LETTER TO THE EDITOR

Massive open star clusters using the VVV survey

III. A young massive cluster at the far edge of the Galactic bar⋆,⋆⋆

S. Ramírez Alegría1,2, J. Borissonov1,2, A. N. Chené3, E. O’Leary3, P. Amigo1,2, D. Minniti2,4, R. K. Saito5, D. Geisler6, R. Kurtev1,2, M. Hempel2,4, M. Gromadzki1, J. R. A. Clarke1, I. Negueruela7, A. Marco7, C. Fierro1,8, C. Bonatto9, and M. Catelan2,4

1 Instituto de Física y Astronomía, Universidad de Valparaíso, Av. Gran Bretaña 1111, Playa Ancha, Casilla 5030 Valparaíso, Chile
2 The Millennium Institute of Astrophysics (MAS), Santiago, Chile
3 Gemini North Observatory, USA
4 Pontificia Universidad Católica de Chile, Instituto de Astrofísica, Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile
5 Universidad Federal de Sergipe, Departamento de Física, Av. Marechal Rondon s/n, 49100-000 São Cristóvão SE, Brazil
6 Departamento de Astronomía, Casilla 160-C, Universidad de Concepción, Chile
7 Departamento de Física, Ingeniería de Sistemas y Teoría de la Señal, Universidad de Alicante, Spain
8 Escuela Superior de Física y Matemáticas del Instituto Politécnico Nacional, Unidad Profesional Adolfo López Mateos, Mexico
9 Universidade Federal do Rio Grande do Sul, Departamento de Astronomia, CP 15051, RS 91501-970 Porto Alegre, Brazil

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ABSTRACT

Context. Young massive clusters are key to map the Milky Way’s structure, and near-infrared large area sky surveys have contributed strongly to the discovery of new obscured massive stellar clusters.

Aims. We present the third article in a series of papers focused on young and massive clusters discovered in the VVV survey. This article is dedicated to the physical characterization of VVV CL086, using part of its OB-stellar population.

Methods. We physically characterized the cluster using JHKs near-infrared photometry from ESO public survey VVV images, using the VVV-SkZ pipeline, and near-infrared K-band spectroscopy, following the methodology presented in the first article of the series.

Results. Individual distances for two observed stars indicate that the cluster is located at the far edge of the Galactic bar. These stars, which are probable cluster members from the statistically field-star decontaminated CMD, have spectral types between O9 and B0 V. According to our analysis, this young cluster (1.0 Myr < age < 5.0 Myr) is located at a distance of 11.5 ± 0.2 kpc, and we estimate a lower limit for the cluster total mass of (2.8 ± 1.4) × 10^3 M⊙. It is likely that the cluster contains even earlier and more massive stars.

Key words. stars: early-type – stars: massive – Galaxy: disk – open clusters and associations: individual: VVV CL086 – techniques: spectroscopic – techniques: photometric

1. Introduction

Young massive clusters (cluster mass $M > 10^3 M_\odot$, Hanson & Popescu 2008) are fundamental pieces for the study of Galactic structure. Because of their youth, they give information related to the recent Galactic massive stellar formation history. They are also excellent tracers of star formation regions.

In the Milky Way, we find regions with intense formation activity in the Galactic centre, where the Arches (Nagata et al. 1993; Figer et al. 2002), Center (Krabbe et al. 1995; Paumard et al. 2006; Figer 2008), and the Quintuplet (Glass et al. 1990; Okuda et al. 1990; Nagata et al. 1990; Figer et al. 1999) clusters are located; in the Carina-Sagittarius arm, which hosts...
near-IR surveys, the ESO public survey VISTA Variables in the Vía Láctea (VVV, Minniti et al. 2010; Saito et al. 2010, 2012), is a perfect tool for this exploration, covering the Galactic bulge and the cluster radius of 35\arcsec (Borissova et al. 2011) with a single slit in the spec-
tral range 2.0\micron – 2.5\micron with a resolution of $R \sim 3000$, using ISAAC at the Very Large Telescope at ESO Paranal Observatory, Chile (on 5 May 2011). The stars were observed using an

ABBA observing mode to later subtract the atmospheric OH emission lines. For telluric standards we observed bright A0 V stars with similar airmass as the cluster stars.

For spectroscopic data reduction (flat-fielding, sky subtraction, spectrum extraction, and wavelength calibration) we used the Interactive Data Language (IDL) and IRAF\footnote{IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.} scripts, following a similar procedure to that described by Chené et al. (2012). For the wavelength calibration we used the OH line, because of sudden shifts along the spectral dispersion direction during the observing night.

