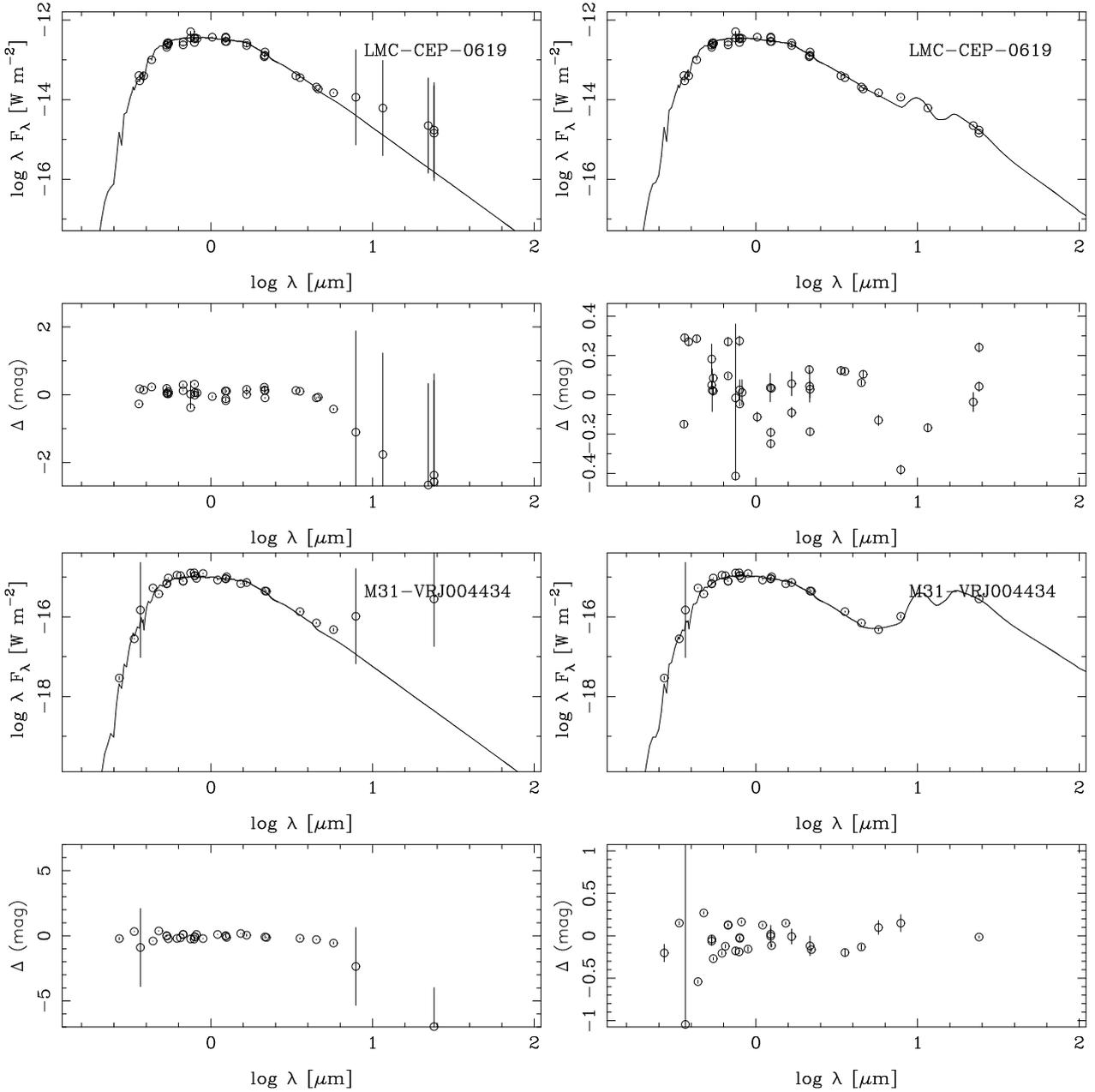


Fig. 3. Examples of best-fitting models assuming dust (right) compared to no dust (left panels). We note the difference in the range of the ordinate in the left and right bottom panels. The other six objects are shown in Fig. C.1. In the models without dust some photometric points are considered outliers and are plotted with a large error bar, instead of omitting them.

(also see G20). Table A.2 includes the distance and A_V estimates from Anders et al. (2022) based on the StarHorse code (Queiroz et al. 2018) that are independent from the initially adopted distances from Bailer-Jones et al. (2021) and the 3D reddening model.

Models for the 20 MW and BUL stars were rerun based on the parameters from StarHorse or, when not available, on plausible estimates based on general 1σ error bars in the distance and on plausible extrapolations of the reddening. The finally adopted parameters and the resulting best fits are listed in Table A.3. Figure 4 compares the standard models with the best-fitting models including dust or the alternative distances and reddenings. Especially for some of the MW objects the change in luminosity and effective temperature are large (e.g. for GDR404357), while the fit quality remains almost unchanged, indicating that the two

parameters are degenerate. While for some stars the alternative models move the object closer to or inside the IS, the location in the HRD of S Vul is moved outside the IS. A special case is GD-CEP-1505. The alternative model is an improvement, but the fit is still the poorest of all stars. Fixing the effective temperature to 4000 K and choosing a distance of 4.0 kpc will result in a luminosity of $1350 L_\odot$, a position consistent with the other T2Cs in the sample and the luminosity predicted for its period, but requires a very high reddening of $A_V = 11$ for its Galactic position of $l = +47.09$, $b = +0.90$. Table A.3 also includes some relevant quantities from the *Gaia* main catalogue, namely the *G*-band magnitude, the parallax, the goodness-of-fit parameter (GoF, expected to follow a Gaussian distribution centred on zero and with width unity), and the renormalised unit weight error (expected to be centred on unity).

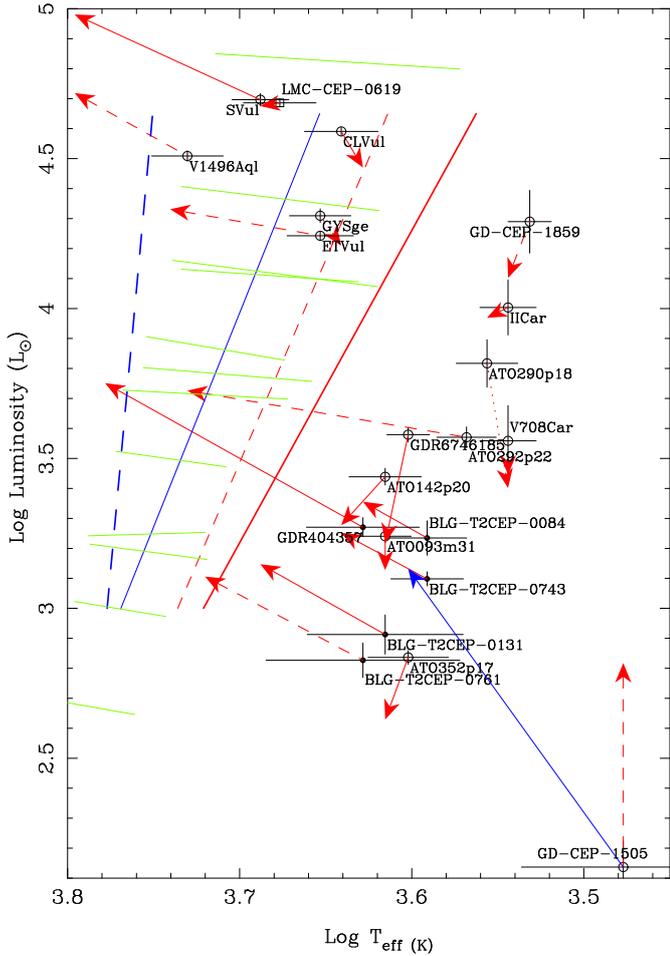


Fig. 4. Hertzsprung–Russell diagram. The symbols and lines largely follow Fig. 2. The standard models are connected to the best-fitting alternative models (i.e. with dust or alternative distances and reddenings) by a red line with arrow. The arrow is dashed when the alternative model has a reduced χ^2 that is lower by 10% or more than that of the standard model, dot-dashed when the alternative model has a reduced χ^2 that is larger by 10% or more, and solid otherwise. The blue line for GD-CEP-1505 indicates yet another alternative model (see text).

The standard adopted distance from Bailer-Jones et al. (2021) uses the observed parallax, the parallax zero point correction from Lindgren et al. (2021), and a prior constructed from a three-dimensional model of the Galaxy to determine the distance and error. A few CCs are located outside the IS, which could point to a distance that is different from that in Bailer-Jones et al. (2021) or the alternative distance. The parallax zero point correction is more uncertain for G magnitudes $\lesssim 12.5$ (e.g. Cruz Reyes & Anderson 2023), the significance of the parallaxes, π/σ_π , is often only 1–3 so that the prior will have a large impact on the derived distance, and some of the astrometric solutions are poor ($\text{RUWE} \gtrsim 1.4$ or $|\text{GoF}| \gtrsim 3$). *Gaia* DR4 is expected to deliver more accurate parallaxes that could resolve these issues.

4.5. Period–luminosity and period–radius relations

Figure 5 shows the PL and PR relations based on the standard model results, together with the PL and PR relations for CCs and T2Cs from Groenewegen & Lub (2023) and Groenewegen & Jurkovic (2017) for the LMC. The alternative models have not

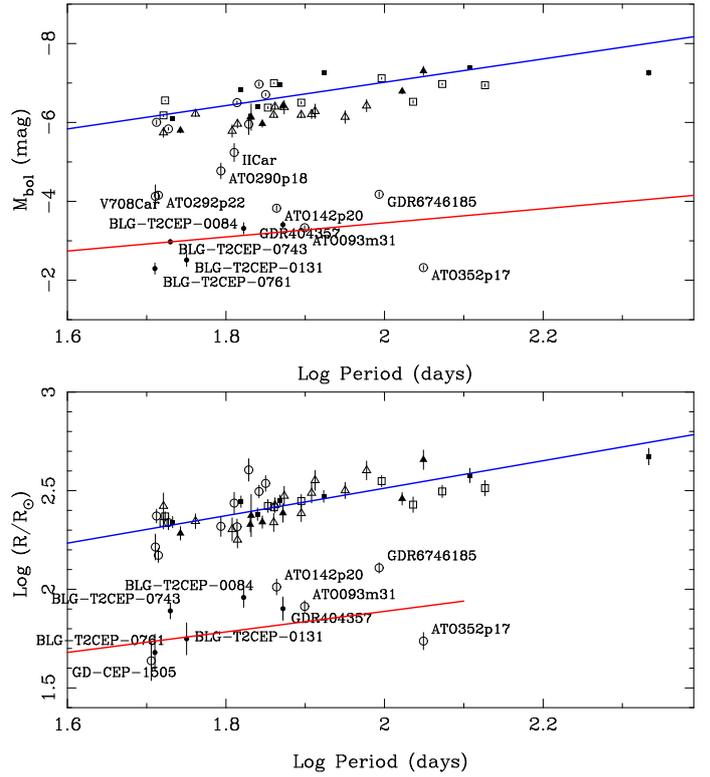


Fig. 5. Period- M_{bol} and PR relations. The error bars in M_{bol} are plotted but are typically smaller than the symbol size. The symbols are follows: filled squares (SMC), open squares (LMC), open triangles (M31), filled triangles (M33), filled circles (Galactic Bulge), and open circles (MW). Stars located outside the bulk of objects are identified. The blue lines give the relation for LMC CCs from Groenewegen & Lub (2023) while the red lines give the recommended solution for LMC T2Cs from Groenewegen & Jurkovic (2017). GD-CEP-1505 is located outside the upper plot at $\log P \sim 1.7$ and $M_{\text{bol}} \sim -0.6$ mag.

been plotted as they do not change the overall picture. These relations confirm largely what is also seen in the HRD. Some stars are located in these diagrams in positions consistent with their being T2Cs, but for some this is true for the PR diagram, but not for the PL diagram. There is more scatter in the relations for T2C than for CCs, but this is related to the fact that most of the CCs are located in external galaxies with better defined distances and reddenings than for the MW and Bulge objects.

Table 3 shows the classification of the 20 MW and Bulge objects based on the position in the HRD, the PL , and the PR diagrams. All ten that were previously classified or re-classified by the *Gaia* team as T2C are confirmed as such. GD-CEP-1505 is most definitely not a CC. It is most likely a T2C, but for its effective temperature and luminosity to be consistent with this requires a distance and reddening that is very different from that derived in the literature. Six stars are certainly CCs, and for four stars the results are not conclusive.

5. Discussion and summary

Table 4 summarises the results of the SED fitting of G20, Groenewegen & Lub (2023), and this paper in terms of the likely presence of IR excess emission based on the SED fitting. The numbers for the MW for $P > 50$ d depend on whether II Car and some of the other objects are considered CC or T2C (see Table 3).

Table 3. T2C and CC classification.

Name/identifier	Type (literature)	Type (PR)	Type (PL)	Type (HRD)
BLG-T2CEP-0743	DCEP *	T2C	T2C	T2C
BLG-T2CEP-0084	DCEP *	T2C	T2C	T2C
BLG-T2CEP-0761	DCEP *	T2C	T2C	T2C
BLG-T2CEP-0131	DCEP *	T2C	T2C	T2C
ATO093m31	DCEP *	T2C	T2C	T2C
ATO142p20	DCEP *	T2C	T2C	T2C
GDR404357	DCEP *	T2C	T2C	T2C
GDR6746185	DCEP *	T2C	T2C	T2C
ATO352p17	DCEP *	T2C	T2C	T2C
GD-CEP-1505	T2CEP	T2C	non-CC	non-CC
V708 Car	DCEP	CC	T2C	T2C
ATO292p22	DCEP	CC	T2C	T2C
II Car	DCEP	CC	?	T2C
ATO290p18	DCEP	CC	?	T2C
GD-CEP-1859	DCEP	CC	CC	T2C
V1496Aq1	DCEP	CC	CC	CC
GY Sge	DCEP	CC	CC	CC
ET Vul	DCEP	CC	CC	CC
CL Vul	DCEP	CC	CC	CC
S Vul	DCEP	CC	CC	CC

Notes. Copied from Table A.1. Column 2 lists the class from the GDR3 `vari_cepheid` table. An asterisk indicates that the star was reclassified as a T2C (see Table 6 in Ripepi et al. 2023). Columns 3, 4 and 5 give the type based on the location in the PR, PL and HRD diagrams as derived in the present paper.