3. Results

In Fig. 2 we present the $(J - K_S)$ vs. $K_S$ colour–magnitude diagram. The diagram is statistically field-star decontaminated for a circle of radius 0.75 arcmin, centered around $\alpha_{2000} = 252^h06^m51^s$, $\delta_{2000} = -45^\circ43'46''$. The decontamination was performed as described by Borissova et al. (2011), using the algorithm of Bonatto & Bica (2010). The algorithm divides the $K_S$, $(H - K_S)$ and $(J - K_S)$ ranges into a grid of cells with sizes $\Delta K_S = 1.0$ mag, and $\Delta (J - K_S) = \Delta (H - K_S) = 0.2$ mag. In each cell, it estimates the expected number density of cluster stars by subtracting the respective field-star number density and, summing over all cells, it obtains a total number of member stars, $N_{\text{mem}}$. Grid shifts of $\pm 1/3$ the cell size are applied in each axes, producing 729 independent setups and $N_{\text{mem}}$. The average of these 729 $N_{\text{mem}}$ (or $\langle N_{\text{mem}} \rangle$) is the limit for considering a star as a possible cluster member. Only the $\langle N_{\text{mem}} \rangle$ with highest survival frequency after all tests were finally considered as cluster members. To ensure photometric quality, the algorithm rejects stars with uncertainties in $K_S$ and colours larger than 0.2 mag. For comparison fields we used two concentric rings, centred on VVV CL086, with inner radius of 0.8\arcmin and 2.5\arcmin, and outer radius of 1.2\arcmin and 5.0\arcmin, and

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two circles with radius 1.4′: one centred on \( \alpha_{2000} = 252.024 \), \( \delta_{2000} = -45.48 \) and the second centred on \( \alpha_{2000} = 252.110 \), \( \delta_{2000} = -45.37 \). The stellar densities were corrected for the area difference. The shape and size of the control field were chosen based on the distribution of stars and extinction clouds on the image.

In the field-decontaminated diagram we see that stars #01, #02, #03 and #04 are probably cluster members. Stars #03 and #04 are located in the cluster main sequence, but would not be the most massive stars in VVV CL086. Observed magnitudes and colours for the cluster stellar population appear to be affected by differential extinction, a characteristic commonly found in young massive clusters. From its location star #05, excluded as possible cluster member, is expected to be a foreground young star, reddened by its surrounding natal gas.

Spectral classification is based on the detection of absorption or emission lines (Bry, He I at 2.06, 2.11 \( \mu \)m, and He II at 2.19 \( \mu \)m) and the comparison of their shape and depth with similar-resolution spectral catalogues: Hanson et al. (1996) (K band) and Hanson et al. (1998) (H band) for OB-type stars. We assumed an error of ±2 subtypes for the assigned spectral type, similar to Hanson et al. (2010) and Negueruela et al. (2010). The observed spectra and the lines used for the spectral classification are shown in Fig. 2.

For spectrum #01 we do not detect any clear spectral feature. The spectrum is very noisy and probably presents faint \( ^{12}\text{CO}(2,0) \) bands at 2.29 \( \mu \)m. Even if the position of this star in the CMD is consistent with cluster membership, the faint CO band head indicates that star #01 is a very late type object.

Star #02 presents a clear Bry line in absorption and HeI at 2.06 \( \mu \)m. Its Bry fits the B2 V HD 19734 and B3 V HD 201254 Bry lines. We adopted spectral type B2-3V for this star. Spectra #03 and #04 both show weak Bry and clear HeI absorption line at 2.11 \( \mu \)m. For star #03, the lines fit the O9 V HD 193322 and B0.5 V HD 36960 spectra. For star #04 we also detected the He I line at 2.06 \( \mu \)m, and He II line at 2.19 \( \mu \)m, indicating that this star is of earlier type than star #03. Spectrum #04 fits O8.5 V HD 73882, and O9 V HD 193322 lines. For star #03 we adopted a spectral type between O9 and B0 V and for star #04, spectral type O9 V. Finally the spectrum of star #05 presents an absorption Bry line that fits a B0 V spectrum.

4. Discussion

4.1. Extinction, distance, and radial velocity

For individual distance estimates we compared the apparent magnitude with the intrinsic magnitude corresponding to each individual spectral type. We adopted the Rieke et al. (1989) extinction law, with \( R = 3.09 \) (Rieke & Lebofsky 1985), and intrinsic magnitudes and colours from Martins et al. (2005)

For stars later than O9.5 V, we used the intrinsic magnitudes and colours from Cox (2000). Distance errors are dominated by the spectral type uncertainty, and we estimated it by deriving the individual distance for the same star assuming ±2 spectral subtypes.