Table 4. Detection of IR excess.

Period (d)	SMC	LMC	MW	M31+M33
>50	0/7	1/9	0/5–1/8	0/19
<50	0/72	0/134	16/350	n.a.

The fraction of CCs with IR excess appears small with the notable exception of the shorter period MW objects (~5%). In view of the Hubble tension (e.g. Perivolaropoulos 2024) it is an interesting question whether the presence of IR excess could impact the derivation of the CC PL relation, especially if the effect were different in the calibrating galaxies and in the galaxies the relation is applied to. The current analysis suggests that the impact should be low at best. Among the Galactic sample studied by Riess et al. (2021) in their preferred HST F555W, F814W, and F160W filter system to calibrate the PL-relation, only S TrA and HW Car possibly have an IR excess, and LMC619 is not among the calibrating sample of 70 LMC CCs studied in Riess et al. (2019).

Nevertheless, the presence and the origin of an IR excess remains intriguing and requires further study. Although it was assumed in the modelling that this is due to dust this origin is problematic (how 1000 K dust can form around a 6000 K central star; see discussion in G20) and free-free emission from ionised gas seems a viable alternative Hócdé et al. (2020a,b, 2025a). Interferometric observations of the MW stars that are claimed to have IR excess emission based on SED modelling would provide additional constraints. An alternative would be to obtain MIR

spectroscopy which would also be done for CCs in the LMC. Even at a low resolution of ~50 any silicate dust feature would become detectable and, if absent, any continuum emission over that expected from the stellar photosphere would put constraints on the underlying mechanism.

Data availability

The complete set of SEDs of the standard models and the alternative models is available at <http://doi.org/10.5281/zenodo.15422721>

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Appendix A: Sample and fitting results

Table A.1. Sample of stars

Name/Identifier	RA (deg)	Dec (deg)	Period (d)	Type	Period (d)	Type	L_{CC} (L_{\odot})	L_{T2C} (L_{\odot})	Remark
M31-PSO009.76	9.765076	40.511659	64.236 ± 0.079	DCEP			30790	1473	
M31-PSO010.11	10.119902	41.077721	52.622 ± 0.046	DCEP			24314	1269	
M31-PSO010.19	10.198750	41.032396	57.743 ± 0.052	DCEP			27140	1360	
M31-LGGS00415	10.313919	40.840238	94.933 ± 0.148	DCEP			48894	1973	
M31-GDR381279	10.474412	41.451470	89.184 ± 0.316	DCEP			45409	1883	
M31-PSO010.63	10.632660	41.486208	74.719 ± 0.084	DCEP			36825	1649	
M31-GDR369249	10.768002	41.076318	80.914 ± 0.118	DCEP			40467	1751	
M31-VRJ004357	10.991504	41.769738	81.734 ± 0.207	DCEP			40953	1764	
M31-PSO011.09	11.091752	41.922604	65.243 ± 0.024	DCEP			31362	1490	
M31-VRJ004434	11.143209	41.883533	72.749 ± 0.090	DCEP			35678	1617	
M31-GDR387319	11.285518	42.099396	78.513 ± 0.084	DCEP			39049	1712	
M31-GDR375422	11.889116	42.404674	72.481 ± 0.036	DCEP			35522	1612	
SMC-CEP-0417	10.431045	-73.723307	128.134 ± 0.107	DCEP	128.197 ± 0.303	F	69739	2469	HV 821
SMC-CEP-0921	11.721307	-72.714377	65.925 ± 0.042	DCEP	65.937 ± 0.010	F	31751	1502	
SMC-CEP-1502	12.619999	-72.752564	83.811 ± 0.025	DCEP	84.300 ± 0.046	F	42188	1797	HV 829
SMC-CEP-1977	13.236712	-71.917574	69.157 ± 0.039	DCEP	68.987 ± 0.013	F	33602	1557	
SMC-CEP-2099	13.427702	-72.287126	73.794 ± 0.044	DCEP	73.621 ± 0.036	F	36286	1634	
SMC-CEP-3611	16.064553	-72.755640	215.479 ± 1.781	DCEP	208.799 ± 0.348	F	129048	3642	HV 1956
SMC-Dachs3-5	18.325909	-73.363507	54.036 ± 0.013	DCEP			25090	1294	
M33-013253	23.224087	30.590259	111.950 ± 0.512	DCEP			59435	2232	
M33-013305	23.273916	30.622201	105.246 ± 0.122	DCEP			55245	2131	
M33-013312	23.301018	30.646657	67.893 ± 0.119	DCEP			32876	1535	
M33-013331	23.379284	30.528734	55.275 ± 0.081	DCEP			25772	1316	
M33-013343	23.432750	30.545848	74.444 ± 0.080	DCEP			36664	1645	
M33-V00021	23.465930	30.664079	67.711 ± 0.284	DCEP			32772	1532	
M33-013405	23.521359	30.647512	70.130 ± 0.080	DCEP			34162	1573	
LMC-CEP-4628	73.918991	-66.428700	99.156 ± 0.063	DCEP	99.200 ± 0.500	F	51480	2038	HV 5497
LMC-CEP-4629	74.111650	-64.694517	108.654 ± 0.159	DCEP	108.700 ± 0.500	F	57369	2183	HV 2883
LMC-CEP-0619	75.031541	-68.450018	133.879 ± 0.342	DCEP	133.779 ± 0.152	F	73456	2551	HV 883
LMC-CEP-0992	76.816636	-68.883485	52.875 ± 0.032	DCEP	52.874 ± 0.532	F	24453	1273	
LMC-CEP-1591	79.877126	-68.686032	118.239 ± 0.372	DCEP	118.624 ± 0.266	F	63409	2325	HV 2447
LMC-CEP-2253	82.840800	-70.957083	52.624 ± 0.026	DCEP	52.374 ± 0.034	F	24315	1269	
LMC-Dachs2-24	84.004780	-66.844926	71.272 ± 0.025	DCEP			34822	1592	
LMC-CEP-4689	85.947133	-66.585814			78.508 ± 0.377	F	39046	1712	
LMC-CEP-4691	86.210752	-67.494585	72.533 ± 0.057	DCEP	73.897 ± 0.164	F	35553	1613	
Milky Way Cepheids									
ATO093m31	93.250231	-31.306365	79.284 ± 0.152	DCEP *			39504	1724	
ATO142p20	142.429652	20.824279	73.081 ± 0.175	DCEP *			35871	1622	
V708 Car	153.907807	-59.551290	51.404 ± 0.016	DCEP			23649	1247	
II Car	162.204346	-60.063040	64.624 ± 0.031	DCEP			31010	1480	
GD-CEP-1859	206.308819	-63.571024	67.418 ± 0.063	DCEP	67.568 ± 0.014	F	32604	1527	
BLG-T2CEP-0743	267.339493	-32.422453	53.672 ± 0.147	DCEP *	52.957 ± 0.009	RVTau	24890	1288	
BLG-T2CEP-0084	267.569466	-30.504683	66.414 ± 0.166	DCEP *	66.431 ± 0.010	RVTau	32030	1510	
BLG-T2CEP-0761	267.647358	-32.545647	51.325 ± 0.204	DCEP *	51.281 ± 0.009	RVTau	23606	1245	
BLG-T2CEP-0131	268.107085	-29.449319	56.276 ± 0.030	DCEP *	56.964 ± 0.006	RVTau	26326	1334	
GDR404357	269.111824	-32.190456	74.463 ± 0.067	DCEP *			36676	1645	
V1496 Aql	283.748048	-0.076784	65.174 ± 0.109	DCEP			31323	1489	
GD-CEP-1505	288.605198	12.992103	50.786 ± 0.029	T2CEP	50.604 ± 0.026	F	23313	1236	
ATO290p18	290.918840	18.378956	62.168 ± 0.018	DCEP			29620	1437	
GDR6746185	291.573786	-31.521751	98.444 ± 0.086	DCEP *			51043	2027	
ATO292p22	292.079775	22.484192	51.844 ± 0.042	DCEP			23889	1255	
GY Sge	293.806771	19.202388	51.566 ± 0.040	DCEP			23738	1250	
ET Vul	293.833756	26.430225	53.375 ± 0.022	DCEP			24727	1282	
CL Vul	294.965439	22.269290	70.797 ± 0.054	DCEP			34548	1584	
S Vul	297.099176	27.286481	69.467 ± 0.046	DCEP			33781	1562	
ATO352p17	352.919044	17.853825	111.980 ± 0.595	DCEP *			59454	2232	

Notes. Columns 4 and 5 give the period and class from the GDR3 `vari_cepheid` table. An asterisk in Col. 5 indicates that the star was reclassified as a T2C (see Table 6 in [Ripepi et al. 2023](#)). Columns 6 and 7 give the period and class (F stands for fundamental mode pulsator) from OGLE. Columns 8 and 9 give the predicted luminosity for the period listed in column 4 (except for LMC-CEP-4689) and the PL-relation for CCs and T2Cs in the LMC from [Groenewegen & Lub \(2023\)](#) and [Groenewegen & Jurkovic \(2017\)](#), respectively. The last column gives the Harvard variable number for the CCs in the MCs.

Table A.2. Results of the fitting without dust

Identifier	d (kpc)	A_V (mag)	T_{eff} (K)	Luminosity (L_{\odot})	χ_r^2	SH_d (kpc)	SH_{A_V} (mag)	d_{max} (kpc)
M31-PSO009.76	761.18 ± (11.0)	0.17	4625 ± 312	16668 ± 2581	58.4			
M31-PSO010.11	754.41 ± (11.0)	0.17	4000 ± 347	16056 ± 1866	47.2			
M31-PSO010.19	757.09 ± (11.0)	0.17	4875 ± 221	24892 ± 1554	19.7			
M31-LGGS00415	764.20 ± (11.0)	0.17	3800 ± 184	30045 ± 4577	33.5			
M31-GDR381279	752.32 ± (11.0)	0.17	4000 ± 134	23101 ± 3654	17.7			
M31-PSO010.63	766.98 ± (11.0)	0.17	4375 ± 198	29078 ± 5035	32.3			
M31-GDR369249	767.51 ± (11.0)	0.17	4125 ± 250	24643 ± 2638	39.1			
M31-VRJ004357	754.68 ± (11.0)	0.17	3900 ± 180	26440 ± 4805	23.5			
M31-PSO011.09	752.91 ± (11.0)	0.17	5125 ± 243	19667 ± 1995	59.2			
M31-VRJ004434	754.86 ± (11.0)	0.17	4625 ± 208	29360 ± 1937	84.7			
M31-GDR387319	752.36 ± (11.0)	0.17	4625 ± 237	24216 ± 1611	47.9			
M31-GDR375422	756.56 ± (11.0)	0.17	4875 ± 289	24191 ± 1252	63.2			
SMC-CEP-0417	62.44 ± (0.94)	0.08	4875 ± 221	72352 ± 2823	59.8			
SMC-CEP-0921	62.44 ± (0.94)	0.10	5000 ± 177	43383 ± 1032	40.2			
SMC-CEP-1502	62.44 ± (0.94)	0.12	5375 ± 198	65640 ± 2687	58.2			
SMC-CEP-1977	62.44 ± (0.94)	0.13	4875 ± 189	29258 ± 677	46.5			
SMC-CEP-2099	62.44 ± (0.94)	0.12	5125 ± 189	48818 ± 1068	37.5			
SMC-CEP-3611	62.44 ± (0.94)	0.10	4250 ± 221	64918 ± 4074	128.8			
SMC-Dachs3-5	62.44 ± (0.94)	0.23	4750 ± 168	21979 ± 365	30.0			
M33-013253	844.54 ± (11.0)	0.17	4375 ± 253	67771 ± 7606	95.2			
M33-013305	843.49 ± (11.0)	0.17	4875 ± 177	42087 ± 2642	31.3			
M33-013312	842.95 ± (11.0)	0.17	4625 ± 627	22999 ± 8364	193.7			
M33-013331	843.10 ± (11.0)	0.17	4750 ± 189	16893 ± 1049	45.5			
M33-013343	842.40 ± (11.0)	0.17	4875 ± 289	30123 ± 2067	100.5			
M33-V00021	840.00 ± (11.0)	0.17	4875 ± 226	22999 ± 1364	46.2			
M33-013405	841.16 ± (11.0)	0.17	4625 ± 153	19762 ± 1690	63.0			
LMC-CEP-4628	49.53 ± (0.55)	0.31	4750 ± 168	57131 ± 1199	24.7			
LMC-CEP-4629	49.14 ± (0.55)	0.15	4750 ± 237	32987 ± 1120	69.6			
LMC-CEP-0619	49.89 ± (0.55)	0.28	4750 ± 236	48544 ± 1538	51.3			
LMC-CEP-0992	49.80 ± (0.55)	0.22	5125 ± 144	33980 ± 366	9.5			
LMC-CEP-1591	49.43 ± (0.55)	0.30	4875 ± 189	49882 ± 1085	32.9			
LMC-CEP-2253	49.88 ± (0.55)	0.31	4875 ± 189	23982 ± 689	23.3			
LMC-Dachs2-24	48.53 ± (0.55)	0.23	4625 ± 189	28762 ± 726	17.8			
LMC-CEP-4689	48.31 ± (0.55)	0.21	4625 ± 188	32283 ± 996	48.4			
LMC-CEP-4691	48.53 ± (0.55)	0.33	5375 ± 125	50872 ± 599	8.6			
Milky Way Cepheids								
ATO093m31	15.78 ± (2.58)	0.10	4125 ± 145	1740 ± 87	31.2			1.12
ATO142p20	9.72 ± (2.43)	0.08	4125 ± 204	2747 ± 181	55.2	7.36 ± 0.15	0.51 ± 0.01	0.59
V708 Car	3.87 ± (0.33)	1.33	3500 ± 134	3619 ± 1130	255.0			3.87
II Car	7.66 ± (1.24)	1.41	3500 ± 134	10082 ± 2377	199.4	5.11 ± 1.75	2.57 ± 0.42	5.27
GD-CEP-1859	10.62 ± (3.02)	3.21	3400 ± 100	19488 ± 5306	230.2			6.43
BLG-T2CEP-0743	8.28 ± (0.03)	4.10	3900 ± 194	1254 ± 70	83.5			5.01
BLG-T2CEP-0084	8.28 ± (0.03)	4.28	3900 ± 212	1716 ± 243	139.1	10.99 ± 0.98	6.31 ± 0.06	5.01
BLG-T2CEP-0761	8.28 ± (0.03)	3.74	4250 ± 588	671 ± 95	478.5	7.99 ± 1.54	4.82 ± 2.12	5.02
BLG-T2CEP-0131	8.28 ± (0.03)	3.85	4125 ± 453	818 ± 133	486.7			5.01
GDR404357	8.28 ± (0.03)	2.96	4250 ± 333	1865 ± 142	132.5			5.02
V1496 Aql	3.54 ± (0.32)	3.95	5375 ± 264	32271 ± 1309	69.8	3.26 ± 0.18	4.85 ± 0.35	3.54
GD-CEP-1505	4.05 ± (2.21)	3.59	3000 ± 438	137 ± 30	1940.0			4.05
ATO290p18	7.82 ± (2.64)	5.44	3600 ± 151	6562 ± 1315	204.9			6.28
GDR6746185	9.16 ± (1.56)	0.32	4000 ± 115	3795 ± 218	22.5	5.70 ± 0.06	0.58 ± 0.01	1.16
ATO292p22	12.55 ± (2.18)	3.01	3700 ± 150	3720 ± 307	60.7	8.51 ± 0.91	5.59 ± 0.50	5.97
GY Sge	2.89 ± (0.18)	3.51	4500 ± 189	20396 ± 1113	43.7			2.89
ET Vul	13.94 ± (2.52)	1.93	4500 ± 204	17489 ± 544	53.7			5.72
CL Vul	4.28 ± (0.38)	4.61	4375 ± 221	38958 ± 1242	43.4			4.28
S Vul	4.32 ± (0.33)	2.58	4875 ± 189	49736 ± 2351	36.5	3.99 ± 0.44	3.79 ± 1.69	4.32
ATO352p17	11.87 ± (2.65)	0.20	4000 ± 221	686 ± 37	46.3			0.62