In Table 1 we present the individual extinction and distance determinations for the spectroscopically observed stars. Although the position of star #02 in the CMD associates it with the cluster population, its individual distance estimate indicates that it is a foreground star. Using the average of individual distances for stars #03 and #04 and the error propagation method described by Barlow (2004), we obtain a cluster distance of 11.3 ± 2.6 kpc. This would locate the cluster in the same region as Mercer 81, a massive cluster found at 11 ± 2 kpc (Davies et al. 2012). The mean extinction value for VVV CL086, \( A_K = 1.5^{+0.03}_{-0.01} \) is lower than the extinction value of \( A_K = 2.5^{+0.5}_{-0.5} \) reported for Mercer 81 and indicates the possible presence of an extinction window in that galactic direction.

We measured the radial velocities with the IRAF tasks FXCOR and RVIDLINES for all the stars with spectral type determination. We used the He I at 2.076 and 2.11 \( \mu \)m and the Bry lines for the estimates. In all cases we measured negative RV, which is expected for the cluster direction, but the dispersion due to the number of used spectral lines and the signal-to-noise ratio from our spectra does not allow us to obtain a reliable estimate for stellar radial velocities.

4.2. Mass and age estimates

To estimate the total cluster mass, we first constructed the cluster present-day mass function using the CMD and then integrated the Kroupa (Kroupa 2001) initial mass function (IMF) fitted to the cluster IMF. Because we did not detect evolved stars, we assumed that the present-day and initial mass functions are equivalent.

We obtained the cluster present-day mass function by projecting all CMD stars, following the reddening vector, to the main sequence located at 11 kpc. The main sequence is defined by the colours and magnitudes given by Cox (2000). After deriving the cluster present-day luminosity function, using 1 \( K_S \)-mag bins, we converted the \( K_S \) magnitudes to solar masses using values from Martins et al. (2005) for O-type stars and from Cox (2000) for stars later than O9.5 V.

The present-day mass function, shown in Fig. 3, is fitted by a Kroupa (Kroupa 2001) IMF and integrated between 0.10 (log \( M = -1.00 \) dex) and 35 \( M_\odot \) (log \( M = 1.54 \) dex). For the cluster VVV CL086 we obtained an approximate total mass of \( 2.8^{+0.8}_{-0.7} \times 10^5 M_\odot \). In our analysis we also included errors associated to the fitting of the Kroupa IMF to the data. In the cluster mass function we can see that the cluster could contain a more massive population.
than that spectroscopically detected by us (i.e. stars earlier than O9-B0 V), but the errors are large and dominated by small number statistics. Future spectroscopic observations will help to characterize this population and improve the mass estimate.

We tried to determine the cluster age by fitting main sequence (Lejeune & Schaerer 2001) and pre-main sequence (Siess et al. 2000) isochrones. However, young (i.e. younger than 10 Myr) pre-main sequence turn-on point and the cluster CMD we were able to deduce that earlier stars than these two observed OB-stars are probably be present in VVV CL086. One star from our spectroscopic follow-up was estimated a cluster age by fitting isochrones to the pre-main sequence turn-on point. We estimated a cluster age >1.0 and <5.0 Myr.

5. Conclusions

We presented the physical characterization of VVV CL086, a new massive cluster discovered using data from the VVV survey, found at the far edge of the Milky Way bar at a distance of \(11^{+5}_{-3}\) kpc. This cluster is the second one found in that region of the Galaxy (the first is Mercer 81), a region highly reddened by gas and dust, which presents a relatively low mean reddening of \(A_K = 1.2^{+0.03}_{-0.1}\) mag, however.

Our spectroscopic follow-up aimed at brightest stars in the cluster area revealed that two objects are part of the disk population (two early-B dwarfs), and two stars form part of the cluster main-sequence population. From their spectral classification and the cluster CMD we were able to deduce that earlier stars than these two observed OB-stars are probably be present in VVV CL086. One star from our spectroscopic follow-up was not classified.

The mass estimate was derived by integrating the Kroupa IMF fitted to our data and gives a lower limit for the cluster total mass of \((2.8^{+1.0}_{-1.4}) \times 10^4 M_\odot\). We also estimated the cluster age by fitting isochrones to the pre-main sequence turn-on point. We estimated a cluster age >1.0 and <5.0 Myr. The upper age limit agrees with the earliest main sequence star found in the cluster (i.e. O9 V star #04). Future spectroscopic observations are planned to confirm this and to investigate the cluster massive population in more detail.

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