Notes. Column 1. The identifier used in this paper. Column 2. The adopted distance. The error in the distance is listed between parenthesis to indicate that this error is not included in the luminosity error estimate. Column 3. The adopted reddening value A_V . Column 4. (photometric) effective temperature with error bar from the SED fitting. Column 5. Luminosity with error bar from the SED fitting (for the fixed distance). Column 6. Reduced chi-squared of the fit. Column 7. Distance with error bar from StarHorse (Anders et al. 2022). Column 8. Reddening value A_V from StarHorse. Column 9. The maximum distance to which the 3D reddening model is available.

Table A.3. Results of the fitting using alternative distances and reddenings, and some *Gaia* parameters

Identifier	d (kpc)	A_V (mag)	T_{eff} (K)	Luminosity (L_{\odot})	χ_r^2	G (mag)	$\pi \pm \sigma_{\pi}$ (mas)	GoF	RUWE
ATO093m31	13.20	0.30	4125 ± 188	1341 ± 42	30.1	13.0	0.035 ± 0.013	1.43	1.05
ATO142p20	7.40	0.50	4375 ± 204	1895 ± 97	51.6	11.6	0.044 ± 0.027	6.09	1.23
V708 Car	3.50	1.24	3500 ± 122	2791 ± 1315	282.4	10.7	0.226 ± 0.023	1.08	1.04
II Car	5.10	2.60	3700 ± 225	6792 ± 927	178.0	11.3	0.105 ± 0.021	-3.09	0.89
GD-CEP-1859	7.60	4.00	3500 ± 115	12649 ± 1769	154.0	12.5	0.070 ± 0.038	-1.91	0.94
BLG-T2CEP-0743	8.28	5.00	4375 ± 277	1786 ± 70	82.0	15.1	0.064 ± 0.031	-2.21	0.91
BLG-T2CEP-0084	8.28	5.00	4250 ± 277	2268 ± 198	139.3	14.9	-0.101 ± 0.047	3.32	1.13
BLG-T2CEP-0761	8.28	5.00	5250 ± 356	1277 ± 118	391.3	15.2	0.043 ± 0.035	-1.87	0.93
BLG-T2CEP-0131	8.28	5.00	4875 ± 315	1404 ± 164	470.9	15.1	0.053 ± 0.040	-0.16	0.99
GDR404357	8.28	5.00	6000 ± 434	5638 ± 481	136.5	13.5	0.026 ± 0.024	-1.18	0.95
V1496 Aql	3.30	4.90	6250 ± 335	52330 ± 2308	55.9	9.1	0.236 ± 0.025	0.33	1.01
GD-CEP-1505	6.30	5.50	3000 ± 283	657 ± 109	722.3	17.2	0.267 ± 0.146	6.57	1.20
(idem)	4.0	11.0	4000 fixed	1355 ± 54	79.0				
ATO290p18	5.20	4.90	3500 ± 122	2520 ± 619	255.9	14.1	0.049 ± 0.052	2.43	1.10
GDR6746185	5.70	0.60	4125 ± 144	1654 ± 50	21.0	11.2	0.079 ± 0.024	5.66	1.30
ATO292p22	8.50	5.60	5375 ± 198	5323 ± 193	46.5	14.0	0.016 ± 0.016	-2.60	0.92
GY Sge	2.70	3.30	4375 ± 189	16229 ± 852	49.9	8.8	0.296 ± 0.022	-1.61	0.95
ET Vul	11.40	3.00	5500 ± 250	21437 ± 827	40.0	11.3	0.040 ± 0.017	3.35	1.10
CL Vul	3.90	4.40	4250 ± 204	29526 ± 923	46.1	9.6	0.181 ± 0.023	-5.99	0.82
S Vul	4.00	3.80	6250 ± 312	95670 ± 7465	39.9	8.2	0.205 ± 0.020	1.13	1.03
ATO352p17	9.20	0.30	4125 ± 204	426 ± 20	45.6	13.5	0.023 ± 0.021	11.40	1.43

Notes. Columns 1-6 as in Table A.2. Columns 7-10 parameters from the *Gaia* catalog; G -band magnitude, parallax with error, goodness-of-fit (GoF, `astrometric_gof_al`), and the renormalised unit weight error (RUWE).

Appendix B: Sources of the photometry

Table B.1. Photometry used to construct the SEDs

Filters	Instrument	Reference	Remark
UV	GALEX	Bianchi et al. (2017)	
V, I	OGLE Shallow Survey	Ulaczyk et al. (2012, 2013)	LMC
V, I	OGLE-IV	Soszyński et al. (2019, 2017, 2020); Udalski et al. (2018)	
B_p, G, R_p	<i>Gaia</i>	Gaia Collaboration (2023); Ripepi et al. (2023)	
U, B, V, R, I		Berdnikov (2008); Berdnikov et al. (2015)	
U, B, V		Szabados (1977, 1980, 1981, 1991)	
U, B, V		Madore (1975); Eggen (1977); Martin & Warren (1979)	
VBLUW	Walraven	Pel (1976); Groenewegen & Lub (2023)	
u, g, r, i	VPHAS+ DR2	Drew et al. (2014, 2016)	
u, g, r, i, z	SMASH DR2	Nidever et al. (2021)	SMC
g, r, i, z	Pan-STARRS DR1	Chambers et al. (2016)	
g, r	ZTF	Chen et al. (2020)	
B, V, g, r, i	APASS DR9	Henden et al. (2015)	
i	AST survey	Ma et al. (2018)	
U, B, V, R, I		Massey et al. (2016)	M31, M33
B, V, I		Pellerin & Macri (2011)	M33
F555W, F814W, F160W	HST	Riess et al. (2019, 2021)	
^a	HST/PHAT	Williams et al. (2014)	M31
^a	HST/PHATTER	Williams et al. (2021)	M33
Y, J, K	VMC	Cioni et al. (2011); Ripepi et al. (2016, 2022)	
Z, Y, J, H, K	VVV DR5	Minniti et al. (2010)	
Y, J, H, K	VHS DR6	McMahon et al. (2013)	
J, H, K	2MASS, 2MASS-6X	Cutri et al. (2003, 2012)	
J, H, K		Laney & Stobie (1992); Monson & Pierce (2011)	
I, J, K	DENIS	Denis (2005)	
J, K		Neugent et al. (2020)	M31
J, H, K		Javadi et al. (2011)	M33
S7, S11, L15 ^b	Akari	Ita et al. (2010); Kato et al. (2012)	
9, 18 μ m	Akari	Ishihara et al. (2010)	
W1, W2	CatWISE	Marocco et al. (2021)	
W3, W4 ^c	AllWISE	Cutri & et al. (2014)	
3.6, 4.5 μ m	<i>Spitzer</i> IRAC	Chown et al. (2021)	
5.8, 8.5 μ m	<i>Spitzer</i> IRAC	IPAC ^d	
IRAC, MIPS 24 μ m		Khan et al. (2015); Khan (2017)	M31, M33
IRAC, MIPS 24 μ m	GLIMPSE, MIPS GAL	Spitzer Science (2009); Gutermuth & Heyer (2015)	
24 μ m	MIPS	IRSA ^e	MCs
A, C, D	MSX	Egan et al. (2003)	
12 μ m	IRAS PSC	Beichmann (1985)	
70 μ m	<i>Herschel</i> PACS	<i>Herschel</i> PSC Working Group et al. (2020)	

Notes. ^(a)F275W, F336W, F475W, F814W, F110W, and F160W; ^(b)For the S7, S11, and L15 filters only errors in the magnitudes were accepted of <0.15, <0.20, and <0.20 mag, respectively; ^(c)In the W3 and W4 filters only errors in the magnitudes were accepted of <0.30, and <0.25 mag, respectively; ^(d)VizieR catalog II/305/catalog; ^(e)<https://irsa.ipac.caltech.edu/applications/Gator/>, the "SAGE MIPS 24 μ m Epoch 1 and Epoch 2 Full List".

Appendix C: Additional figures

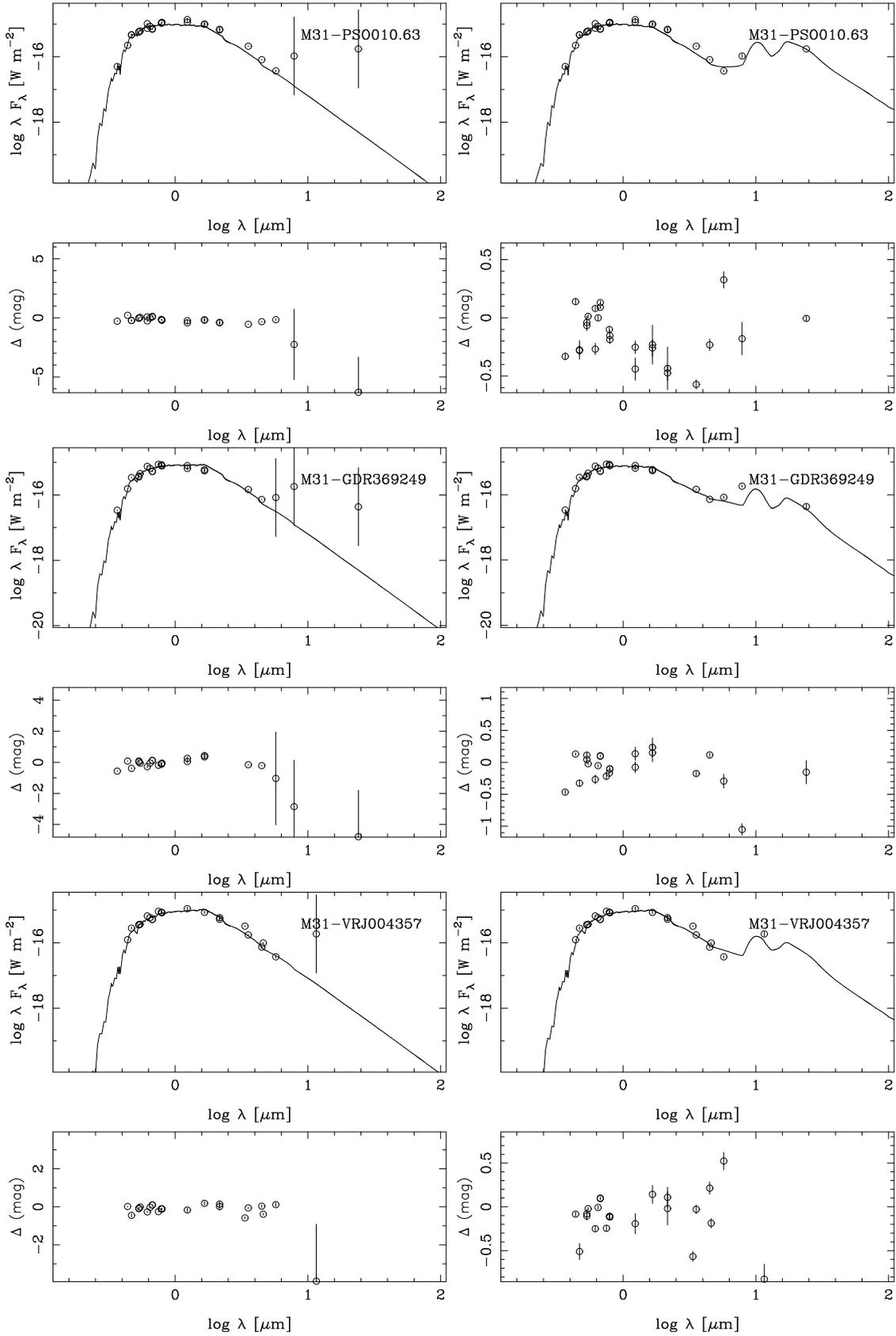


Fig. C.1. Best-fitting models assuming dust (right-hand) compared to no dust (left-hand panels) of the remaining 6 objects (cf. Fig. 3). Note the difference in the range of the ordinate in the left-hand and right-hand bottom panels.

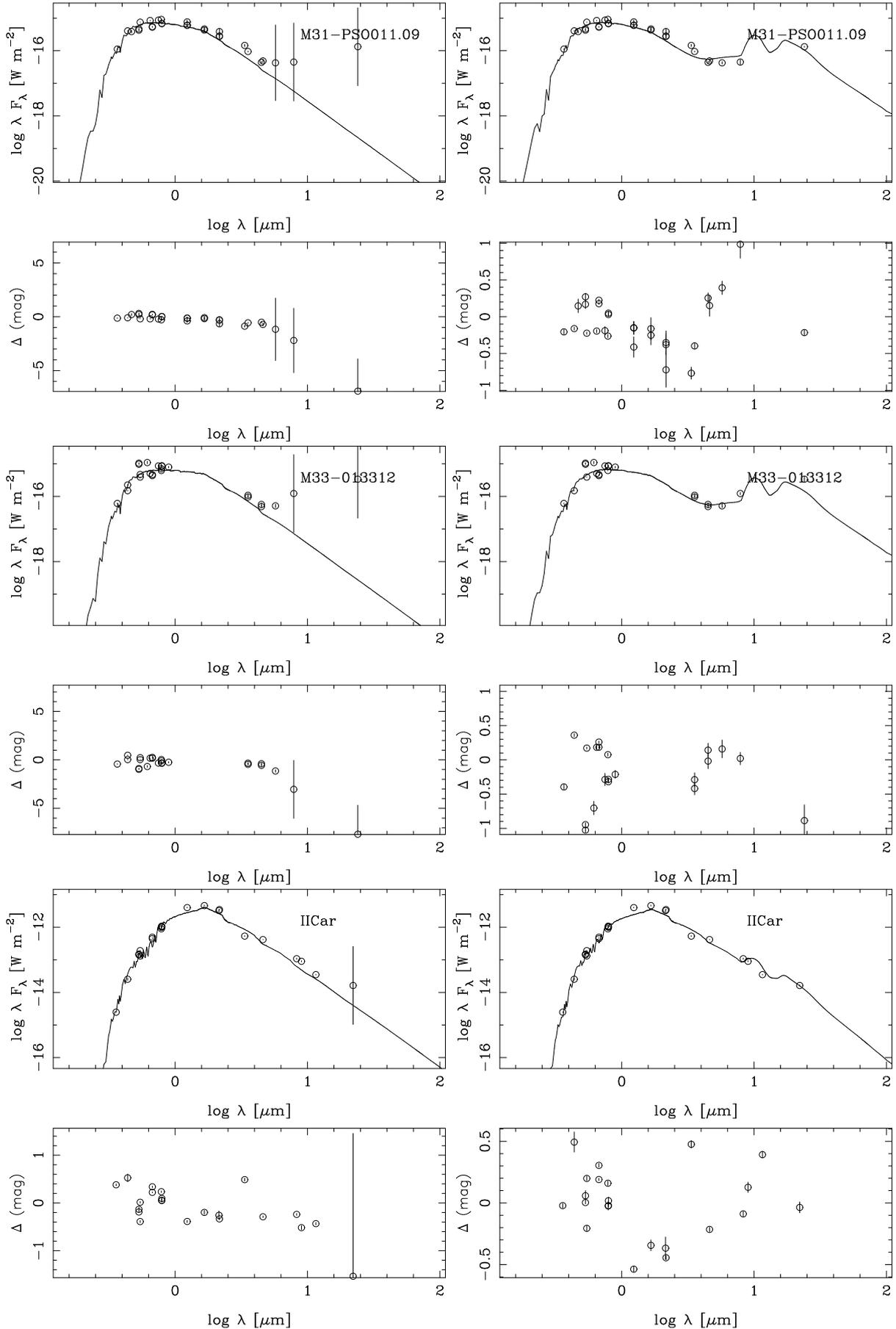


Fig. C.1. continued.

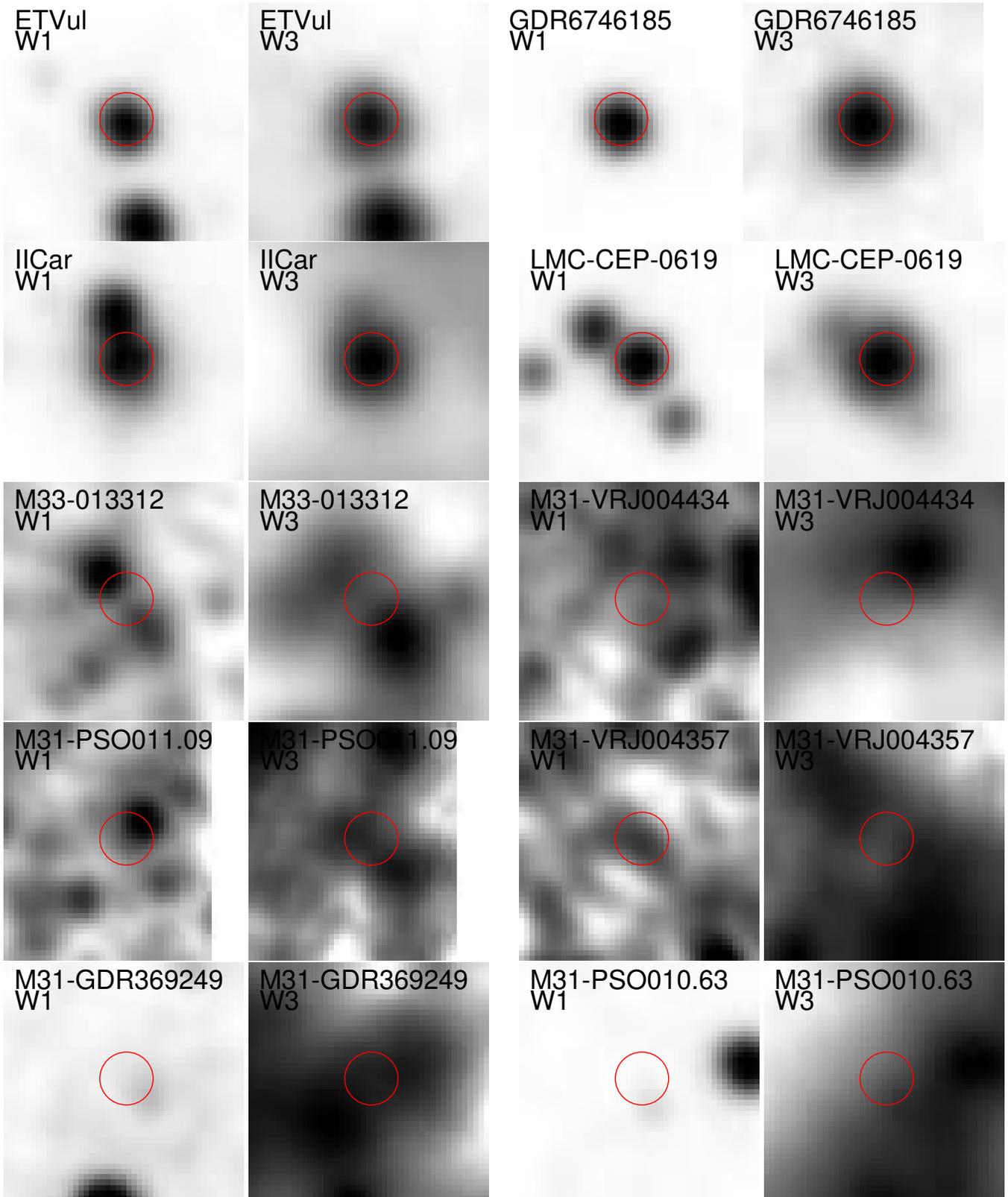


Fig. C.2. Cut-outs of about $1' \times 1'$ (45×45 pixels of $1.37''$) in the W1 and W3 filters centred on the CC. Cut levels are at the 0.5 and 99.5% level. The red circle marks the nominal position and has a radius of 5 pixels, corresponding to approximately 1 FWHM of the point spread function. ETVul and GDR 6746185 are plotted for comparison as MW stars not having an IR excess.

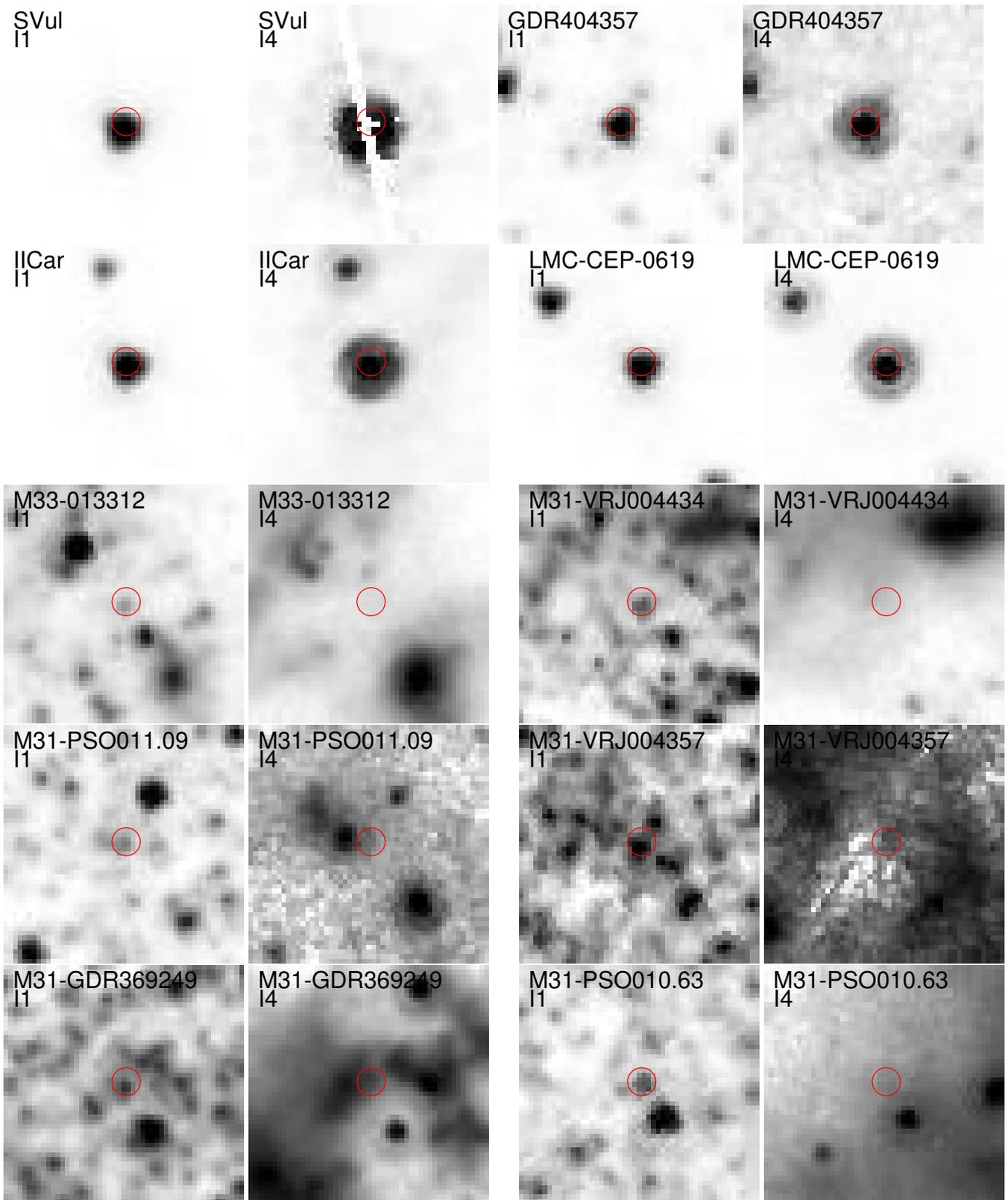


Fig. C.3. Cut-outs of about $30'' \times 30''$ (51×51 pixels of $0.60''$) in the IRAC 1 and 4 filters centred on the CC. Cut levels are at the 0.5 and 99.5% level. The red circle marks the nominal position and has a radius of 3 pixels, corresponding to approximately 1 FWHM of the point spread function. S Vul and GDR 404357 are plotted for comparison as MW stars not having an IR excess.